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Analytical photogrammetry: a method for monitoring slope instability

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Abstract

Developments in analytical photogrammetry provide the engineering geologist and geomorphologist with a quantitative technique capable of monitoring slope instability from ground or oblique aerial photographs. This paper outlines 'analytical' photogrammetry and its applications to the study of slope instability. Procedures and developments in data processing are described that enable both a morphogenetic analysis of slope form and the derivation of displacement vectors for monitoring unstable slopes. The methods are illustrated by research work carried out by the authors in Nepal and southern England.

Introduction

Photogrammetry is a technique used to extract three-dimensional information from a series of two-dimensional photographs. Traditional usage has been the compilation of topographic maps from near-vertical aerial photographs (Slama 1980; Wolf 1983). Analytical photogrammetric techniques have become practicable more recently because of the development of computerized numerical methods. These advances permit photogrammetric measurement of a wider variety of imagery, including ground based or *terrestrial* photographs and oblique aerial photography.

Finsterwalder first used photogrammetric techniques to study glacial movement in 1897 and the technique is still important to glaciologists today (Stirling 1982; Jania, Lipert & Mechlinski 1984; Brecher 1986). The method has occasionally been used for monitoring unstable slopes. Wickens & Barton (1971) applied photogrammetric techniques to assess the stability of excavated rock slopes. Similar work was carried out in the Soviet Union during the 1960s by Blagovolin & Tsvetkov (1972) who studied slope dynamics with the help of sequential photogrammetric surveys. Photogeology or Air-photo Interpretation (API) has been applied to engineering geology and geomorphology, especially by Norman (1969, 1970), Norman & Huntington (1974), Norman, Leibowitz & Fookes (1975), Mollard (1962), Fezer (1971), Carney (1974), Svatos (1975) Beaumont (1977), Speight (1977) and Matthews & Clayton (1986). The methodology typically used in this form of photographic analysis is described by Rengers & Soeters (1980). Kalaugher, Grainger & Hodgson (1987) and Grainger & Kalaugher (1987) have recently assessed coastal cliff instability from sequential oblique aerial photographs and produced geomorphological sketch maps. Although the use of API in engineering geology is well publicized (Mollard 1962, Fezer 1971, Griffiths & Marsh 1986) the method is qualitative and restricted in use. Quantitative use of photogrammetry in mass movement studies has involved the use of analogue stereo-plotters and vertical air photographs; for example McConchie (1986). Collins & Madge (1981, 1985) described a method of 'photo-radiation' and applied this to monitoring a landslide in South Wales. Recent experiences of the authors indicate that these methods lack the flexibility and rigorous accuracy obtainable with analytical photogrammetry.

The main advancement of analytical photogrammetry has been made in the USA (Ghosh 1979); although West German, British and Canadian photogrammetrists have also made important contributions. Veress & Sun (1978) used the technique to monitor a gabion wall at the side of a U.S. State highway. Similarly, Fraser (1983) carried out a stability study of Turtle mountain using 'free networks', a pure photogrammetric solution. More recent UK based research and commercial work includes a discontinuity analysis of rock slopes by Atkinson & Stethridge (1980) and monitoring of chalk cliffs and cuttings in Sussex by Kennie & McKay (1987). Research aimed directly at assessing morphological change of unstable hill slopes in Nepal was carried out by Chandler, Clark, Cooper & Stirling (1987). Moore (1988) carried out similar work when monitoring a mudslide in southern England.

The advantages of using analytical photogrammetry for monitoring unstable slopes are twofold, photogrammetric and analytical. A photograph is an unbiased data source which records an infinite number of points; consequently there is total flexibility in the amount of data that can be extracted. The retrospective quality enables the analysis to be carried out in the laboratory, free from problems associated with field work. The measurement technique is also 'non-contact' and so dangerous and inaccessible sites such as coastal cliffs and near-vertical rock faces can be accurately monitored, perhaps where no other technique would be feasible. The photograph can also form an archive of data, which can be accessed at any time in the future, for instance after a significant geomorphological event.

Many of these natural photogrammetric advantages have in the past been offset by the numerous disadvantages inherent with the traditional photogrammetric approach. Previously the data extraction procedures could only be performed by complex and expensive pieces of equipment called *stereo-plotters*. These optical or mechanically based *analogue* instruments physically recreate the spatial relationships between the photographs and the ground at a reduced scale. Mechanical constraints are inevitable, including the type and focal length of the camera used to obtain photographs. Most importantly cameras have to be located in regular positions, regardless of the physical constraints of a site.

The analytical photogrammetric solution replaces the optical and mechanical stereo-plotter with a computerised mathematical model. This *functional* model is totally numerical and so the photogrammetric project is freed from the physical limitations of the older stereo-plotting instrument. Most of the constraints on camera position and orientations are relaxed, so that it is easier to gain photo coverage of the site. Previously all survey photographs had to be taken with *metric cameras* (Fig. 1), which have stable and calibrated internal geometries. With the analytical

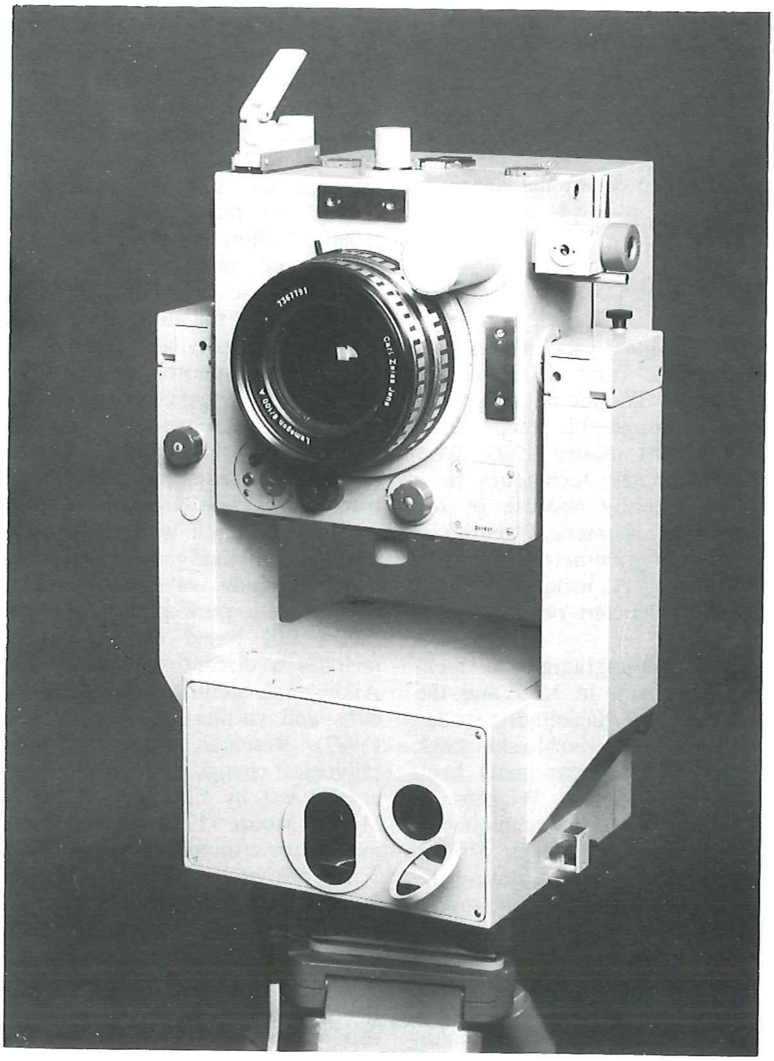

FIG. 1. Jenoptik Jena UMK. 10/1318 metric camera.

approach, the functional model can be extended to correct for the lens and film distortions associated with cheaper conventional cameras. The analytical solution also benefits from a full 'error analysis', so that the quality of the spatial positioning of points can be estimated. The analytical photogrammetric solution is therefore more informative, accurate, flexible, and practicable than the traditional analogue approach.

Analytical photogrammetry

Theoretical aspects

One of the most efficient methods of storing and manipulating three-dimensional information is within a three-dimensional cartesian coordinate system. In photogrammetry this is often referred to as the *object space coordinate system.* A *photo-coordinate system* can be used for defining the spatial relationship between points imaged on the photographic negative. A right-handed coordinate system is used, with the origin at the lens or *perspective centre,* the z-axis in the direction of the camera axis and the x- and y-axes parallel to the plane of the negative. If the photo-coordinate system is placed into the object space coordinate system, a point in the object space can have object coordinates (X, Y, Z) and photo-coordinates $(x, y, -c)$, where c is essentially the focal length of the camera (Fig. 2, photo 1).

Assuming that the object point 'A', the perspective centre O_1 and the image point a_1 lie upon the same line, then the points can be related by the *projective transformation.* This transformation is the functional basis for the two *collinearity equations*:

$$x = \frac{-c[r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)]}{[r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)]} \quad (1)$$

$$y = \frac{-c[r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)]}{[r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)]} \quad (2)$$

where X_0, Y_0 and Z_0 are the coordinates of the perspective centre in the object space coordinate system; r_{11} to r_{33} are the elements of the *rotation matrix* which are functions of the orientation of the camera axis in the object system; c is the focal length of the camera, constant for any one photograph.

These equations relate the object coordinates of a point to the associated image coordinates on a single photograph, and form the foundation of analytical photogrammetry. A fuller discussion can be found in Albertz & Kreiling (1975) and Slama (1980).

In Fig. 2, all points on the line aA in the object space will be imaged at a. It should be apparent that measuring the photo-coordinates of a point on one photograph is not enough to define the ground coordinate, as a one-to-one correspondence does not exist. However, if a second photograph is introduced (Fig. 2, photo 2) and measurements are taken to the image of the same object point, then a unique solution

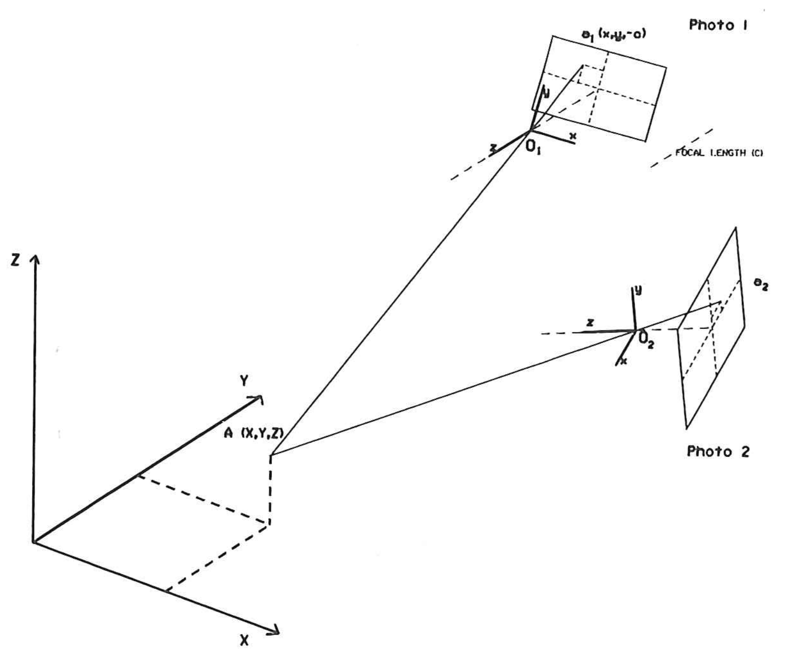

FIG. 2. Theoretical aspects of photogrammetry.

for the ground coordinates can be obtained. The process is analogous to that of *intersection* in conventional field survey. For this computation it is necessary to know the positions and orientations of the cameras in the object space coordinate system. These are defined by the *camera parameters* and are the elements X_0, Y_0 and Z_0 and r_{11} to r_{33} in the collinearity equations (equations (1) & (2)).

The camera parameters may be obtained by direct field survey, at the same time as obtaining the photographs. However, a far more efficient method of determination is to perform a numerical calculation in the laboratory. A variety of computational procedures exist, the most flexible being a *bundle adjustment.* By coordinating some points in the object space by traditional survey techniques and then measuring the photo-coordinates of their images it is possible to compute the camera parameters. A minimum of three coordinated points are necessary, these being well distributed around the object space. If more than three points are available for measurement then the extra or *redundant* measurements can be used in a *least-squares solution* to improve the result and to assess the precision of the estimation.

When camera parameters have been determined it is possible to compute the coordinates of new object points by measuring the image coordinates of any desired feature on two photographs. Stereoscopic measurement is not essential, but is quicker and more convenient, and the stereoscopic perception also assists interpretation of the object. The image-coordinate measurements are then transformed into object space coordinates and stored on magnetic disc. This process can then be repeated for other points on the site.

Practical aspects of analytical photogrammetry

Two distinct tasks need to be performed in a photogrammetric survey: to obtain the photographs from the field and to measure photo-coordinates in the laboratory. Although in principle these tasks are not difficult, each application is unique. Factors such as the size and accessibility of the site and the desired form and accuracy of data analysis will affect the type of photography that is commissioned.

Field survey

Field survey involves taking suitable photographs and sufficient survey measurements to enable the camera parameters to be computed. A critical consideration in the field survey is the selection of suitable camera stations and whether these require the use of ground-based or aerial photography. The choice of photography will depend upon the area of site to be covered, accessibility, visibility and the availability of equipment. Ground-based photography enables relatively low-cost surveys to be commissioned but many photographs may be required to record large sites. Oblique aerial photographs obtained from either a light aircraft or helicopter often provide more suitable photographs, but at greater cost.

An important consideration when positioning the camera stations is the proposed techniques of data acquisition and processing. If a large number of data points are required, perhaps for the derivation of a digital terrain model, stereoscopic measurement of the photographs is required. The geometrical arrangement between the photographs and the object must not be too convergent or the operator will experience undue eye-strain. A related influence is the ratio between the distance between the cameras and the object. This ratio is known as the *base/distance* ratio and should be between 0.1 and 0.25 for comfortable viewing and measurement. This is only a human restriction and if a limited number of well defined points are required, perhaps for the derivation of displacement vectors, then convergent photographs are preferable. The greater intersection angle produced by convergent photography with large base/distance ratios increases the precision of the estimates of point coordinates and also makes precision more homogeneous in space (Granshaw 1980). Each photograph can be measured independently and the measurements from two or more photographs combined to estimate the coordinates of the point.

The camera used to obtain the photographs affects the quality of coordinates finally extracted. Photogrammetric cameras (Fig. 1) are designed to fulfil the condition of collinearity and produce optimum results. The analytical photogrammetric approach allows the use of cheaper non-metric cameras such as large-format or even 35 mm cameras. Most of the distortions inherent with these cheaper alternatives can be corrected mathematically and although less accurate than the metric camera can often produce acceptable results (Chandler & Cooper 1988, Chandler & Robson 1989).

Before the photographs are taken, identifiable control points should be coordinated in the object computed. Natural points can be used, but to avoid mis-identification, targets are preferable. These must be large enough to be visible on the photographs and arranged over the whole site so that a minimum of three targets appear on each exposure. The coordinates of the control are derived by taking conventional survey observations to each point or target. Several survey methods can be adopted, the choice depending upon available equipment and desired precision. The most efficient method is to take tacheometric observations from two points (Fig. 3), which will provide redundant data and allow checks to

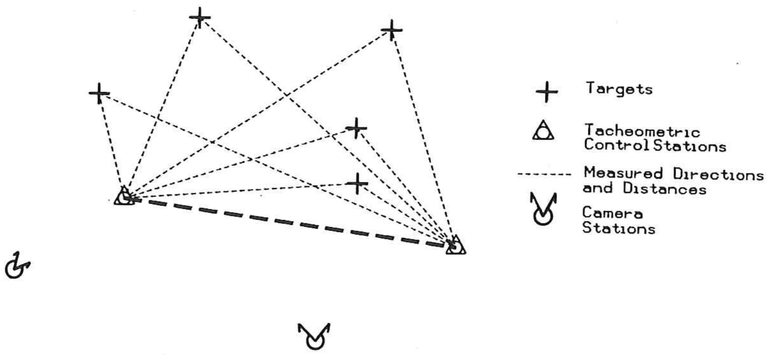

FIG. 3. Plan view of camera, target and station configuration.

be made. Typical survey equipment would be a theodolite with electro-magnetic distance measuring (EDM).

If sequential surveys are to be carried out it is essential that all work is performed upon the same coordinate system, to enable true spatial comparison. The simplest method is to define the survey datum by assigning coordinates to the two tacheometric survey stations. For this reason the stations should be monumented and sited upon stable ground. If this proves impracticable then suitable datum points can be established away from the site and the control points re-established at each subsequent survey by measuring a small survey network.

Once targets have been installed and the most suitable camera stations located, photographic exposures may be taken of the site. All the usual photographic requirements and limitations apply, including: focusing and the relationship between film ASA rating, shutter speed, aperture and depth of field. The quality of the photographs will always be an important factor governing the precision of the photogrammetric measurements so that certain limitations should be borne in mind. Lighting conditions are important as direct sunlight produces shadows and dull conditions reduce contrast. Poor film resolution will prevent detailed measurement and the inclusion of dead ground will impose discontinuities in the data set. If the object is slow moving or stable a single camera can be used to obtain all the photographs. If rapid movements are encountered two cameras should be used with facilities for simultaneous exposures.

The amount of fieldwork required for an analytical photogrammetric survey is comparatively small as the main phase of measurement is transferred to the laboratory. Depending upon the size of the site, it is usually possible to carry out the necessary field work within one day. Two people are preferred, although this is only essential if target distances are measured using EDM equipment.

Laboratory

The process of extracting spatial data from the photographs requires access to specialized hardware and software. The most expensive piece of hardware is a *stereo-comparator.* This versatile instrument is designed to measure the relative image positions of a pair of photographic images to an accuracy of 3 μm and is commonly available in photogrammetric establishments. Several other methods exist, including the manual measurement of photographic enlargements using a digitizing tablet and cursor. All have their advantages and disadvantages, according to the particular application and precision required.

The first phase of the laboratory work is the computation of the coordinates of the control points. If redundant survey measurements are available, a 'variation of coordinates' least-squares estimation should be used. This provides a unique solution for the control coordinates and enables their precision to be assessed. The control survey can normally be computed within a few hours, as typically only a few coordinates require estimation.

The next stage is to measure the positions of the images of the control points on the photographs using the stereo-comparator. These measurements and the computed coordinates of the control points are then used in the bundle adjustment to determine the camera parameters. If more than three control points are imaged on each photograph then a least-squares technique can be used. The computation can generally be achieved within one to two hours.

When satisfactory camera parameters are obtained, the coordinates of any point imaged on a pair of photos can be determined. All that is required is to measure the two image positions using the stereo-comparator. As there are an infinite number of points that can be extracted, the process of 'data extraction' should be supervised or undertaken by a geomorphologist or engineering geologist who will be able to extract the relevant data points. Several data extraction techniques exist; so guidance from the photogrammetrist can be helpful. The time required to extract the data depends upon the technique selected and the experience of the operator.

Following data acquisition, further processing is feasible and necessary. It is possible to produce:

(i) maps and plans, either on a graphics screen or a plotter;
(ii) profiles and contours;
(iii) digital terrain models to provide contour and isometric plots and additional processing;
(iv) dimensional vectors of strain or movement from sequential surveys.

All of these options require additional software, and in some cases powerful processors, to be practicable. The potential of additional processing is very high and will be discussed with suitable applications.

Applications to the study of slope instability

Photographs will always provide an important record and data source for the geomorphologist. Analytical photogrammetry equips the geomorphologist with an adaptable measurement technique that can be used to obtain high quality spatial data. The technique is very versatile as the scale and quality of the survey can be controlled simply by altering the camera configuration. Changes in site area can be accommodated by making use of either vertical or oblique aerial imagery, although terrestrial photographs enable low-cost surveys to be performed. Recent research (Chandler & Cooper 1988) has shown that historical photography can be an alternative photogrammetric data source of great importance to geomorphology. Morphogenetic sequences spanning substantial periods of time can be quantitatively compared and displayed. This can be particularly informative when considering the dynamics of slope instability.

It should be remembered that the raw data unit used for all photogrammetric based methods is the coordinate. As with any spatial measurement system, the coordinate can only be used to detect the consequences of slope instability. The causative stress components cannot be quantified and if necessary should be investigated by alternative methods. The main advantage of analytical photogrammetry is that the coordinate can be obtained with an enhanced density and with an efficiency unobtainable by other techniques.

The photogrammetric technique can be used to provide simple planimetric information, to detect changes in morphology and to obtain three-dimensional components of strain. These approaches will be discussed and illustrated by recent research work.

Morphological and morphogenetic analysis

The description of form is a fundamental requirement in many sciences. Perhaps of greater importance is a quantitative understanding of the change of form over a known period of time. Several photogrammetric based methods are available to perform both of these functions. These include the observation and display of profiles and contours, and the extraction and manipulation of digital terrain models.

Profiles and contours

The down-slope vertical profile and cross section are commonly used in geomorphology and engineering geology to illustrate the mechanisms of slope failure. They often provide the basic framework for subsequent slope stability analyses and for the design of remedial measures. Photogrammetry can provide a detailed and accurate surface profile to which sub-surface detail may be added. Contours are similarly used to represent relief and form on most maps; photogrammetry can be used to contour an area directly and may provide the only practical means of obtaining up to-date contours of high quality.

Both the profile and the contour are conceptually the same: they are lines representing the intersection of a plane with the ground surface. This plane is horizontal and at a specific elevation in the case of a contour, but vertical and in a specific direction for a profile. The plane could in fact be any plane in space, but convention has preferred the simpler vertical and horizontal planes. The boundary between the ground surface and the selected plane can be represented by a sample or subset of the infinite number of possible points. This can be displayed in the form of a graphic plot and allows instant appraisal of form or shape.

The analytical photogrammetric solution is ideal for obtaining both profiles and contours for several reasons. The measurement technique is 'non-contact' and retrospective; consequently any plane can be measured with a variable density of data points. Observation of these data can be controlled by interactive software (Stirling 1982), so ensuring that only points representing the desired profile or contour are collected. Providing the density of data points is high, an accurate representation of the shape or form of the ground surface along the plane of interest can be displayed. The observation process can be repeated for the same plane but using photography from a different epoch. A single plot combining these data enables a direct and quantitative *morphogenetic* comparison to be made.

Digital terrain models

A digital terrain model (DTM) or digital elevation model (DEM) can be regarded as a statistical representation of the continuous surface of the ground by a large number of selected points with known *XYZ* coordinates (Lo 1976). A dense DTM comprising many thousands of data points, will provide a representation that is of high quality. Such a DTM can take many hours to measure and also requires increased computer power for processing. With powerful fourth-generation computers the processing restrictions are becoming less critical and so the photogrammetrically measured DTM is becoming ever more practicable and useful.

Photogrammetric data acquisition is not only rapid, it retains flexibility in the type of DTM that can be observed. Several DTM types can be identified: string, random and grid. In the former the points have some linear association with each other, such as a line of points which represent a shear surface, gully or other boundary. Random DTMs are simply composed of a network of points which have no such association, except that they all lie on the ground surface. Grid DTMs are observed by measuring data points at the intersection of a regular lattice or grid. Each type of DTM has its own merits and drawbacks. For example, grid DTMs provide an even distribution of points but miss important breaks of slope, the opposite being the case for the string DTM. It is perhaps most prudent to combine DTM types, which is possible with the analytical photogrammetric technique.

Despite the efficiency of the photogrammetric observational procedure, the process of observing a DTM is still time consuming. The required time depends on the experience of the operator and the suitability of the photography but it should be possible to obtain 5000 points per day. Once a DTM of satisfactory coverage, density and type has been created, it must be processed and presented in a form which can be readily understood and interpreted. Several processing possibilities are feasible, the choice depending upon the available software, the power of the host computer, project requirements and experience of the operator. Principally the DTM can be used to produce:

(i) a contoured plot;
(ii) views from different directions, either isometric or perspective.

Additionally the DTM can be used to:

(iii) produce cross sections and profiles along any desired plane;
(iv) perform volume calculations;
(v) subtract DTMs produced at different epochs, so that a 'DTM of difference' may be determined.

The contoured plot can give a reasonable representation of site morphology, indicating steep areas and breaks of slope. An isometric view can be useful when the site is unfamiliar, principally because the surface can be viewed from any direction and at any scale. Cross sections and profiles can also be obtained from anywhere on the site. These sections can only be as accurate as the DTM itself, so a major factor is the density of the constituent DTM points. The best results are obtained by observing a profile or section directly, as indicated in the section headed 'Profiles and contours'.

The real advantage of a DTM package is the ability to produce information that in some way summarizes the whole data set. The possibility of calculating volumes, either over the whole site or in specific regions, is one example. With surveys at different epochs these volumes can be used to show net gains or losses of material which may be correlated with geomorphological processes. With many DTM packages there also exists the facility to subtract DTMs of different epochs, so producing a new DTM that represents a surface of change. This itself can be further processed and plotted in the same way as the original DTMs, so producing graphical and numeric data that accurately quantify the rate of change at any specific point (Chandler & Cooper 1988). This type of processing is particularly beneficial.

Computation of displacement vectors and strain rate tensors

The analytical photogrammetric technique can be modified in order to provide three-dimensional vectors of specific points. These vectors represent the rate of movement in time and with a network of such points, the pattern of displacements over a site. It should be remembered that a single photogrammetric survey can only provide the spatial positions of points, at any one instant, in some arbitrary three-dimensional coordinate system. In order to monitor strain or movement a minimum of two photogrammetric surveys are required; the dimension of time being the period between surveys or epochs. Vectors of strain or movement may be calculated simply by subtracting the three-dimensional coordinate of a point at the first epoch from the coordinate of the same identifiable point at the subsequent epoch. This may be repeated for any number of points distributed over the whole site, so providing three-dimensional vectors of displacement which are in their correct spatial relationship to each other. The main problem with the approach is one of targeting a site with suitable points. Obviously to obtain accurate three-dimensional vectors of displacement it must be possible to identify and coordinate points on the slope at each survey epoch. Two groups of target types can be used: man-made and natural. Each group has its own advantages and disadvantages.

Man-made targets are preferable from a photogrammetric viewpoint as they can be designed to be readily identifiable on the photography. Wooden stakes are suitable for rapidly changing environments but their size depends upon the scale and activity of the site. For small areas, targets such as flat top nails, similar to the traditional erosion pin, would be suitable. As the scale of the photograph decreases, the targets need to be larger for visibility. If a site is not totally inaccessible or dangerous, man-made targets can also be placed in a semi-regular pattern. This will provide a good distribution of points, so enabling the pattern of strain over an area to be analysed. The disadvantages of man-made targets will always be their susceptibility to vandalism and whether the recorded movement is fully representative of the material surrounding them.

Natural targets, such as large pebbles, boulders and pieces of vegetation, can be used as alternatives. However, surface processes may affect these targets so that it may be difficult to measure the true displacement. The main problem with natural targets is one of identifying the selected points at subsequent survey epochs. The interval between surveys and the rate of processes are extremely important in this respect. Boulders can look very similar to one another, especially if topographical changes have been large. The retrospective quality of the photogrammetric survey can help greatly with this problem. All photogrammetic measurements can be delayed until after the second epoch and restricted to those points clearly identifiable on both sets of photographs. This problem is considerably reduced by obtaining photographs in subsequent surveys from locations similar to those used in the original photography. This is not essential for the co-ordination of points, but stable areas will appear unchanged, so highlighting areas of which have experienced movement.

Illustrations

The advantages and disadvantages of analytical photogrammetry for monitoring slope instability may be illustrated by research undertaken on Nepalese hill slopes and on the south coast of Britain. The Transport and Road Research Laboratory commissioned the Nepalese study to assess the nature of slope instability and to monitor the performance of remedial measures (Brooks & Lawrence 1985; Cooper, Clark & Chandler 1987; Chandler *et al.* 1987). The British example was chosen to assess the performance of the technique with respect to more traditional methods of monitoring previously installed at the site (Moore 1988). Each example differs with respect to the extent, nature and mechanisms of slope failure.

In Nepal, the recently constructed 'East–West' highway passes through an upland area known as the Dauney Hills. This small spur of the low Himalaya is composed of alternating sequences of micaceous sandstones and silty mudstones, known as the Silwalik sediments. These beds are naturally stable but the construction of a number of deep road cuttings has induced several types of mass movement. These become active during the monsoon period and the resultant deposition of large volumes of debris onto the highway causes frequent disruption to communications and road damage. Photogrammetric surveys of several unstable sites were undertaken in May 1985 and May 1986.

Terrestrial photographs were taken using either the Jenoptik Jena UMK 10/1318 (Fig. 1) or, as in this example, the Wild P32 metric camera (Fig. 4). Targets were coordinated by conventional ground survey methods using a Wild TC1 tacheometer. The photographs were restituted using the techniques indicated in the section headed 'Practical aspects of analytical photogrammetry' and the precision of all derived coordinates was ± 0.05 m. A series of profiles and contours were extracted from the photographs at the May 1985 and May 1986 epochs. A quantitative interpretation of one vertical profile (Fig. 5) showed that the upper debris slide exhibit a 3.0 m horizontal and 2.2 m vertical displacement. Digital terrain models were also extracted from each epoch and used to compile contour plans (May 1986, Fig. 6). Changes of form were apparent by comparing the two contour plots; of particular interest was the toe slope bulging observed at the base of the mudslide (Point A, Figs. 5 & 6). As far as this study was concerned the local conditions precluded any further integration of spatial detail with sub-surface geotechnical information.

Analytical photogrammetry was applied to a study of mass movement at Worbarrow Bay, Dorset (Moore 1988) and further work is near completion at Black Ven, Dorset (Chandler & Cooper 1988). Moore (1988) undertook three surveys over as many years in a study of the behaviour of mudslides on coastal cliffs. The translational mudslides were small and so terrestrial metric photography from the beach was employed (Fig. 7). Some areas were obscured due to this low perspective, and the photographs included areas of 'dead ground'. Oblique aerial photographs would have minimized this problem but resources were limited. However, sufficient detail was extracted to enable planimetric, profile and contour comparisons (Moore 1988). The site showed considerable alterations to the rear scarp, mudslide source and lobe, by up to 4.76 m (± 0.05 m) in one season, (Fig. 8). The volume changes in the source and track of the slope were found to have significant effects upon stability analyses of the shallow translational mudslide (Moore 1988, ch 6).

In order to determine movement vectors, wooden pegs were used as targets. These were coordinated at two epochs and displacement vectors were computed to a precision of ± 0.05 m. These represented the movement of each point in three spatial directions. It is difficult to represent three-dimensional vectors on a two-dimensional plot. One solution is to produce a plan (Fig. 9) and a sectional view in which the scale of the vectors can be exaggerated, if necessary.

The timing of the survey epochs for both studies

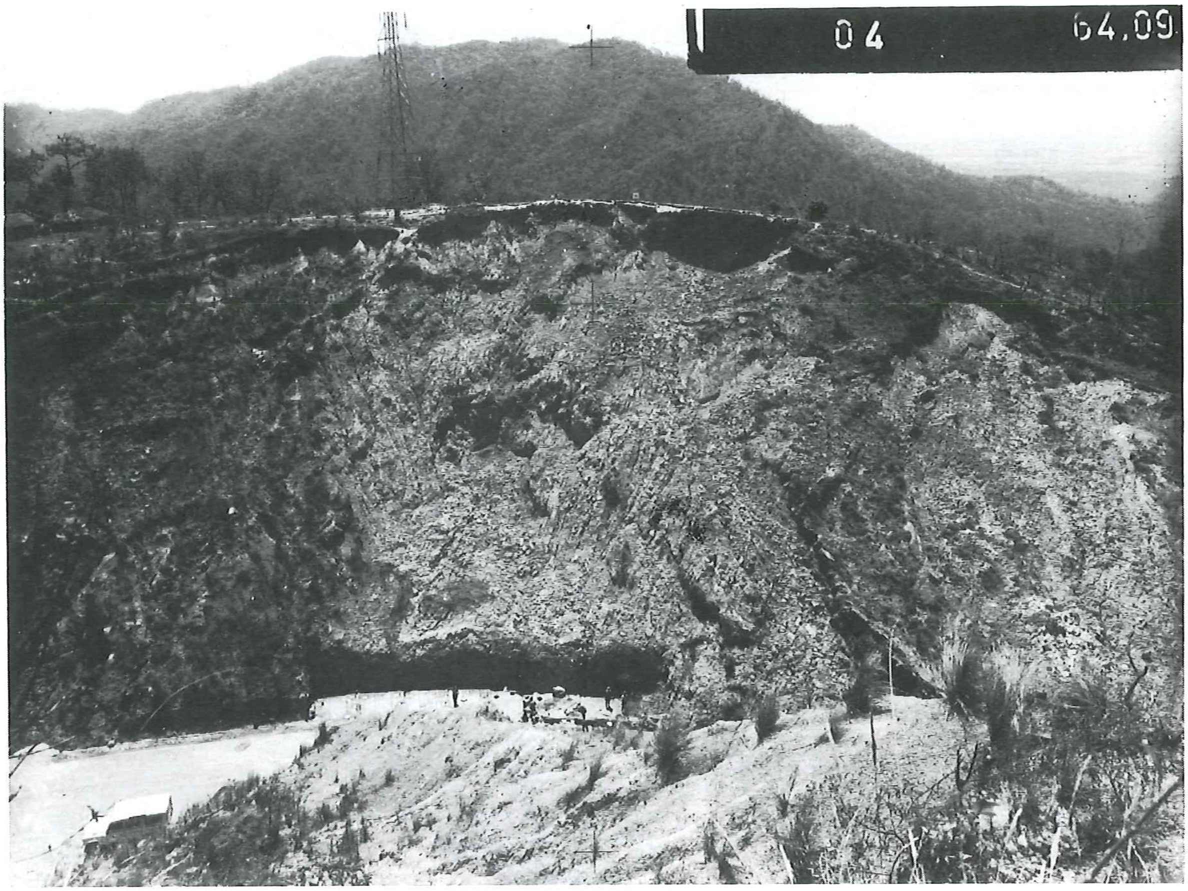

FIG. 4. P32 metric photograph showing the degration of a road cutting in the Dauney Hills, Nepal.

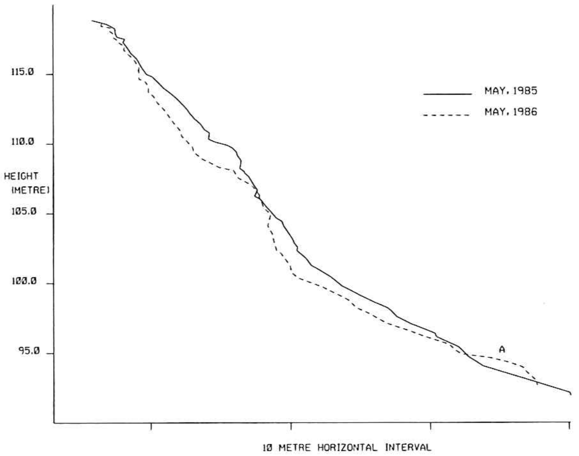

FIG. 5. Changes in the vertical profile of the Nepalese study site between May 1985 and May 1986.

was found to be a critical consideration. If process rates are high then frequent surveys will be required during active periods of geomorphological activity. In the UK, several surveys may be necessary during the active winter period, with only one during the summer. Generalizations are difficult as timing depends upon the aims of the analyses. However, analytical photogrammetry should be considered as a 'variable time base' measurement system, survey intervals being an important component of initial planning.

The observation of profiles and contours was found to be a rapid and direct way of monitoring change in the direction of the selected plane. The software data processing requirements were small so that results were rapidly displayed. Of the two, the vertical profile was easier to interpret and generally contained more information than the contour. However, the vertical plane must follow the maximum gradient if further meaningful measurements such as slope angle are to

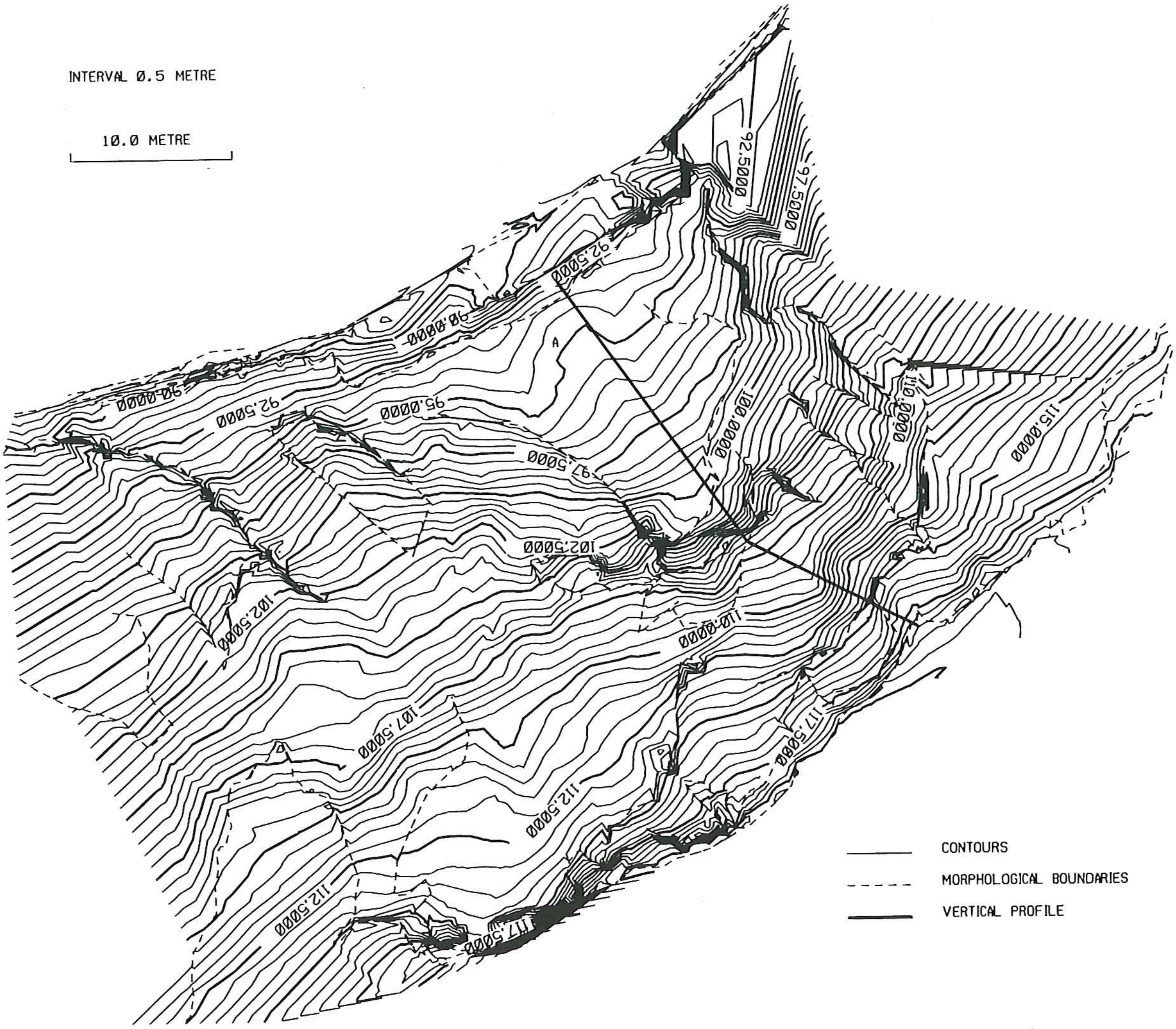

FIG. 6. Contour Plot, Nepalese site, May 1986.

be extracted. As most processes have a vertical grain, certain aspects are best shown by the contour. The major limitation of the planar method is that any knowledge regarding the change can only be two dimensional.

A DTM approach can allow for a full three-dimensional analysis because the data set coordinates are fully three dimensional. The DTM is slower to measure simply because of the high number of data points that are necessary to fully describe any complex shape or surface. The amount of useful information that can be derived from such data is potentially very high, including volumes, slope angles, contour plots and profiles at any point. The possible analysis of the 'DTM of difference' is perhaps the strongest aspect of such an approach: the rate of change between surveys can be computed and may be used in subsequent correlations between lithological, hydrological, geotechnical and climatic parameters (Moore 1988). The major restrictions upon all of these procedures is the availability of suitable software to manipulate the DTM. It should also be remembered that the quality of the computed data can only depend upon the quality and density of the constituent DTM itself.

The quantitative display of the pattern of movement is undoubtedly beneficial when monitoring landslides. As Bentley (1985) points out, it can provide 'watch-dog' information on sites which pose a threat. If slope failure does occur the sequence of photographs can be re-examined, concentrating only

FIG. 7. Jenoptik Jena UMK.100/1318 metric photograph of a translational mudslide at Dorset, England.

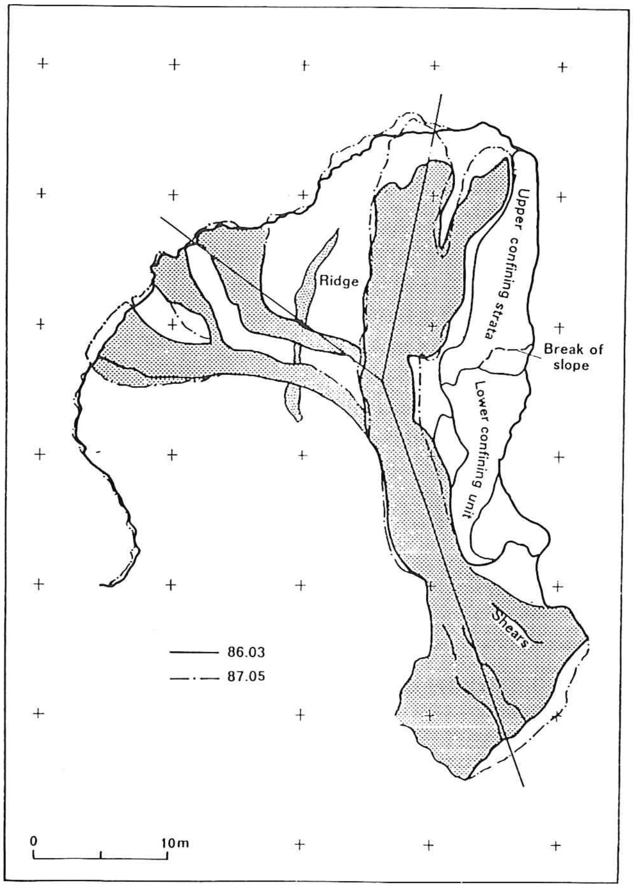

FIG. 8. Morphological change at Worbarrow Bay revealed in plan by photogrammetric analyses between March 1986 and May 1987.

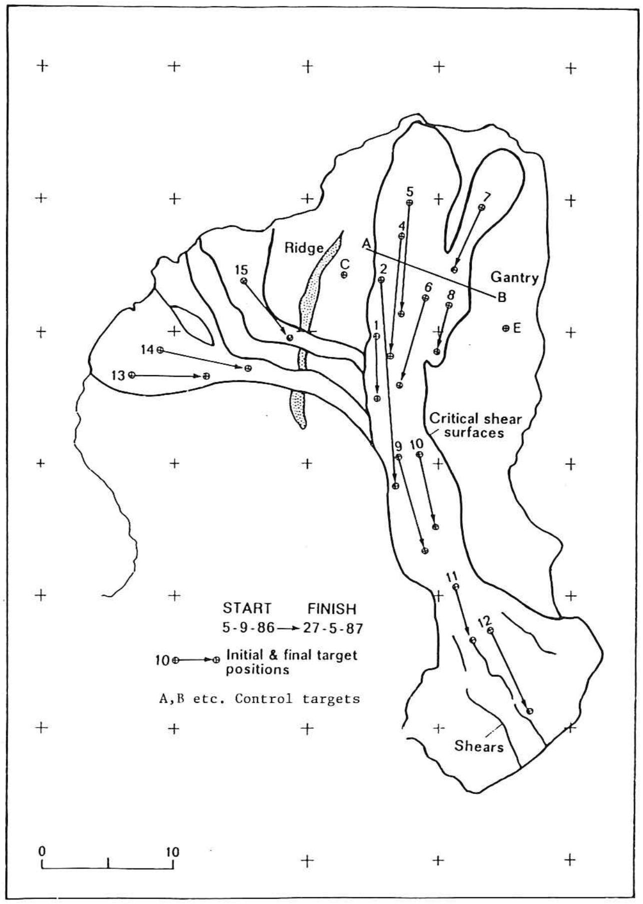

FIG. 9. Movement trajectories of targets installed at Worbarrow.

upon the area of failure so that the development and probable causal factors can perhaps be identified. The only deficiency of analytical photogrammetry is that sub-surface vectors cannot be provided. If necessary these must be obtained by geotechnical methods and combined with the photogrammetric data, this would provide the necessary information for a comprehensive spatial analysis of slope instability.

Conclusion

Analytical photogrammetry can be of particular value in detecting and monitoring slope instability. Initially the method can be used to provide simple spatial data in a variety of conventional forms; map, contour, profile and isometric plots. More advanced data extraction and processing techniques enable a quantitative analysis of the change in slope morphology and also the determination of movement vectors.

The technique may also be applied to large landslides using oblique aerial imagery from a hand-held camera. It can provide accurate, detailed and unique information about the scale and magnitude of slope instability at poorly studied sites. This would aid the future decisions of the planners, designers and perhaps insurance companies who may become involved with landslides.

Finally, it should be stated that only a limited understanding of geomorphological processes is possible from an isolated photogrammetric survey. For a detailed understanding of the complex interrelationships it is necessary to supplement the coordinate with geological, geotechnical, groundwater, climatic and vegetational measurements.

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