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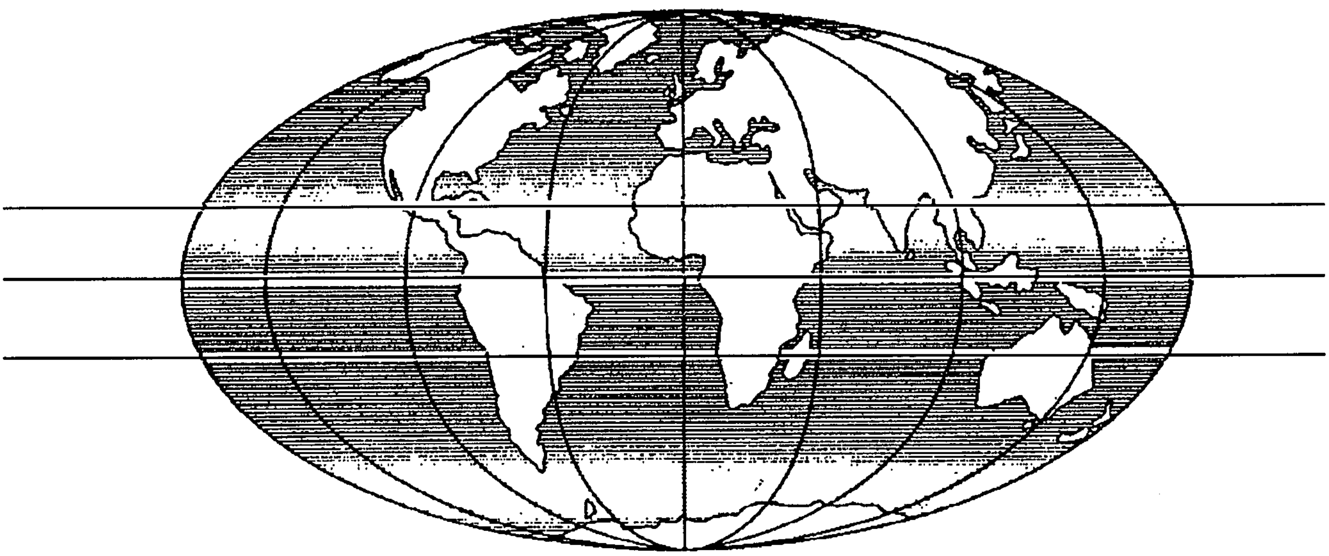
TITLE **Photographic recording and measurement techniques for monitoring slope failures**

by **W Heath**



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HEATH, W, (1989). Photographic recording and measurement techniques for monitoring slope failures. First South American Symposium on Landslides, Piapa, Colombia.

METODOS FOTOGRAFICOS DE REGISTRO Y MEDICION PARA LA VERIFICACION DE LA ROTURA DE TALUDES.

PHOTOGRAPHIC RECORDING AND MEASUREMENT TECHNIQUES FOR MONITORING SLOPE FAILURE.

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SYNOPSIS.

As part of its research programme into slope failure problems in Britain and overseas the Transport and Road Research Laboratory has used a range of techniques to monitor slopes. In recent years there have been significant developments in such techniques which has made them more adaptable, reliable and economical. They range from inexpensive photographic recording systems, fully automated to take pictures at defined intervals, to highly precise photogrammetric surveying techniques that provide digital terrain models of changes in slope profiles which occur as slopes deform. Such methods provide valuable information about stages of slope failure previously unobserved. This enables other features of a landslide investigation, including geomorphological and hydrological studies, to be carried out more efficiently. The paper describes the use of such monitoring techniques in Britain, Colombia, Nepal and other countries and, in addition, provides guidelines on their use in a variety of terrain conditions.

INTRODUCTION.

Road and railway transport infrastructures as well as buildings are often at risk when constructed on slopes subject to instability. In such circumstances many of the engineering design solutions reflect geotechnical uncertainties and can result in projects that are either too expensive or are exposed to excessive risks.

The information obtained from monitoring unstable slopes provides one of the prime means of gaining an understanding about potential slope movement, both in relation to the mechanisms involved and the effectiveness of slope stabilization design policies. One important aspect of such studies is to observe and, when possible, measure both the rate of failure and the mass of material involved. In this respect there are a wide range of techniques which may be employed. However the task of monitoring slopes is sometimes complicated by the extensive nature and unpredictability of some slide movements. Also some uncertainty exists, prior to failure, regarding the number and precision of measurements that will be required once the slope starts to move.

Photo-recording and photogrammetric techniques are methods that overcome such difficulties because the initial task of taking photographs is not too demanding. Also once the state of the failing slope is known a back-analysis can be made using an almost infinite range of measurements from the photographs. This approach has been successfully applied by TRRL to gather information about slides that affect road development programmes in a number of countries including Colombia, Britain, Indonesia, Nepal and Malaysia. Of particular significance to such studies has been the rapid advancements in the development of equipment for photo-recording and survey methods and this has resulted in considerable improvements in the consistency and quality of the results obtained. In broad terms these developments have been accompanied by reductions in the costs of carrying out slope monitoring tasks.

This paper describes the techniques which have been used together with the more important advances. The fields covered include very simple recorders that can be left on sites to obtain a continuous record of slope behaviour over periods of several years. At the other extreme modern analytical plotting instruments allow the use of photographs which a few years ago would have been unacceptable for geodetic purposes but, in some instances, now provide survey accuracies of a few millimetres.

2. MONITORING SLOPE FAILURE.

Slopes fail for a wide variety of reasons, often unpredictably, and not infrequently with devastating social and economic cost. Consequently there is considerable scientific activity connected with finding ways to predict failure events, classify hazardous regions of terrain, determine the processes by which soil and groundwater conditions lead to failure and design ways of opposing the forces or processes initiating failure. A large number of methods of accomplishing these tasks have been developed and relate to determining the mechanism by which the slope failure occurs. In this respect there are three methods of evaluating such factors.

The first consists of determining the relevant properties of slope materials in terms of shear stress and strain forces and carrying out a statistical analysis based on limit equilibrium conditions for the slope. This classical method of analysis provides an index of likely hazard; expressed as a factor of safety. However it has its limitations in the need to determine slope parameters within a reasonable degree of precision. There are generally high costs and a large amount of effort needed to achieve this.

The analysis of many slope problems is based on a simpler technique of back analysis, after the failure has occurred. In this case attempts are made, using any available documentary evidence, to reconstruct the state of the slope prior to failure and from this to determine the factors associated with landsliding. However applying such an analysis to any further failure of the slope or even to other slopes, in terms of empirical relationships, is not straightforward because of the relatively large number of uncertainties that exist about the pre-failure condition.

Finally there are methods based on the monitoring of a sample of slopes of which examples have been described by Bulman J.N.(1967) and Oyagi N.(1977). This may consist of a single study from which patterns of failure can be determined by analysing the characteristics of a large sample. Such studies are often carried out using a discriminatory analysis of different slope features. Alternatively the changes occurring to slopes can be observed or measured based on a monitoring technique to record slopes. Such information provides good data for extrapolation as, providing a representative sample of slopes is selected, a complete record showing both short and long term factors associated with failure can be obtained.

In the past this approach has tended to rely on general observations of a range of slopes; using occasional photographs and optical surveying measurements to record surface features which are changing. However improvements in survey and photorecording techniques now enable continuous records of a sample of slopes to be obtained and this provides a more concise and complete set of data. However all systems of monitoring slopes have inherent limitations dependant upon the characteristics of the slopes, the comparisons being made and the features being assessed.

Such limitations include the poor accessibility onto certain slopes, such as steep rock outcrops or mudslides, so that remote methods of monitoring become essential. Other slopes are too shallow or obscured by vegetation so that suitable viewpoints, from which to record or survey the slope, are difficult to find. Consequently the need to have a knowledge of a range of techniques and choose the most suitable for the particular conditions is important.

3. TECHNIQUES.

There is a wide range of transducer type instruments which may be used to measure deformations of slopes including inclinometers, extensiometers and settlement gauges. However all of these

techniques, which are buried or connected to small parts of the slope in some manner, only allow the measurement of relative values of change, in small areas, from which general patterns need to be extrapolated. Of more value are systems that allow remote monitoring of absolute movements from which the extent of slope failure may be more precisely determined.
With the exception of direct optical-survey systems all methods of monitoring slopes tend to be based on photo-recording techniques. The photographs provide an historic record that can be evaluated in terms of changes to slopes but in addition measurements can usually be made from the photographs based on different techniques that produce a range of accuracies. These include relatively crude and simple measurements to highly precise 'digitised terrain models' and their employment will depend on the particular application. Many of the techniques, described in Table I. have been used by TRRL in Britain and also overseas in Colombia, Nepal, Indonesia and Malaysia in the study of slope problems.

3.1 <u>Survey measurement:</u> Optical survey methods are considered briefly because they have formed an important aspect of slope monitoring in the past. Generally they employ one of three methods of measurement to produce survey results;

Table I. Methods of monitoring failing slopes.

TECHNIQUE	METHOD OF ASSESSMENT	MONITORING INTERVAL	EFFECTIVENESS AND COSTS
1)VISUAL	RELIES ON MEMORY OR NOTES:	FLEXIBLE	LOW COSTS BUT INEFFECTIVE.
2)TRADITIONAL SURVEYS	PLANS & PROFILES	RESTRICTED BECAUSE EFFORT REQUIRED	LIMITED VALUE & HIGH COSTS.
3)PHOTO-RECORDERS	PURELY QUALITATIVE	DAILY TO WEEKLY RECORDS	EFFECTIVE WITH LOW COSTS.
4)SOPHISTICATED PHOTO-RECORDERS	QUALITATIVE & MEASUREMENTS	DAILY TO WEEKLY RECORDS.	EFFECTIVE WITH MODERATE COSTS.
5)CONVENTIONAL PHOTOGRAMMETRY.	QUALITATIVE & QUANTITATIVE.	USUALLY LIMITED TO ONCE/TWICE YEAR	RELATIVELY HIGH FOR BOTH
6)ANALYTICAL PHOTOGRAMMETRY	VERY VERSATILE TECHNIQUE	ADOPTABLE TO MOST SITES. SURVEY WORK RELATIVELY SIMPLE	DATA REDUCTION DEMANDS HIGH COSTS.

1) Triangulation: The measurement of distance and direction from measured angles, using a theodolite, between two base stations of known distance apart.
2) Trilateration: The determination of the position of a point from its known distance from three survey stations.
3) Triangulateration: A combination of methods 1) and 2) and one which provides cross checks, from two results, and the

highest degree of overall accuracy.

For the surveying of slopes the latest technique, the electro-optical distance meter (EDM), has proved to be the most effective. This relates to the large distances that such systems operate at which is an important advantage when repeated surveys are used to detect changes to a slope and the survey stations have to be outside the landslide area on stable terrain. The theoretical survey accuracy, based on triangulateration, of such systems can be expressed as;

$$\pm\ dD = 5mm \times 1 \times 10^{-6} \times D. \qquad 1.$$

when (dD) is the smallest measurement possible, (D) is the survey distance and the constant (5mm) includes errors in positioning and equipment.

However in practice other factors, such as atmospheric conditions and the establishment of datum points affect the overall accuracy of such systems. Also the main limitations are that complete access to the slope being measured, in order to place the EDM reflector, is essential and in many situations this is hazardous.

Over short distances, or when EDM equipment is not available, other more traditional survey procedures may be considered on slopes were access is possible. For example repeated surveys, by triangulation or levelling, were made on a range of slopes in Indonesia. The study of these landslide problems has been described by Heath W. and Saroso B. S. (1988). The slopes, which had angles of between 12 and 15 degrees, were generally too shallow to be recorded photographically or surveyed with photogrammetry. Nevertheless the conditions, where heavy rain brought about slope creep and translational sliding, was most relevant to a monitoring procedure and the determination of the rates of such failure.

To provide an indication of the relative effort required to achieve this survey task details of one survey are provided. Figure 1. shows a sector of a contour plan of an unstable slope in West Java produced by chain and levelling and plotted to a scale of 1: 200 with 2m contours. The total length of the slope is 900 m.

For a survey team consisting of two people five days were required for the field work, living on site, and two days for the data reduction and mapping. Pilot G. (1988) indicates that levelling errors over 1,000 m of a double traverse are, in ideal circumstances, in the order of ± 2.5 mm; however the confidence in the accuracy of surveys in Indonesia was not of this order.

Examples of structure monitoring of movement, by Ashkenazi V. et. al. (1981), indicate that such surveying techniques are of value for monitoring deformations. Other opinions support the conclusions reached in Indonesia that the technique lacks consistency when slopes, without any defined features, are surveyed. This probably reflects limitations in the surveyors skills or concentration over lengthy periods on uninteresting slopes particularly in hot tropical conditions

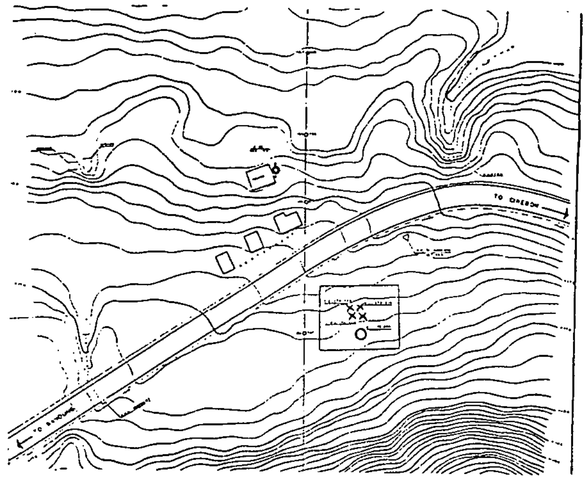

FIGURE 1. Part of a contour plan produced by levelling.

In addition there are limitations with all traditional survey procedures when the exact detail to be measured is not known. This applies to most slope monitoring tasks when failure patterns cannot be defined beforehand and therefore a very close density of points must be measured. Consequently in the light of the large amount of effort that must go into such survey methods their application for any long term monitoring of slopes is rarely justified.

3.2 <u>Photo-recording techniques:</u> Photographic records of slopes are often an important component of a back-analysis into the mechanism that has caused the slope to fail. However such records are not always readily available and when suitable photographs are located they tend to show the slope from differing perspective angles. There are also inconsistent gaps in the periods the photographs were taken and consequently they do not provide complete records. Therefore some degree of extrapolation regarding certain phases of failure must accompany the analysis. The main advantages of such methods is the extremely low cost and the fact that the technique can be used to monitor any type of slide except when a suitable viewpoint is not available. This applies in particular to very shallow slopes unless there is a suitably high vantage point.

Continuous records from a fixed position provide more useful information than random photographs and a number of techniques have been developed to provide this. For example as part of a study into embankment slopes on Britains motorways a monitoring technique consisting of a pair of Nikon cameras and timer have been used to monitor three slopes; two of which have failed during themonitoring period, Crabb G. I. et. al. (1987). The cameras are set in a housing 0. 75 m apart to provide a stereoscopic model and take a pair of images each day. Using analytical procedures and digitising the images on plotting tables measurements can be obtained that have an accuracy of about $\pm$ 125 mm in ideal circumstances. However attempts to obtain such results have been frustrated by distortions caused by a lack of film flatness. This is now being overcome by fitting a glass reseau plate in the film plane of each camera. The approximate cost of each monitoring unit is $3,000 (US).

A similar technique has been described by Ballantyne J. D. et al. (1987) in terms of making measurements from photographs for monitoring purposes. The cost of equipment to carry out the task of data reduction has been estimated at $7,000 (US).

In many instances there will be little need for semi- precise measurements and the more important requirements of monitoring a large sample of slopes will often call for simple low-cost techniques. Such records provide an improved cross-representation of slope failure events over a wide area. The results can be evaluated, in terms of qualitative values, or simple measurements can be made from single images by projective geometry, Moffat F. H. and Mikhail E. M. (1980). The concept is based on a perspective grid, with squares chosen to represent any convenient ground dimension, and lines of the grids converging at a nadir point.

A monitoring system developed at TRRL meets these aims and is being used both in Nepal and Malaysia in relatively large numbers to monitor slopes there. Plate 1a. shows the simplicity of the installation set up at TRRL.

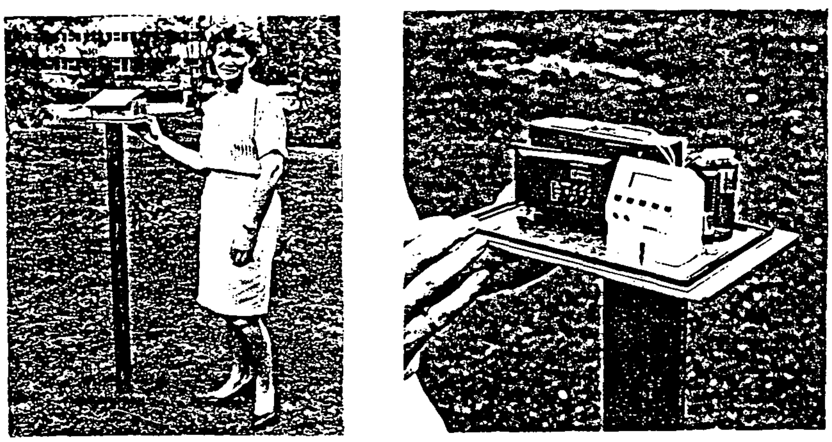

PLATE 1a & 1b. Photographs showing a photo-recording unit.

It consists of a standard 35mm Ricoh camera which features automatic exposure and film transport. This is controlled by a domestic type 'plug-in' timer, converted to operate from dry batteries. The microprocessor of the timer can be programmed to switch from seven times a day up to once per week. The entire system is contained within a metal 'environment-proof' container measuring 190mmx120mmx100mm. When set to record a photograph every five days the unit can be left unattended for six months at which point the film is changed and four standard penlight batteries are replaced, see Plate 1b. Each image has either the time or date encoded onto it, by means of the camera data-back, and the photographs are filed until the slope starts to fail and the data is needed for analysis.

As mentioned measurements can be made from such photographs, within the order of $\pm$ 250 mm, using perspective geometry. Alternatively the images can be examined in a stereoscope and changes to a slope then become readily apparent. Overall costs of producing batches of approximately 25 monitoring units are in the order of $125 (US) per unit.

Essentially the techniques of photo-recording are very reliable and there are no risks associated with people or equipment being on the unstable slopes.

3.3 <u>Photogrammetry:</u> Photogrammetry is defined here as a precise surveying technique using cameras with a highly accurate optical geometry and carrying out image restitution on machines that are capable of measuring to 5 um or less. As part of a general investigation into road building problems in rugged terrain photogrammetry was used to record and contour-map more than 80 landslides in Colombia, Heath W. et.al. (1978). The technique was based on the newly introduced small format Wild P32 metric camera. At the time this was the only system that was light and portable enough to be used on the difficult sites. Since then a much wider range of small format metric cameras have become available for such purposes.

The technique used consists of taking two photographs of the landslide, from suitably separated positions, using a camera that provides a relatively distortion free image. Placed on the landslide and within the view of each camera are a minimum of three accurately positioned and measured targets. The pair of photographic images, when viewed in a suitable stereoscopic device, provide a three dimensional model of the slope. The surveyed targets then provide scale and can also be used to finely adjust the orientation of the images to produce a geometrically correct model. The same targets can also be used to adjust the model position to some previously defined geodetic reference such as a map grid, to obtain an absolute orientation, if necessary. The measurement process consists of aligning a floating reference mark onto a relevant part of the slope, within the orientated stereo model, and using its position to control the pen location on a cartographic plotting table.

In practice the overall precision of photogrammetric surveys is dictated mainly by the intersection angle of image points of the two photographs and this depends on the separation of the two camera positions during the survey. This is illustrated in Figure 2a. in terms of image parallax for two different base lengths. The dependence of 'survey' accuracy in terms of the smallest distance measurable, expressed as (d)D., in terms of the survey base length (B) can be defined with the following equation;

$$\pm (d)D. = D^2 \times 0.01/FL. \times B. \qquad 2.$$

Where (D) is the distance from the slide to the survey station, 0.01 is a constant, and (FL) is the camera focal length. Ideally the survey base length should be within the range of 1:4 to 1:16 of the survey distance.

The instruments used to make measurements, the plotters, are defined as rigid in that only very small adjustments to the orientation and geometric relationship of the two images can be made. This implies that most of the exacting conditions relating to the alignment of the two photographs, as shown in in terms of six rotational components, see Figure 2b., must be satisfied at the landslide site at the time the survey is made. These conditions are that the optical centres of the two cameras are parallel and perpendicular to the survey plane of the landslide. This is achieved by precisely orientating the camera positions, to within a few seconds of arc, using a theodolite which is also employed to survey the control targets.

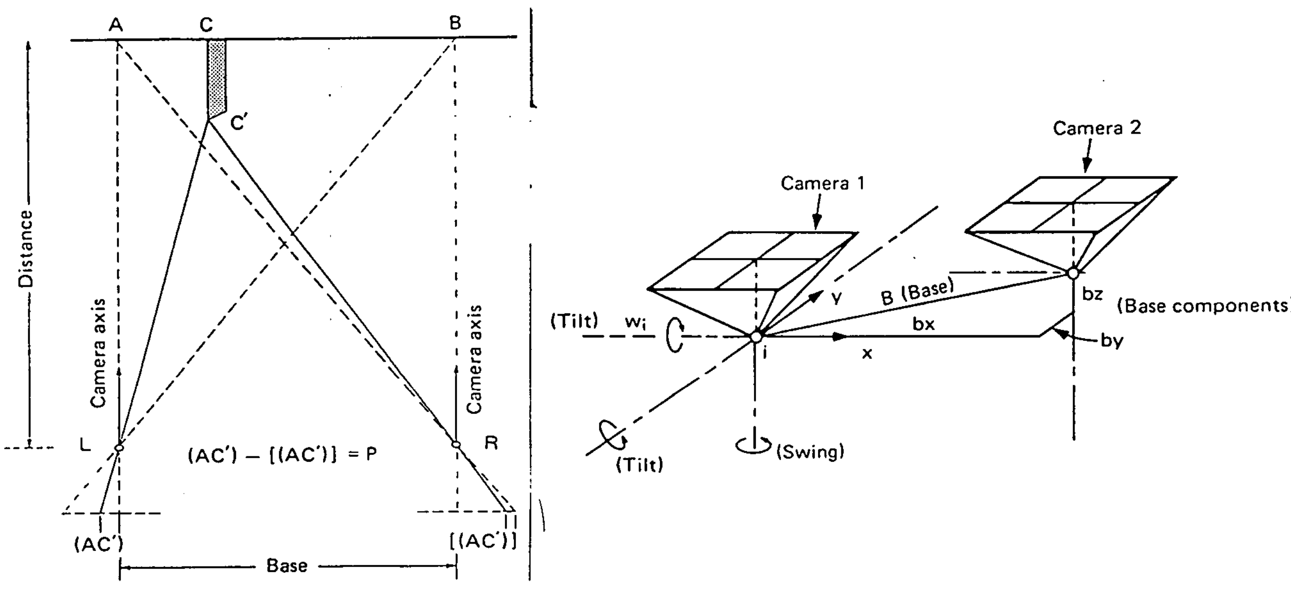

FIGURE 2a & 2b. Image parallax and spatial alignment components

In practice the important aim of locating a survey base of suitable length, that is also aligned perpendicular to the landslide face and not obscured by trees or terrain features, is rarely achieved in rough mountainous terrain. The only compromise permissible is that the base length is reduced and consequently survey accuracy suffers. Within the group of landslides surveyed in Colombia base length to distance ratios of between 1:12 and 1:80 were achieved and contour heights of between 0.5 and ten metres could be plotted.

As an example of the technique used in Colombia one of a pair of photogrammetric images of a slide at Caraza, km 38. on the Bogota-Villavicencio road is shown in Figure 3.

The circled areas are where survey control was placed on the slide and five targets have been chosen to provide a degree of redundancy. Figure 3. shows a small section of a contour plan of the hillside with contour intervals of 2 and 10 metres. This was plotted on the Wild A40 instrument.
Using equation 1. the expected accuracy at a distance of 400m, for a survey base of 31.143m and a (FL) value of 64mm, can be determined;

$$\frac{(400m \times 10^3)^2}{64 \times (31.143m \times 10^3)} \times \frac{1}{100} = \pm 802.75mm$$

At the extreme distance of 1.5km to the top of the landslide slope a base ratio of 1:48 reduced this accuracy and only contour intervals of 10m could be achieved. However such results are adequate for monitoring very large slides, such as the one at Caraza, and the technique proved efficient both in terms of time and cost as well as the quality of results. Plans are now in hand to re-survey some of the slopes in order to determine the changes which have occurred over a period of 15 years and relate these to the geological conditions and predictions made at the time of the initial surveys.

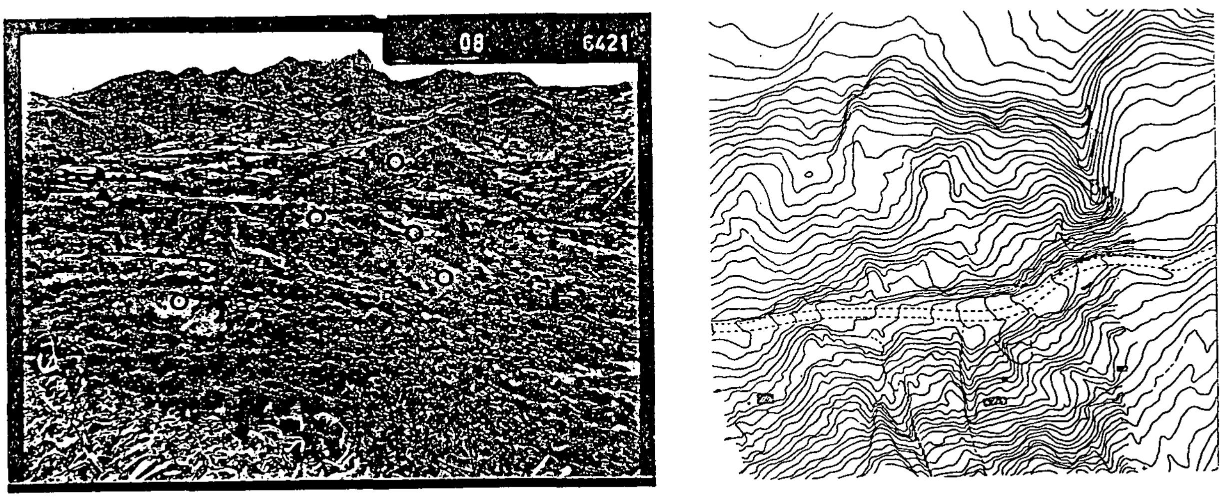

FIGURE 3. Metric image and contour plan of slide in Colombia.

However when the same technique was used in the more rugged terrain of Nepal and Indonesia, to carry out a similar study, it was found that the restraints, imposed by the plotting machines, were too severe. Suitable survey base stations could not always be found, because of the topography, and locating identifiable control targets on the forested slopes also presented problems. In such conditions the technique would be unlikely to replace conventional surveying procedures.

3.4 <u>Analytical methods of photogrammetry.</u> Such problems of locating suitable survey stations had been anticipated and an analytical approach considered. This simplified the restraints on selecting survey sites by allowing more freedom for the position of the base station and the tilt of the cameras. This easing of camera position restraints was achieved through an analytical rather than machine controlled orientation of the photogrammetric model.

Without going into detail this is based on the functional model of the image as a perspective projection in which mathematical equations are used to relate object space coordinated to image positions by means of vector equations of the object space. The terms used to express the collinearity condition are;

$$x = -\ Pd.\ \frac{M_{11}(X_A-X_L)+M_{12}(Y_A-Y_L)+M_{13}(Z_A-Z_L)}{M_{31}(X_A-X_L)+M_{32}(Y_A-Y_L)+M_{33}(Z_A-Z_L)}$$

3.

$$y = -\ Pd.\ \frac{M_{11}(X_A-X_L)+M_{12}(Y_A-Y_L)+M_{13}(Z_A-Z_L)}{M_{31}(X_A-X_L)+M_{32}(Y_A-Y_L)+M_{33}(Z_A-Z_L)}$$

were; (x) and (y) are photo coordinates, Pd is the lens principal distance, (X_A) (Y_A) (Z_A) are landslide coordinates and (X_L) (Y_L) (Z_L) are coordinates of the ground perspective centre. M_{11}-M_{13} to M_{33} are elements of an M rotation matrix representing three planes of rotation about each camera axis, see Figure 4. Further details of numerical relative orientation procedures have be described by Heath W. (1983) and Thompson E.H. (1959).

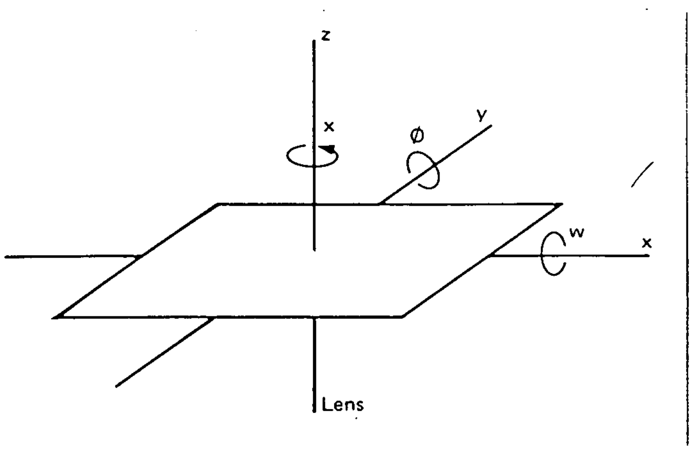

FIGURE 4. Planes of rotation about an image axis.

By simplifying the field work, in the way described, problems arise in making measurements from the photographs. Such images no longer provide an ideal stereoscopic model and consequently there is often a need to define the exact position of each and every photographic image point for the analytical model. This produces difficulties in identifying and labelling such points amongst the somewhat vague detail of a landslide slope. The task of making measurements from the photographs, using a stereo-comparator, therefore became very demanding and makes the technique relatively uneconomical.

A subsequent study was made into further methods of simplifying the photogrammetric field work and the problems of employing rigorous photogrammetric techniques in steep and rugged terrain. This showed that an approach using a photogrammetric bundle adjustment procedure, employed by Veress S.A. and Sun L.L.(1978) to monitor gabion walls, could be made extremely flexible in terms of camera positions. This removed the need to accurately define the camera orientation parameters. In addition if several photographs are used a solution for all of the unknown orientation parameters can be solved by a method termed the Stochastic Model, described by Cooper M.A.R.(1983) This provides a solution with a greater degree of accuracy as a result of the larger number of image intersection points used.

This technique was used to monitor a number of slopes in Nepal as part of a TRRL study into aspects of highway maintenance in rugged terrain. The monitoring, on the East- west highway in Nepal, has been described by Chandler J.H. et.al. (1987). This recently constructed road passes through an elevated region of terrain, the Dauney Hills, which is composed of alternating sequences of micaceous sandstone and silty mudstone. Such sequences tend to be naturally unstable when saturated and consequently road cuttings have a high hazard risk. Soil erosion on such slopes is also severe. The problems were to determine when failure occured and what caused it, what were the rates of erosion to the slopes and also to determine the effectiveness of remedial methods of slope control.

As an example of what was obtained by analytical methods Figure 5. shows a contour plan, with 0.5 m contours, produced from a digital terrain model, consisting of 3,000 data points, and profile changes to a slope in Nepal over a period of one year.

Whilst the contouring is somewhat coarse and angular in comparison with what is obtainable by analogue photogrammetric methods the advantages of processing data statistically using digital terrain models needs to be taken into account.

Problems with the method again relate to the difficult and often tedious task of identifying and labelling image points on a number of separate photographs. In particular the large degree of freedom in terms of each image axis implies that few sets can be viewed through a stereoscope and consequently measurements must be made on a monocomparator. In practice the method appears to be most suited to monitoring structures, such as walls, where there is good detail and relatively few measurements are required.

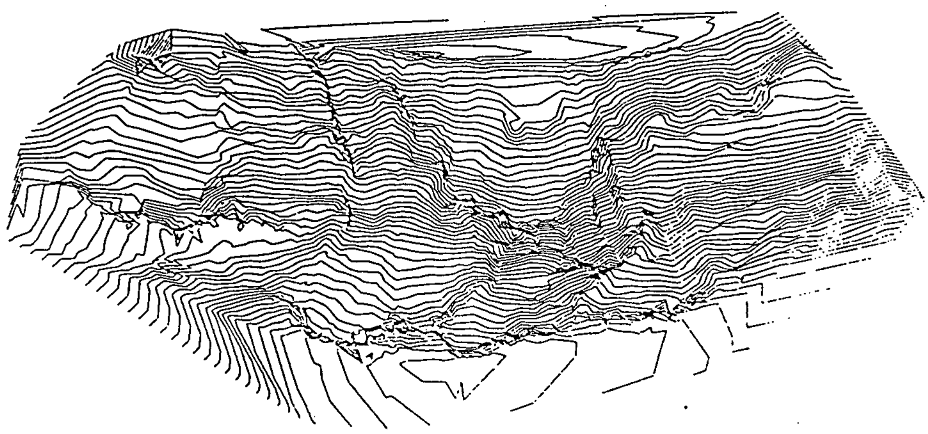

FIGURE 5. Contour plan from 3,000 point DTM. (City University)

3.5 <u>Analytical plotting instruments:</u> Many of the problems, both in conventional and analytical (bundle adjustment) photogrammetry have been largely overcome in the last few years, with the introduction of analytical plotting instruments. The concept of how these work is shown in Figure 6.

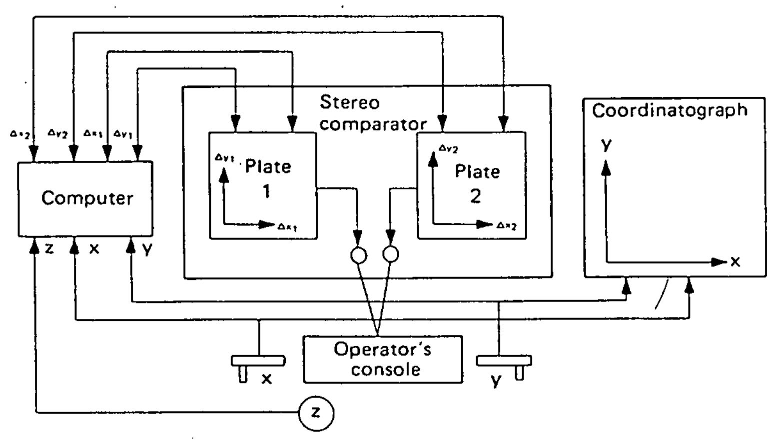

FIGURE 6. Simplified schematic diagram of an analytical plotter

The system can be considered as being equivalent to a non-rigid plotter in that all of the geometric parameters connected with the stereoscopic model are controlled analytically whilst retaining the simplicity of data reduction of an analogue plotting system. Consequently there are few restraints in terms of defined survey requirements, in the field, and the technique allows a rapid reduction of data to produce maps, etc.

The method has recently been reported, Chandler J. H. and Cooper M. A. R. (1988). as providing very useful data in terms of monitoring, by back analysis, the changes in a landslide at Black Ven in Dorset (UK). This was accomplished using a collection of historic and recent aerial photographs. The landslide is shown in Plate 3. and segments from three very detailed contour maps, showing changes over a period of thirty years, are shown in Figure 7.

PLATE 3. Aerial view of landslide at Black-Ven in Dorset, UK.
(City University)

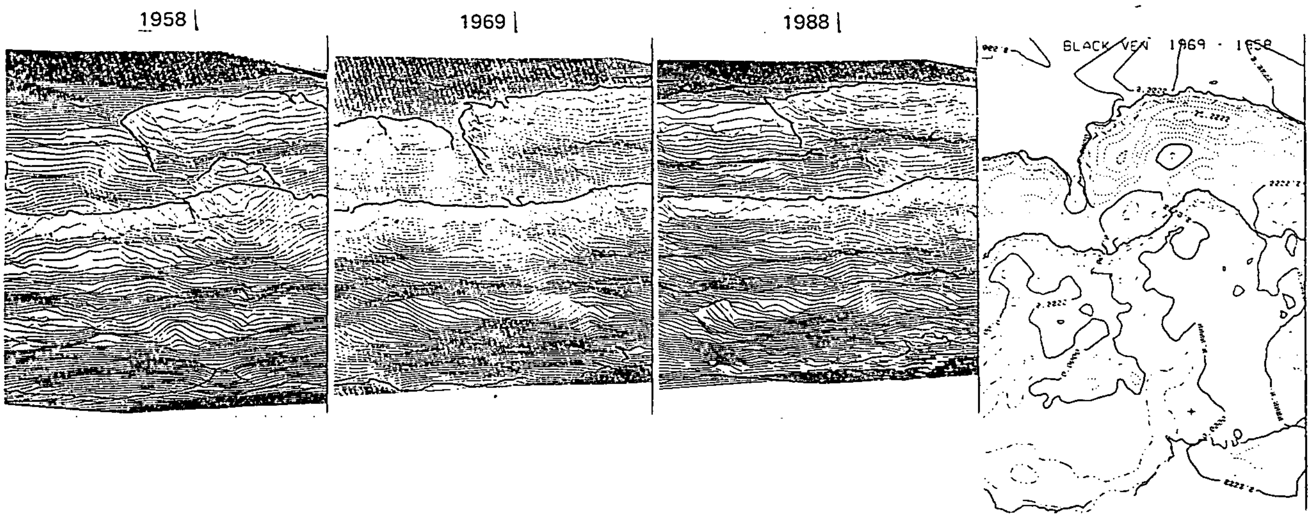

FIGURE 7. 30 year contours and resultant DTM difference.
(City University)

This example of slope monitoring, over extended periods, using analytical plotting techniques provides an example of the excellent potential that such methods will have for slope studies in the future. The limitations are in the need for measurements to be made on specialised equipment that few laboratories own and the high expense attached to such systems.

4. SELECTING A METHOD.

Whilst, with recent developments, there is now less need for skills in carrying out the field work for slope monitoring tasks, and this increases the flexibility of the range of techniques that may be used, the careful selection of the most appropriate method remains important. Such selection depends on the site conditions as well as the monitoring task, see Table II.

Table II. Range of slope monitoring tasks

TASK:	SUGGESTED TECHNIQUE:	NEED FOR EXPERTS QN SITE:
) LONG-TERM MONITORING. OF FAILURE MECHANISMS.	1) SURVEYING? 2) PHOTOGRAMMETRY 3) PHOTO-RECORDS	SOME SKILL NEEDED YES NO
2) CRACK & DEFORMATION	1) PHOTOGRAMMETRY 2) SURVEYING	YES. SOME SKILL NEEDED
3) HAZARD ASSESSMENT	PHOTO-RECORDS	NO
4) EROSION ASSESSMENT	PHOTO-RECORDS	NO.
5) VEGETATION ASSESSMENT	PHOTO-RECORDS	NO.
6) ASSESSING REMEDIAL TECHNIQUES.	1) PHOTO-RECORDS 2) PHOTOGRAMMETRY	NO. YES.

This shows the range of such tasks and the techniques which are considered to be most appropriate together with the general availability of resources and need for expert skills.

Table III. shows some relative costs for different aspects of slope monitoring in terms of an arbitrary price unit. These are only approximate figures based on material expenses, field work time and equipment hire or purchase costs.

Quantifying the potential survey accuracy of different systems, in terms of the capability of the technique, tends to be misleading in that such accuracies depend to a large extent upon the condition of a slope and the care used in carrying out survey work. This applies in particular to conventional photogrammetry and traditional optical surveying techniques. In adverse situations such methods may achieve little more than can be accomplished using simple photo- recording systems and yet the costs and efforts involved could be much greater.

Table III. Approximate relative cost relationships for different slope monitoring tasks.

TASK:	EQUIPMENT COST:	FIELD TIME:	DATA REDUCTION.
SURVEYS	5 UNITS	5 UNITS	2.5 UNITS
PHOTO-RECORDS	1 UNITS	1 UNITS	1 UNITS
PHOTO-GRAMMETRY	10 UNITS	2 UNITS	10 UNITS
ANALYTICAL PHOTO-GRAMMETRY	10 UNITS	1 UNITS	20 UNITS

NOTE:
* 1) Data reduction costs do not include analysis time.
2) All are shown in arbitrary units.
3) Material expenses, field time and data reduction are for one year/two surveys in terms of measurements or records of the slopes every five days.

Table IV. provides an indication of the highest survey accuracy of each technique.

In practice photogrammetric systems do not have the same level of accuracy for measured values along the image axis and perpendicular to this axis. This relates to the requirements of using image intersection angles for the former and simple image geometry for the latter. From widely separated base stations measurements based on angles of intersection will tend to have a higher overall accuracy particularly when image scale is small. However most measured values of a survey consist of the two components although to simplify Table 4 only accuracies based on intersection angles are provided.

Finally it needs to be appreciated, in terms of the selection of any monitoring technique, that simple records are generally of more value than precise survey measurements if the reliability of such measurements is poor. Such reliability almost always relates to the care and skill employed in carrying out the field work.

Table IV. Approximate survey accuracy of a range of techniques.

TECHNIQUE:	METHOD:	ACCURACY $\pm$ dD:
LEVELLING:	DOUBLE TRAVERSE	$\pm$ 2.5×10^{-6}m (HEIGHT)
EDM:	TRIANGULATERATION:	$\pm$ 1×10^{-6}m
PHOTORECORDS: (PAIRS OF IMAGES)	SIMPLE PHOTOGRAMMETRY	$\pm$ 1×10^{-3}
PHOTORECORDS: (SINGLE IMAGES)	PERSPECTIVE GEOMETRY	$\pm$ 1×10^{-2}
PHOTOGRAMMETRY:	ANALOGUE PLOTTERS	$\pm$ 1×10^{-4}
PHOTOGRAMMETRY:	BUNDLE ADJUSTMENT	$\pm$ 1×10^{-5}

*NOTE:
All, apart from levelling, expressed as a small part of the survey distance (D) under ideal conditions

CONCLUSION.

Before attempts are made to use precise survey techniques to monitor slope failure the reason for such measurements needs to be clearly defined. Whilst photogrammetry provides a record from which measurements and a qualitative assessment can be made it does not entirely remove this need to specify the range and accuracy of measured values prior to the commencement of the monitoring task. This can be decided by commencing with a purely qualitative assessment of the failure, using simple photo-recorders. In some instances these records may be sufficient to answer many of the questions relating to the landslide mechanism.

When photogrammetry is employed there are a choice of techniques available. In conditions such as those that exist adjacent to the majority of slopes in Colombia the conventional method of photogrammetry, using plotting instruments, provides an ideal survey tool for monitoring failing slopes. It generally requires less data reduction time than analytical methods and therefore produces an overall saving in total costs. However there are certain limitations in the survey accuracy that can be achieved using such methods. There is also a need to fully understand the constraints imposed by mechanical plotting instruments and to ensure that the field work is carried out within such constraints.

The more recently developed analytical plotting techniques need to be considered when adverse site conditions make the use of other photogrammetric techniques difficult. They are also of value when archival photographs of landslides are available, for which some geometric features of the image are known, and data from these can often be incorporated into the survey results. However analytical plotters require a high investment and consequently the high operating costs of this technique need to be born in mind.

ACKNOWLEDGEMENTS.

Within TRRL the development of slope monitoring techniques has been carried out in the Overseas Unit and Ground Engineering Division and the Author acknowledges the contribution of colleagues in these departments. Part of the studies connected with TRRL's landslide research programme have also been conducted at City University, (Mr N Lindsey). The paper is published by permission of the Director of TRRL Mr D.F. Cornelius.

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