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ANALYTICAL PHOTOGRAMMETRY APPLIED TO NEPALESE SLOPE MORPHOLOGY

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Abstract

Site procedures and methods of analytical close range photogrammetry are described. The derived data are discussed in relation to the geomorphology of unstable hill slopes in Nepal. Acquisition of low cost multispectral aerial photography for a study of overall slope erosion is also described.

INTRODUCTION

PHOTOGRAMMETRY has been used in this project to monitor quantitatively the development of erosional hillslopes in Nepal. The project strengthens the links between geomorphology and photogrammetry.

Nepal is interesting geomorphologically because of the potent combination of the Himalayan mountains and powerful monsoon storms. These have given rise to a steeply dissected landscape with the potential for very rapid change (Brunsden *et al.*, 1981). These rapid changes are considered important only when they threaten life or property. The City University has monitored sites adjacent to two new road alignments for the Transport and Road Research Laboratory (TRRL). The Dharan-Dhankhuta road was constructed in 1982. It crosses the Low Himalaya, which at this point are precipitous and prone to slope failure. The second area lies adjacent to the East-West highway. This road climbs over a naturally stable spur of the Low Himalaya known as the Dauney Hills. The road construction has reinitiated many old slides which now threaten the alignment.

At both of these locations there was a need to monitor and analyse certain specific sites. The monitoring system had to be free of contact because of the hazardous nature of the slopes, and flexible in its methods of data collection as the required form of output was unknown at the time of survey. An analytical close range photogrammetric solution seemed to fulfil these criteria, with the additional advantage that camera positions and orientations were flexible. Surveys have so far been carried out in May 1985 and May 1986.

AERIAL PHOTOGRAPHY

Just before the start of the project, a further request was received from TRRL for assistance in acquiring low cost aerial photography of the Dharan-Dhankhuta road for a general assessment of erosion in the area. The TRRL multispectral mount (Heath, 1980) consisting of four 70 mm Hasselblad 500 EL/M cameras with 100 mm lenses, intervalometer and synchronous firing was to be used (Fig. 1). Only three cameras were available and it was decided to use panchromatic negative (Agfa Aviophot Pan 200), natural colour diapositive (Kodak Ektachrome 64) and false colour infrared (Kodak Aero 8443). The infrared film proved difficult to obtain at such short notice in the United Kingdom and was eventually purchased in Australia

* Now with Wild Heerbrugg (UK) Ltd.

by the University of Melbourne and air freighted to London two days before departure for Kathmandu. Some test flying was carried out in the UK for checking film and filter combinations for the Pan 200 and Ektachrome 64. The TRRL single camera mount (Fig. 2) was used. It fits behind the rear seats of a Cessna 172 and the camera hinges out through the baggage door of the aircraft. This door is removed before flight and no other modification to the aircraft is necessary.

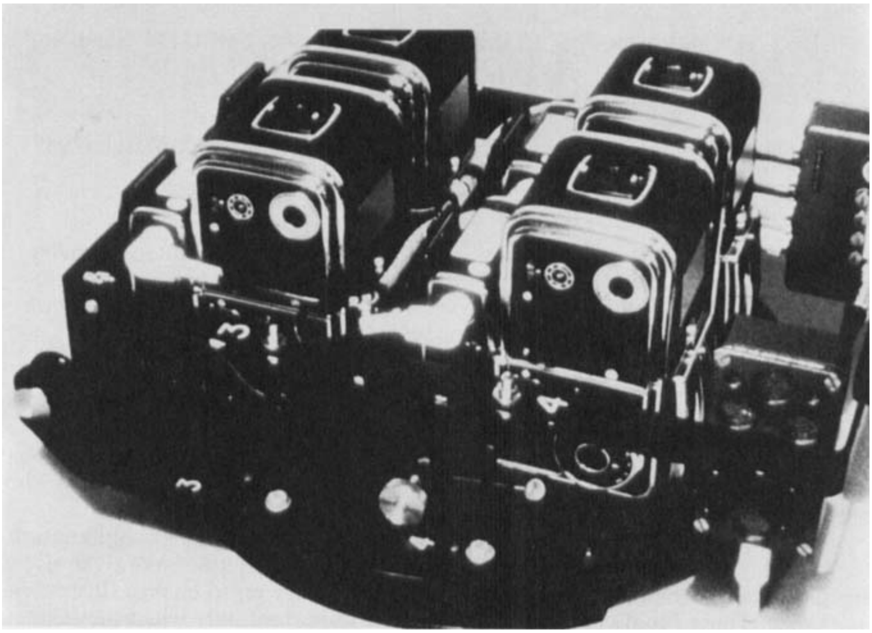

FIG. 1. TRRL small format multispectral camera mount. © Crown Copyright reserved.

The aircraft used in Nepal was a Twin Otter, with camera port, of the United Nations Development Programme. The aircraft was used six days a week airlifting supplies to remote communities. Saturday was set aside for routine maintenance, a crew rest day and for *ad hoc* charters provided an alternative crew could be found. Royal Nepal Airlines Corporation (RNAC) also operated Twin Otters and was able to provide a crew for the photographic sortie.

The only document available for flight planning was a colour photographic print of an old Survey of India 1:63 360 map sheet with the road alignment drawn by hand. The deeply dissected terrain made a choice of flying height difficult as relief varied between 300 m and 1500 m. An altitude of 2900 m was selected, giving a photoscale of 1:13 500 on the ridges and 1:25 000 on the valley floors. The separation between flight lines was to be 750 m. No navigation sight was available so it was intended to use the aircraft's Omega navigation system coupled to the autopilot. However it was discovered that the accuracy of Omega in the area was ± 700 m so it was decided to use visual navigation with distant landmarks for alignment.

Over a month was spent in Nepal obtaining permission for the flight and the attachment of an accompanying Army Liaison Officer. Towards the end of this period the weather deteriorated rapidly, with great quantities of dust being blown from the exposed hillsides until, on the day of the photography, the forward visibility was less than 3 km. This made the visual navigation extremely difficult and, coupled with the RNAC flight crew's lack of experience of photographic flying, resulted in a flying time of over five hours with much circling searching for landmarks. In retrospect it would have been better to have relied on the Omega's high relative precision as opposed to its absolute accuracy and flown extra strips on each side of the area. The Omega was used to obtain groundspeed readouts for the

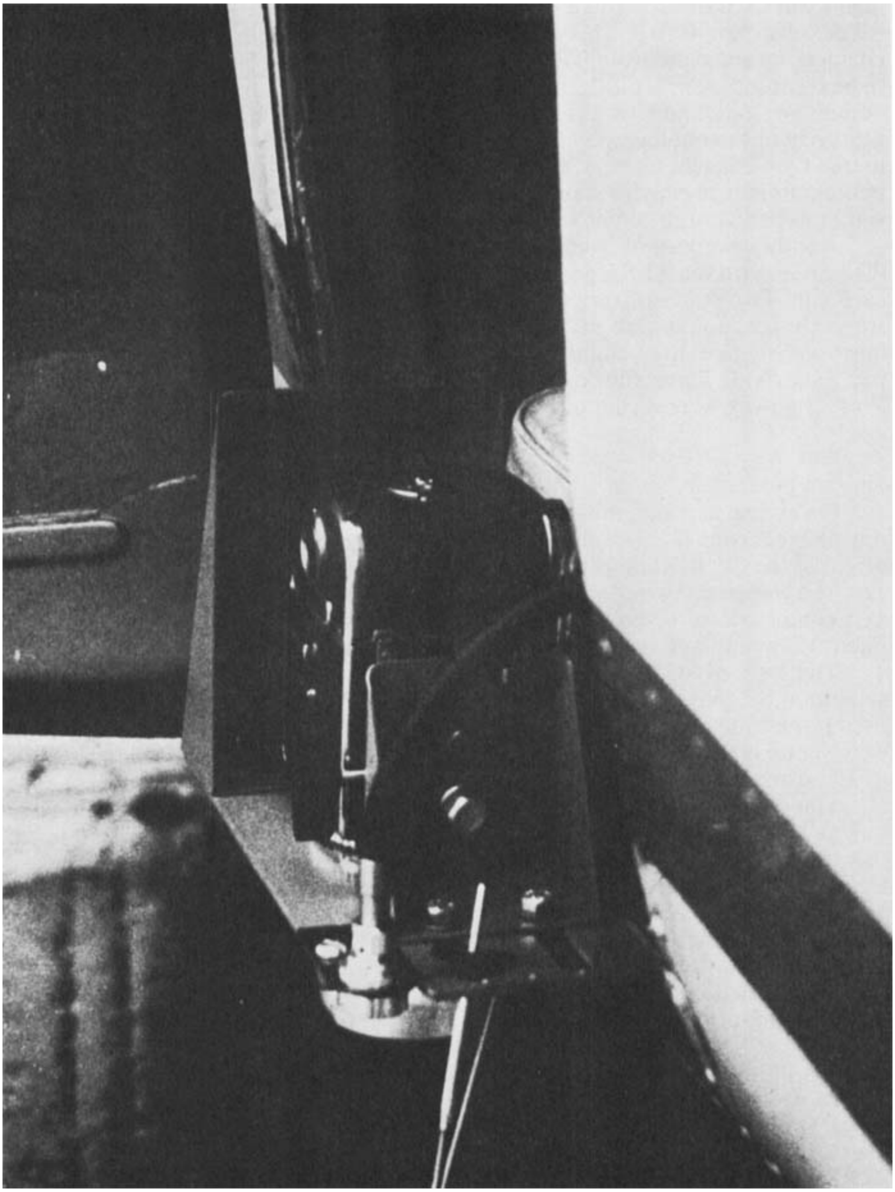

FIG. 2. TRRL small format single camera mount on a Cessna 172 aircraft. The baggage door is removed before flight and a blanking plate placed over the top half of the opening.

intervalometer setting. An attempt to obtain oblique photographs of certain sites using a hand held F 24 camera was abandoned after heavy turbulence was encountered when descending into the valleys.

All film was processed back in the UK. Processing of the infrared film was undertaken at RAF Brampton. Considering the extreme haze encountered, the resultant photography was surprisingly good.

SITE RECONNAISSANCE

The time in Nepal, which was spent awaiting permission for the photographic flight, was used to carry out a ground reconnaissance of the sites selected by TRRL for detailed monitoring. This entailed visiting each site with a civil engineer and an engineering geologist from TRRL and discussing the relevant features which were to be recorded. Numerous 35 mm photographs were taken from various positions to obtain an indication of the coverage obtainable and the effectiveness of the geometry of the photography for measurement purposes. All camera positions were marked on sketches for discussion back in the UK for the selection of the photogrammetric camera stations by the following field party. The positions of the sun at each site at different times of day were also noted.

Another important aspect of the reconnaissance was the selection, after discussion with the TRRL geologist, of suitable, probably stable, datum stations for each site. Two stations were selected for most of the sites with three for the larger sites. Designs for station markers were made with sketch maps of their required locations so that they could be constructed by the contractor prior to the field party's arrival. Three sites on the Dharan-Dhankhuta road and eight on the East-West Highway were reconnoitred in this fashion.

Site Procedures

On arrival at a site, the datum stations which had been defined and constructed during the reconnaissance were located. One of these stations was used to define the origin of the (X, Y, Z) object co-ordinates. The X axis was aligned with approximate east by a compass bearing and the Z axis was in the upward vertical direction. The Y axis completed an orthogonal triad and was directed towards approximate north. Each site was therefore surveyed on a local datum.

The lack of suitable terrain for positioning cameras to obtain near normal stereophotography of a site meant that analytical methods of restitution had to be used if the time spent on site was to be kept to a minimum. Black and white targets were set up on the site. The number of targets varied from five on the smallest sites to 13 on the largest. The images of some of these targets can be seen in Fig. 3.

The control survey and photography were carried out simultaneously once the targets had been positioned. A Wild TCl electronic tacheometer was used for the control survey. Automatic recording of data was not used because of the difficulty of transporting and maintaining data transfer devices in remote areas. Measurements of horizontal and zenith angles and slope distances were made from each datum station to the other datum station, or stations, and to the targets. A prism reflector housed in a plastic shield with a spike at the rear was held against each target for distance measurements.

The prism/spike combination was found to have a "prism constant" of $+0{\cdot}096$ m $\pm$ 1 mm by calibration. Each target was observed from at least two datum stations. At the second epoch (1986), the measurements between the datum stations and to a distant reference object were compared with those obtained at the first epoch (1985) to check for possible relative movement. No significant movement of the datum stations was detected at any of the sites.

Two cameras were selected for photography: a Zeiss (Jena) UMK 10/1318 and a Wild P32. The wider angle and larger format of the UMK were advantages offset by its weight, although a lightweight mount was constructed for the work in Nepal (Fig. 4) to replace the normal orientation base. The P32 was adapted so that it could be used on an ordinary camera tripod. These two modifications were possible because of subsequent analytical instead of analogue restitution. A camera and its positions were selected to give complete cover of a site with the minimum number of photographs. On most sites, either the UMK or the P32 was found to be more suitable, but at some sites both cameras were used: the UMK for general overall coverage from longer distances and the P32 for coverage of smaller areas from shorter distances. In each case, all photographs were used in a bundle adjustment.

At each camera station the approximate values of the six elements of exterior orientation were needed as starting values for the iterative least squares bundle adjustment. The three orientation elements were determined by a compass bearing of the camera axis and by estimating the other two rotations by eye. Accuracies of

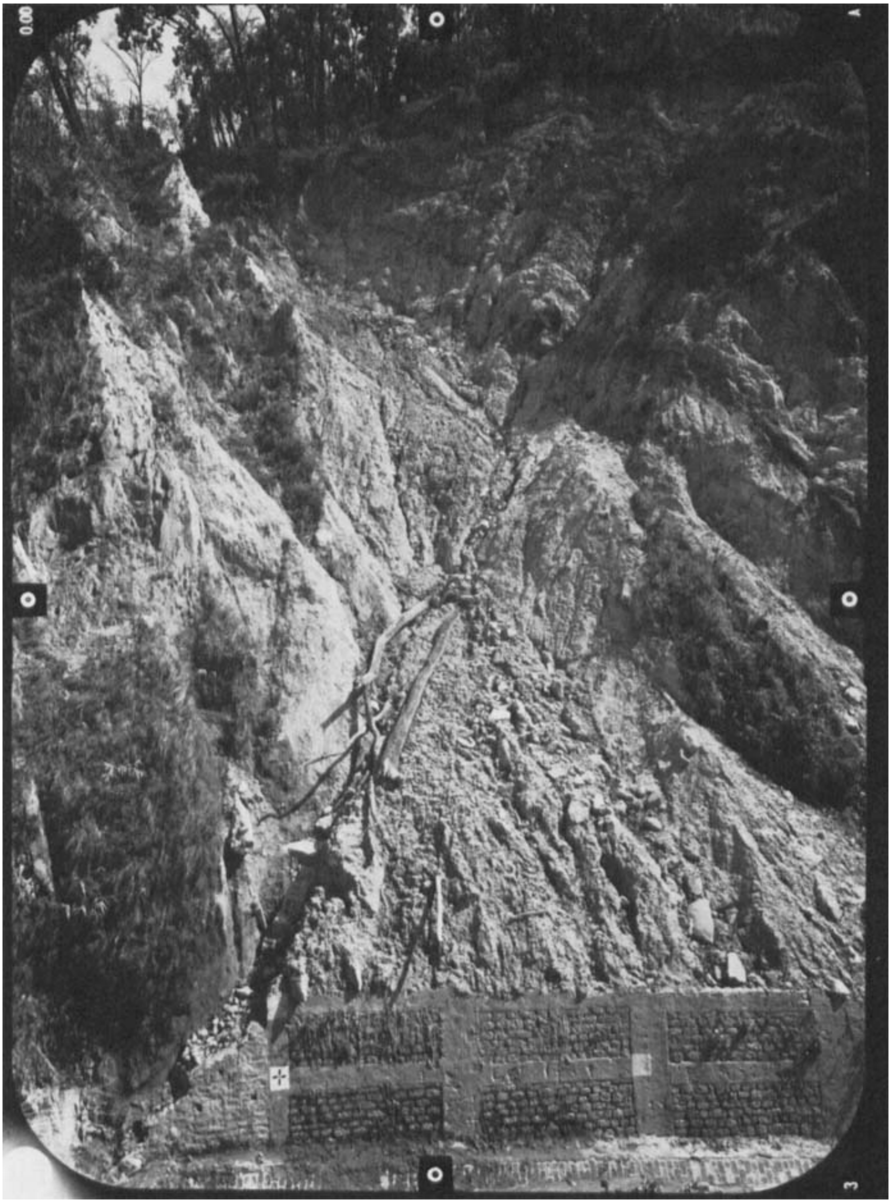

FIG. 3. Zeiss (Jena) UMK 10/1318 photograph of site 50+900 on the East-West Highway.

about 10 gon were found to be adequate and easily obtainable. The approximate three positional elements were found by various methods: by eye or by pacing or compass bearing if the camera station happened to be close to a datum station, or by tacheometer observations from a datum station to the camera station. Accuracies of about 5 m were found to be adequate.

When a camera had been set up with its axis in an appropriate direction, the shutter was held open and the field of view examined. If it was found that one or more targets fell just outside the format, the camera was rotated slightly to bring those targets into the field of view. Although it is not necessary for the minimum number of three targets to be imaged on each photograph in order to perform the

FIG. 4. Zeiss (Jena) UMK 10/1318 camera with lightweight mount.

bundle adjustment, the solution is strengthened if this is the case. It was generally possible to do this without sacrificing satisfactory coverage.

Agfa Pan 100 emulsion on glass plates was used in the UMK and the P32. Also 120 roll film (Ilford FP4 and Kodak Ektachrome 200) was used in the P32. Glass plates were processed in the Nepal Remote Sensing Centre in Kathmandu halfway through and at the end of the work. All roll film was processed in the UK. About 100 plates were used each year.

Following the control survey and photography of a site, all targets were removed and used at the next site. Work at two small sites or one large one could be completed in a day. Leaving targets in position overnight was inadvisable. The local inhabitants or domestic and wild animals would almost certainly disturb or remove them.

At the end of a day's site work, measured data were abstracted from the fieldbook, means determined and corrections applied. Co-ordinates to be used as starting values in the iterative least squares estimation were derived.

COMPUTATIONS AND PHOTOGRAMMETRY

The equipment used for measurement and computation was as follows:

(a) Zeiss (Jena) Stecometer (stereocomparator) for measurement of comparator co-ordinates *x*, *y*, *px* and *py*;
(b) MDR-1s/4 registration unit for recording and displaying comparator co-ordinates (to the nearest 1 μm) and an eight digit point identification number;
(c) Fortune 32:16 microcomputer, linked to the registration unit, operating under UNIX with C and Fortran compilers;
(d) two computer terminals with keyboards and screens, one at the computer and one at the Stecometer/MDR-1s/4 combination;
(e) Hitachi 672 A3 *x*/*y* plotter;
(f) Tektronix 4010 graphics terminal; and

(g) Gould PN 9005 computer, accessed from the Fortune, also operating under UNIX with Fortran and C compilers.

The procedure followed in the laboratory for each site, at each epoch, consisted of three main stages: computation of the control survey, the bundle adjustment and the detailed point by point measurement of a site from stereopairs. These stages are illustrated in Fig. 5.

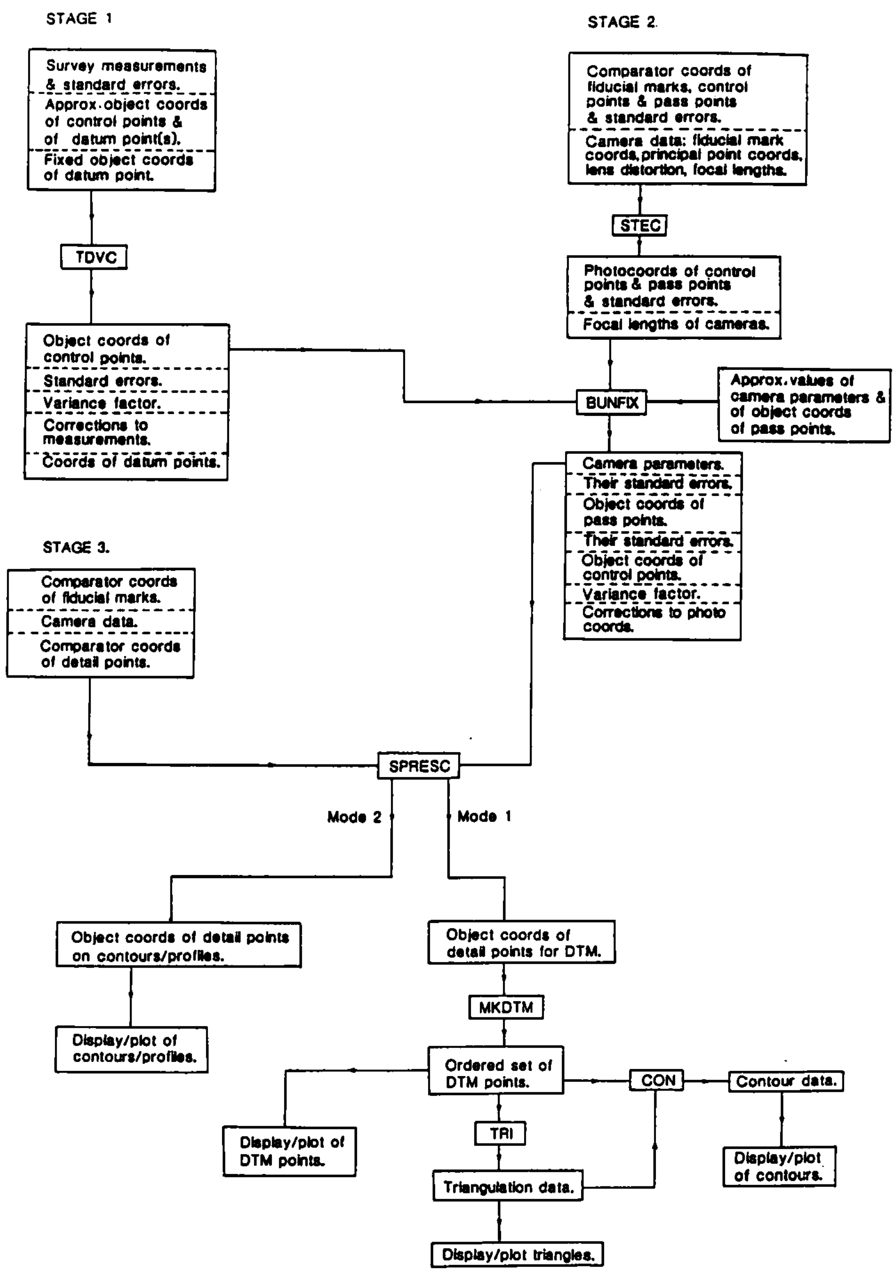

FIG. 5. Computations and analytical procedures.

In the first stage, program TDVC (Three Dimensional Variation of Co-ordinates), written in Fortran and executed on the Fortune, was used in an iterative least squares solution for the object co-ordinates of the control points and of at least one datum point. Only one datum point (and a reference object) was held fixed. The number of iterations necessary for the solution to converge depends largely on the accuracy of the approximate (or starting) values of the co-ordinates. Generally, no more than five iterations were necessary. The least squares corrections to the measurements and the variance factor were examined to see whether or not the measured and computed data were acceptable. Any gross or significant systematic errors were detected and either rectified or the relevant measurement was deleted and the procedure repeated. The standard errors of the resultant object co-ordinates were derived. When a satisfactory solution had been obtained, a file of control point object co-ordinates was created and stored, to be used later as part of the input to program BUNFIX.

In stage 2, all photographs necessary for adequate cover of the site to be surveyed in detail in stage 3 were selected and control points marked on the prints. Any pass points necessary were selected and marked. The first pair of photographs was placed in the Stecometer and comparator co-ordinates of the fiducial marks were measured first. Means and standard errors of comparator co-ordinates (x, y, px, py) of the fiducial marks were derived and displayed by Fortran program STEC on the Fortune. The operator could delete or add observations until the means were satisfactory. The parameters of the transformation from comparator co-ordinates to photograph co-ordinates

$$(x, y, px, py) \rightarrow (x_1, y_1, x_2, y_2)$$

were derived by program STEC according to the camera data (co-ordinates of principal point, co-ordinates of fiducial marks). By means of these transformation parameters, the effects of film deformation can to some extent be corrected. The comparator co-ordinates of control and pass points were then measured until the means and standard errors were satisfactory and this transformation was then used to derive photograph co-ordinates. Corrections can also be made for lens distortions, if these are known and significant. Further corrections for film deformation can be made to give refined photograph co-ordinates. The procedure was repeated for each pair of photographs.

For each photograph measured, program STEC produced a file of refined photoco-ordinates of control points and pass points with their associated standard errors. These files were used with the object co-ordinates of control points derived by program TDVC and the starting values of the camera parameters (including the focal length) and of the object co-ordinates of the pass points as input for program BUNFIX on the Gould. The output from this program consisted of exterior orientation parameters for all cameras, object co-ordinates of pass points and their standard errors, object co-ordinates of control points and the variance factor. The number of iterations needed varied from about five to 15, depending largely on the accuracy of the approximate (or starting) values of the object co-ordinates of the pass points and of the camera parameters. The variance factor and corrections to photograph co-ordinates were examined to see whether or not adjustment was satisfactory. Photograph co-ordinates given large corrections were examined, remeasurement of the relevant photographs made if necessary and program BUNFIX re-run with the new measurements.

For stage 3, the first stereopair selected for detail measurement was placed in the Stecometer and comparator co-ordinates of the fiducial marks were recorded, meaned and processed by program SPRESC to determine the parameters of the transformation from comparator co-ordinates to photograph co-ordinates. The comparator co-ordinates of each detail point in turn were measured, transformed to object co-ordinates by program SPRESC on the Fortune, working in one of two possible modes and making use of the camera parameters determined by program BUNFIX. Subsequently other stereopairs of the site were measured in the same way.

The awkwardness of manipulation of the four handwheels of the Stecometer so that the measuring mark is made to lie on the surface of the slope depends largely on the convergence of the camera axes. When the stereopair is near normal, the mark is easier to set than when the convergence is 10 gon or more. The analytical solution can work for all types of photography, unlike the analogue solution, which is also less accurate, but the detailing is done point by point and can be tedious for highly convergent stereopairs. Ways of overcoming this difficulty are discussed in the conclusions.

Program SPRESC in mode 1 allows data points to be collected for a digital terrain model which are then processed by programs MKDTM, TRI and CON written in C and executed on the Gould. The number of points which can be included in the DTM depends on which computer is used. The maximum is about 4000 in the case of the Fortune and about 1 million in the case of the Gould, but because the display and plot of DTM data are at present made using the Fortune, the maximum number of points was 4000. This was found adequate for the sites studied. Although the data points appear to be randomly distributed, they are selected far from randomly. The contouring program CON makes a linear interpolation between adjacent points so it is appropriate to collect data points at changes of slope. Points on breaklines are not given a distinctive code because where an important breakline occurs, closely spaced points along the breakline are collected. The triangulation program will, in general, place triangle boundaries along the breakline. The onus for selecting appropriate points for the DTM is on the operator who must also be knowledgeable about the engineering geology and geomorphology of the site. Points, triangles and contours can be displayed on the Tektronix screen or plotted on the Hitachi plotter.

In mode 2, program SPRESC allows the operator to collect only those points which lie on or sufficiently close to the intersection of the ground surface with a specified horizontal or vertical plane. This procedure was devised by Stirling (1982) and used by Small, Beecroft and Stirling (1984). To collect points lying on a contour, the contour value must be specified and the band width within which a point may be considered to be sufficiently close to the nominated contour value must also be specified. If the band width is too wide, the contour will be inaccurate; if it is too narrow, an undue amount of time will be spent finding acceptable points. To specify a profile, the measuring marks were set on the starting and finishing points of the desired profile thereby defining their object co-ordinates through program SPRESC. Choice of a band width depends largely on the distance from the camera to the slope and also on the irregularities in the slope surface. Band width values of the order of 0·05 m for contours and 0·1 m for profiles were found appropriate for the sites detailed.

To find a point within the band width of a specified contour, the operator places the measuring mark on the surface at a point which is judged to be on the contour. When the footswitch is pressed, the comparator co-ordinates are transformed to object co-ordinates and then tested to see whether or not that point is acceptable, that is within the specified band width. Program SPRESC causes two bleeps if the point is above the band width, one if it is below and none if it is within. In the last case only, the point and its co-ordinates are accepted and written to a file, otherwise the point is ignored. The operator is thus able, without the need to look away from the viewing system, to choose the next point.

The standard errors of object co-ordinates of control points were in nearly all cases less than 5 mm. It was decided that holding these co-ordinates fixed in the bundle adjustment would not degrade the accuracy of the geomorphological data. If this had not been the case, then the bundle adjustment would have been carried out using either the control survey measurements and their standard errors or the object co-ordinates from TDVC and their covariance matrix as well as the refined photograph co-ordinates and their standard errors in a combined adjustment. Program BUNFREE has been developed to do this or to make up any datum deficiencies by applying inner constraints.

Maintenance of the 5 mm precision of object point co-ordinates was achieved in the bundle adjustment provided glass plates were used. However, P32 Ektrachrome photography exhibited significant distortion, with asymmetric scale errors along the fiducial axes of the order of 1 in 1000. It was not possible to correct for distortions except along the fiducial axes, so significant systematic errors remained in areas away from these axes. Instead of using standard errors of about 5 μm for photoco-ordinates (as was the case with glass plates), values of the order of 20 μm were assigned. This was expedient, but not rigorous, and led to standard errors of object point co-ordinates from the bundle adjustment of between 20 mm and 50 mm. The effect of adopting this procedure on the geomorphological data was not significant in the context of the Nepalese slopes and allowed more detailed interpretation from the colour images than was possible from the more accurate black and white plates.

Further degradation of accuracy occurred in the measurement of detail points from stereopairs, mainly because each point was observed only once and it was a natural feature and not a target. To assess the final accuracy of the data, the same profile was derived from two different stereopairs. The resultant profiles agreed closely when plotted at a scale of 1 : 150 and the final accuracy of the position of a detail point was found to be of the order of 0·1 m, even when the distorted colour photography was used.

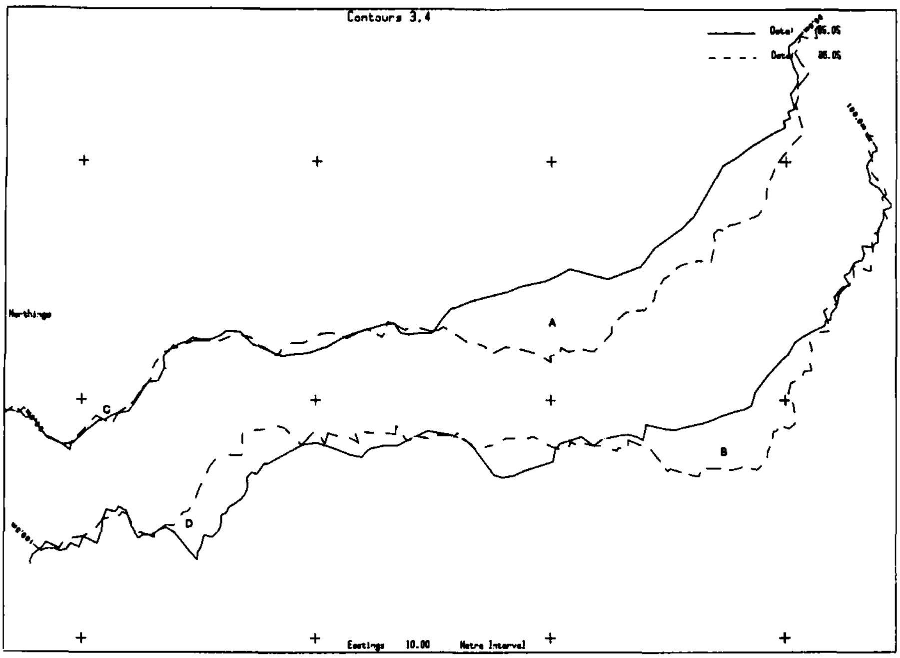

FIG. 6. Contour plot showing two contours in 1985 and 1986.

The collection of about 3000 points for the DTM contoured in Fig. 8 took about 1½ days. About one hour was necessary to obtain points which resulted in each profile and contour shown in Figs. 6 and 7.

GEOMORPHOLOGICAL INTERPRETATION OF EXTRACTED PHOTOGRAMMETRIC DATA

Perhaps the fundamental unit of any analytical photogrammetric survey is the coded co-ordinate. With this as a basic building block, the photogrammetrist is able to supply the geomorphologist with relevant positional information. Point selection and methods of point combination are obviously important and one can envisage an optimum where the maximum usage can be obtained from the minimum number of points. The possible approaches, with their associated advantages and disadvantages, are now illustrated with reference to the TRRL site 45+300 on the East-West Highway. A basic understanding of the geomorphological processes is necessary.

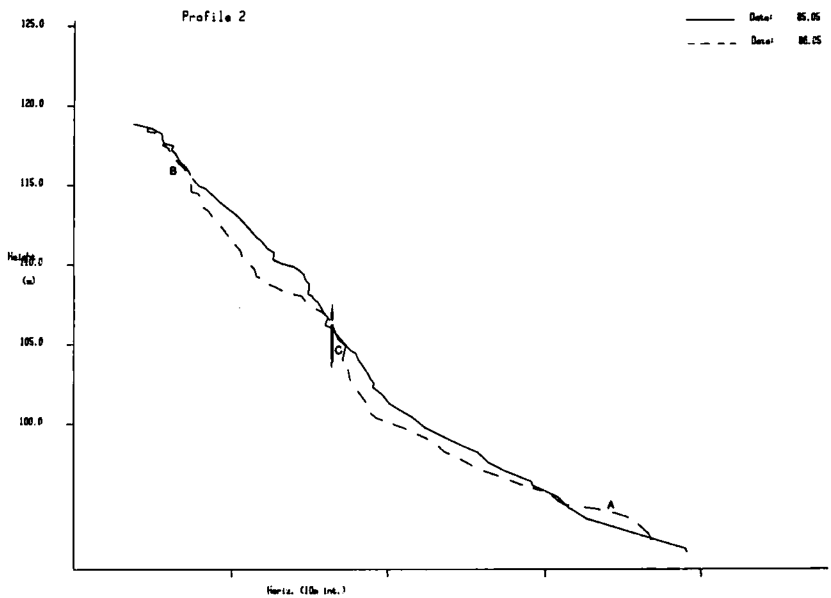

FIG. 7. Vertical profile, measured in 1985 and 1986.

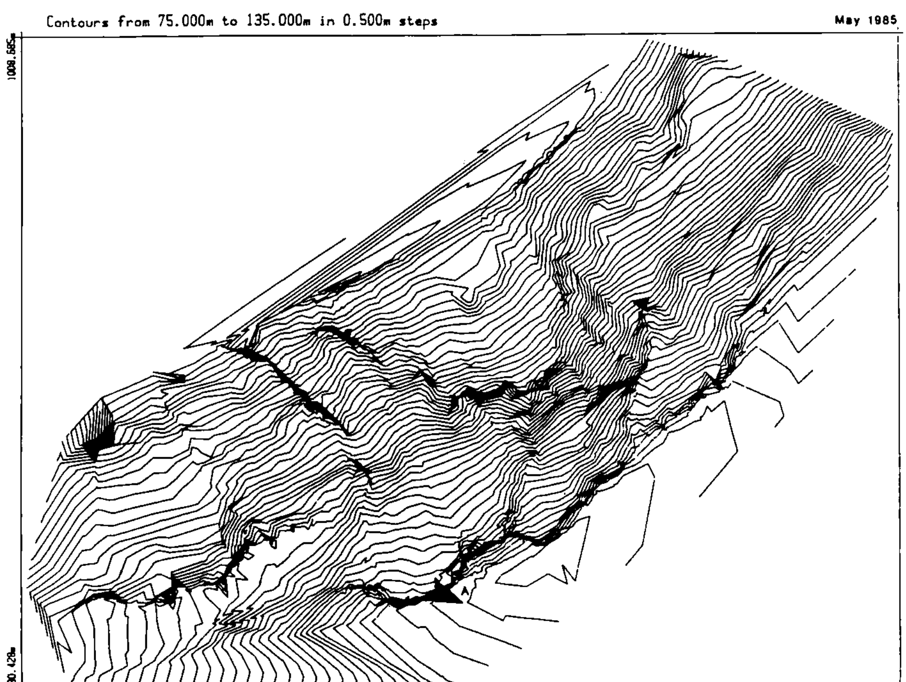

FIG. 8. Contour plot (vertical interval 0·5 m) produced from the DTM.

Very high rates of geomorphic activity are experienced at this site, for a variety of reasons. The regional factors, the elevated Himalayan rock masses, and fluvial erosion from the monsoonal storms, are augmented by more local factors. The geological factors include the anticlinal structure and a consequent weakness at the cleavage plane. Associated with this is the general weakening of the Siwalik sediments as a result of weathering (Brooks and Lawrance, 1985). By far the most important factor is that the construction of the road cutting has oversteepened the natural slope. This has probably initiated slope failure, so enabling the subsidiary regional and local factors to become important.

Referring to the annotated site photograph (Fig. 9), it is possible to identify a general pattern of processes. Headward retreat is backwearing the top of the cut slope. Material is deposited beneath the free face, notably within the bowl feature (A), so feeding the debris slide (B). At (D) the material is feeding a "mass movement catchment", a term used to describe the source areas for a general area of mass movement by sliding and slow flow. Slides (B) and (C) eventually deposit material onto the larger mudslides at (E) and (F). This material is augmented by debris from the rills and gullies (G), a result of concentrated overland flow. Also, occasional boulders are added by block failure from the sandstone outcrops (H) and (I). The major features of the site are the two large mudslides. Their state of stability plays a major controlling role in the overall activity of the site. The remedial measures designed to contain these mudslides are the conventional gabions at (J) and the experimental cylindrical gabions at (K) which are under construction. These are illustrated in the *Frontispiece.* By containing the toe of the slide, it is expected that the slope of the slide will fall below a critical angle so that stabilisation and revegetation can eventually occur.

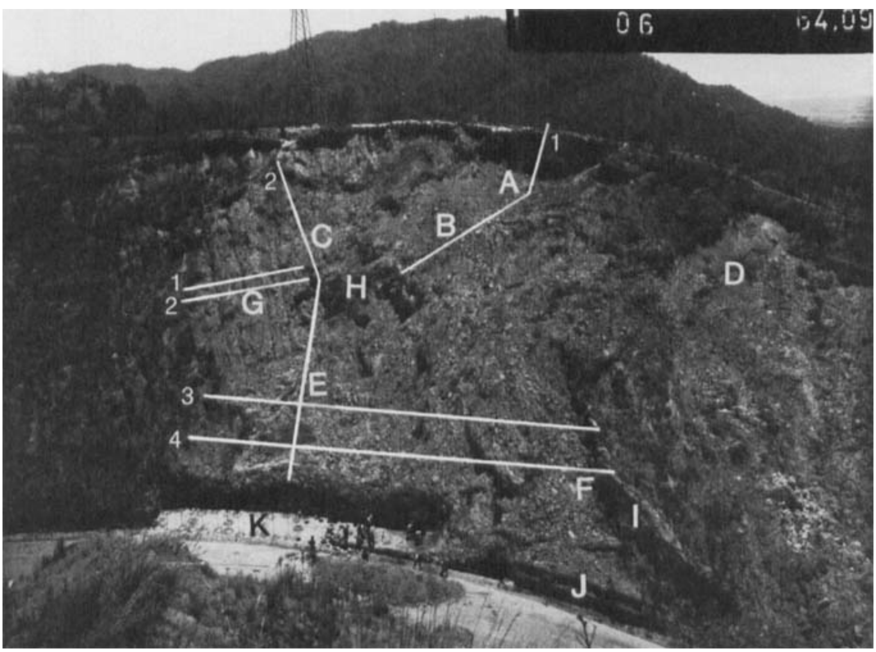

FIG. 9. Wild P32 photograph illustrating the pattern of processes and the approximate positions of the measured sections.

Although, in general terms, the pattern of processes is relatively straightforward, all the processes outlined here appear to interact. Consequently no process should be viewed in isolation and must be seen in the context of the whole slope.

There are four ways in which the coded co-ordinate can be used to supply geomorphologically useful data:

(a) total monitor the movement of all particles in all spatial directions;
(b) DTM record the shape or morphology with a digital terrain model;
(c) planar extract points which lie on specified planes, such as contours and vertical profiles; and
(d) point monitor the changes in positions of specific points.

The first and fourth method imply point identification or premarking and are therefore not suitable for non-contact measurement. Both the DTM and the planar methods were used at this site.

Planar Method

The critical aspect of the planar method is the selection of plane type, either contour or vertical profile, and the plane location. Six planes were observed at this site from the May 1985 and May 1986 photography and these are marked approximately in Fig. 9. However, space limitations can allow a discussion of only three of these planes.

Contours 3/4 (Fig. 6)

These cut across the base of the site and show the changes in dimensions of the mudslides. The major slide is at (A) and (B), where it is clear that the slide has receded in position by 3·0 m at (A) and 2·5 m at (B). This is a very major change and illustrates the high rate of geomorphic activity. The changes agree well with the history of this particular location as during the 1985 monsoon, the slides spilled large quantities of material onto the road. Interestingly, the secondary mudslide shows an advance of 2·5 m at (D) but comparatively little change at (C) of 0·5 m. The advance is not unusual as kinematic waves of sediment are often transported by such a system. However, a lack of morphological change at (C) does not necessarily mean inactivity. It is perfectly possible that a condition of steady state is in operation. In this the rate of input of debris from above is equalled by the rate of output below and so no change of form or form position will be seen. It is clear that a basic understanding of the processes occurring at a site is necessary. Therefore it is possible to interpret correctly the lack of change of some areas of the contours due to the comparative strength and stability of the sandstone outcrops and their resistance to subaerial erosion.

Profile 2 (Fig. 7)

This vertical profile passes through an area of headward recession, across a small debris slide to a sandstone rock band. Here a change in direction enables the section to pass through the axis of the major mudslide.

An interpretation of the changes agrees with that derived from Contours 3 and 4, with a horizontal change in position of approximately 2·0 m. However, vertical displacements are also apparent with a lowering of up to 1·8 m of the mudslide. The development of the mudslide toe at (A) has also been very noticeable. The upper mudslide seems to have been the most active with a maximum of 3·0 m of horizontal and 2·2 m of vertical displacement. The rock bands have remained relatively uneroded, except possibly at (B) and (C) where block removal seems to have occurred.

The planar method is quick, simple and it is relatively easy both to extract and display these data. The two major problems with the method are the subjectivity involved in the selection of suitable planes and that the information is only two dimensional, so true shape or morphology is not being compared.

DTM Method

The DTM method is more useful in this respect as three dimensional shape or form is recorded. In addition the DTM method has a far greater potential for producing useful data by further computerised processing. The model can be used to produce contoured and isometric plots and volume calculations can be performed. The greatest benefits can perhaps be obtained by subtracting DTMs at different epochs, so producing a "DTM of difference". This can itself be plotted, interrogated and analysed. These benefits can only be obtained with a good hardware and software combination. At The City University only the initial component of a DTM package, that of producing a contoured plot, has been developed so far.

At site 45+300, a composite DTM was formed at each epoch by the addition of a semi-random and a string DTM. The former consisted of approximately 2000 points observed in approximately parallel lines 0·5 m apart, the density of points along each line depending upon the topographic variation. The string DTM consisted of approximately 1000 points and was compiled by observing all linear features such as breaks of slope, channel boundaries and intercatchment divides. The DTMs were assembled for each epoch, triangulated and plotted with the software developed at The City University.

Fig. 8 is a contoured plot from the May 1985 DTM and a reasonable representation of shape and site morphology is indicated, although overhanging areas, such as at (A), are misinterpreted by the triangulating algorithm. Several landform features can be identified such as the top of the cut slope, the sandstone outcrops, the mudslides and even the area of rilling and gullying. The contoured plan can also be used to identify the preferred water movements, or the directions that water and consequently material will tend to move. This can be useful when assessing sediment source areas. It would have been preferable to have included the boundaries of the string DTM on the plot; this would help an interpretation greatly. A single contour plot is useful, though much depends upon the experience of the interpreter.

A similar plot was produced from the May 1986 photography and can be compared with the plot from the earlier epoch. With this it is possible to identify areas of change, but these are not immediately apparent. By overlaying the two plots, the situation is certainly not clarified. The positions of all contour lines have changed, both because of the use of different sampling points between the two epochs and the result of natural processes. The best way of separating these components is to observe the same sampling points at the two epochs, subtract the two resulting DTMs, so obtaining the true DTM of difference. This DTM would be directly proportional to the rate of process and can itself be further analysed and plotted.

Conclusions

The methods by which the coded co-ordinate can assist a geomorphologist have been indicated. Unfortunately the ideal solution of monitoring all particles, in three dimensions, will be unavailable for a long time. However the alternative methods, those of DTM processing and observing profiles and contours, are very powerful. Each method is probably best suited to different situations and so they tend to complement one another.

The observation of profiles and contours is a rapid and direct way of monitoring change in the direction of the selected plane. The software data processing requirements are small so that results are also displayed rapidly. Of the two, the vertical profile tends to be easier to interpret and does contain more information than the contour. However, the vertical plane must be downslope if further meaningful measurements such as slope angle are to be extracted. The major problem with the planar method is that any knowledge regarding the change can only be two dimensional.

The DTM method can allow for a full three dimensional analysis, as the data set is fully three dimensional. The DTM is slow to observe, simply because of the high number of data points that are necessary to describe fully any complex shape. The amount of useful information that can be derived from such a data source is potentially very high and includes volumes, contour plots and profiles. The possible analysis of the DTM of difference is perhaps the strongest aspect of such a method.

Rate of change can be computed and this could be correlated with lithology, vegetation, microclimate and possibly even process. This would give a far greater insight to slope behaviour.

The major requirement for a DTM approach is a powerful DTM computer package. Data acquisition is faster and easier with an analytical plotter, especially with superimposition of observed data in the eyepiece. In addition, a powerful database management system, interactive colour graphics and comprehensive DTM software will enable data of geomorphological relevance to be derived efficiently. The City University's acquisition of an Intergraph IMA photogrammetric graphics workstation is intended to meet these objectives.

Only a limited understanding of the relationship between lithology, climate, vegetation and process is possible by a photogrammetric survey in isolation. To begin to unravel the complex interrelationships between the factors outlined, an integrated approach is necessary. In this, the coded co-ordinate must be supplemented by geological, geotechnical, climatic and vegetational measurements. These data must be obtained at regular and planned intervals and interpreted by an array of earth scientists, if the data are to be used properly.

It has been shown that an analytical photogrammetric survey can be of considerable use to a geomorphologist. Such a survey can produce data of a quality and quantity far superior to those to which geomorphologists have been accustomed. Further developments and opportunities are highly likely.

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Note

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Résumé

On décrit dans cet article l'emploi sur un site du Népal de méthodes de photogrammétrie analytique à courte distance. Les données qui en résultent sont examinées en liaison avec la géomorphologie des pentes instables des montagnes népalaises. On mentionne également le recours à des photographies aériennes multibandes à faible coût pour une étude globale de l'érosion des versants.

Zusammenfassung

Beschreibungen von Geländemessungen und Verfahren der analytischen Nahphotogrammetrie. Die gewonnenen Daten werden in bezug auf die Geomorphologie instabiler Berghänge in Nepal diskutiert. Ebenso wird die Beschaffung billiger multispektraler Luftbilder zum Studium der Hangerosion beschrieben.