Monitoring Landslide Movement with a 35-mm Camera

J. D. BALLANTYNE, D. R. DEAN, JR., AND B. L. THOMPSON

The methods of analytical photogrammetry and microcomputer technology are combined to generate contour maps or cross sections, or both, of landslides along roadways with minimal conventional surveying. A conventional 35-mm camera and 8- by 10-in. photographs are used for the mapping. A minimum of two overlapping photographs are needed of the area to be mapped. Also, a minimum of six well-distributed control points are needed. Control points are points for which position (*X* and *Y* coordinate pair) and elevation (*Z*) must be obtained by conventional surveying techniques. The photogrammetric model used is the direct linear transformation model. This model uses *x* and *y* coordinates of corresponding images on two or more photographs to determine the position and elevation of such images in a ground-based coordinate system. A microcomputer performs the calculations and an electronic digitizer connected to the microcomputer is used to obtain the image coordinates on the photograph. The output can be in the form of a coordinate list of desired points, cross sections, a contour map, or three-dimensional perspective plot. The graphics are generated by a pen plotter connected to the microcomputer. Studies indicate that the error vector at about 400 ft is 0.4 ft for this system of mapping. A slope in distress can be monitored over a period of time. To eliminate resurvey, the six control points have to be located in a stable area.

A system for economically monitoring unstable slopes along roadways would enable highway departments to predict where to concentrate remedial measures for such slopes. This concept provided the impetus for developing a monitoring system that uses photogrammetric techniques and computer technology. At the outset, the goal was to develop a mapping system that would predict the position of points to within 1 ft. How the system was developed, how it was tested, and how it is applied in the field are described.

SYSTEM DEVELOPMENT

System Components

The mapping system includes two primary components, the hardware and the software. The hardware consists of a 35-mm camera (any amateur camera), a microcomputer, a monitor, a digitizer, a printer, and a plotter. The microcomputer used with the system software must have 256K of random access memory, two floppy disk drives, a color graphics adapter card, two serial ports, and a parallel port. The hardware is "off-the-shelf" equipment and would most likely be found in many modern design offices.

The software, which enables the system to be operational, has two aspects. One is the software that performs the photogrammetric calculations or reductions and the other is the software that performs the graphics or display operations such as outputting cross sections, contour maps, and perspective views. Both the photogrammetric and the graphics software are menu driven; that is, the user responds to prompts displayed on the monitor in order to use the system once the fieldwork has been done and photographs have been obtained. The graphics software was obtained from the U.S. Geological Survey in Denver, Colorado, as "freeware" and was modified to include the capability to output cross sections. The photogrammetric software was developed by the authors using the direct linear transformation (DLT) photogrammetric model developed by Abdel-Aziz and Karara *(1)* and modified by Bopp and Krauss *(2)*. In addition, lens distortion terms, both symmetrical and asymmetrical, developed by Brown *(3, 4)*, were included in the photogrammetric software. At this point a discussion of photogrammetric theory may be in order.

Photogrammetric Theory

Photogrammetric calculations for the position and elevation of points of interest may be thought of as involving two distinct operations. The first one is called space resection and the other is called space intersection. The resection calculations are performed one photograph at a time and the outcome of the calculations is the position and orientation of the camera. The intersection calculations are performed with two photographs and the outcome provides the position (*X* and *Y*) and elevation (*Z*) for the points of interest. Note that the intersection calculations must be performed with two or more photographs in order to determine the elevation and position of any point of interest. The photographs must be obtained from different locations.

Consider a camera focused on a point on a landslide. If the camera shutter is tripped, it is assumed that light will travel in a straight line from the point on the landslide through the camera lens to the film behind the lens and the point will then be imaged on the film. Now consider two coordinate systems, a two-dimensional system and a three-dimensional system. The two-dimensional coordinate system is in the plane of the film

J. D. Ballantyne and D. R. Dean, Jr., Department of Civil Engineering, West Virginia University, Morgantown, W.Va. 26506-6101. B. L. Thompson, Materials Control, Soil and Testing Division, West Virginia Department of Highways, 312 Michigan Avenue, Charleston, W.Va. 25305.

and the three-dimensional coordinate system defines the position and elevation of the point on the landslide. The former is referred to as the photo coordinate system and the latter is referred to as the object space coordinate system.

The photo coordinates of the image may be expressed as functions of the object space coordinates for the point on the landslide. These functions are as follows:

$$x = (L1*X + L2*Y + L3*Z + L4)/(L9*X + L10*Y + L11*Z + 1)$$

$$y = (L5*X + L6*Y + L7*Z + L8)/(L9*X + L10*Y + L11*Z + 1) \quad (1)$$

where

x and y = photo coordinates of the image of a point,
X, Y, and Z = the object space coordinates of an imaged point, and
$L1, L2, \ldots, L11$ = the transformation parameters.

The eleven transformation parameters ($L1$ through $L11$) are functions of

- The position (X and Y) and elevation (Z) of the camera lens in the object space coordinate system;
- The three orientation angles of the camera: one about the photo coordinate x-axis (ω), one about the photo coordinate y-axis (ϕ), and one about the lens axis (κ);
- The photo coordinates ($x\omega$ and $y\omega$) of the principal point, which is the point on the film where a perpendicular line from the camera lens would intersect the film; and
- The focal length of the camera lens.

It should be noted that the 11 transformation parameters are functions of only 9 camera orientation elements, which were listed previously. This point will be considered again later. When the transformation parameters are determined, the resection step will be complete.

How are the transformation parameters determined? First, consider six points on the landslide or in object space and that the position (X and Y) and elevation (Z) of these six points have been determined by conventional surveying techniques. The six points that have a position and an elevation determined by conventional surveying techniques are called ground control points. Next, the photo coordinates of the six control points are measured. The mapping system under consideration measures the coordinates with an electronic digitizer. Using the photo coordinates and object space coordinates of the six control points, 12 DLT equations, 2 for each point of the type in Equation 1, may be written. These 12 equations include the 11 unknown transformation parameters as well as the photo coordinates and the object space coordinates of the 6 ground control points. A least squares technique is used to solve the redundant, that is overdetermined, system of equations for the 11 unknown transformation parameters.

After the transformation parameters have been obtained for a particular photograph, they apply to any point imaged on that photograph or film so the photo coordinates of images of other points of interest can be measured and substituted into Equation 1. Even when the 11 transformation parameters are known, only two equations can be written for each image point, and these two equations are not enough to solve for the unknown X, Y, and Z for a point of interest. However, if a second camera position, hence a second photograph, is used, the transformation parameters for the second photograph can be determined as they were for the first photograph. Consequently, when the transformation parameters of the first and second photographs are known, four DLT equations similar to Equation 1 can be written for each point of interest, provided that the photo coordinates of such a point are measured or digitized on each of the two photographs. Again, with four equations and three unknowns, redundancy exists so another least squares solution for the X, Y, and Z of each point of interest is possible. Solving the set of four equations for X, Y, and Z for each point is known as performing the space intersection mentioned previously.

In summary, the photogrammetric reductions or calculations include two basic operations, space resection and space intersection. The resection operation requires the use of at least six control points or points of known position and elevation in object space to calculate the transformation parameters that are unique to each photograph. The resection operation is performed on one photograph at a time. The analytical intersection operation requires the use of at least two photographs for which the transformation parameters have been determined. The outcome of the intersection operation is the X-, Y-, and Z-coordinates for a point of interest in object space. In the next section some numerical considerations in solving for the transformation parameters for each photograph will be addressed.

Numerical Considerations

It was pointed out in a previous paragraph that the 11 transformation parameters are functions of only 9 camera orientation elements; consequently, the 11 transformation parameters are not all independent. This was recognized by Bopp and Krauss *(2)* and they developed two constraint equations to account for the lack of independence of the 11 transformation parameters. The use of constraint equations when calculating the transformation parameters makes the least squares solution more rigorous. The authors used these constraint equations as well as the DLT equations to compute the transformation parameters by the method of least squares.

The DLT equations are nonlinear in terms of the transformation parameters; therefore, the Taylor series expansion including only the first-order term was used to linearize the DLT equations. A least squares algorithm was applied to the linearized equations to arrive at a solution for the transformation parameters. During the linearization stage, an approximation of the transformation parameters is needed even before they are calculated. For the DLT equations, the first approximation for the transformation parameters may be set to zero. This is a great advantage compared with another popular photogrammetric model based on linearized collinearity equations. In the case of the collinearity equations, all zero approximations cannot be used for the camera parameters. The camera parameters include the camera lens position and elevation, the photo coordinates of the principal point, the focal length, and the three orientation angles. Realistic approximations must be substituted into the linearized collinearity equations before a solution can be obtained. A possible advantage of the collinearity equations over the DLT equations is that because there are two fewer unknowns, 9 versus 11, one fewer control point is needed.

Solving the nonlinear equations for the transformation parameters requires an iteration technique whereby a least squares algorithm is used to solve for corrections to the approximations for the transformation parameters. The iterations are continued until the corrections to the approximations are sufficiently small to terminate the iterations and assume that a solution has been obtained.

Software Coding

The photogrammetric software was written to include the theoretical considerations discussed. As mentioned before, the software is menu driven and using it typically involves typing in names of files that hold data or answering "yes" or "no" to prompts for selecting options for weighting, constraints, lens distortion correction, or output options. The photogrammetric software also includes routines for reducing transit and stadia notes in order to create data files that contain the object space coordinates for the control points. These specialized routines are addressed through the main menu that appears on the screen when the program disk is "booted." The use of the electronic digitizer to measure the photo coordinates of the images of points and to place these coordinates in a data file is also controlled by the photogrammetric software. The graphics software operates completely independently of the photogrammetric software, but it uses a data file created by the photogrammetric software. It should also be noted that the data file required by the graphics software may be created independently of the photogrammetric software.

SYSTEM TEST

The goal was to develop a mapping system that would predict the position of points to within 1 ft. Abdel-Aziz *(5)* developed general equations to predict the accuracy of object space coordinates derived from convergent photographs. However, the equations were for points located at special positions within the object space being measured. Points, for which coordinates are desired, are frequently distributed throughout the photograph so a practical test of accuracy for the system was needed. Also unknown was the kind of accuracy that would be possible using an electronic digitizer to measure photo coordinates on enlarged photographs obtained from amateur or nonmetric cameras. Consequently, a test field was established to test the system. The test field is an array of points on the tower and east wing of the Engineering Sciences Building at West Virginia University. Test points are located at the corners of window frame moldings and at other discrete marks present on the building. The *X*-, *Y*-, and *Z*-coordinates of 47 such test points were obtained by conventional surveying methods. A test of the mapping system consists of comparing the *X*-, *Y*-, and *Z*-coordinates for each point as determined by conventional surveying methods and as determined by photogrammetric surveying.

Establishment of Test Points

The position of the test points on the Engineering Sciences Building was determined from two baselines that were connected by conventional surveying methods. The method of angle intersection, both vertical and horizontal, was used to determine the position of the test points. Because two baselines were used, the position of each test point could be determined by two independent sets of measurements and calculations; thus a check for the position of each point was possible. As an estimate of the test point position, the average of the two independent determinations was obtained, and this average *X*-, *Y*-, and *Z*-coordinate became the standard against which the photogrammetrically determined values were compared.

The mean difference between the two independent conventional determinations of the *X*-, *Y*-, and *Z*-coordinates for the test points on the Engineering Sciences Building and the standard deviations of the differences of the *X*-, *Y*-, and *Z*-coordinates are as follows:

Coordinate	*Mean (ft)*	*Standard Deviation (ft)*
X	0.006	±0.113
Y	0.037	±0.081
Z	0.003	±0.021

Some of the test points were used as required control points for the photogrammetric reductions, but the points used for control were not used in subsequent tests for accuracy.

Photogrammetric Procedures

Photography

Photographs were obtained with a 35-mm camera using black-and-white film. A 50-mm lens and a zoom (70- to 200-mm) lens were used. The concept was to simply get a picture of the test points by centering the camera axis on the test field. Photographs were obtained at a number of positions, with respect to the test field, with both the 50-mm lens and the zoom lens. The various test combinations are given in Table 1. For example Test A was from a two-photograph model and the zoom lens was used. Note that there are three-photograph models and four-photograph models. Even with the multiple-photograph models, each exposure was obtained with the camera axis centered on the test field.

Film and Print Processing

After the film was exposed, it was sent to a local photo lab for developing and printing. There were no special instructions other than to make full-frame prints on 8- by 10-in. resin-coated paper. These 8- by 10-in. photographs were the prints on which the photogrammetric measurements were made.

TABLE 1 SYSTEM TEST RESULTS

	Difference Between Conventional Survey and Photogrammetric Survey								95% Confidence Interval for Mean of Error Vector	No. of Test Points	Avg Camera Distance to Center of Site	B/D Ratio
	X-Coordinate		*Y*-Coordinate		*Z*-Coordinate		Error Vector					
Test	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev				
A	0.08	±0.17	0.19	±0.36	−0.01	±0.11	0.41	±0.20	0.34 to 0.48	38	471	0.60
B	0.08	±0.17	0.17	±0.38	0.01	±0.12	0.42	±0.22	0.35 to 0.49	38	463	0.61
C	−0.01	±0.18	0.16	±0.33	0.07	±0.14	0.39	±0.20	0.32 to 0.46	38	356	0.47
D	0.05	±0.19	−0.18	±1.78	0.11	±0.22	1.49	±0.99	1.16 to 1.82	38	435	0.23
E	0.03	±0.16	0.25	±0.32	0.04	±0.11	0.39	±0.21	0.32 to 0.46	38	401	0.56
F	0.28	±0.53	−0.43	±0.60	−0.15	±0.19	0.88	±0.38	0.64 to 1.12	12	135	0.64

Note: Confidence interval = Mean ± Stdev * $t_{0.025,df}$/[No. of points]$^{1/2}$. Error vector = [(difference in $X)^2$ + (difference in $Y)^2$ + (difference in $Z)^2]^{1/2}$. Engineering Sciences Building test field (high precision control): A = two photos, 70- to 200-mm zoom lens; B = three photos, 70- to 200-mm zoom lens; C = three photos, 50-mm lens; D = two photos, 50-mm lens; E = four photos (2 from Test A, 2 from Test C). Alternative test site (Cooper's Rock) (low precision control) stadia: F = two photos, 50-mm lens. Units are in feet unless otherwise noted. Stdev = standard deviation.

Photogrammetric Measurements and Reductions

The photo coordinates of the images of the test points on each photograph were measured with an electronic digitizer connected to a microcomputer. As the photo coordinates were measured, a file was created in which all of the photo coordinates of the test points on a particular photograph were saved or stored. These files of photo coordinates were used to run repeated photogrammetric reductions, space resections, and space intersections to obtain the *X*-, *Y*-, and *Z*-coordinates of the test points in the ground coordinate system that was established by conventional techniques. The photogrammetric reductions were made using the photogrammetric software described previously.

Weighting, Constraints, and Lens Distortion Corrections

Multiple photogrammetric reductions were performed on the data files of photo coordinates. These multiple runs were performed to study the effect of various weighting techniques, the effect of including constraint equations as suggested by Bopp and Krauss *(2)*, and the effect of correcting for both symmetrical and asymmetrical lens distortion as modeled by Brown *(3, 4)*. The photogrammetric software enables the user to select any combination of these options before performing the photogrammetric reductions.

There are two weighting options that may be used during the least squares solution for the 11 transformation parameters. One weighting option permits the user to assume that all photo coordinates have equal weights; that is, no one photo coordinate is more accurate than another. The other weighting option permits the user to assign weights to the photo coordinates on the basis of the variances for each photo coordinate. The weight is made equal to the inverse of the variance for each photo coordinate. Consequently, photo coordinates with small variances will have larger weights than coordinates with larger variances and will contribute more to the least squares solution for the transformation parameters. The least weighting option may only be selected when multiple measurements have been made for each photo coordinate or if the user assigns individual variances to each coordinate.

There are just two constraint options. Either the constraint equations for the 11 transformation parameters as developed by Bopp and Krauss *(2)* are enforced or they are not.

There are several possible options for corrections for symmetrical and asymmetrical lens distortions. It has been shown that three terms in an odd-powered polynomial are sufficient to model symmetrical radial lens distortion. Consequently, the user has the option of correcting for such distortion by using one, two, or three terms when making photogrammetric reductions. Two terms are always required to model asymmetrical lens distortion. The user has the option of either correcting or not correcting for asymmetrical lens distortion during photogrammetric reductions.

If the same options were selected for every photograph in a set of photographs used in a photogrammetric reduction for the *X*-, *Y*-, and *Z*-coordinates of test points, there would be 20 possible combinations of the options or 20 different possible photogrammetric reductions. Not all possible reductions were made, but enough were made to determine which options were important for the system under consideration.

Index of Accuracy

The accuracy of the photogrammetric reductions is indicated by observing the difference between photogrammetrically determined *X*-, *Y*-, and *Z*-coordinates and the conventionally determined *X*-, *Y*-, and *Z*-coordinates for test points on the Engineering Sciences Building. A single index of accuracy is the error vector that is computed as follows:

$$EV = [(dx)^2 + (dy)^2 + (dz)^2]^{1/2} \quad (2)$$

where

EV = error vector,
dx = difference in X coordinates,
dy = difference in Y coordinates, and
dz = difference in Z coordinates.

The error vector was computed for each test point, and the average error vector for all test points was computed for each condition tested. If the error vector was less than 1 ft, the accuracy requirements that were established at the outset had been met.

Alternative Test Site

The system was also tested on a cut slope. At this test site the test points and control points were determined by the method of stadia. Photographs were obtained and the photogrammetric reductions were made in a manner similar to that used for the test field on the Engineering Sciences Building. The main difference was the accuracy with which the control point positions were known.

Discussion of Test Results

The test conditions are identified as A through F. The conditions are as follows:

A = two photos, zoom lens, Engineering Sciences Building (ESB);
B = three photos, zoom lens, ESB;
C = three photos, 50-mm lens, ESB;
D = two photos, 50-mm lens, ESB;
E = four photos (two from A and two from C) ESB; and
F = two photos, 50-mm lens, alternative site, control by stadia.

It should be noted that the control points and the test points were known with greater accuracy on the Engineering Sciences Building than on the alternative test site. Also, the error vector, as previously defined, is the index used to measure the accuracy of the system.

Effects of Options

The weighting, constraints, and lens distortion correction options were exercised in various combinations for each of the test conditions while the photogrammetric reductions were executed to determine the X-, Y-, and Z-coordinates of the test points. The same control points were always used. The average error vector for each of these reductions was studied to determine the effects of the various options used. These studies indicated that the weighting technique of assigning weights on the basis of the variance of the photo coordinate gave a slightly better error vector than did assigning weights equally to all photo coordinates. Invoking the constraint equations did not change the error vector; that is, there was no improvement in accuracy when the constraint equations were used. An unexpected result occurred when the lens distortion terms, both symmetrical and asymmetrical, were exercised. With the addition of terms to correct for lens distortion, the error vector increased in size or the accuracy decreased. It is hypothesized that the lens distortion correction terms that were used did not adequately model the lens distortion for the photographs. This is because there is not only distortion due to the camera lens but also distortion due to the enlarger lens used to print the photograph. Some distortions may also occur because the principal point of the negative cannot be aligned with the lens axis of the enlarger. Perhaps a better model for these distortions could be derived.

On the basis of the average error vector from the multiple reductions while various options for weighting, constraints, and lens distortion correction were exercised, it can be concluded that the only option that need be applied is weighting. The weighting option that assigns weights on the basis of photo coordinate variances should be selected. In the present study, weighting the photo coordinates in this manner decreased the error vector slightly but not significantly. Exercising the constraint equations had no beneficial effect on accuracy. The lens distortion terms, when exercised, were actually detrimental to the accuracy. Because the lens distortion terms are not required for this system, the minimum number of control points to permit redundancy in the least squares solution for the transformation parameters is six. The results of all tests discussed hereafter were obtained by executing the photogrammetric software so that only the weighting by variances option was selected. This is the recommended procedure for using the photogrammetric software.

Test for Accuracy

Photographs of the test site were obtained from a number of different positions and with different camera lenses. Camera position and lens type make up a test condition. The test conditions were identified and listed previously. The average error vector for each condition was the index for accuracy. Results of the test for each condition are given in Table 1.

The 95 percent confidence interval for the mean of the error vector was used to determine whether the mapping system met the accuracy requirement that was specified initially. If the confidence interval was within ±1 ft, the mapping system met the accuracy requirements. An inspection of Table 1 shows that the mean error vector as determined under Test Conditions A, B, C, and E was within the required limits. Condition A was a two-photo model obtained with a zoom (70- to 200-mm) lens at about 450 ft. Condition B was similar to A except that a third photograph was included. Including the third photograph did not improve the accuracy of the system. Condition C was a three-photo model obtained with a 50-mm lens at about 350 ft. Note that the mean error vector for this condition is better than for Conditions A and B, but not significantly better. Condition E consists of the two outside photographs from Condition A and the two outside photographs from Condition C. Again, use of more than the minimum of two photographs did not increase the accuracy of the mapping system.

The mapping system did not meet the accuracy requirements under Condition D, which was a two-photo model obtained with a 50-mm lens at about 450 ft or less. The distance of about 450 ft probably was not the reason the accuracy requirement was not met. The test for Condition D probably failed because the two camera axes intersected at such a small angle that the photogrammetric intersections were weak. Note that the B/D ratio for condition D is quite small whereas the B/D ratio for the successful conditions are near 0.5 or greater. The B/D ratio

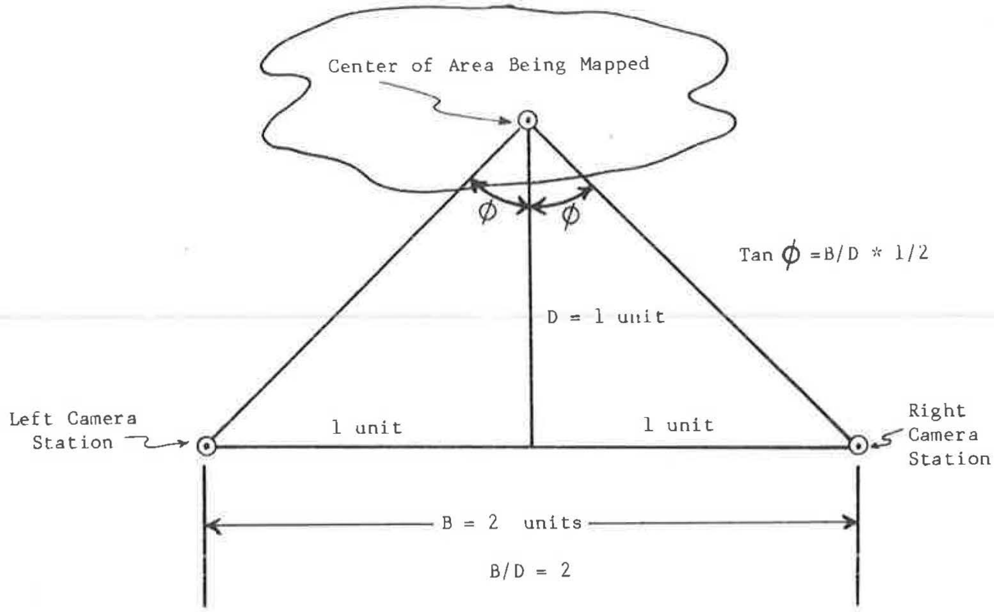

FIGURE 1 Optimum camera configuration.

is the base length between camera stations divided by the perpendicular distance from the base to the point being photographed (Figure 1). The B/D ratio is not necessarily an indication of convergent camera axes. But, if the two camera axes are directed toward the center of the object being mapped, the B/D is an indication of the amount of convergence of the two camera axes. As shown in Figure 1, if the B/D ratio is 2 and the two camera axes are directed toward the center of the object, the intersection angle of the two camera axes is 90 degrees. Such an angle of intersection is optimum for computing intersections. The convergence angle of the two camera axes in Condition D is small. The distance between the camera stations was only about 100 ft ($0.23 \cdot 435 = 100$). If the distance between the camera stations had been increased and the depth to the test field maintained as before, perhaps the results would have been better.

The mapping system also failed to meet the accuracy requirement under Condition F. It should be noted that under Condition F the mean error vector was less than 1 ft and that the upper level on the confidence limit was over 1 ft by a small amount. Because the control and test point positions were established by the method of stadia, their positions were only known to within ±1 ft to begin with.

It appears that establishing the six control points by stadia may not be adequate to meet the accuracy requirements of ±1 ft. The method of angle intersections from each end of a measured baseline would be adequate. Other possibilities exist and additional studies are ongoing.

USE OF THE SYSTEM

Use of the proposed mapping system to monitor an unstable slope requires both field and office procedures. The procedures are not complex, but they do require some planning.

Field Procedures

Field procedures are to

1. Determine the number of photographs required,
2. Determine where control points should be located,
3. Determine position of control points,
4. Determine if artificial targets are necessary, and
5. Obtain photographs.

Number of Photographs

The number of photographs required for stereo coverage of the site is determined simply by looking through the viewfinder of the camera, visualizing the frames, and moving around the site to select the camera stations. Of course, the minimum number of photographs is two. Previous studies by Abdel-Aziz *(5)* and Kenefick *(6)* have shown that the best accuracy is obtained when the two camera axes intersect at about a 90-degree angle. This should be kept in mind when selecting camera stations, and an attempt should be made to obtain convergent photographs such that the camera axes will intersect near the center of the site being mapped at an angle close to 90 degrees (Figure 1). Because of varying site conditions this may not always be possible, but it is a rule that should be followed whenever possible. A third camera station may be selected. However, the third photograph is not necessary if 100 percent overlap is obtained with the first two photographs. In some situations the third photograph may be needed just to get stereo coverage of the entire site. The system will handle a total of four photographs. It is important to remember that every point to be mapped must appear on at least two photographs.

Location of Control Points

When the number and orientation of photographs have been determined, the next step is to determine where control points must be located. The points to keep in mind are that there must be at least six control points visible in every photograph and that they should be well distributed over the site and not clustered together. Also, to avoid having to reestablish the control before every remeasurement on the site, the control points should be located in stable areas around the border of the active landslide. Another point to remember is that if lens distortion terms are used in the photogrammetric software, an additional control point should be obtained for every lens distortion term that is added. However, it should be noted that the results of tests that were discussed in the previous section indicate that, because paper print enlargements are being used, including lens distortion terms for the system produces no significant gain in accuracy.

Determination of Control Point Position

The *X*-, and *Y*-, and *Z*-coordinate position of the control points may be obtained by a number of methods. The stadia method may be used if slope angles are not great. Also, the angle intersection method may be used. The angle intersection method involves measuring a horizontal and a vertical angle to the control point from each end of a measured baseline. The horizontal angle is the angle to the right from the baseline and the vertical angle may be measured from a horizontal line, zenith, or nadir. The photogrammetric software includes routines for reducing the field data from either of these methods to a file of *X*-, *Y*-, and *Z*-coordinates for the ground control points. Other conventional surveying methods may also be used to obtain the *X*-, *Y*-, and *Z*-coordinates for the ground control points. As a rule, the more accurate the control data, the more accurate the results from the photogrammetric reductions will be.

Targeting

The mapping points (that is, the high points, the low points, and the points in between where the slope changes) and the ground control points must be discernible on at least two photographs. If there are no natural features such as rocks or clumps of soil to be used to mark the mapping points, these points must be artificially targeted. Some targeting materials are sheets of paper, lime, and stakes with paper wrapped around the bottom and secured with a rubber band. It is best for the target to be larger than the crosshairs on the digitizer. If the target is slightly larger than the crosshairs, pointing precision on the digitizer is optimum.

Obtain Photographs

At this stage everything should be ready for taking photographs; that is, camera stations have been located, ground control point locations determined and measured, and targeting completed if necessary. Care should be used to obtain photographs in sharp focus and with good depth of field. It is important that the photographs be of good quality in order to get good results from the photogrammetric reductions. A suggested practice at this point is to make a rough sketch of the site from the perspective of the camera station and note rough locations of mapping points and ground control points. The sketch will be helpful in the office in identifying and labeling mapping and ground control points.

Office Procedures

Office procedures have been simplified by the photogrammetric software. After the film has been developed and 8- by 10-in. photographs have been printed, the photographs must be studied so that conjugate mapping and ground control points can be identified with the same symbol or labeling mark. It is at this identification stage that the sketches made in the field at the camera stations may be beneficial.

After the points have been identified on the photographs, the remaining office procedures are controlled by the photogrammetric software. All that is required is that the digitizer, plotter, and printer be properly connected to the computer and that the computer equipment be in proper working order. Three floppy disks are required, one for holding the photogrammetric software, one for holding the graphics software, and one formatted blank disk to be used as a project data disk. To perform the photogrammetric operations, the photogrammetric software disk is put in Drive A, the formatted blank data disk is placed in Drive B, the microcomputer is switched on, the system is automatically booted, and a menu of instructions is displayed on the monitor. From this point on it is a matter of following instructions and responding to prompts displayed on the monitor. All office steps from inputting the ground control point data file to outputting the data file required by the graphics software are controlled by the photogrammetric software.

To produce the graphics output, the graphics software disk is placed in Drive A and the data disk is left in Drive B. The program is booted and, again, a menu prompts the user on what is needed to execute the various graphics programs to output point plots, contour plots, cross sections, or perspective plots.

CONCLUSIONS

If the proposed mapping system is used under the right conditions, an accuracy of ± 1 ft can be achieved. Desired conditions include

1. The two camera axes intersecting at about a 90-degree angle;
2. A maximum distance of about 450 ft from the camera to the site being mapped;
3. Preferably a 100 percent overlap of the site on two photographs, although three or four photographs can be used if there is sufficient ground control;
4. Six or more ground control points must be visible on each photograph;
5. The position of each ground control point should be known to within 0.1 ft; and

6. The control points and other mapping points should be distinctly visible on each photograph.

There are a number of advantages to using the proposed mapping system. One big advantage is that it allows any design office with a microcomputer, a digitizer, and a pen plotter to perform limited photogrammetric mapping without highly specialized (expensive) equipment or training. Also, the proposed system saves both field survey time and office drafting time. An estimate of the time savings would be between 25 and 50 percent. Output from the photogrammetric software can also be plotted by hand or further manipulated by other software. In addition, the photographs provide a nearly permanent record of site conditions.

An advantage from the standpoint of safety is that the mapping of inaccessible or unsafe sites such as unstable rock slopes can be accomplished with a minimum of exposure of personnel to hazardous conditions. Photographs may be obtained from a light plane or helicopter, but the requirement for the six ground control points and the B/D ratio must still be met.

The system is user friendly in a number of ways. The software is menu driven, so training to use the system is quite easy, particularly compared with systems that require the use of the floating dot. Also, the hidden error trapping or checking routine that checks the data during input reduces the possibility of the user unknowingly crashing the program.

The equipment can also be used for other tasks. This is attractive in that equipment costs can be spread among several activities. Many design departments have most of the hardware equipment necessary to perform the mapping. Cost of the equipment, exclusive of the camera, about 2 years ago was around $7,000. Today the cost would no doubt be less. Any type of camera may be used, but an SLR 35-mm camera that can accept different lenses such as telephoto lenses is the most versatile.

The proposed mapping system also has some disadvantages. There must be at least six ground control points for each photograph. The accuracy of the photogrammetric reductions depends to some degree on the accuracy of the ground control points. Because of the need for control points on each photograph there is some limit to the size of the area that can be mapped using the system. If the site is extremely uniform in texture, targeting of mapping points is also required.

The accuracy achieved is not as great as that obtained by more sophisticated methods. However, given that paper prints, rather than glass diapositives, are being used and that an electronic digitizer, rather than a precise photogrammetric comparator, is being used, it is the opinion of the authors that the advantages of the system outweigh the disadvantages. All indications are that, under the restrictions noted, the proposed mapping system can be used to monitor slopes with an accuracy of ±1 ft.

REFERENCES

1. Y. I. Abdel-Aziz and H. M. Karara. Direct Linear Transformation from Comparator Coordinates into Object Space Coordinates in Close-Range Photogrammetry. *Symposium on Close-Range Photogrammetry*, University of Illinois, Urbana, Jan. 26–29, 1971, pp. 1–18.
2. H. Bopp and H. Krauss. An Orientation and Calibration Method for Non-topographic Applications. *Photogrammetric Engineering and Remote Sensing*, Vol. 44, No. 9, 1978, pp. 1191–1196.
3. D. C. Brown. *The Simultaneous Determination of the Orientation and Lens Distortion of a Photogrammetric Camera*. Technical Report 56-20. Air Force Missile Test Center, Patrick Air Force Base, Fla., 1956.
4. D. C. Brown. Decentering Distortion of Lenses. *Photogrammetric Engineering*, Vol. 32, No. 3, 1966, pp. 444–462.
5. Y. I. Abdel-Aziz. Expected Accuracy of Convergent Photos. *Photogrammetric Engineering*, Vol. 40, No. 11, 1974, pp. 1341–1346.
6. J. Kenefick. Ultra-Precise Analytics. *Photogrammetric Engineering*, Vol. 37, No. 11, 1971, pp. 1167–1187.

Publication of this paper sponsored by Committee on Soils and Rock Instrumentation.