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# Measurements of Slope Movements with a Simple Camera

## La Mésure des Déformations des Pentes avec un Appareil Photographique Simple

D.H. SHIELDS Head, Civil Engineering Department, University of Manitoba, Winnipeg, Manitoba, Canada
E.J. HARRINGTON Geotechnical Engineer, Hardy Associates (1978) Ltd., Vancouver, B.C., Canada

SYNOPSIS The use of photogrammetry to obtain slope movement data for mine expansion designs was dictated by environmental constraints which included data acquisition by essentially untrained personnel over a prolonged period in a remote location. It was judged that the appropriate technology for the situation required a simple, mass-produced camera and the use of suitably modified and simplified standard photogrammetric methods. Good correlation was proved by comparison of calculated dimensions from stereopairs with surveyed distances in the field. Although the equipment used on this project could not resolve small creep movements, fairly detailed information concerning the major features of slope movements can be obtained. Photogrammetry is highly developed as a separate discipline and should be used much more often in the geotechnical sciences in the future.

## INTRODUCTION

Photogrammetry was chosen as the preferred method with which to monitor movements of the slopes at an open pit coal mine in Indonesia. The advantages of photogrammetry are:

1) Measurements can be made from relatively stable positions remote from the slope themselves, thereby ensuring consistency, continuity and the safety of personnel involved with monitoring.

2) Large areas of slopes can be monitored practicably and economically.

This latter point is particularly important since it is often impossible to predict in advance which areas of a given slope or pit face are likely to move and it is necessary to observe the entire area which may be potentially unstable.

Photographs, in addition to providing a permanent record, free of human error and bias, also provide a visual record of what happens. Relatively unskilled people taking photographs can be the 'eyes' of an engineer who may visit the site only infrequently. Photographs taken at regular intervals will show the evolution of a particular movement or failure and this information is often invaluable as an indicator of failure mechanism and when planning remedial measures or designing the next phase of the project.

In order to meet both budget restrictions and the level of sophistication of the engineers and technicians carrying out the work at the mine, the equipment and procedures were made as simple as possible. It is these simplications which provide the basis of this paper. The results should be of interest to any geotechnical engineer on any project where fairly large movements are anticipated.

The following sections describe the camera equipment which was chosen, a typical field set up, the procedures followed to take the photographs, and the calculations of movement. The presentation starts off with a detailed description of how the 'mystique' was removed from photogrammetry so that the techniques were readily understood by both office and field personnel.

## SIMPLIFYING PHOTOGRAMMETRY

Photogrammetry is the science of making measurements from photographs. A pair of photographs, with a certain amount of ground common to both views, a stereo pair, is the basic unit in photogrammetry. A stereo pair can be used to build a true three dimensional model of the scene being photographed. When used for slope movement studies, it is the direction and distance a reference point on the slope moves in the time interval between sets of a photograph that is of interest. This movement can be measured photogrammetrically by comparing the location of a point in space at one instant in time with its location at a second instant in time; the change in location is the measure of the movement. The location of the point at any instant must be described with relation to a known position - in this case the position of the camera.

In standard photogrammetry a considerable amount of auxilliary equipment and effort is required to locate the camera with precision and to determine exactly the direction of the camera axis (or line of sight). To measure relative movement of a point, it is not necessary to know the exact position of the camera in space; it is only necessary to know the position of the camera when the second set of photographs is taken relative to its position when the first set was taken. This means that the distance and direction the camera was moved has to be known in order to account for the changing camera position when calculating the movement of a point on the slope.

If the exact same camera position and camera axis direction are used from one series of photographs to the next (and the position is truly fixed), then the location of the camera in space does not have to be known in order to measure slope movements nor does movement of the camera have to be considered in the calculations. Fixing the camera position, then, dramatically simplifies the use of photogrammetry to measure movement. The apparent movement of a point from one series of photographs to the next series is the true movement of the point.

The same process of simplication and elimination can be followed in the case of other variables which are involved in photogrammetry. The other variables include:

1) The distance between camera locations which are used for a stereo pair (if this distance is a constant for all set-ups then the value of this constant can be built into the equations).

2) The direction of the camera axis with respect to the vertical or horizontal (there are advantages in keeping the axis truly horizontal in, for example, the calculation of elevations).

3) The covergence or divergence of the camera axes when taking the stereo pair of photographs (in general the axes should be kept parallel).

4) The number of photographs which should be taken in different directions from one camera position at any one time (theoretically an infinite number of shots could be taken as the camera is rotated around a given position).

5) The distance between the camera position and the slope.

6) The elevation of the camera with respect to the slope and,

7) The elevation of one camera position with respect to the second position used for a stereo pair (there is considerable advantage in keeping these elevations the same).

If:

1) A parallel stereo pair is used, i.e. the optical axes for the two photographs are parallel,

2) The optical axes are horizontal, and perpendicular to the base line between the camera positions,

3) The elevations of the two camera positions are identical, then the location of a point with respect to the camera positions can be found simply from the relations:

$$x = \frac{b \times x_1}{(x_1 \pm x_2)} \; ; \quad y = \frac{b \times f}{(x_1 \pm x_2)} \; ; \quad z = \frac{b \times z_1}{(x_1 \pm x_2)}$$

where x, y and z are the three mutually perpendicular distances from one of the camera locations. These formulae are easily developed using simple geometrical constructions and are illustrated in Figure 1.

If, in addition, the exact same camera location and axes directions are used at times $t_1$ and $t_2$, then

$$\Delta x = x_{t2} - x_{t1},$$

$$\Delta y = y_{t2} - y_{t1},$$

$$\Delta z = z_{t2} - z_{t1} \text{ and total movement } = \sqrt[2]{\Delta x^2 + \Delta y^2 + \Delta z^2}$$

While in theory at least, the movement of an infinite number of points on a slope could be monitored in this fashion, in practice only a manageable, i.e. limited, number of points is monitored. Usually a few distinctive features on the slope are chosen such as a particular tree or shrub, a boulder, or a break in the ground contours. An alternative is to set markers on stakes into the slope and to monitor these.

A major advantage of photogrammetry over normal survey techniques is that if markers and stakes are placed in the wrong area, and some other part of the hill or pit face moves, it is only a matter of working back through the photographs to build up a history of how the movement took place (assuming there is good photographic coverage of the entire site). No such opportunity exists if survey points or slope indicators are installed in the wrong location.

## EQUIPMENT

### The Camera

The ideal camera for terrestrial stereo photogrammetry is a purpose-built phototheodolite, but this equipment is relatively very expensive and may not be economical in all environments, locations and for all purposes.

A standard Mamiya 645 camera costing a few hundred dollars was purchased off-the-shelf for this particular project. The Mamiya is a single lense reflex camera producing 6 cm by 4.5 cm negatives. In general, the larger negative, the greater the accuracy in measurement but, on the other hand, the greater the cost of the equipment. The 6 x 4.5 cm size of the Mamiya seemed to give a reasonable compromise between size and cost.

To achieve some flexibility in the choice of locations for the camera two lenses were provided with the camera. It was judged that the standard 80 mm lens and a 150 mm long focus lens would be suitable for most situations. The long focus lens could be used for detail at close range or provide a broader picture with some detail at long range. Because the Mamiya lenses were relatively inexpensive, mass produced items, only the middle two thirds of a photograph were used in order to minimize the effects of optical distortion.

The normal focusing screen was exchanged for a checkered screen to aid orientation of the camera. It was assumed that the center of the screen marked the optical center of the lense and that the center of the negative was equivalent to the optical centre.

### Auxilliary Equipment

The camera must be attached to a strong firm tripod and the shutter must be operated using a cable release to improve image definition. The plate on the tripod head was removed and replaced with a larger plate which was fitted with a sensitive bubble for coarse levelling. It should be noted that a horizontal camera axis was assured by obtaining the camera elevation and aiming at a point (usually a hand on a levelling staff) in the target area.

A standard good quality (Wild or similar) level with a graduated horizontal circle was used to locate the camera position with respect to the targets described in subsequent sections.

## TYPICAL FIELD SET-UP

### Camera Positions

Photography is relatively very economical when compared with the effort (cost) of detailed surveying. Therefore, a large number of photographs can be obtained to provide complete coverage of the subject. Evidence of both current active movements in the shape of large tension cracks and the scars and debris of past failures was abundant on the site.

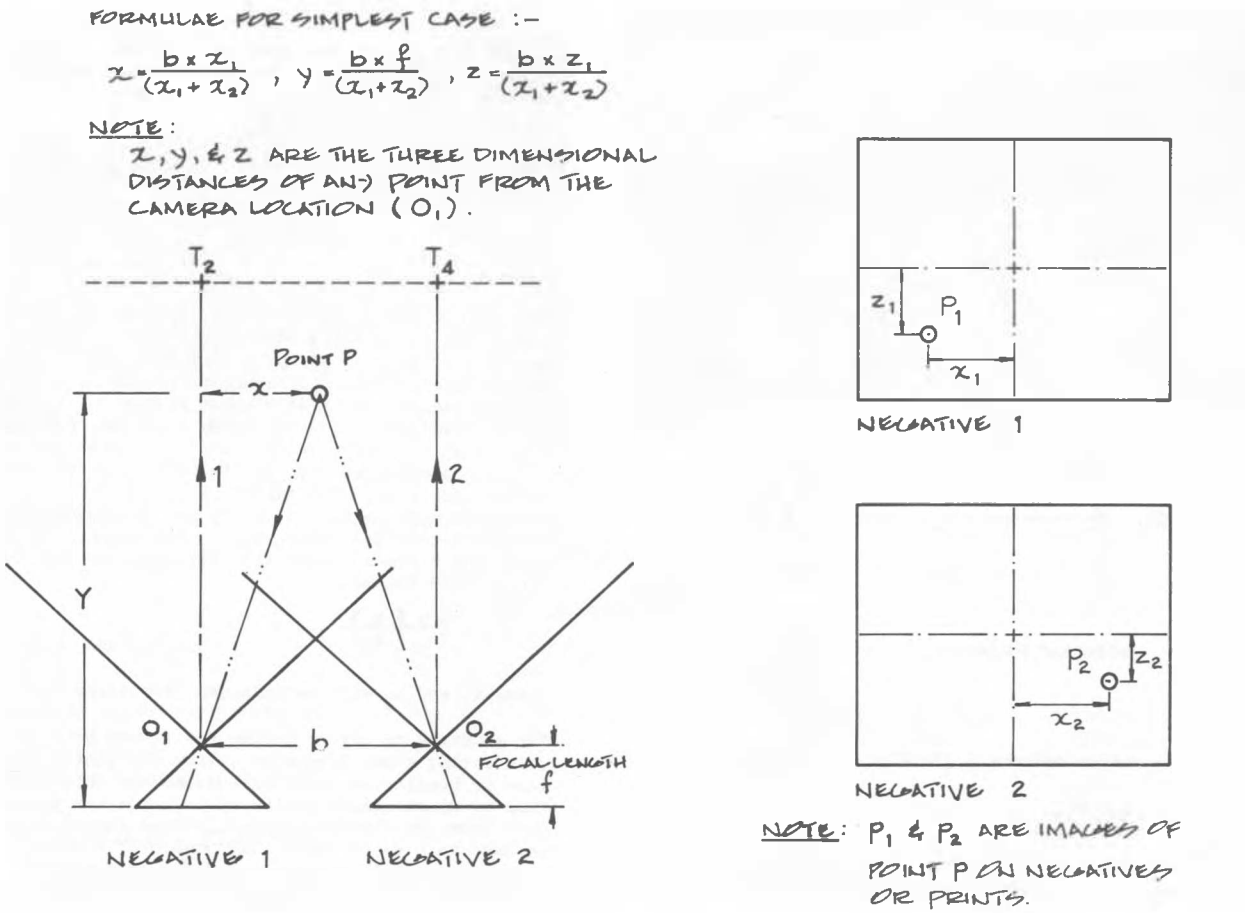


Figure 1 - Illustration of Simple Photogrammetric Formulae

A series of long distance photographs of the potentially unstable pit wall were obtained from the more stable side of the pit. Another series of photographs were obtained from positions much closer to actual current movements. The part of the pit which was being actively mined could be covered with a single series of six photographs based on the distance across the mine and the angle of view of the long focus lens. The base length between the camera locations was 30 m. Base lengths for the closer series were 8 to 10 m. Much more care was required to locate stable ground on which semi-permanent camera locations could be established.

Building in Redundancy

If the movement of a given point can be calculated separately in two or more stereo pair views, then a comparison of the results will enable checks to be made on the calculations as well as give an appreciation of the error involved in the measurements. Good photographic coverage of a subject, from both the point of view of completeness of coverage as well as for checking of calculations and error definition, can be obtained by taking a series of six photographs shown in Figure 2. The camera is set up over a peg at 01 and three photographs are taken, aiming at targets T1, T2 and T3. The camera is then moved to the peg at 02 and three photographs are taken, aiming at the targets T3, T4 and T5.

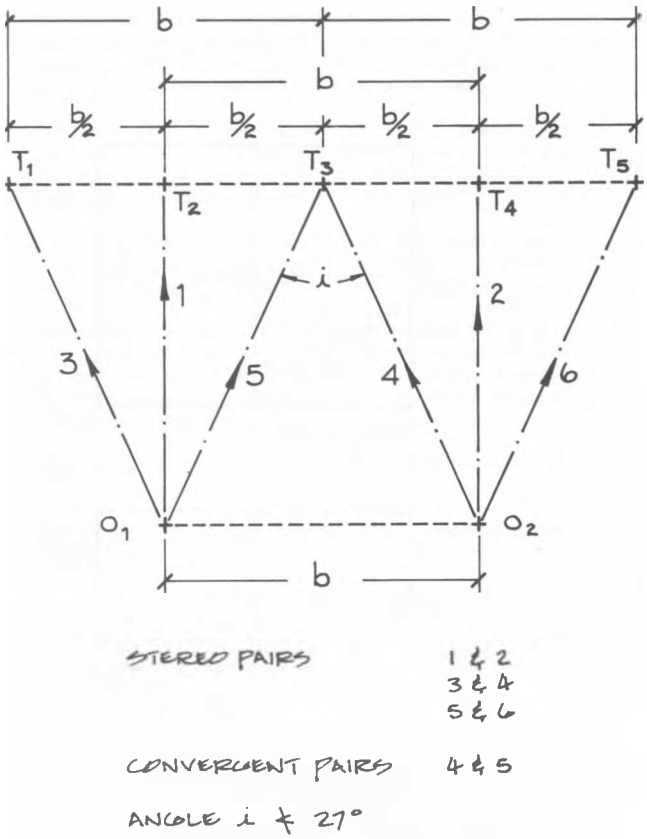


Figure 2 - Suggested Relationship Between Camera Locations 01/02 and Targets T1 to T5.

## Orienting the Camera

It is recommended that five pegs be installed on the slope face with the positions of the pegs related to the two fixed camera positions as shown in Figure 2.

As shown on Figure 2, this layout yields three parallel stereo pairs (for which the camera axes are parallel) and one convergent stereo pair (for which the camera axes converge). The internal angle for the convergent pair should be somewhat larger than 27° so that images on the two photographs have easily measurable displacements.

In practice, the size of the subject is roughly estimated and suitable positions for the pegs are determined in the field. The pegs are installed using first quality surveying equipment and techniques and the co-ordinates and elevations of all seven pegs are then determined. If the target pegs are themselves moving, they must be re-established for each set of photographs.

The camera was set up and the elevation of the center of the lens obtained by direct measurement. A horizontal sight line can be assured if a levelling staff is held on the target peg and the correct elevation marked, with say, a hand.

Other techniques which achieve the same objectives can, of course, be used and each situation may require some modification of the method which has been outlined.

## Analysis

The photographs are analyzed in a similar fashion to that shown in Figure 1. All co-ordinates and elevations are with respect to the co-ordinates and elevation of peg 01.

The co-ordinate formulas can be rapidly solved using a programmable calculator. Although undoubtedly more time consuming and less accurate than machine analysis, acceptable results can be obtained in a reasonable time. The layout used for measurements and subsequent analysis is shown in Table 1.

The photogrammetry formulae are given in most standard texts, see for example, Moffitt, (1967), although there is at least one aspect that most textbooks may not consider. Much photogrammetric work is done with large negatives or large contact prints. It is clear from an examination of the three formulae in Figure 1 that if enlarged prints are used, the formulae for the x and z co-ordinates are unaffected. However, the formula for y has only constants in the numerator and therefore must be multiplied by the enlargement to match the enlarged denominator. For example if the print was 5 times larger than the negative the formula for y would become:

$$y = \frac{b \times f \times 5}{(x_1 \pm x_2)}$$

since $x_1$ and $x_2$ will be enlarged five times.

The accuracy of the technique was proven both by calculating known dimensions, from the photograhs, and also by predicting other dimensions and then confirming them by measurements in the field. For the stereo pair shown as Figures 3 and 4, errors ranged from 3.87 percent to 0.44 percent. The predicted dimensions were consistently too small and for this particular stereo pair and it is thought that it is valid to multiply all calculated dimensions by the average factor of 1.0225.

## CONCLUSIONS

Given the particular constraints applying to this project, the monitoring system was judged to be the most appropriate technology to achieve the desired results. Although the equipment used on this project cannot be expected to resolve small creep movements, the photogrammetry was certainly capable of providing a mass of fairly detailed information concerning the major features of slope movements.

A carefully obtained photograph is without equal in recording a mass of information. Surveying alone would necessarily require subjective exclusion of many features which might subsequently be essential for an understanding of the failure mechanism.

References:

Moffit, F.H. (1967) "Photogrammetry"
Second Edition, International Textbook Company.

Figures 3 and 4. A Typical Stereopair (Gravel layer indicated by arrow.)

Table 1

Example Calculations

| Point Description | x1 mm | ±x2 mm | x1 mm | x | y | z |
|---|---|---|---|---|---|---|
| Thickness of gravel over mudstone | 6.1 | +24.1 | 14.6 | 1.621 m uphill | 45.938 m away | 3.880 m higher |
| Top of gravel minus base of gravel | | | 4.2 | | | 1.116 m thick |

$$x = \frac{8.026 \times 10^{3}\ \text{mm} \times 6.1\ \text{mm}}{30.2\ \text{mm}} = 1.621\ \text{m}$$

$$y = \frac{80\ \text{mm} \times 8.026 \times 1000\ \text{mm}}{30.2\ \text{mm}} \times \frac{24.2}{11.2} = 45.938\ \text{m}$$

$$z = \frac{14.6\ \text{mm} \times 8.026 \times 1000\ \text{mm}}{30.2\ \text{mm}} = 3.880\ \text{m}$$

$$\text{Thickness, z top - z base} = \frac{4.2\ \text{mm} \times 8.026 \times 1000\ \text{mm}}{30.2\ \text{mm}} = 1.116\ \text{m}$$

where $\frac{x}{x1} = \frac{y}{f \times m} = \frac{z}{z1} = \frac{B}{(x1 \pm x2)}$ and B = 8.026 m, f = 80 mm and m = 2.160