RAPID MONITORING OF COAL REFUSE EMBANKMENTS

PREPARED FOR

UNITED STATES DEPARTMENT
OF THE INTERIOR
BUREAU OF MINES

PREPARED BY

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FINAL REPORT
CONTRACT NO. HO262009

JUNE 1977

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OFR 11-78

REPORT DOCUMENTATION PAGE

1. Report No.

2.

3. Recipient's Accession No.

4. Title and Subtitle
"Rapid Monitoring of Coal Refuse Embankments"

5. Report Date
June 1977

6.

7. Author (s)
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8. Performing Organization Report No.
R-10173.A0

9. Performing Organization Name and Address
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10. Project/Task/Work Unit No.

11. Contract or Grant No.
HO262009

12. Sponsoring Organization Name and Address
Office of the Assistant Director--Mining
Bureau of Mines
Department of the Interior
Washington, D.C. 20241

13. Type of Report
Final

14.

15. Supplementary Notes
This work was performed under Contract No. HO262009, "Feasibility Study of Rapid Determination of Embankment Stability."

16. Abstract

Past failures of coal refuse embankments have resulted in more intensified efforts in inspections of coal refuse sites. Inspections, however, are mainly qualitative and time consuming. In August 1975 CH2M HILL was awarded a contract to identify, develop, and test a rapid system for monitoring coal refuse embankments to aid in inspections. The rapid monitoring system developed uses convergent and vertical photography from conventional fixed-wing aircraft. The system was tested on an active landslide and on two coal refuse facilities using both black and white and color infrared film. Field tests showed the system was capable of accurate measurement while providing qualitative data through photointerpretation. The accuracy of the system allows it to be used to monitor coal refuse embankments, tailings dams, major earth dams, and natural slopes.

Bibliographies of literature reviews in the area of past coal refuse embankment failures, monitoring instruments and methods, and photogrammetry are included.

17. Originator's Key Words
Embankment Monitoring
Coal Refuse Embankments
Analytical Photogrammetry
Aerial Photogrammetry

18. Availability Statement

19. U.S. Security Classif. of the Report	20. U.S. Security Classif. of This Page	21. No. of Pages	22. Price
Unclassified	Unclassified	110	

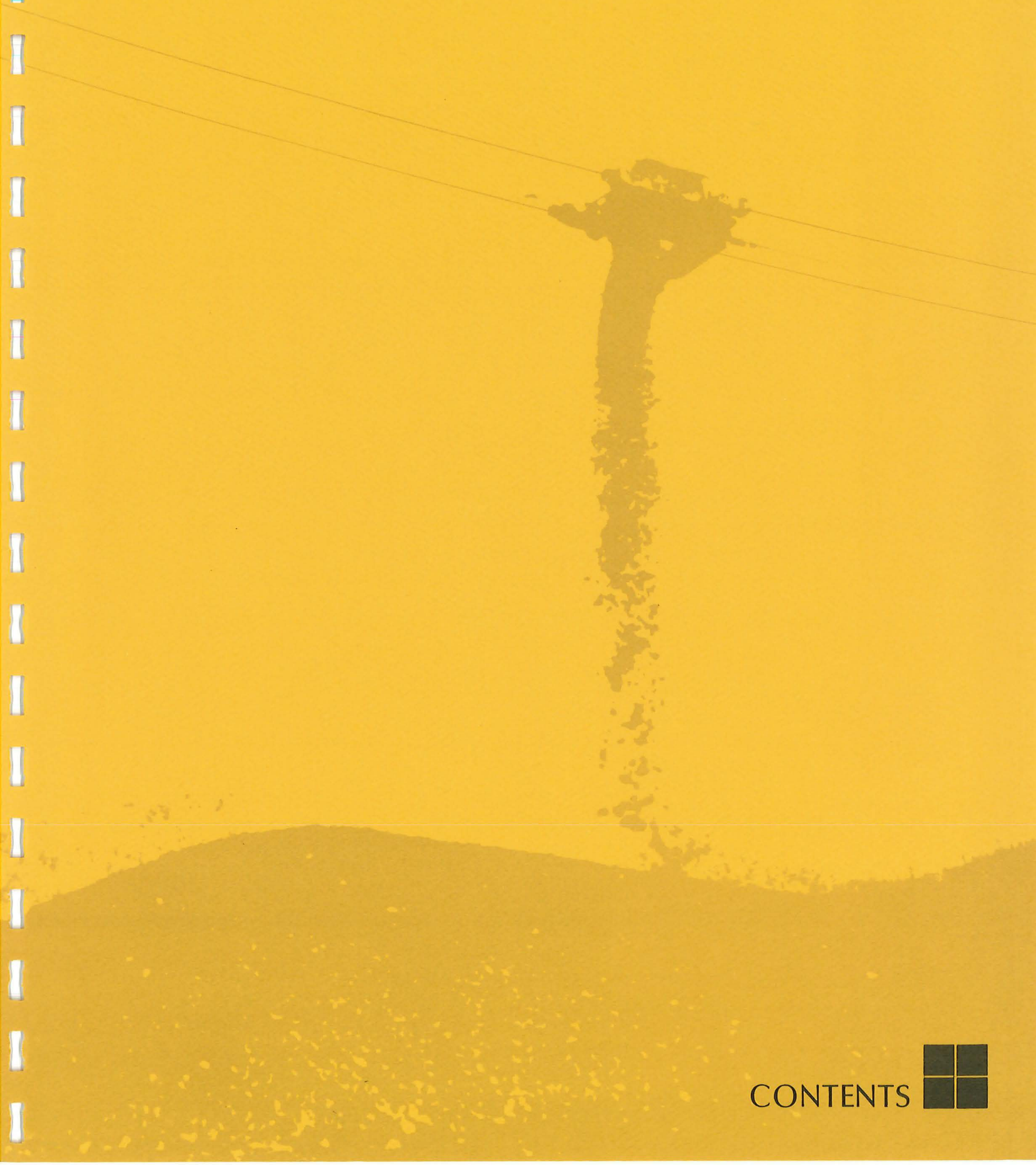
FOREWORD

This report was prepared by CH2M HILL, Redding, California under the U.S. Bureau of Mines Contract Number HO262009 initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of the Spokane Mining Research Center with Mr. R. R. Backer acting as the Technical Project Officer. Mr. D. J. Askin was the contract administrator for the Bureau of Mines. This report is a summary of the work completed as part of this contract during the period August 1975 to April 1977.

ACKNOWLEDGEMENTS

CH2M HILL would like to acknowledge and thank the U.S. Bureau of Mines for their enthusiastic support of the work performed in this project. Special thanks also to Mr. James Krese, District Manager, and to the staff of MESA District 4, Mt. Hope, West Virginia; to the Federal Aviation Administration for permission to use their landslide near Roseburg, Oregon for monitoring; to Eastern Associated Coal Corporation and the W-P Coal Company for permission to use their refuse disposal facilities for monitoring; and to Dr. S. A. Veress, University of Washington, Dr. D. J. Barr and Dr. S. P. Clemence, University of Missouri-Rolla, and Dr. N. C. Schwertman, California State University-Chico for special consulting on this project. Air Photographics of Purcellville, Virginia obtained photography for coal refuse monitoring.

Mr. Ed Worth, Project Director, died of cancer on 29 June 1976. His leadership during formulation of the project plans and during Phases I and IIA were invaluable to the success of the entire project.



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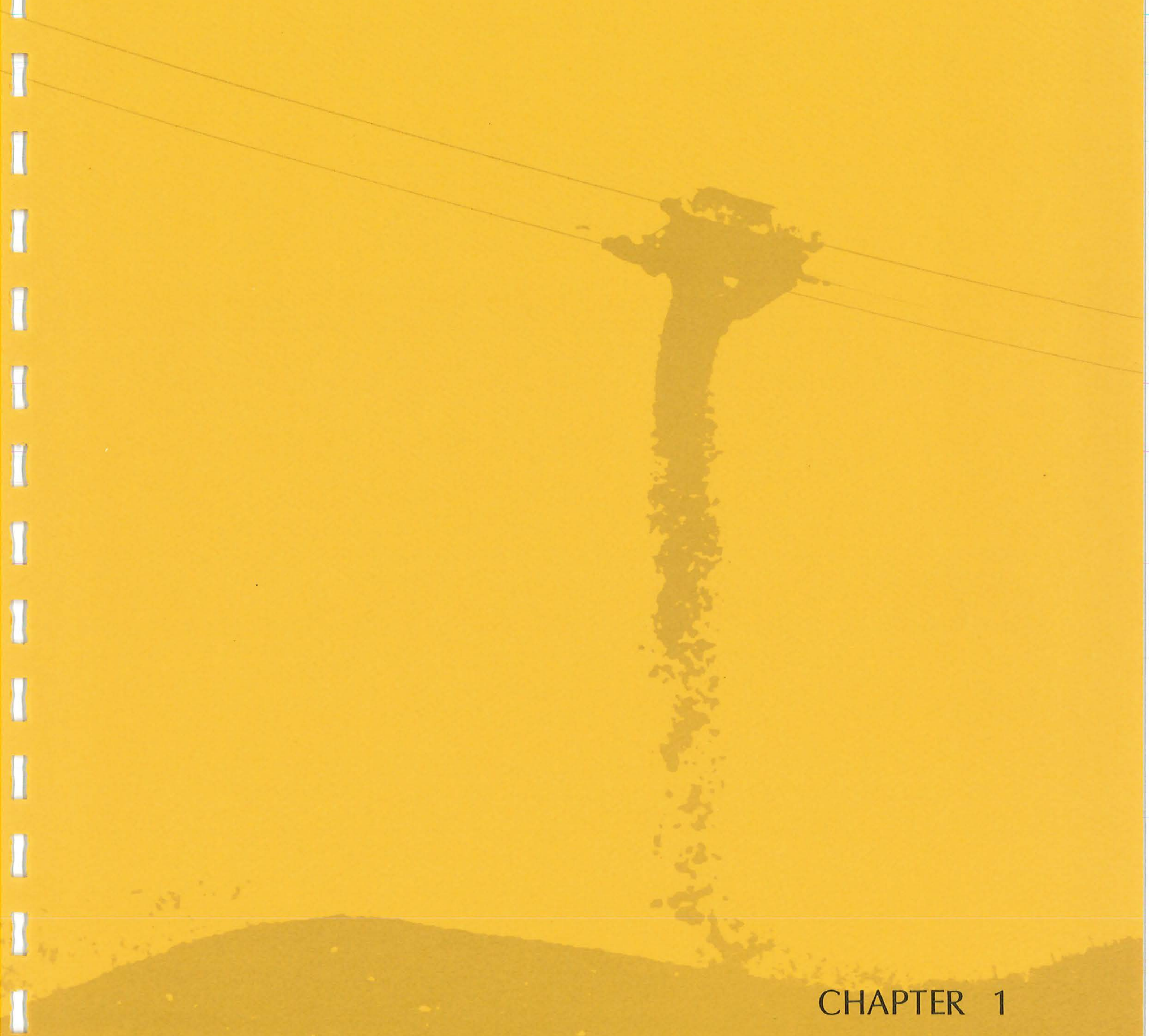


CHAPTER 1

GENERAL SUMMARY

Chapter 1
GENERAL SUMMARY

In August 1975 the U.S. Bureau of Mines awarded a project entitled "Feasibility Study of Rapid Determination of Embankment Stability" to CH2M HILL. The specific objective of this project was to identify, develop, and test a fast, reliable, and accurate reconnaissance system to gather data on the safety of coal mine refuse embankments. The Bureau of Mines wanted the selected system to be able to obtain observation data and physical measurements, to provide a permanent record of embankment performance versus time, and to more adequately detect and monitor safety problems of embankments. The Bureau of Mines also wanted the system to facilitate more efficient allocation of inspection resources to closely monitor suspect embankments while maintaining periodic checks on presumably safe embankments.

During this project a rapid monitoring system using aerial photography from fixed-wing aircraft was identified, developed, and tested. The rapid monitoring system consists of vertical and slightly oblique (convergent) photography of embankments instrumented with targets. Photogrammetric measurements are made on these photographs to determine X, Y, and Z coordinates for the targets, and periodic photography is used to develop movement versus time plots. In addition, stereophotographs obtained during overflights for the rapid monitoring system can be used for topographic mapping and photointerpretation. Both black and white (B&W) and color infrared (CIR) films were used. The rapid monitoring system provides permanent records of embankment conditions, quantitative measurement data, and qualitative photointerpretation data.

PAST FAILURES

The need for coal refuse embankment monitoring is demonstrated by two disastrous embankment failures. One failure occurred at a coal refuse complex in Aberfan, Wales on 21 October 1966, causing the death of 144 people. Another failure occurred on Buffalo Creek at Saunders, West Virginia on 26 February 1972, resulting in the death of 125 people and over $65 million in damages.

Case histories at both Aberfan and Buffalo Creek indicate that unstable conditions were apparent long before the failures. If a program of monitoring and evaluation of data had been carried out by people knowledgeable in earth structures, both disastrous failures probably could have been avoided.

To help prevent future disasters, regulatory agencies inspect refuse facilities. Inspections of coal refuse dumps by the Federal Government are performed by the Mining Enforcement and Safety Administration (MESA).

Inspections of coal refuse embankments generally consist of visual observations by inspectors on the ground. These inspections are often time consuming, and inspection procedures are mainly qualitative. Subtle signs of instability may be overlooked until failure is imminent.

The relative hazard potentials of coal refuse embankments are quite different. Well-engineered embankments are designed to be safe, and extensive inspection and monitoring programs on these embankments may not be necessary. On the other hand, many coal refuse embankments have severe, inherent stability problems that may be overlooked because of insufficient time and inspection resources. For these reasons, the Bureau of Mines felt that development and implementation of a fast, reliable monitoring system would enable better allocation of inspection and evaluation resources.

SYSTEM DEVELOPMENT

In order to identify and develop a rapid monitoring system for coal refuse embankments, it was necessary to review current (1975) coal refuse inspection procedures. The review was made to determine current methods of inspection as well as inspection criteria. The review consisted of interviews with MESA inspectors and members of MESA's technical support staff. It also consisted of examination of inspection manuals, attendance at MESA training sessions, and participation in site inspections with MESA personnel. The review of inspection procedures provided valuable information used in developing a system that could assist in inspection of coal refuse embankments.

The next step was evaluation and review of observation and measurement techniques that have been applied in monitoring the stability of slopes and embankments. This step involved making a complete list of available techniques from areas of in-place geotechnical instrumentation, remote sensing methods, conventional surveying, simplified telltale warning systems, and instrumentation with telemetry. These observation and measurement techniques were compared with evaluation factors such as staffing requirements, ability to rapidly detect and monitor indicators of instability, and cost and practicality.

From this evaluation, aerial photogrammetry proved the most promising for a rapid monitoring system. Use of aerial photogrammetry enables rapid collection of both quantitative data, in the form of measurable movement of targets on an embankment, and qualitative data from photointerpretation of indicators of instability such as cracks, slumps, bulges, or seeps. In addition, aerial photography provides data for general site mapping and enables calculation of embankment quantities. Finally, the aerial photographs are an easily maintained, permanent visual record of conditions that can be used to reconstruct past conditions at any future date.

Precision surveys using photogrammetric methods have been made in the past using either terrestrial cameras or low-level helicopter photography. The dimensions and vertical relief of coal waste embankments, however, often preclude use of these photogrammetric methods. The accuracy of standard photogrammetric measurements on photographs taken by conventional mapping cameras from fixed-wing aircraft is about equal to 1/10,000 of the flying height above the terrain.

By using special refinements developed in this project, the accuracy of aerial photography with conventional equipment was further improved.

SYSTEM DESCRIPTION

The rapid monitoring system developed in this project incorporates least-squares computations for deriving ground coordinates of objects from measured coordinates of their images on three overlapping aerial photographs. The system uses fixed-wing aircraft to obtain vertical and convergent photographs. This flight scheme provides superior accuracy when compared to conventional fixed-wing mapping photography using only vertical photographs. Increased accuracy is achieved by redundant measurements and by using convergent photography. Quantitative data in the form of X, Y, and Z coordinates of survey targets are obtained using analytical photogrammetry.

To provide for least-squares adjustment, the rapid monitoring system requires at least four control points with known ground coordinates. The four control points are placed on stable ground outside the area to be monitored. The rapid monitoring system can determine the coordinates of any number of targets placed on the ground in the monitoring area. Target movement can be detected and monitored by determining coordinates with successive photography over time. Targets and control points are 11-inch-diameter (27.9-cm-diameter) aluminum disks. The aluminum disks are painted flat white and are attached to lengths of 1-inch-diameter (2.5-cm-diameter) galvanized pipe hand-driven into the ground.

Analytical photogrammetry for the rapid monitoring system consists of measuring X and Y image coordinates on one vertical and two convergent film negatives and processing measurement data through computer programs. Measuring is done by a monocomparator which determines image coordinates to the nearest 1×10^{-6} m. Measured image coordinates are corrected for systematic errors such as lens distortion, film shrinkage, and atmospheric refraction. Image coordinates of the control points with known ground coordinates are used to determine coordinates of the focal point of each photograph, and the orientation of the image coordinate system with respect to the ground coordinate system. A subsequent computer program uses this information along with measured image coordinates of interior targets to solve a three-ray intersection resulting in ground coordinates for each target in the monitoring area.

Photography scale is dependent on the size of the area to be monitored, characteristics of the camera, and flying height. A conventional Wild RC-8 6-inch (15.2-cm) focal length mapping camera with a 9-inch by 9-inch (22.9-cm by 22.9-cm) format size was used to obtain photographs with average scale between 1:4500 and 1:5400 for testing the rapid monitoring system. The maximum area that can be monitored at this scale is approximately 4,000 feet by 4,000 feet (1.22 km by 1.22 km). The area is based on mean flying height above the terrain of 2,700 feet (823 m) and use of three photographs (one vertical, two convergent) with 100 percent overlap. A maximum vertical relief of one-third of the flying height can be accommodated without loss of accuracy. The system's theoretical accuracy is on the order of 1/35,000 of the flying height above the terrain; this is 3.5 times the accuracy of conventional aerial photography.

TESTING THE RAPID MONITORING SYSTEM

An active landslide located near Roseburg, Oregon was selected for monitoring to evaluate the ability of the rapid monitoring system to detect movement. The evaluation program consisted of comparing the rapid monitoring system with conventional ground survey methods for accuracy, cost, and practicality.

The landslide was monitored once per month, beginning in February 1976 and ending in May 1976. The rapid monitoring system was used to determine X, Y, and Z coordinates of targets on the ground; conventional ground surveys were made to verify the accuracy of the coordinates determined by analytical photogrammetry and for comparison of cost and practicality.

The rapid monitoring system was capable of detecting and measuring slide movements. Two of the targets moved about 8 feet (2.4 m) horizontally and about 2 feet (0.6 m) vertically during the monitoring program. These were the only targets that moved as determined by both the rapid monitoring system and ground survey.

Statistical analysis of data showed that the coordinates determined by the rapid monitoring system agreed closely with those determined by ground survey. Approximately 20 percent of all coordinates determined by the rapid monitoring system agreed within ±0.05 foot (1.5 cm) of the coordinates determined by the ground survey; approximately 80 percent agreed within ±0.10 foot (3.0 cm); and almost all agreed within ±0.25 foot (8.0 cm).

After completion of system testing at the landslide, the rapid monitoring system was used at two coal refuse embankments in southern West Virginia. The system was tested for its ability to monitor active coal refuse embankments. This monitoring program tested the system for its ability to accommodate difficult terrain and atmospheric conditions common to the Appalachian coal fields. These conditions include atmospheric haze, smoke and steam from nearby coal preparation plants, and shadows caused by rugged topography.

Coal refuse embankments at the Wharton preparation plant near Barrett, West Virginia and at the Stirrat preparation plant near Omar, West Virginia were monitored once per month beginning in July 1976 and ending in December 1976. As with monitoring at the Roseburg landslide, both B&W and CIR films were used.

Overall results from landslide and coal waste embankment monitoring showed that 90 percent of all X and Y coordinates determined by the rapid system for B&W and CIR films were within ±0.10 foot (3.0 cm) of X and Y coordinates determined by ground surveys. For the Z coordinate, 90 percent of all coordinate values determined from B&W were within ±0.15 foot (4.6 cm) of ground survey values, and 90 percent of all coordinate values from CIR were within ±0.23 foot (7.0 cm) of ground survey values.

The major reasons for differences between coordinates determined by the rapid monitoring system and the ground surveys resulted from random errors in the system and from difficulty in maintaining flight lines and intentional aircraft tilt (for convergent photography) while still maintaining site coverage. When proper aircraft tilt is not achieved, the accuracy of the horizontal coordinate values are slightly reduced. Errors are compounded in the vertical coordinate since it is mathematically determined from the X and Y image coordinates.

Both film types have the same theoretical resolution. However, low sun angles and cloud cover sometimes require longer shutter speeds for CIR film. As a consequence, there is some image blur at high magnification; this loss of resolution makes CIR film slightly less accurate for mensuration. B&W film is available at various film speeds and is therefore less susceptible to resolution problems.

During landslide and embankment monitoring, both film types proved useful for identifying qualitative slope stability indicators such as cracks, bulges, slumps, and erosion patterns. Using successive photographs, cracks in the landslide were seen to widen because of downslope soil creep. The wider range of color tones of CIR photography enabled more subtle changes in surface conditions to be distinguished, such as the response of vegetation to increases in soil moisture from seeps. In general, atmospheric haze posed no problems for photography. The low sun angles during late autumn and early winter reduced the photogrammetric qualities of the CIR film and caused long shadows from surrounding foliage that made photointerpretation difficult in affected areas.

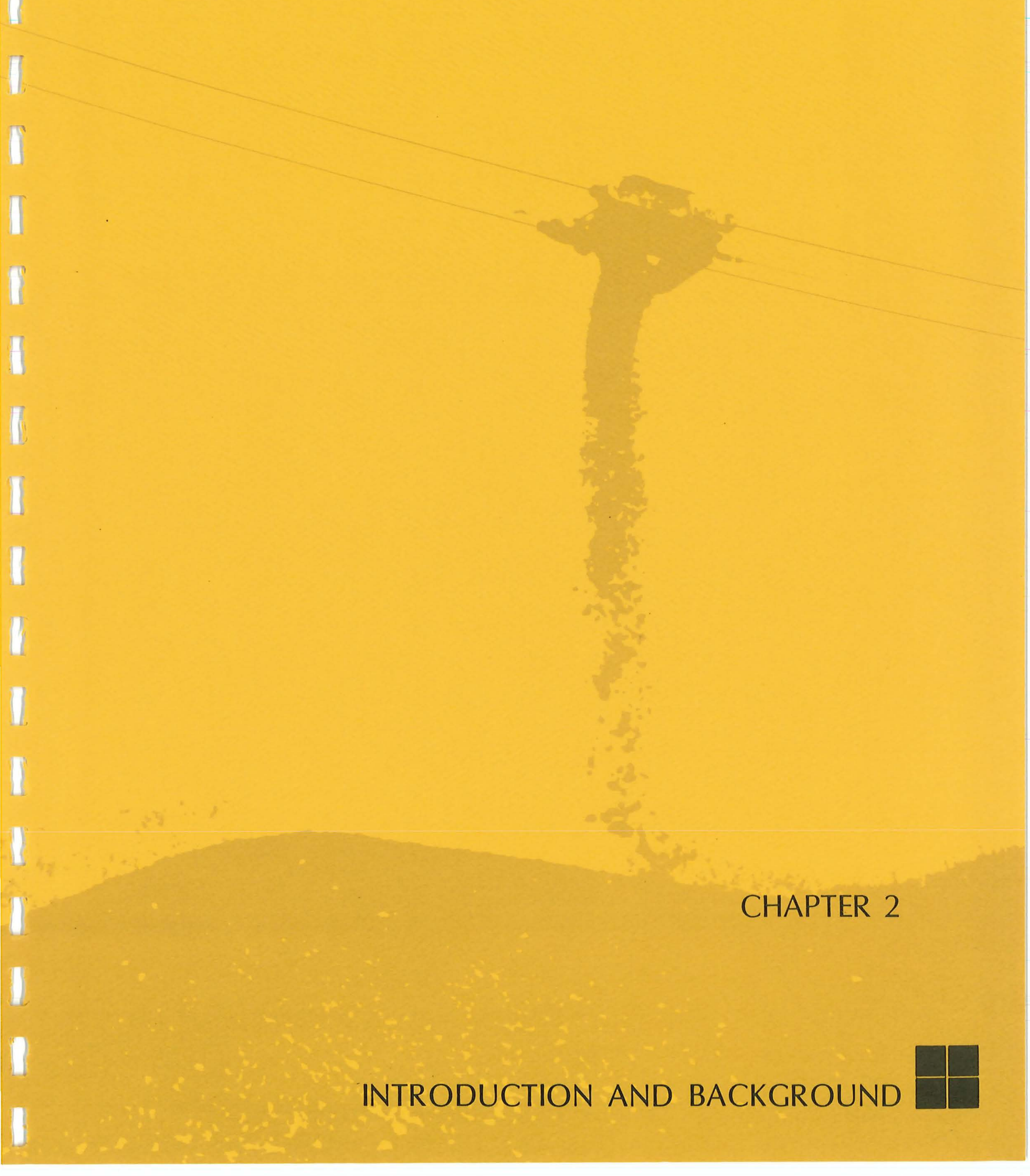
FINDINGS AND CONCLUSIONS

In this project the rapid monitoring system has been shown to be an effective, economic, and powerful monitoring tool. The system obtains high accuracy by using convergent and vertical photography from conventional fixed-wing aircraft. Either B&W or CIR film may be used; B&W film is superior from the standpoint of accuracy while the CIR film offers better evaluation of qualitative stability indicators through photointerpretation techniques. The rapid monitoring system also provides a method for maintaining a permanent, visual record of site conditions.

The rapid monitoring system of aerial photography proved to be practical for detecting and recording movement of targets on slopes and embankments. The system uses existing technology and conventional aerial photography cameras with fixed-wing photo aircraft. Targets for the rapid monitoring system are readily available, economic, and easy to install. A destroyed target can be replaced easily, and base coordinates for detection of movement can be determined at the next monitoring. The rapid monitoring system could be readily implemented for embankment inspection. Economics are enhanced when several areas can be photographed in a single photo mission.

Cost of monitoring is often the most decisive factor in planning the scope of monitoring programs. Many factors influence the cost of monitoring such as site location and size, vertical relief, accessibility, vegetation, weather, frequency, and urgency of monitoring. For the landslide and the coal refuse embankments, costs of monitoring by the rapid monitoring system was 15-40 percent of the costs of monitoring by conventional ground survey methods.

The rapid monitoring system not only provides a useful inspection tool for coal refuse embankments, but also provides a monitoring tool for a wide variety of other types of mining problems such as the stability of mine spoil piles, open-pit mines, and tailings dams. The system's accuracy is such that major earth dams and the stability of natural and manmade slopes can also be monitored to detect and record movement.



CHAPTER 2

INTRODUCTION AND BACKGROUND

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This report presents the results of a project to identify, develop, and test a rapid monitoring system to aid in assessing the safety and stability of coal refuse embankments. Past failures of coal refuse embankments have resulted in more intensified efforts to inspect coal refuse disposal facilities. However, present inspection efforts are mainly qualitative and are often time consuming. Use of a rapid monitoring system as an inspection tool would permit better allocation of inspection and evaluation resources.

BACKGROUND

Coal refuse is the unavoidable by-product of the preparation of raw coal. The disposal of wastes from coal mining and preparation is a problem that affects both mine owners and the public. Methods for safe and economic disposal of coal wastes are necessary; they require the assistance of both private and governmental agencies. As coal production increases, more wastes can be expected. About 20-30 percent of all run-of-mine coal cleaned in preparation plants is waste. The amount of coal waste is projected to reach 200 million tons (182×10^6 metric tons) annually by 1980 (Wahler et al, 1973).

Before 1920 coal seams were excavated and loaded by hand underground. Coal was transported to the surface, and wastes were left in the mine. Around 1920, coal mining became mechanized. Mechanized mining is more rapid and enables mining of thinner, less productive seams. This less selective process results in increased amounts of waste that are transported with the coal to the surface.

When run-of-mine coal reaches the surface, a preparation process is used to sort marketable coal from waste. Early methods of preparation consisted of simply separating the coarse refuse from the coal and dumping the refuse in areas near the preparation plants. Preparation procedures eventually became more sophisticated; simple separation yielded to crushing, sizing, and washing procedures that, in turn, produced a fine coal waste in the form of a slurry. The slurry required disposal along with the coarse refuse.

Locations of most coal waste dumps were based on convenience rather than engineering, geologic, or environmental considerations. As a consequence, embankments were not always located in suitable areas. Foundation preparation, embankment design, material strength, drainage, construction control, and hydrology were rarely considered in planning. The resulting coal refuse embankments generally consist of loose end-dumped or aerial tram-dumped material that has been placed with little or no compaction. Embankment slopes are often at or near the waste material's angle of repose, and the factors of safety against failure are marginal.

PAST FAILURES

Figure 1 shows a coal refuse embankment in West Virginia that has experienced slope failure. The slumping of the embankment and subsequent erosion were caused by poor embankment design and construction practices.

FIGURE 1 - *Slope Failure at a Coal Refuse Embankment*

Two disastrous coal waste embankment failures have occurred because of poor construction techniques and the lack of stability monitoring. Case histories of these two failures supply insight into signs of instability that could precede a coal refuse embankment failure. One failure occurred at a coal refuse complex in Aberfan, Wales, on 21 October 1966 when Tip 7, a large conical waste pile approximately 120 feet (37 m) high, failed. The resulting slide and mudflow traveled approximately 2,000 feet (610 m) downslope into the city of Aberfan causing the death of 144 people. Failure occurred because of excess pore pressures in the foundation of the embankment and piping at the toe of the waste pile. Another failure occurred at Saunders, West Virginia. On 26 February 1972, a coal waste impoundment on Buffalo Creek failed as the combined result of piping, high pore pressures, overtopping, and a low shear strength foundation. This failure resulted in the death of 125 people and over $65 million in damages.

Following each of these disasters, special committees developed thorough case histories of the embankments to explain the causes of failure. These examinations showed that obvious signs of instability existed years before both disasters occurred. Instabilities prior to the failure of Tip 7 at Aberfan (The Engineer 224, 1967) included a rotational slip at Tip 4 followed by a flow slide in 1944. Between 1947 and 1951 there was a rotational slide on Tip 5, and in 1963 there was a rotational slip and flow slide on Tip 7. From November 1964 to October 1966, slipping and settlement in excess of 5 feet (1.5 m) occurred at Tip 7. From April to October 1966, settlement at the top of Tip 4 was as great as 12 feet (3.7 m), and downslope movement was on the order of 20-30 feet (6-9 m). Finally, on 21 October 1966, settlement of 20 feet (6 m) was followed by the total failure of Tip 7.

The coal refuse dump at Buffalo Creek consisted of a series of three embankment dams constructed of coarse coal refuse. These embankments retained slurries of fine coal refuse and runoff water. In 1969 while Dam 3 (farthest upstream) at Buffalo Creek was being constructed, over 100 feet (30 m) of the dam sank and disappeared into its foundation of fine coal slurry. In 1971 boils of black water were reported in the pool downstream of Dam 3 and a portion of the downstream side of Dam 3 slumped. On 26 February 1972 complete failure occurred at Dam 3 resulting in overtopping and progressive failure of the two downstream dams (Davis et al, 1973).

At both Aberfan and Buffalo Creek, indications of unstable conditions were apparent long before failures occurred. The signs of instability that preceded failure were obvious but were not acknowledged. A relatively simple monitoring program could have detected the gross movements that occurred at both Aberfan and Buffalo Creek, warning that corrective efforts were required to prevent failure.

It is not likely that all potential embankment failures will exhibit such obvious signs of instability so far in advance of failure. However, the experience gained from both Aberfan and Buffalo Creek strongly suggests that the monitoring of surface movements and the evaluation of data by trained personnel could contribute substantially to prevent future failures.

CURRENT INSPECTION PROCEDURES

The framework for current inspection procedures for coal refuse embankments is the result of two recent Federal acts. In 1969 the Coal Mine Health and Safety Act (PL 91-173) transferred the responsibility for mine-related health and safety to the newly created Mining Enforcement and Safety Administration (MESA) within the Department of the Interior. The act included responsibility for inspection of active coal refuse disposal operations. As a direct result of the Buffalo Creek disaster, Congress passed the National Dam Safety Act (PL 92-367) of 1972 authorizing the Corps of Engineers to evaluate the stability of all dams in the United States (except those owned by the U.S. Government). Although coal refuse impoundments fall under the requirements of this act, MESA has retained responsibility for inspecting coal refuse construction and enforcing regulations concerning safe operation.

State regulatory agencies are also involved in coal refuse inspection. For example, in West Virginia the responsibility for coal refuse inspection and regulation enforcement is with the Department of Natural Resources, Division of Coal Refuse and Dam Control. This agency, similar to MESA's coal refuse inspection effort, also has inspection responsibility for inactive and abandoned coal refuse dumps in West Virginia.

MESA performs three types of inspections on coal refuse operations. The Periodic Inspection is a regularly scheduled inspection for all coal refuse facilities. Its frequency depends on the hazard potential and relative stability of the embankment. Generally, the inspections are made on a quarterly basis. However, if there are safety hazards or a possibility of failure, inspections may be as frequent as once each week. The results of inspections are recorded on standard forms, and the mine operator is notified of any violations or hazards requiring corrective action.

The Interim Inspection is a special inspection for the purpose of obtaining specific information on the refuse disposal operation, embankment construction, or other aspects of the disposal practice at a particular facility.

The Annual Inspection is the summary of the year's periodic inspections. Its purpose is to provide a record of embankment conditions and performance.

The MESA inspection effort is divided by districts according to geographic areas. In each district, the district manager and his staff are responsible for inspection of coal refuse operations. Potential hazards and violations are noted by the MESA coal refuse inspectors, and mine operators are ordered to take corrective action by the district manager.

MESA coal refuse inspectors are trained in special sessions to perform regular inspections on coal waste embankments. They are supplied with inspection manuals and other publications for methods of coal refuse embankment design, construction, and inspection.

In addition to the district-level inspection effort, MESA has a technical support staff to assist the field inspectors. The technical support staff evaluates the adequacy of plans for new refuse disposal facilities. It also reviews and evaluates plans for correcting hazardous conditions on existing embankments. The technical support staff monitors construction through inspection reports to ensure that disposal operations conform to the approved plans. The technical support staff works closely with district-level personnel to establish efficient and reliable methods for coal refuse inspection.

Present coal refuse inspection practices by MESA and other agencies consist of visits to each refuse facility to evaluate current conditions, construction methods, and refuse disposal operations. The inspections are visual evaluations made at periodic intervals. These inspections provide some assurance for the integrity of construction methods and materials and ensure that obvious signs of instability will be acknowledged.

However, coal refuse inspections are often time consuming and are mainly qualitative. Instrumentation is rarely used and physical measurements are seldom made. Time and resources for inspection of coal refuse construction are often limited because of the large number of coal waste dumps in certain areas. In general, inspectors are equipped to detect only obvious signs of instability and safety hazards; subtle indicators of problems can be overlooked without the help of quantitative measurements.

Coal refuse inspections are mainly visual evaluations. This makes it nearly impossible to detect and monitor mild, continuous signs of instability. Indicators of potential instability such as creep or slow, progressive downstream movement of an embankment are often difficult to distinguish until movements have progressed considerable amounts. When these signs become evident in visual evaluations, the structure is often in an advanced stage of failure.

To further complicate inspections, coal refuse embankments are most often unique structures. They differ in type and size as well as in the methods of design, construction, operation, maintenance. Active refuse embankments are dynamic structures. The size and shape of the embankment as well as the properties of the embankment material change as new waste is added. As a result, the safety and stability of a particular embankment are only relative; they are subject to distinct changes with time.

PROJECT OBJECTIVES

Since there are a number of problems with coal refuse inspection as it is currently practiced, the U.S. Bureau of Mines contracted to develop a rapid monitoring system to assist in inspection activities. The Bureau of Mines' goal was to devise a rapid monitoring system that would provide a reliable reconnaissance system for improved coal waste embankment safety evaluations.

On 16 January 1975 the Bureau of Mines issued a Request for Proposals entitled "Feasibility Study of Rapid Determination of Embankment Stability." The objective of the request was to determine the feasibility of developing a fast, reliable, and effective method of measuring the stability of coal refuse embankments. The Bureau of Mines requested examination of photogrammetric capabilities and comparison of photogrammetric methods with other possible rapid surveying measurement and mapping techniques for cost, accuracy, and speed. The request also included a field demonstration to validate the selected rapid monitoring system's capabilities in comparison to standard surveying methods.

According to the request, the selected rapid monitoring system should be capable of:

- Mapping and recording slope conditions.
- Monitoring embankment quantities and movement with ease, speed, and reliability.

- Providing surveillance of embankment conditions in a fraction of the time currently required by standard transit methods (e.g., permitting three people to monitor 100 embankments in 1 month).

- Being integrated with suitable methods for cataloging, evaluating, and analyzing the gathered data.

In August 1975 CH2M HILL was awarded the contract to identify, develop, and test a rapid monitoring system. The original contract consisted of identifying and developing a rapid monitoring system in Phase I, and testing the selected rapid monitoring system in Phase II. On completion of Phase I, it became apparent that the actual system testing should be expanded, and the contract was modified to split Phase II into Phase IIA and Phase IIB.

The scope of Phase I included performing six specific tasks:

- Review of inspection procedures to define the state-of-the-art for coal refuse inspection.

- Review of surveying and mapping literature to provide information for identification and development of a rapid monitoring system.

- Review of geotechnical engineering literature to develop monitoring criteria for slope and embankment stability; i.e., what can or should be measured. This task also included review of in-situ instrumentation for potential as a rapid monitoring system.

- Design, production, and installation of suitable markers, or targets, for the selected rapid monitoring system.

- Selection of a prototype coal refuse embankment for field testing of the selected rapid monitoring system.

- Development of plans and procedures for field testing of the selected rapid monitoring system.

The scope of Phase IIA consisted of field testing the selected rapid monitoring system on a slope that was known to be moving. The selected rapid monitoring system was compared against standard ground survey methods for accuracy, cost, and practicality.

Phase IIB tested the selected rapid monitoring system for its ability to monitor active coal refuse embankments. It also tested the system for its potential as an inspection tool for coal refuse embankment construction.

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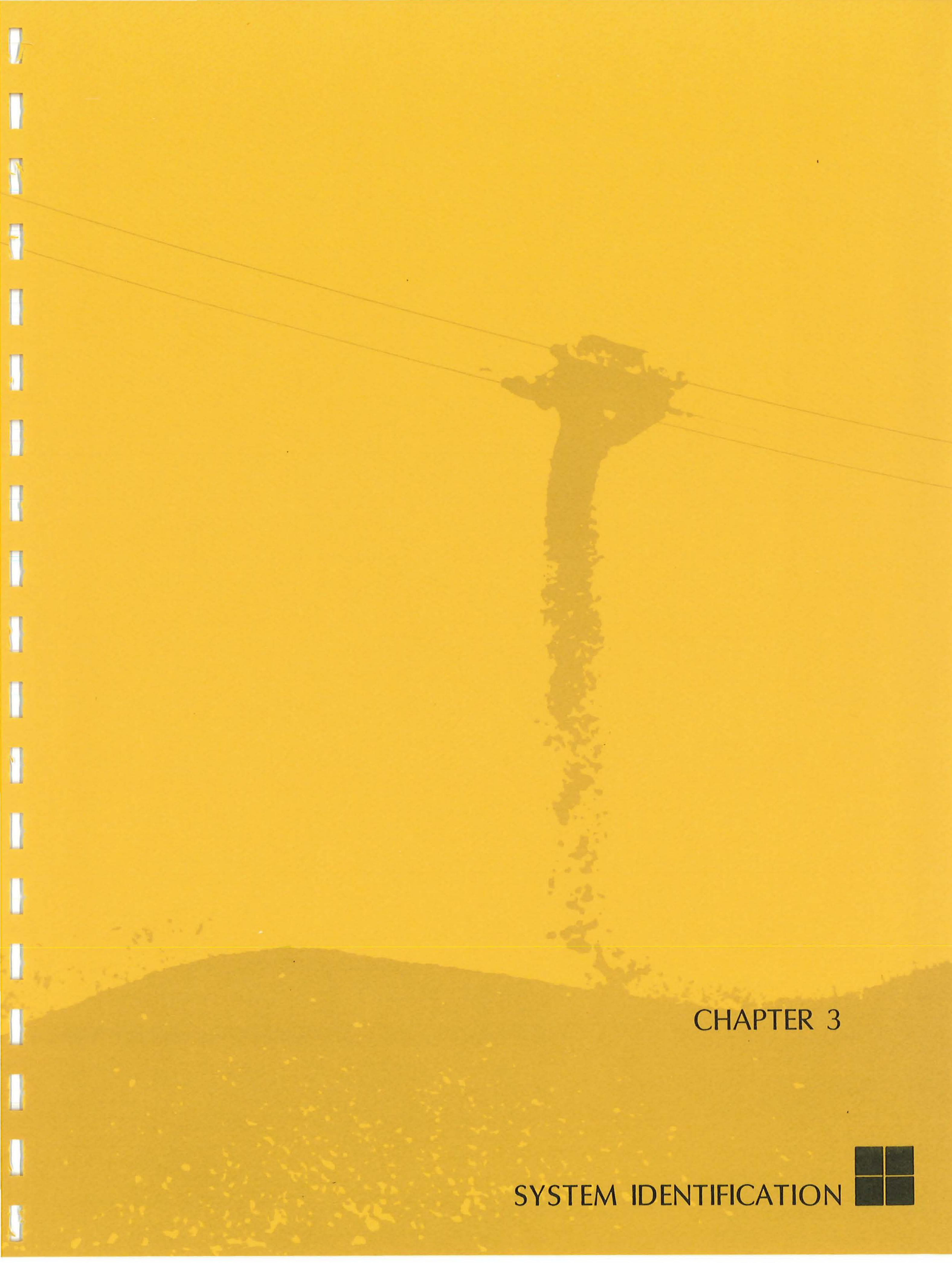

CHAPTER 3

SYSTEM IDENTIFICATION

Chapter 3
SYSTEM IDENTIFICATION

Coal refuse embankments vary in size, type, method of construction, hydrology, operation, and foundation geology. Regardless of how they vary, the mechanics of embankment and slope stability for earth structures apply to coal refuse embankments. In general terms, the stability of refuse embankments is dependent on the following factors:

- Site and foundation geology
- Physical properties of the refuse material
- Method of placement of refuse material and construction procedures
- Geometry of the embankment
- Site hydrology
- Hydraulic operation of the impoundments (i.e., inlet-outlet works, spillway)
- Changes in the physical properties of refuse material and embankment geometry with time
- Seismicity

The possibility of instability and potential failure can be reduced by accounting for these factors in design. Controls on methods of placement, embankment geometry, drainage, and hydraulics can guard against failure.

These measures are difficult to provide in existing, nonengineered embankments. Instead, intensive investigations and analyses must be conducted to determine the stability of the embankment. If it does not possess adequate stability, then modifications are required for increased safety. In lieu of investigations, conservative modifications are often made to increase the stability of questionable embankments.

EMBANKMENT STABILITY

Two sets of forces must be analyzed in embankment stability determinations. These sets are driving forces which tend to cause movement and failure and resisting forces which tend to resist deformations and instability. When these forces are in balance, the embankment is stable. The greater the resisting forces, the greater the factor of safety against embankment failure. The factor of safety is the ratio of resisting forces to driving forces.

When driving forces become as large or larger than the resisting forces, the embankment fails.

The causes for change in the factor of safety are external, internal, or intermediate. External causes result in a change in the appearance of the embankment. They are associated with steepening of embankment slopes, addition of surcharge to the top of the slope, undercutting at the toe of the slope, or other unusual conditions that cause increases in shearing stresses of the material comprising the embankment.

Internal causes are associated with reduction of shearing resistance that occurs without changes to the external appearance of the structure. The most common internal cause is hydrostatic pressure from seepage. Other important internal causes are loss of strength of refuse material with time, and creation of voids by the burning of coal in waste embankments.

Intermediate causes are a result of action from the environment and from complex interaction of external and internal causes. Such problems as liquefaction by earthquakes, erosion, piping, and abnormal pore pressures due to hydraulic operation of the embankment facilities are intermediate causes.

Except for earthquake induced movement, embankment failures do not usually begin as rapid movement. In order for an existing embankment to fail, the factor of safety must be reduced to one or less. This reduction is accompanied by progressive deformations of material susceptible to failure and downward movement of the embankment surface. As deformation occurs and failure planes develop, the embankment becomes less stable and the potential for rapid movement increases. The rate and amount of deformation are dependent on the stiffness of the embankment material and the magnitude of the forces tending to cause failure. In essentially all slope failures, however, the impending instability is broadcast prior to failure. If the indicators of instability are overlooked or if corrective measures are not made, then ultimate failure can result. Failures at Aberfan and Buffalo Creek occurred in this manner.

MONITORING METHODS

To assess performance and to forewarn of stability problems, embankments should be monitored. Monitoring incorporates observation and physical measurement to determine if embankments are performing adequately. Monitoring can warn of potential stability problems and is of critical importance in nonengineered embankments where no analysis or design modifications have been made.

Monitoring of embankments is one method of detecting advanced warnings of potential failure. In general, four types of measurements can be obtained to provide necessary data for coal refuse embankment monitoring:

- Measurements of deformation, both internal and external

- Measurements of seepage
- Measurements of internal pore pressure
- Qualitative visual observations to detect signs of instability such as:

  Excessive slope
  Excessive height
  Toe undercutting
  Severe erosion
  Cracking
  Potential for overtopping
  Slumps
  Burning
  Wet spots
  Springs and seeps

Some of these qualitative visual observations are shown on Figures 2-5.

FIGURE 2 - *Oversteepened Slope and Erosion on a Coal Refuse Embankment*

FIGURE 3 - *Surface Crack in a Coal Refuse Embankment*

FIGURE 4 - *Oversteepened Slope and Example of Inadequate Spillway Design*

FIGURE 5 - *Burning of a Coal Refuse Embankment*

The following techniques can assist in obtaining these measurements:

- Onsite visual inspections
- Conventional methods (in-situ instrumentation and surveying)
- Innovative techniques such as telltale warning systems
- Remote sensing (detecting the nature of an object without direct contact)

Table 1 shows a matrix which enables comparison of monitoring methods with evaluators to determine applicability for rapid monitoring.

Present methods for coal refuse embankment monitoring consist of onsite visual inspection by personnel trained to note signs of instability. Table 1 shows that this method is suitable for detecting most external stability indicators. Visual inspection is a low to moderate cost, reliable, all-weather method. It results in fairly rapid collection of data for one embankment but is time consuming for analyzing many embankments in a short period of time. Small, subtle surface movements and strains are often overlooked, and it is not useful for determining embankment volumes or mapping embankments.

Conventional monitoring systems including surveying, in-situ monitoring devices, and strain gauges are extensively used in embankment monitoring. These methods are proven techniques for earth embankment monitoring and

LEGEND

- ● Suitable
- ■ Possibly Suitable
- X Not Suitable
- Blank Not Applicable or Unknown
- H High
- M Medium
- L Low to None
- O None

EVALUATORS			Remote Sensing: Photogrammetry		Remote Sensing: Radar	Remote Sensing: Scanning			Remote Sensing: Field Strength Measuring Devices	Remote Sensing: Geophysical	Conventional							Visual Observations	Simplified "Conventional" Devices						Innovative
			Various Emulsions	Various Filters		Multi-Spectral	Thermal Infra-Red	Radiometry (Long Wave)	Radio, Gravity, Magnetic, Radioactive	Seismic, Resistivity, Well Logging, Acoustic Emissions	Ordinary Surveying	Extensometers	Inclinometer	Weirs and Flumes	Stream Gaging	Sampling See Page Water	Piezometers		Qualitative Slope Indicators	Simple Extensometers	Weirs and Flumes	Simple Visual Range Lines	Repetitive Photographs	Surface Tiltmeters	
Staffing	Data Collection: Method	On-Site							●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
		Off-Site							●			●					●		■	■					■
		Remote Sensing	●	●	●	●	●	●	■																
	Data Collection: Primary Personnel	Professional			●	●	●	●	●	●															
		Senior Technician	●	●	●	●	●	●	●	●	●							●							●
		Technician									●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Data Analysis Primary Personnel	Professional	●	●	●	●	●	●	●	●								●					●		
		Senior Technician	●	●	●	●	●		●	●						●		●							●
		Technician									●	●	●	●	●		●		●	●	●	●		●	●
Embankment Stability Indicators	Slope Movements	Horizontal	●	●	■	X	X	X	X	X	●	●	●	X	X	X	X	■	■	■	X	■	■	X	■
		Vertical	●	●	X	X	X	X	X	X	●	●	■	X	X	X	X	■	■	■	X	X	■	X	■
		Tilting	■	■	X	X	X	X	X	X	●	X	●	X	X	X	X	■	■	X	X	X	X	●	■
		Surface Strains	●	●	X	X	X	X	X	X	●	●	X	X	X	X	X	X	■	■	X	X	■	X	■
	Seepage	Flow Rate	■	■	X	X	X	X	X	X	X	X	X	●	●	X	X	■	X	X	●	X	X	X	
		Suspended Solids	■	■	X	X	X	X	X	X	X	X	X	X	X	●	X	■	X	X	X	X	X	X	
		New Outlets	■	■	■	■	■	X	X	X	X	X	X	X	X	X	X	●	X	X	X	X	●	X	
		Infer From Vegetation	●	●	X	■	X	X	X	X	X	X	X	X	X	X	X	●	X	X	X	X	●	X	
	Piezometric Levels	Direct Measurement	X	X	X	X	X	X	X	■	X	X	●	X	X	X	●	X	X	X	X	X	X	X	■
		Infer From Outlets	●	●	■	■	■	X	X	X	X	X	X	X	X	X	X	●	X	X	X	X	●	X	
		Infer From Vegetation	●	●	X	■	X	X	X	X	X	X	X	X	X	X	X	●	X	X	X	X	●	X	
	External Stability Indicators	Excessive Slope	●	●	■	■	■	X	X	X	●	X	X	X	X	X	X	●	X	X	X	X	■	X	
		Excessive Height	●	●	■	■	■	X	X	X	●	X	X	X	X	X	X	●	X	X	X	X	■	X	
		Toe Undercutting	●	●	■	■	■	X	X	X	X	X	X	X	X	X	X	●	X	X	X	X	●	X	
		Severe Erosion	●	●	■	■	■	■	X	X	X	X	X	X	X	X	X	●	X	X	X	X	●	X	
		Cracking	■	■	X	X	X	X	X	X	X	X	X	X	X	X	X	●	X	X	X	X	■	X	
		Impending Overtopping	●	●	■	■	■	■	X	X	●	X	X	■	X	X	X	■	X	X	■	X	■	X	
		"Rock" Noise	X	X	X	X	X	X	X	●	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
		Fire	X	X	X	■	■	X	X	X	X	X	X	X	X	X	X	■	X	X	X	X	■	X	
		Headwater & Tailwater	●	●	■	■	■	■	X	X	●	X	X	■	X	X	■	●	■	X	X	X	■	X	
Practicality	Cost	Initial Cost	M	M	H	H	H	H	M	M	L	H	H	L	L	L	H	L	M	M	L	L	L	L	
		Operating Cost	M	M	H	H	H	H	H	H	H	M	H	M	H	M	M	M	M	M	M	M	M	M	
	Rapidity	Data Collection	H	H	H	H	H	H	L	L	L	L	L	M	L	M	M	M	M	M	M	M	M	M	
		Data Analysis	M	M	M	M	H	H	L	L	M	M	L	H	M	L	L	M	H	M	H	H	M	H	
	Manpower	No. of People Required	L	L	L	L	L	L	L	L	H	M	M	M	H	M	M	M	M	M	M	M	M	M	
		Average Training Level	M	M	H	H	H	H	H	H	L	L	L	L	L	L	L	M	L	L	L	L	M	L	
		Reliability (Longevity)	H	H	H	H	H	M	H	H	H	L	H	H	H	H	H	H	H	M	H	M	H	H	
		All Weather Capability	L	L	H	L	L	M	H	M	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
		Development Required	L	L	M	L	L	M	L	L	O	O	O	O	O	O	O	O	M	L	O	L	O	L	
		Quantify Volumes	●	●	X	X	X	X	X	X	●	X	X	X	X	X	X	X	X	X	X	X	■	X	
	Success Probability	To Assess Stability	H	H	L	L	L	O	O	O	H	M	M	L	L	L	M	M	M	M	L	L	L	L	L
		Meet Overall Aims	H	H	O	O	O	O	O	O	L	O	O	O	O	O	O	O	O	O	O	O	L	O	L

Table 1
MATRIX OF MONITORING METHODS AND EVALUATORS

are applicable to coal refuse. Initial costs range from low to high depending on the type of surveying or monitoring equipment used and the methods of data collection.

Surveying is a low initial cost but high operating cost method of monitoring. It requires skilled technicians and can give accurate information on surface movements, mapping, and determination of embankment quantities. Surveying is commonly used as an embankment monitoring system. However, the time required for surveying and data reduction does not make it a potential rapid monitoring system.

In general, in-situ devices are reliable and provide repeatable results that are not affected by weather. Each in-situ device, however, only measures a few embankment properties. For example, inclinometers measure horizontal and tilting movements and piezometric levels. Extensiometers measure horizontal and vertical movements and surface strains but cannot measure tilting. No single type of in-situ device is capable of monitoring enough facets of embankment performance so that it could be used without additional monitoring methods or devices. In-situ instrumentation is also limited to providing accurate measurements at certain points in the embankment. A series of devices are required to fully assess the entire embankment.

In-situ devices, unless equipped with a reliable telemetry system, would require onsite visits for readings. This would augment the existing qualitative visual assessments but would not provide a viable rapid system. Telemetry systems for in-situ instrumentation could speed data acquisition but pose practical and technical problems. The harsh environment of coal refuse embankments would require continuous maintenance of electrical and pneumatic systems and the expected life of most in-situ devices would be limited. Data from instrumentation would require analysis by experienced personnel to determine the presence of potential instability. Conventional instrumentation is not capable of mapping or determining embankment volumes.

Innovative monitoring techniques were not extensively considered during the project. A search of existing innovative methods showed that most devices are simple strain gauges that detect surface movement. These devices require either onsite visits for readings or electrical telemetry systems. Onsite visits were not considered compatible for a rapid system. Electrical telemetry systems would require maintenance and could be unreliable in the harsh environment of coal waste. No innovative methods were identified that could map or determine embankment volumes.

Remote sensing methods range from no potential to high potential for success as rapid monitoring systems. Geophysical and field strength devices offer no practical means of rapid refuse embankment monitoring. Radar and scanning methods could provide some qualitative data depending on scale but could not provide information on slope movement or embankment quantities.

Photogrammetry by airborne or terrestrial methods shows potential to obtain information on embankment stability indicators similar to visual observation. In addition, photogrammetry has high potential for detecting movement and can map embankments and provide embankment quantities. The photogrammetric approach, however, requires trained personnel in data acquisition, reduction, and analysis.

SYSTEM SELECTION

Except for aerial photogrammetry, no monitoring methods had the potential speed and versatility and provided information commensurate with the project objectives. Development of innovative techniques or combinations of conventional instrumentation may also have met the needs of the rapid monitoring system. However, research and development costs would have been high, and the development of technical data on their performance, operations, and maintenance would be required to ensure reliable operation in the field.

In a single system, aerial photogrammetry provides quantitative data in the form of measurements of movement, mapping, and embankment quantities. It also provides qualitative data from photointerpretation. Based on the review of available techniques, aerial photogrammetry was judged to have the most chance for success and was selected for tests as a rapid monitoring system.

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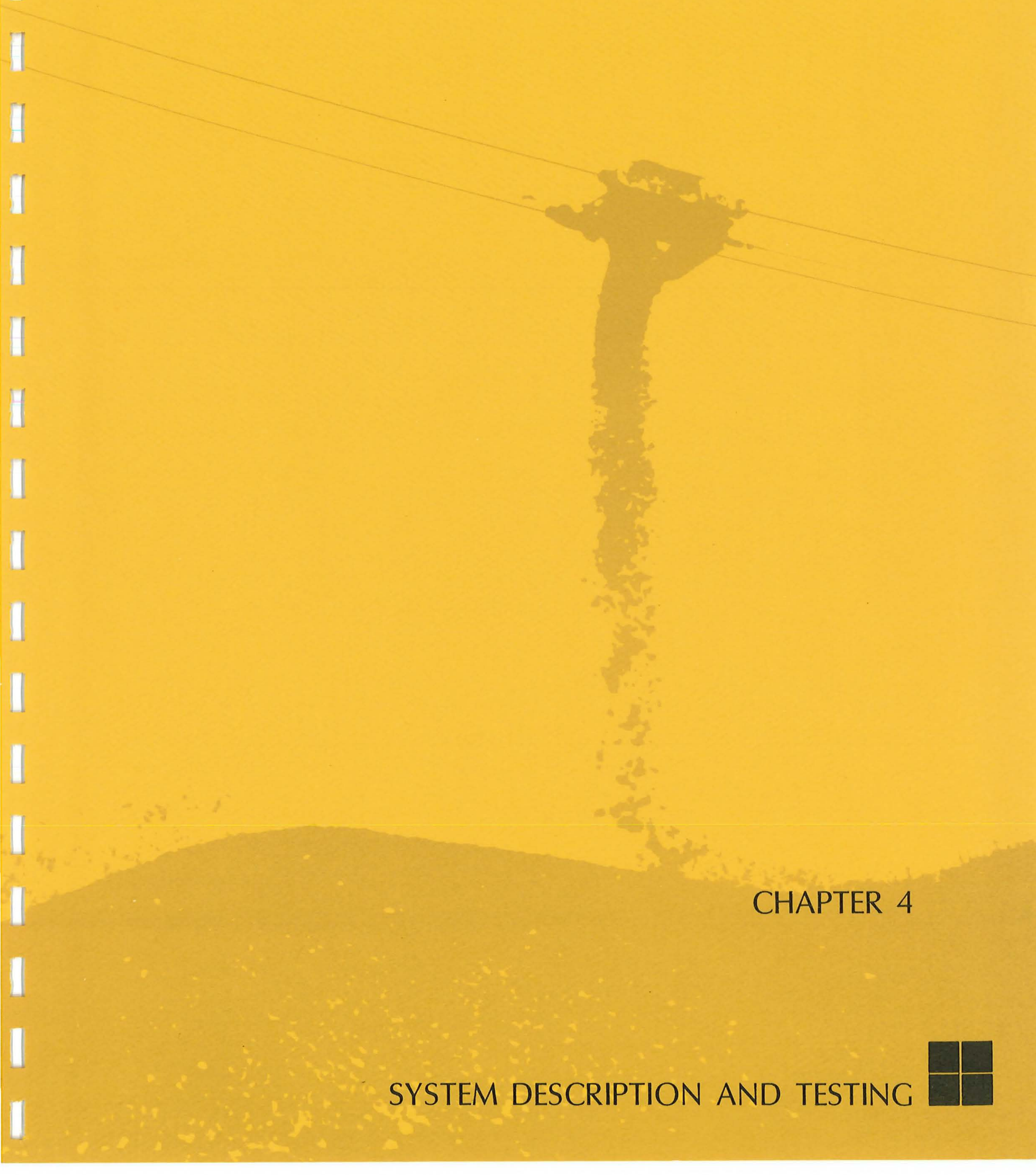

CHAPTER 4

SYSTEM DESCRIPTION AND TESTING

Chapter 4
SYSTEM DESCRIPTION AND TESTING

Two branches of photogrammetry, aerial and terrestrial, were considered applicable to this project. Terrestrial photogrammetry has been used with much success for monitoring structures and earth dams. The dimensions of coal waste embankments and characteristics of phototheodolites (focal length, photo coverage) would not permit a coal refuse embankment to be covered in one photograph. As a result, the embankment would have to be studied in sections to achieve the desired accuracy. A terrestrial photogrammetric system would also require onsite visits and would be quite time consuming. However, an aerial monitoring system with its rapidity and ability to record the entire embankment in one photograph would be more desirable if accuracies comparable to those of a terrestrial system could be obtained. The developed rapid monitoring system uses aerial photography methods with terrestrial photogrammetry techniques for increased accuracy.

SYSTEM DESCRIPTION

The rapid monitoring system incorporates least-squares computations for deriving ground coordinates of objects from their measured image coordinates which appear on a set of three overlapping aerial photographs. In addition, photointerpretation and mapping can be done if stereophotographs are obtained.

Flight Planning

The rapid system uses a combination of convergent and vertical photography as shown on Figure 6. This flight scheme provides superior accuracy when compared to conventional mapping photography. Increased accuracy is achieved by redundancy in measurement (3-ray intersection) and by increased parallactic angle of the convergent photography.

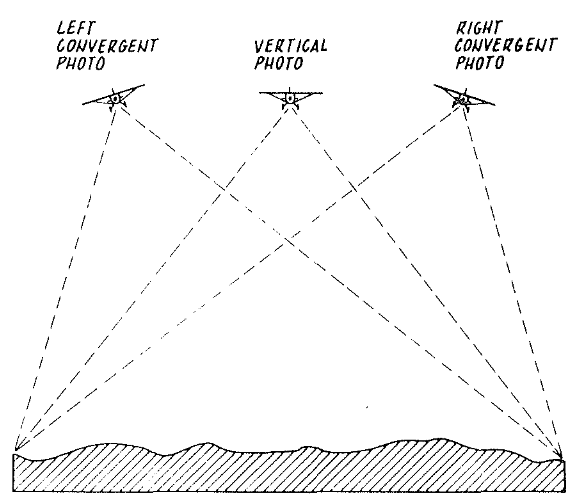

FIGURE 6 - *Flight Scheme*

The photographic scale is determined by the dimensions of the area to be monitored and the format size of the camera. For example, using a 9-inch by 9-inch (22.9 cm by 22.9 cm) format size camera to photograph an area of 3,750 feet by 3,750 feet (1.4 km by 1.4 km) requires a minimum scale of 1:5000. For this project, using a Wild RC-8 6-inch (15.2-cm) focal length mapping camera with a 9-inch by 9-inch (22.9-cm by 22.9-cm) format size, the scale of photography ranged from 1:4500 to 1:5400.

The flying height for the photography is determined by the following photo scale formula:

$$S = \frac{f}{H-h} = \frac{f}{PD}$$

Where:

S = Scale of photography as a representative fraction.

f = Focal length of camera (ft).

H = Flying height of airplane above datum (ft).

h = Average terrain elevation above datum (ft).

PD = Principal distance or flying height minus average terrain elevation (ft).

Conventional aerial photography requires approximately 60 percent overlap of photographs or a base-to-height ratio of approximately 0.60 to obtain stereophotographs. The rapid monitoring system of convergent photography requires three photographs having 100 percent overlap or identical photo coverage. Figure 7 shows the relative position of the plane for the three exposures. Each exposure is taken at the altitude determined by the photo scale formula. The flight line for the vertical exposure typically bisects the area to be monitored. The flight lines for the convergent photography are determined by achieving a base-to-height ratio of 1.0-1.2. In other words, the minimum base distance between flight lines for convergent photography is equal to the flying height. In order to obtain 100 percent overlap, the camera must be tilted for convergent photography. The amount of camera tilt required is determined by the following formula:

$$\frac{\tan^{-1}\phi}{2} = \frac{B}{2(PD)}$$

Where:

B = Base distance between flight lines (ft).

ϕ = Intentional tilt angle of each camera (degrees).

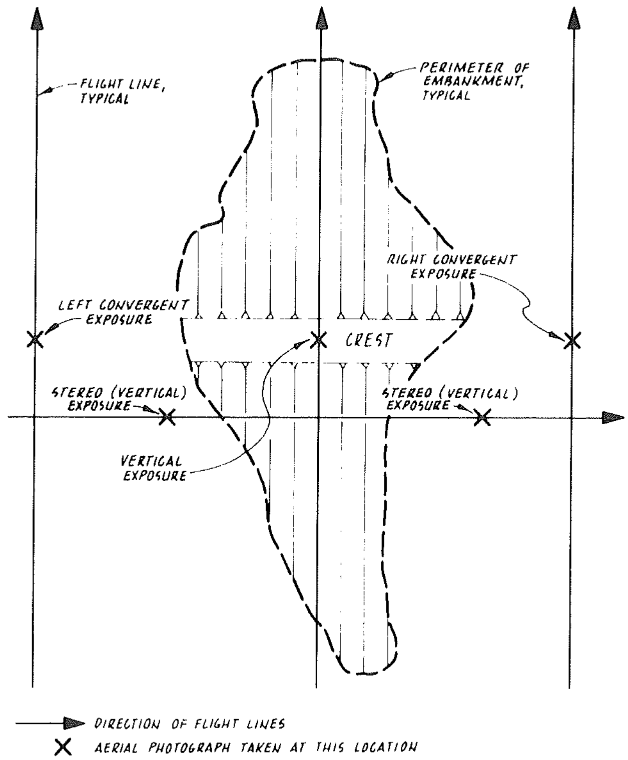

FIGURE 7 - *Typical Exposure Layout*

The increased base-to-height ratio provided by convergent photography enables greater precision for determination of elevations by aerotriangulation. This can be seen on Figure 8; the strength of the position of an intersected point depends on the angle of intersection and the length of the sides. By increasing the base-to-height ratio, all three sides of the triangle formed by intersecting rays approach equal length. In addition, the angle formed by intersecting rays becomes larger. The larger angle affords greater precision; an angular error of 1 second corresponds to a linear error of about 0.3 foot per 1,000 feet (0.3 m per km). By using convergent photography, the difference in precision of computed angles and computed distances is small, thereby increasing the accuracy of coordinates.

Ground Control

The accuracy of the rapid monitoring system is sensitive to both the control point layout as it relates to photo coverage and the accuracy of the original survey which establishes the coordinates of those control points.

The system requires at least three ground control points for which Cartesian coordinates have been determined. The ground control points provide information necessary to determine the relationship of the photographic-coordinate system with respect to the ground-coordinate system. While three ground control points are required, four or more control points are recommended so that a least-squares solution may be performed to determine the relationship of the two coordinate systems.

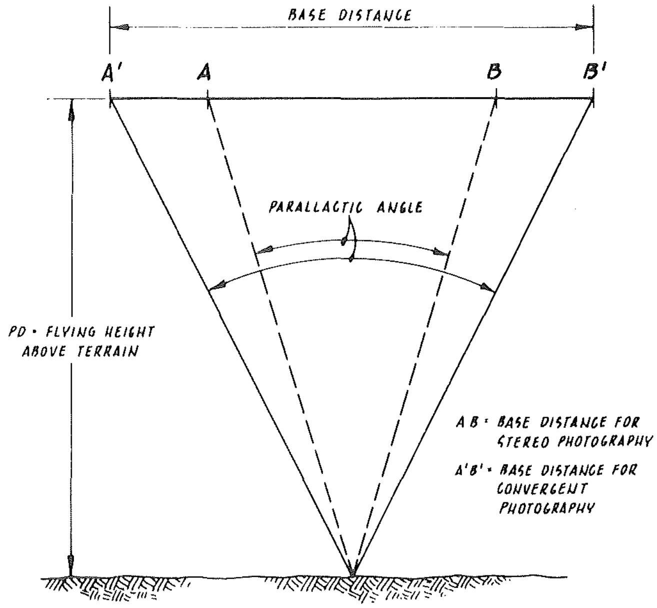

FIGURE 8 - *Base-to-Height Ratio for Stereo and Convergent Photography*

Ideally, images of the control points should appear near the four corners of the photograph. Terrain characteristics and vegetation may preclude ideal location. Therefore, control points should be located outside the area to be monitored to provide the maximum X- and Y-base.

The ground survey of the control points should be of first-order accuracy. First-order accuracy may be obtained using second-order methods by performing redundant observations. Field survey work for this project used a triangulateration scheme in which all angles and sides of polygons formed by the control points were measured.

Film Type

Four types of aerial film were considered for use: black and white (panchromatic), black and white infrared, color, and color infrared. Theoretically, both black and white emulsions and color emulsions have equal resolution characteristics so either type could be used for image point measurements. From an interpretation standpoint, color emulsions offer an advantage since the human eye can separate more than 100 times more color combinations than the gray combinations of black and white emulsions. The added dimension of color tones permits easier detection and differentiation of small low-contrast objects. The relative advantages of color film versus color infrared film vary according to the specific interpretation problem. Color film is normally best for general interpretation because it most closely records natural colors. However, at the same photographic scale, more information will be lost due to atmospheric scattering and absorption for color film than for color infrared film.

The major advantage of black and white film is its economy and ease of use. The film, processing, and reproduction costs are less expensive than those for color films. There is little advantage to using black and white infrared film unless filters are used. The use of filters greatly increases contrast but also reduces image sharpness. Additionally, black and white infrared film has poor shadow penetration inhibiting identification of features or mapping within shadowed areas.

Black and white (B&W) film and color infrared (CIR) film were chosen for use on this project to enable comparison of mensuration and interpretation characteristics. Kodak Double-X Aerographic 2405 (estar base) was used for black and white film and Kodak Aerochrome Infrared Film 2443 (estar base) was used for color infrared film.

Data Reduction

On completion of field work and aerial photography, the film is processed and used for image measurements. In general, the data reduction step consists of measuring image coordinates on the film negatives and processing the information in a series of computer programs as illustrated on Figure 9.

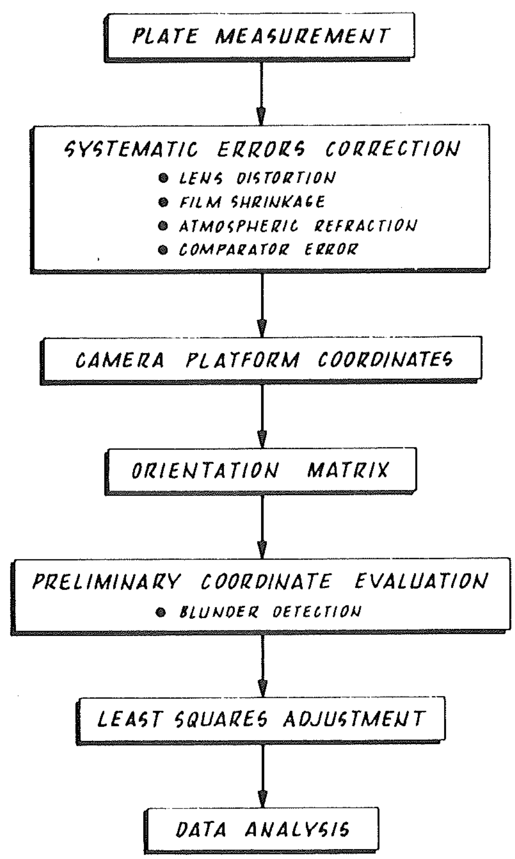

FIGURE 9 - *Data Reduction*

The actual measuring is performed using a monocomparator (Figure 10) which measures X and Y image coordinates to the nearest 1×10^{-6}m. The measured image coordinate data are processed by computer to correct for systematic errors (lens distortion, film shrinkage, atmospheric refraction, and monocomparator calibration) to determine refined image coordinate data.

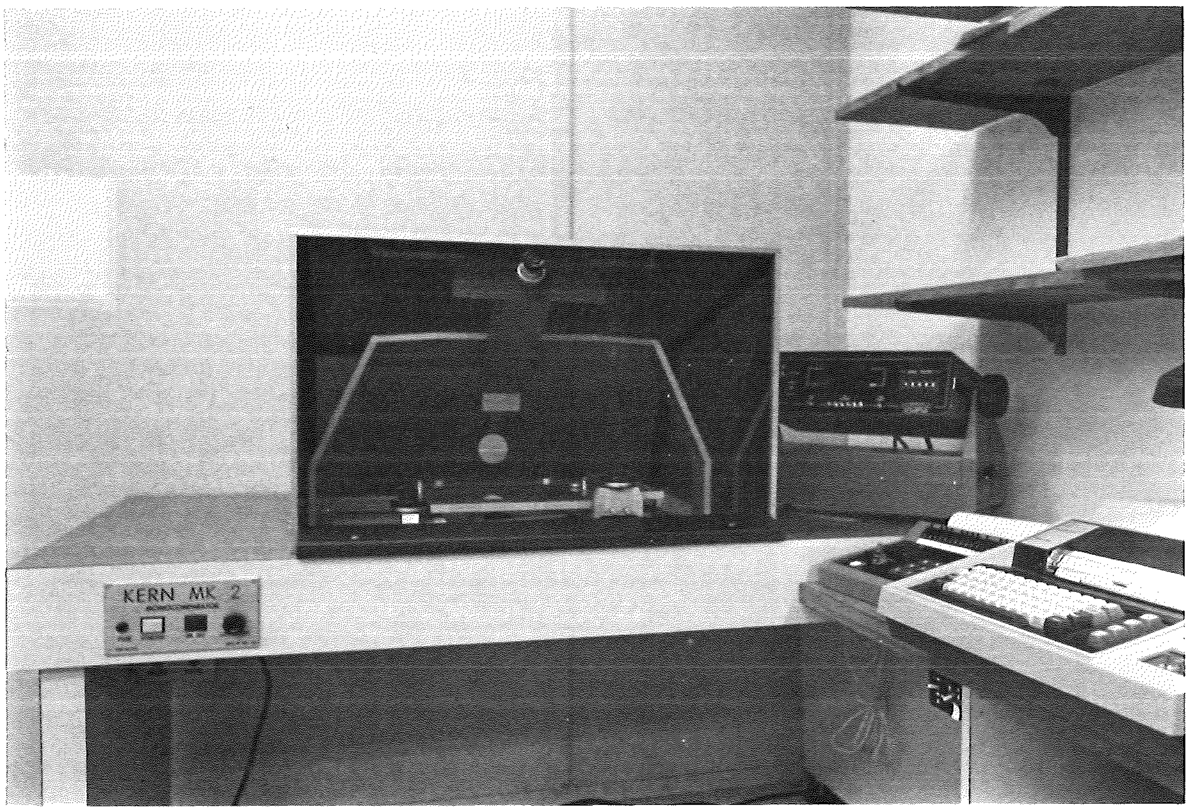

FIGURE 10 - *Kern MK2 Monocomparator*

The refined image coordinates are used in subsequent programs. By using the image coordinates of the known ground control point coordinates, the X, Y, and Z exposure station coordinates of the camera are determined for each photograph. The image point data of the ground control point coordinates and the X, Y, and Z exposure station coordinates are used in another program to determine the rotational relation of the image-coordinate system to the ground coordinate system as shown on Figure 11.

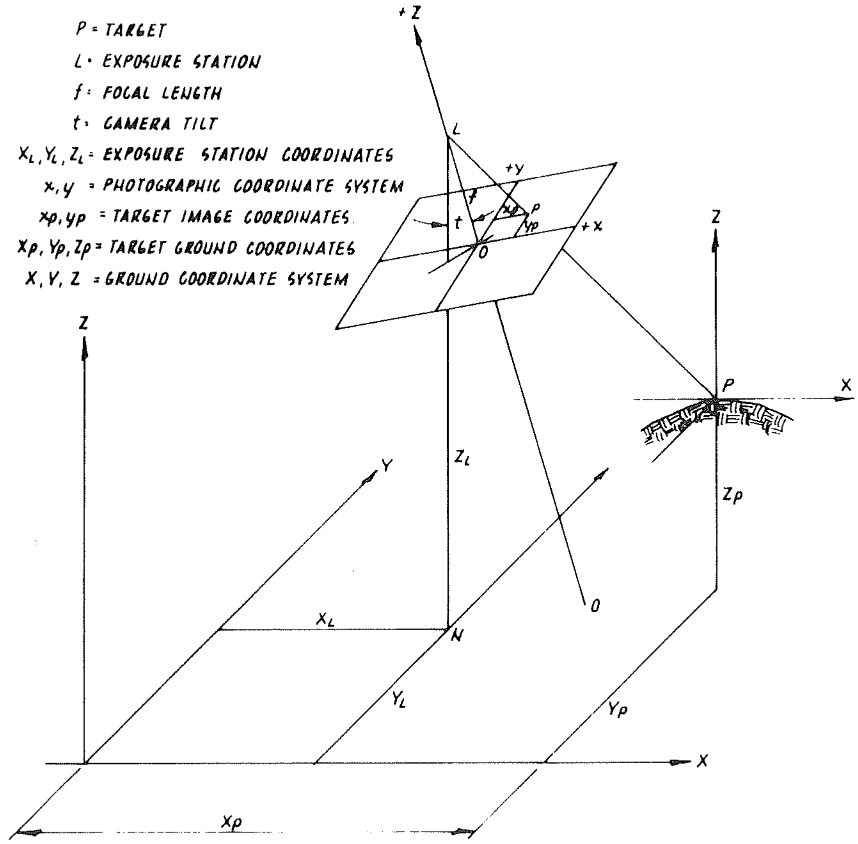

FIGURE 11 - *Geometry of an Aerial Photograph*

The computer programs completely define the relationship of the image-coordinate system with respect to the ground-coordinate system for each photograph. Using this information and the image coordinates of unknown points (unknown in respect to their ground position) for each photograph, ground coordinates can be determined. Since each of the unknown points is defined in space by the intersection of three lines (one line from each photograph), a least-squares adjustment can be made to provide the most probable ground coordinates for each point.

Target Design

Design considerations included durability, corrosion resistance, reflectance properties, availability of materials, and ease of construction and installation. In general, target size should be 1/2000 of the flying height above the point of lowest elevation. On photographs target points of higher elevations will appear larger than those of lower elevations. Therefore, for this project, the diameter chosen was an average of the minimum diameter required for the lowest point and the minimum diameter required for the highest point; the diameter selected for targets was approximately 1 foot (30.5 cm). White, nonreflecting, exterior paint was used to paint the targets.

Photointerpretation

Using an optical stereoscope, stereophotographs can be viewed to identify qualitative slope stability indicators such as cracks, bulges, slumps, and erosion patterns on both B&W and CIR imagery. The time lapse between flights enables the photointerpreter to discern changes in stability indicators. This information, along with the X, Y, and Z coordinate data, enables the user to evaluate the embankment for potential or existing stability problems.

Mapping Capabilities

Topographic mapping was made for Wharton from aerial photographs obtained on the first and last month of monitoring. The downstream face of the refuse embankment was mapped to show progress of construction of the earthfill buttress.

Stereophotographs were used to develop the topographic mapping. The stereophotos were printed on glass plates, and the plates were placed in a Santoni IIC stereoplotter for map generation. The topography was developed by conventional mapping techniques using the known location and elevation of the control points. Accuracy of the topographic mapping varies with the type of stereoplotter, steepness of ground, and amount of ground cover. In general, accuracies of 1/500 to 1/2000 of the flying height can be attained.

After topographic mapping, cross sections of the embankment were made. The cross sections were used for quantity determinations. Results of this work are presented in Chapter 5.

TESTING THE RAPID MONITORING SYSTEM

Roseburg

It was not possible to locate and secure permission to monitor a coal refuse embankment which could be expected to move during the monitoring period. The rapid monitoring system was, therefore, tested for accuracy and speed on an active landslide with a known history of movement. The testing program consisted of comparing the rapid monitoring system with conventional ground survey methods for cost, technique, and practicality. It also determined which film types were best for mensuration and photo-interpretation, and the type of implementation problems that could arise.

A landslide near Roseburg, Oregon was chosen for monitoring. This landslide had a history of movement extending over 15 years and was known to be moving at the time of testing. The slide was progressing downslope by slow continuous soil creep in its lower portions. The movement accelerated during periods of heavy rain.

The landslide covers approximately 10 acres (4 hectares). It is about 1,200 feet (366 m) long and 200-300 feet (61-92 m) wide. The vertical relief of the slide is approximately 550 feet (168 m). Vertical photographs of the slide area are shown on Figures 12 and 13.

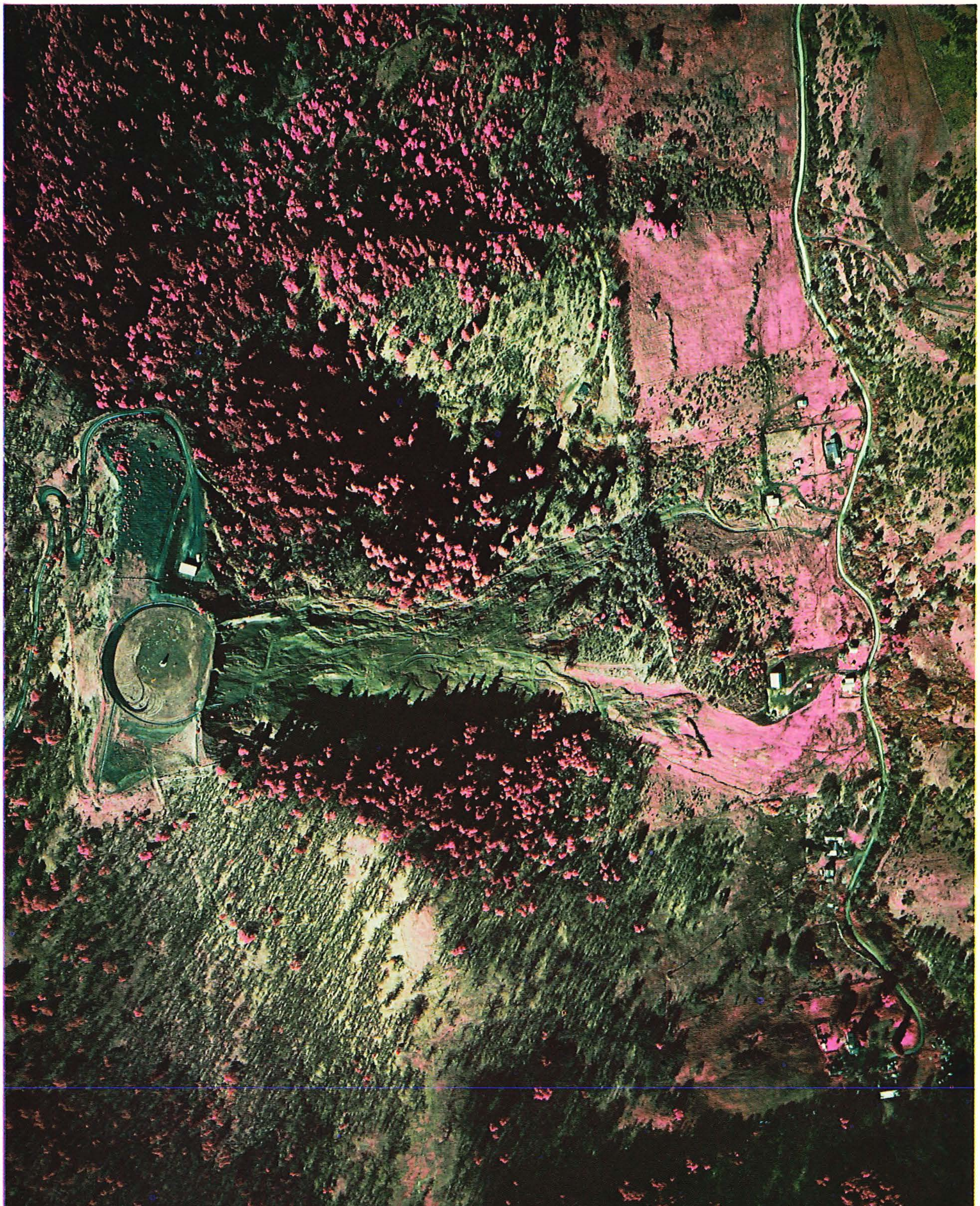

FIGURE 12 - *CIR of Roseburg Landslide*

FIGURE 13 - *Roseburg Landslide*

The landslide was monitored once per month between February and May 1976. The rapid monitoring system was used to determine X, Y, and Z coordinates of ground targets, and conventional ground surveys were performed to verify the accuracy of coordinates determined by aerotriangulation. Ground surveys were performed on the same days that the photography was obtained to ensure that no target movement took place between data collection by either method. The ground surveys were made using second-order methods, achieving an accuracy of ±0.02 foot (0.61 cm). In addition to aerial photogrammetry, terrestrial photogrammetry was tested for use when atmospheric conditions would not permit flying.

Twenty-two targets were installed on active portions of the landslide, and 13 control points were placed outside the active slide area. More control points were established than required for the rapid monitoring system to facilitate ground surveys. The targets and most of the control points at Roseburg consisted of 2-inch-diameter (5.1 cm) galvanized pipe ranging in length from 24-48 inches (0.6-1.2 m) with a 6" x 6" x 1/4" (15.2 cm x 15.2 cm x 0.6 cm) steel plate on the bottom and a 12" x 12" x 1/4" (30.5 cm x 30.5 cm x 0.6 cm) steel target plate on the top. Targets used for terrestrial photogrammetry were equipped with a 2-inch- (5.1 cm) diameter ball atop the steel plate. The pipes were set in holes made with a gasoline-powered hand auger. Figure 14 shows a schematic of the Roseburg targets and Figure 15 shows a photograph of an installed target. The holes were backfilled with soil and tamped before the target was attached.

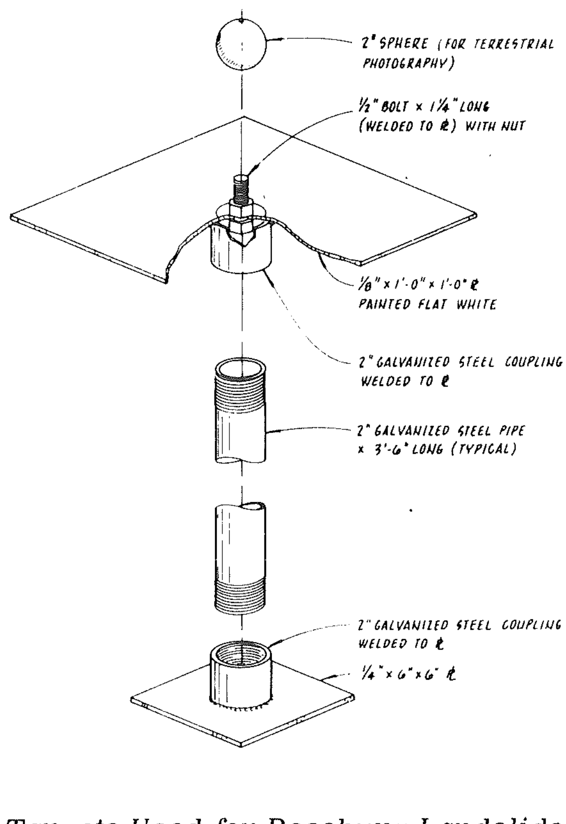

FIGURE 14 - *Targets Used for Roseburg Landslide Monitoring*

FIGURE 15 - *Photograph of Installed Target at the Roseburg Landslide*

Both B&W and CIR films were used in the aerial photography, and monocomparator measurements were made on both film types. Qualitative indicators of slope stability were observed and evaluated by photointerpretation; coordinates were determined for the targets by photogrammetric methods. Measurements were made on photographs from successive flights to detect movement and to produce movement versus time plots.

The specific questions to be answered by the Roseburg monitoring included:

- Can the rapid monitoring system measure terrain movement?
- Is there a difference in accuracy between the conventional ground survey and the rapid monitoring system?
- Is there a difference in accuracy between the two film types?

- Are the aerial photographs useful for identifying qualitative slope stability indicators?
- Is terrestrial photogrammetry a possible alternative for the rapid monitoring system?
- What refinements are needed to make the rapid system applicable to coal waste embankment monitoring?

Results. The rapid monitoring system used at Roseburg demonstrated that it was capable of measuring terrain movement. Furthermore, it showed that when flight geometry is correct, accuracies comparable to conventional ground surveys can be obtained. Figure 16 shows a plot of the horizontal and vertical movements for the two targets that moved as measured by both conventional surveying and by the rapid monitoring system. These were the only targets that moved during monitoring.

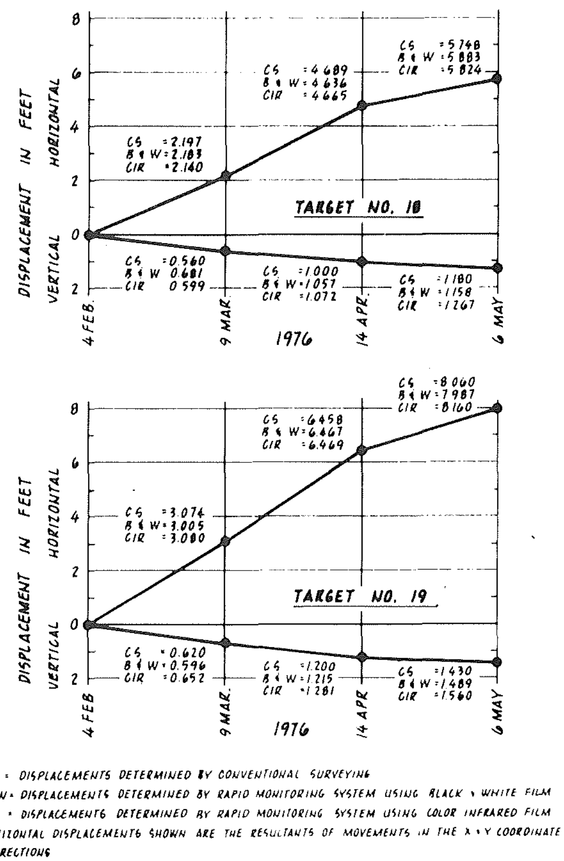

FIGURE 16 - *Target Movement at the Roseburg Landslide*

As shown on Figure 17, 20 percent of the coordinates determined by the rapid system agreed within ±0.05 foot (1.50 cm) of those determined by conventional surveying; 80 percent agreed within ±0.10 foot (3.0 cm); and almost all agreed within ±0.25 foot (7.6 cm).

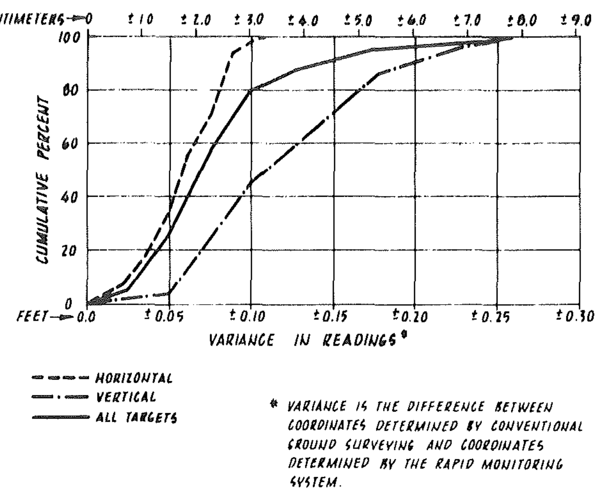

FIGURE 17 - *Frequency Distribution Curve for Coordinate Determination During Roseburg Landslide Monitoring*

The largest differences occurred between conventional surveys and rapid monitoring systems when proper flight lines and aircraft tilt were not maintained. When the proper tilt is not achieved, the accuracy of the horizontal coordinate values are reduced. As a consequence, errors are compounded in the vertical coordinate because it is mathematically determined from the X and Y image coordinates.

For the first monitoring, photogrammetric measurements were made on B&W negatives, B&W diapositives, and CIR transparencies. Each exposure was read two and four times on the monocomparator to determine if any obvious differences in accuracy occurred. Results showed that the number of times the plates were read did not make a difference in accuracy. Statistically there was no difference between the coordinates determined from measurements on the B&W negatives and the CIR transparencies. However, the B&W diapositives showed a marked loss of accuracy compared with the B&W negatives and CIR transparencies. This loss was due to poor image clarity caused by the photographic process for producing diapositives. Because accuracy was one of the major factors in selection of film types, the use of B&W diapositives was discontinued, and all subsequent measurements were made on B&W negatives and CIR transparencies. The B&W negatives and CIR transparencies were not statistically different from each other for accuracy. However, the CIR coordinates varied more from the ground survey coordinates than the B&W coordinates did.

During landslide monitoring, both film types proved useful for identifying qualitative slope stability indicators such as vegetation, soil moisture, slumping or bulging of the embankment, cracks, and soil erosion.

Within the zone of observed movement a definite increase in vegetation was visible on the CIR photos. This was due to increased soil moisture in this zone and the deposition of topsoil which had eroded from upslope. The increase in soil moisture was inferred by vegetation but was not directly visible on the film. Subsequent surface investigations confirmed this correlation. The subsoil above the zone of observed movement was barren and distinct from the slide material.

Cracks in the soil comprising the zone of observed movement were identifiable on both B&W and CIR film. One large crack perpendicular to the direction of movement appeared to widen and lengthen during monitoring. Areas where slumping or bulges had occurred in the past were observed. No new bulges or slumps appeared during monitoring. Figures 18 and 19 illustrate typical cracks in the landslide.

In general, terrestrial photogrammetry gave results that were less accurate than the aerial method. Terrain characteristics permitted only two camera stations compared to three used for aerial photography. The extra camera station provides redundancy that is needed for increased accuracy. Terrestrial photography was difficult to obtain and could not cover the entire site. Target coordinates determined by this method generally disagreed with ground survey results by 0.30 foot (9.1 cm). It was determined that the accuracy and practicality of terrestrial photogrammetry, as such, was not feasible for a rapid monitoring system.

The rapid monitoring system was considered capable of monitoring coal waste embankments because of its ability to detect terrain movement. Target design, however, would have to be altered. Target installation at Roseburg was cumbersome and difficult. The pipes and targets were heavy and difficult to carry. Augering required more than one person, and the steep terrain slopes made all aspects of installation difficult. The targets were rugged and withstood abuse but were not practical for one-man installation.

Coal Refuse Monitoring

After testing the system at the Roseburg landslide, the rapid monitoring system was used at two coal refuse embankments in southern West Virginia. This monitoring program tested the system for its ability to accommodate difficult terrain and atmospheric conditions common to the Appalachian coal fields. These conditions include atmospheric haze, smoke and steam from nearby coal preparation plants, and shadows caused by rugged topography. The system was also tested for its ability to monitor an active coal refuse disposal operation. Finally, the system was tested for its usefulness to detect and monitor movement and its potential as an inspection tool.

FIGURE 18 - *Surface Crack at Roseburg Landslide*

FIGURE 19 - *Surface Crack at Roseburg Landslide*

Refuse embankments at the Wharton preparation plant near Barrett, West Virginia and at the Stirrat preparation plant near Omar, West Virginia were monitored once per month from July 1976 to December 1976.

The Wharton refuse embankment is built across Rock House Hollow in Boone County and has a high phreatic surface because of an upstream impoundment. Construction began in 1956 and has continued until the present (1976) using aerial tram-deposited material. The embankment is approximately 500 feet (152 m) high with a 1,500-foot (457 m) crest length and occupies 50 acres (20 hectares). Vertical photographs of Wharton are shown on Figures 20 and 21.

Thirty-six targets and seven control points were installed for monitoring the Wharton embankment, and an initial ground survey was made to provide base X, Y, and Z coordinates. During monitoring, 20 targets were destroyed by construction of a toe buttress and an access road. A final ground survey of all remaining targets was performed in December to provide a check for accuracy of the rapid system.

The Stirrat refuse embankment covers 40 acres (16 hectares), is approximately 480 feet (146 m) high with a crest length of 1,700 feet (518 m), and is over 1,400 feet (427 m) wide at its base. The embankment dams Rockhouse Branch in Logan County forming a permanent impoundment with freeboard of approximately 250 feet (76 m). The embankment was constructed by aerial-tram-dumping of refuse material beginning in 1945 and ending in 1970 when the height of the refuse pile made the tram inoperable. Since 1970 the coarse coal wastes have been mixed with fine coal waste slurry for hydraulic discharge behind the embankment. Figures 22 and 23 show vertical photographs of the Stirrat site.

Thirteen targets and four control points were installed at the Stirrat embankment for monitoring. The monitoring program at Stirrat was established as a coal refuse inspection prototype. Ground surveys were performed to provide coordinates for the control points only; initial target coordinates were determined by aerotriangulation. A final ground survey was made on the control points to make sure they had not moved during monitoring. A target that showed movement during monitoring and a neighboring target were also surveyed. As with monitoring at the landslide, both B&W and CIR films were used at Wharton and Stirrat. Photographs were obtained of both embankments in the same photo mission.

The targets used in the coal refuse embankment monitoring were different from those used at Roseburg. Targets consisted of 11-inch-diameter (28-cm) aluminum disks painted flat white as shown on Figure 24. A photograph of an installed target is shown on Figure 25. They were attached to 3-foot (91.4-cm) lengths of 1-inch-diameter (2.5-cm) galvanized pipe with bolts and multiset expansion anchors. The pipes were driven into the ground using a pipe driver and a sledge hammer. Couplings could be used to add more pipe if greater depth was desired.

FIGURE 20 - *Wharton Refuse Embankment*

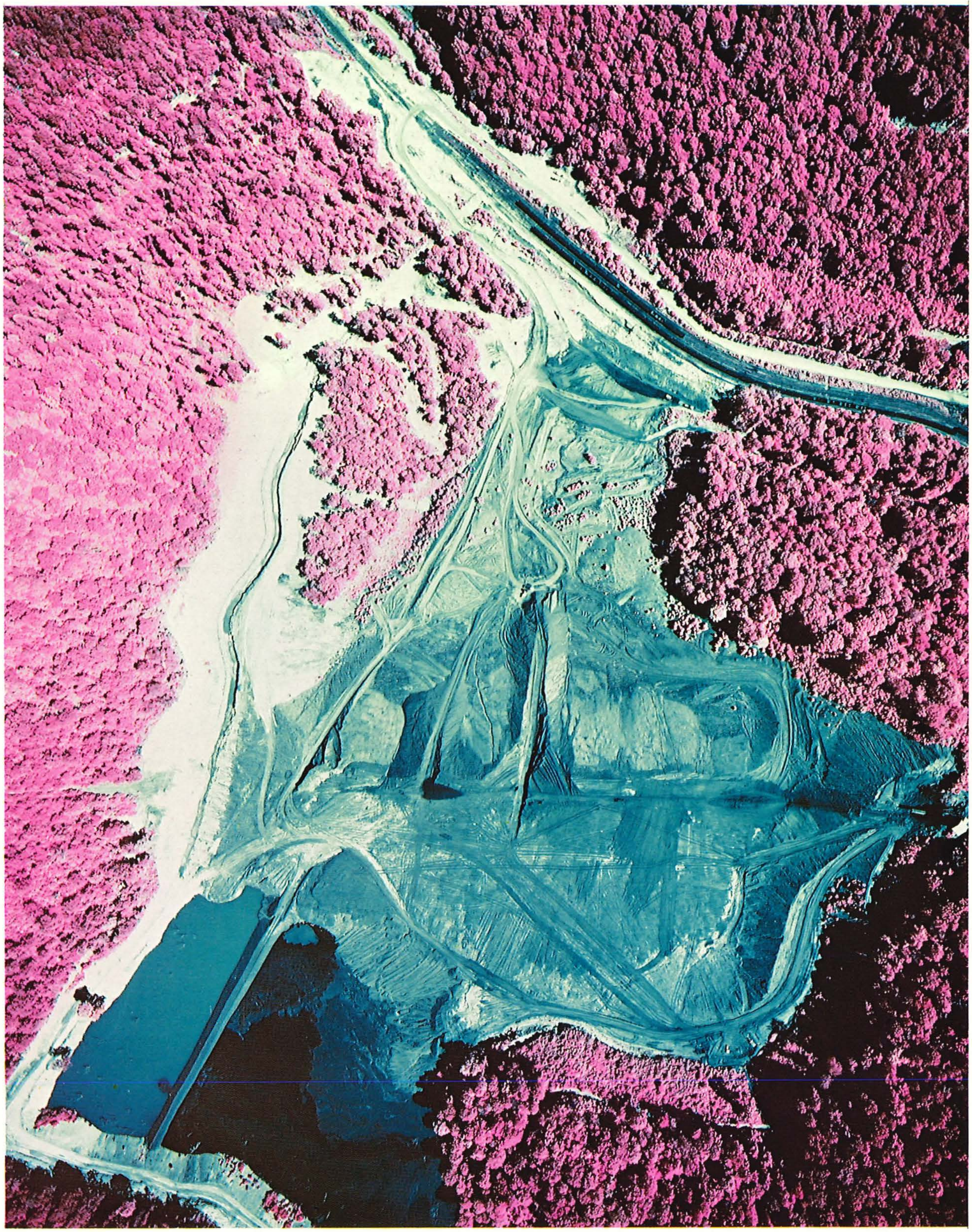

FIGURE 21 - *CIR of Wharton Refuse Embankment*

FIGURE 22 - *Stirrat Refuse Embankment*

FIGURE 23 - *CIR of Stirrat Refuse Embankment*

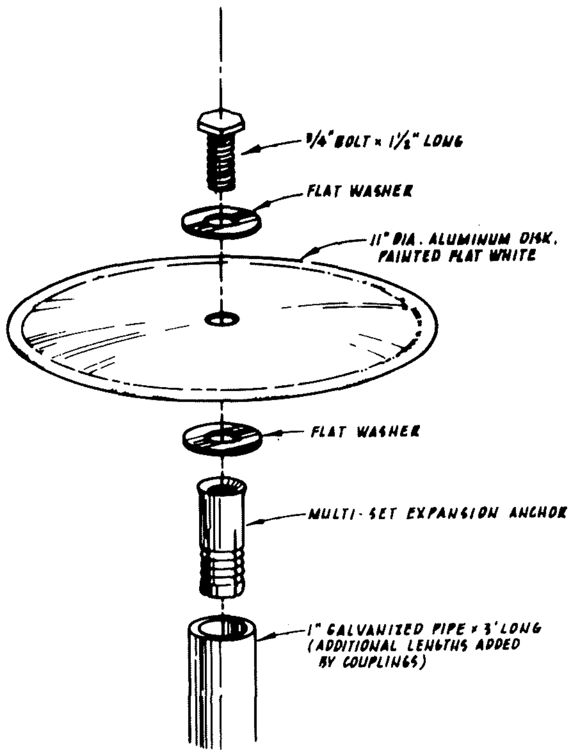

FIGURE 24 - *Target Used for Coal Refuse Embankment Monitoring*

FIGURE 25 - *Photograph of Installed Target for Coal Refuse Monitoring*

The loose nature of the surface coal waste made installation of the targets rather easy. Two men were able to install 36 targets at Wharton and 13 targets at Stirrat in less than 1 day at each site. The light weight of the targets made them easy to carry and possible for one person to install.

Results. The rapid monitoring system accurately recorded the coordinates of targets installed at Wharton. Incomplete photo coverage with CIR film for the first flight at Wharton and Stirrat permitted determination only of B&W coordinates for that month. Field surveys were performed in conjunction with the first and last aerial surveys. A comparison of field survey coordinates and rapid monitoring system coordinates at the Wharton site show X and Y coordinates generally agreed within ±0.10 foot (3.0 cm), and the Z coordinate within ±0.15 foot (4.6 cm). A more detailed comparison of accuracies at both sites is presented in Chapter 5.

During the period of monitoring, movement of targets was observed at both sites. At Stirrat, one target moved approximately 2 feet (0.6 m) horizontally and approximately 1 foot (0.3 m) vertically. During field inspection, it was noted that this target was in an erosion gully. The weight of erosion debris trapped behind the target eventually moved it downslope.

At Wharton, eight targets located on the upstream face of the embankment moved between July and December. Magnitude of movement was generally less than 0.20 foot (6.1 cm) both horizontally and vertically. The movement can be attributed to the loose composition of the surface coal waste and the construction activity nearby. Both the rapid monitoring system and conventional surveying confirmed that movement had occurred.

Target measurements on CIR film were difficult during the fall and winter months. Low sun angles required slow shutter speeds for proper exposure and produced image blur. During this same period targets were clear and sharp on B&W photography.

The only problem encountered during photointerpretation was long shadows covering much of the embankments on the December photos. Interpretation was difficult because shadows caused portions of the film to be underexposed. This type of problem will be difficult to avoid. During the winter months, the best time of day with respect to available light for photography occurs when long shadows from surrounding foliage are present. Some embankments will be more affected than others, depending on the sun's attitude with respect to the embankment. Image blur which affected the mensuration process did not affect photointerpretation since less magnification is used.

Evidence of previous instability was apparent at the Stirrat site. A large scarp where slumping had occurred in the past was visible on the face of the embankment. Numerous old slide scarps were also observed.

No seepage was observed at either embankment, although the Stirrat slurry disposal site was definitely darker from the water present there. Only normal seasonal vegetation changes were visible on the color infrared photos. The greater amount of vegetation on the face of the Stirrat embankment suggests that the Wharton embankment is more active than the Stirrat embankment.

Erosion gulleys were observed on both sites, and they appeared to increase in number and size as monitoring progressed.

"Reddog," or burned coal waste, was observed by field personnel at the Stirrat site. Identification of reddog was difficult due to false color tones on the CIR film. Reddog areas appeared white or overexposed on this film and could be confused with the sun's reflection off the embankment. Reddog could not be detected on B&W. No smoke from burning waste was visible on either B&W film or on CIR infrared film. It was concluded that color photography would be best suited for detecting burned or burning areas because it shows natural colors allowing reddog to be more apparent.

The photography sequence and topographic mapping enabled the interpreter to monitor construction of the embankments. This was particularly apparent at the Wharton site where work on the toe buttress was recorded and easily observed.

The findings of the coal refuse monitoring agreed with those from Roseburg in terms of accuracy and repeatability. Atmospheric haze posed no problems in West Virginia, but the increased cloud cover in autumn and early winter made it difficult to obtain proper CIR film exposure resulting in a loss of accuracy for photo measurements. Inclement weather and snow cover also caused delays in aerial photography.

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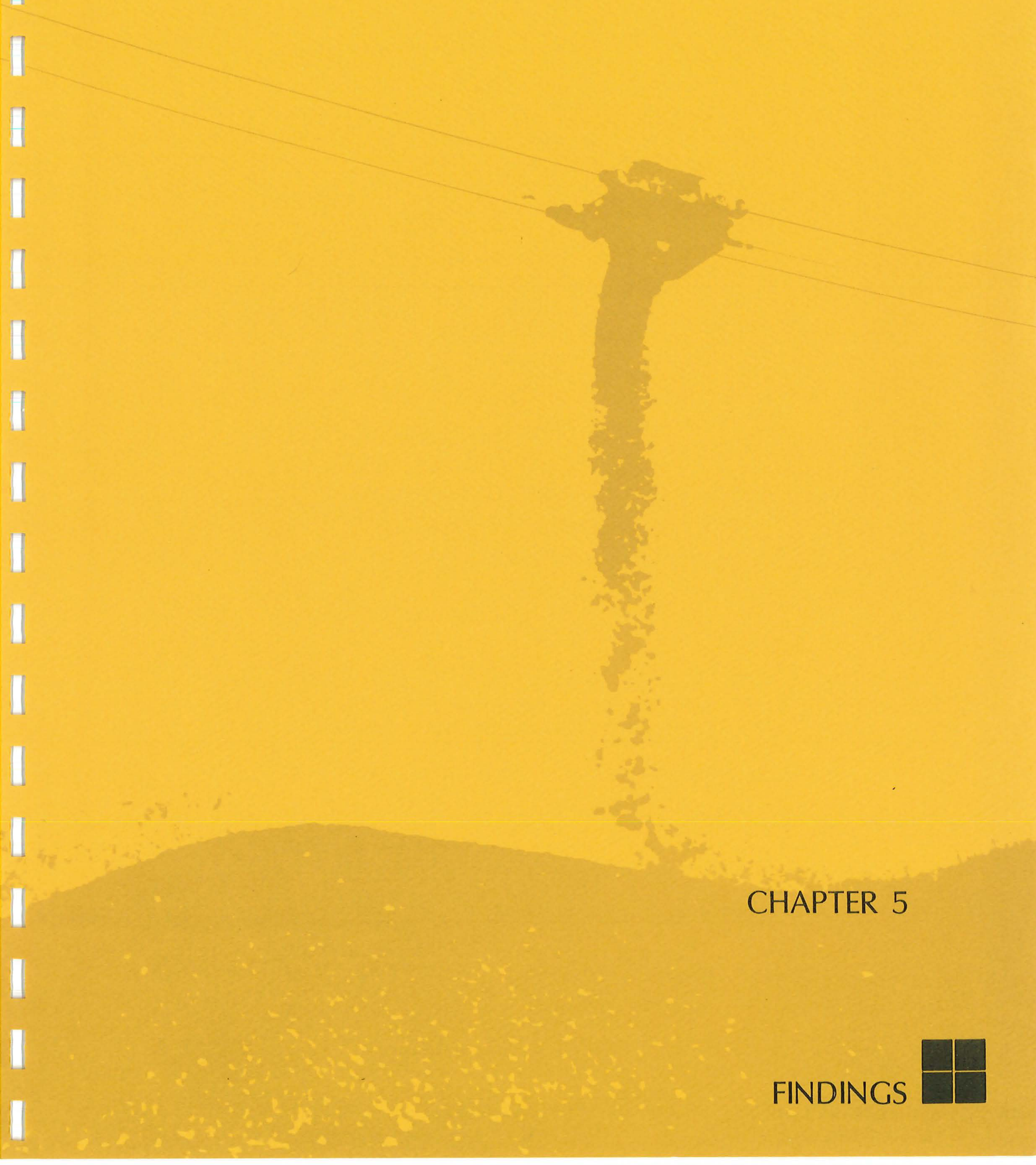


CHAPTER 5

FINDINGS

Chapter 5
FINDINGS

The rapid monitoring system was tested under three separate programs during the study. The first program at the Roseburg landslide incorporated rapid monitoring and conventional ground surveying of targets on the same days. Monitoring results were used to compare the accuracy of the rapid monitoring system and conventional surveying.

The second program at the Wharton refuse embankment included ground surveying for all targets by conventional methods coincident with the first and last monitorings using the rapid monitoring system. This program provided practical information on instrumentation of waste embankments for the rapid monitoring system and supplied additional data on the accuracy of the rapid monitoring system versus conventional ground surveying.

The third program at the Stirrat refuse embankment was designed to simulate actual implementation of the rapid monitoring system for coal waste inspection. Initial coordinates were determined by ground survey for the control points, but no initial ground survey was performed on the targets. On completion of the program, one target that moved during monitoring and a neighboring target that did not move were surveyed using conventional techniques. Final coordinates for these targets obtained by both methods were compared to determine if their differences were within the accuracy limits defined by the Roseburg and Wharton monitoring data.

STATISTICAL ANALYSIS

During all four monitorings at Roseburg and the first and last monitorings at Wharton, X, Y, and Z coordinates were determined by ground survey for each target. These coordinates were assumed to be error free, whereas the ground surveys are probably only accurate to within ±0.02 feet (0.6 cm). X, Y, and Z coordinates were also determined by the rapid monitoring system for each target. The two sets of coordinates were compared and the difference between the values for each coordinate gave a measure of the departure of the rapid monitoring system from the ground survey.

The departure values were analyzed statistically to determine an average value of departure from the ground survey for each coordinate for each month. In addition, a range of values which would include 90 percent of all departure values was determined about this average departure.

Figure 26 shows the average departures and the 90-percent range of values for the Roseburg and Wharton monitorings. Improper aerial photographic coverage of the Wharton site with CIR on 20 July made rapid monitoring data unavailable for that month.

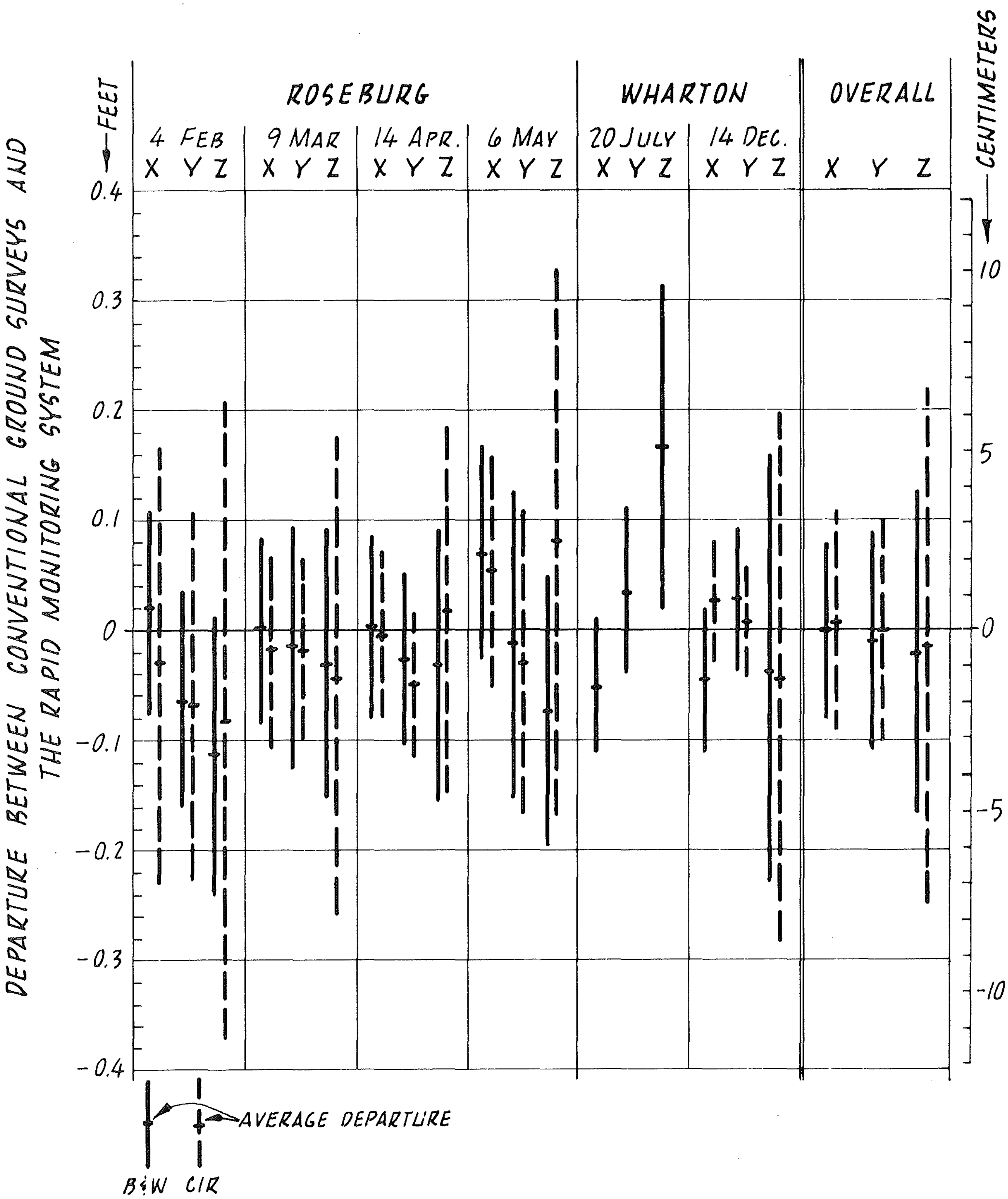


FIGURE 26 - *Accuracy of the Rapid Monitoring System*

The average departures ranged between approximately +0.17 to -0.11 foot (+5.2 to -3.4 cm) for B&W and +0.08 to -0.08 foot (+2.4 to -2.4 cm) for CIR. Overall results combining Roseburg and Wharton data showed the average departures ranged from 0.00 to -0.02 foot (0.0 to -0.6 cm) and +0.01 to -0.01 foot (+0.3 to -0.3 cm) for B&W and CIR, respectively.

ACCURACY

The results from Roseburg and Wharton show that over the entire monitoring program, the average departure values tend toward zero. The average departure values can therefore be considered random errors that will compensate for each other over the duration of monitoring. Coordinate values determined by the rapid monitoring system group in a normal distribution about the theoretically correct coordinate values. The accuracy of the system is therefore determined by the extent that the departure values range about the theoretically correct coordinate value.

Results of the Roseburg and Wharton monitorings show that 90 percent of all rapid system coordinates agreed with the ground survey coordinate values by the following amounts:

Table 2
Rapid Monitoring System Accuracy

	Coordinate		
Film	X	Y	Z
B&W	±0.08 foot (±2.4 cm)	±0.09 foot (±2.7 cm)	±0.15 foot (±4.6 cm)
CIR	±0.10 foot (±3.0 cm)	±0.10 foot (±3.0 cm)	±0.23 foot (±7.0 cm)

Table 2 shows that in comparison to B&W, CIR is slightly less accurate in all coordinates. B&W gave accuracies on the order of 1/29,000 and 1/26,000 of the flying height above the terrain for the X and Y coordinates and 1/15,000 of the flying height for the Z coordinate. In comparison, CIR gave accuracies of 1/23,000 of the flying height for X and Y coordinates and 1/10,000 for the Z coordinate.

Conventional aerial photography from fixed-wing aircraft using vertical photographs is capable of accuracies on the order of 1/10,000 of the flying height above the terrain. Using B&W film and the convergent photographic method this accuracy was increased 1.5-2.9 times. CIR was capable of achieving 1.0-2.3 times this figure. These figures show a significant increase in accuracy over conventional methods but were below the 1/35,000 that is theoretically possible. This deviation from theoretical accuracy is believed to be a result of less than perfect tilt angles of the aircraft and unavoidable operator errors in making monocomparator measurements.

Coordinate values determined during the Stirrat monitoring for the two targets surveyed by both methods showed the following differences:

Table 3
Rapid Monitoring System Results at Stirrat

Film	Target	Coordinate X	Coordinate Y	Coordinate Z
B&W	1	-0.07 foot (-2.1 cm)	-0.05 foot (-1.5 cm)	+0.28 foot (+8.5 cm)
	2	-0.02 foot (-0.6 cm)	-0.01 foot (-0.3 cm)	+0.08 foot (+2.4 cm)
CIR	1	-0.01 foot (-0.3 cm)	-0.02 foot (-0.6 cm)	+0.20 foot (+6.1 cm)
	2	+0.04 foot (+1.2 cm)	-0.09 foot (-2.7 cm)	+0.11 foot (+3.4 cm)

The values fall within the expected accuracy for the rapid monitoring system shown in Table 2, except for the Z coordinate using B&W film on Target 1. These results are in reasonable agreement with the predicted accuracy of the system.

INTERPRETATION

B&W and CIR film were also compared to determine which is more effective for detecting slope stability indicators. The film types were compared by analysis of stereophotographs observed under 1.5x and 4.5x magnification. Factors considered were: versatility; cost; resolution; interpretability (the ability of the film to differentiate tones); shadow penetration; detection of seepage and vegetation conditions; and identification of erosional features along with slides, slumps, cracks, and bulges. Each type of film has specific advantages and disadvantages. Neither is clearly superior to the other for both qualitative and quantative assessments. Results indicate B&W should be used for mensuration and CIR for photointerpretation for optimum use of the rapid monitoring system.

B&W

B&W is suitable for detecting features relating to embankment stability. It has good shadow penetration and good resolution, or clarity. Some advantages of B&W include its low cost, fewer restrictions on weather conditions, and ease in making prints for field use. Problems associated with B&W film are its poor tonal differentiation (limited to shades of gray), poor vegetation analysis, and poor moisture detection capabilities. No special handling techniques are required for B&W film; however, refrigeration of unprocessed film will increase its shelf life.

CIR

CIR is excellent for vegetation studies, good for moisture detection, and good for erosion analysis. Its resolution is generally excellent but deteriorates considerably in poor weather conditions. Longer shutter speeds required for low sun angle photos during fall and winter may cause targets to be slightly blurred under high magnification. Tonal differentiation is good because color is used, but the false color image may be confusing to the inexperienced interpreter. Disadvantages of this film are its sensitivity to weather conditions, requiring clear skies, and its poor shadow penetration.

CIR film is more seriously affected by storage conditions than B&W film. It is extremely sensitive to variations in temperature and relative humidity prior to exposure. The infrared-sensitive layer of the film loses sensitivity and causes a color shift toward blue when not stored properly. The film must be kept in a freezer or refrigerator prior to use. It can be stored up to 14 days at temperatures not exceeding 2°C (35°F) but is best maintained at -18°C (0°F). It should also be removed to room temperature at least 8 hours before opening the container to prevent condensation of atmospheric moisture on the film.

The exposure difficulties encountered during the fall and winter months make CIR film less suitable than B&W film for mensuration purposes. However, the added dimension of color makes CIR film more suitable for interpretation purposes. If both qualitative and quantitative data are to be obtained, B&W film should be used for photography required by the mensuration process and CIR should be used for stereophotographs for interpretation.

Photointerpretation requires people knowledgeable of the characteristics of the film emulsions used and the information being sought. The amount and reliability of the information obtained depends upon the training of the observer. Therefore, B&W or color films might be more suitable than CIR film for less experienced observers.

An important aspect of the rapid monitoring system is the permanent visual record provided by photographs which can be viewed by many people. Inspection reports accompanied by aerial photographs permit better evaluation of embankment conditions by all personnel involved regardless of their interpretation experience.

MAPPING AND QUANTITY DETERMINATION

Topographic mapping and quantity determination were performed using the July and December photographs of Wharton. The downstream face of the embankment was mapped to monitor progress of the earthfill buttress construction. Figure 27 shows the area mapped and Figures 28 and 29 show the topography for July and December, respectively. The progress of construction can be monitored by noting the changes in the contours on the downstream face.

Figure 30 shows an example of cross sections that were developed from the topographic maps. Cut and fill operations for a road can be seen near the crest of the embankment, and buttress construction can be seen between Elevation 1120 and Elevation 1180.

From topographic maps, cut and fill volume determinations can be made by standard earthwork quantity calculations. Cross sections can be developed at convenient stations; the sections can be digitized by computer or plotted by hand. Volumes can then be determined using average end area methods. Based on volume calculations for Wharton, an estimated 18,000 cubic yards of material were placed on the downstream face between July and December 1976.

FIGURE 27 - *Area Topographically Mapped*

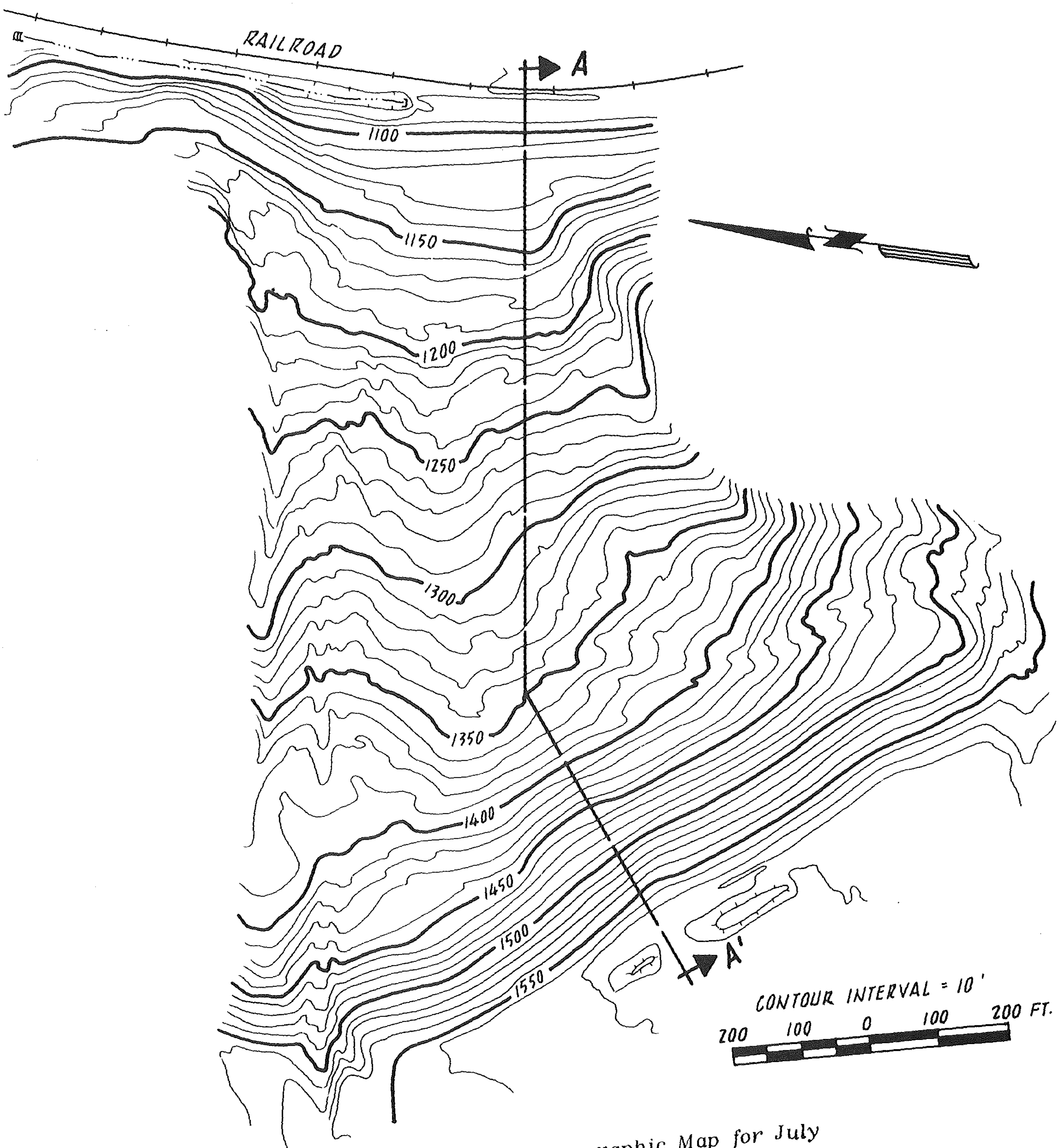


FIGURE 28 - Topographic Map for July

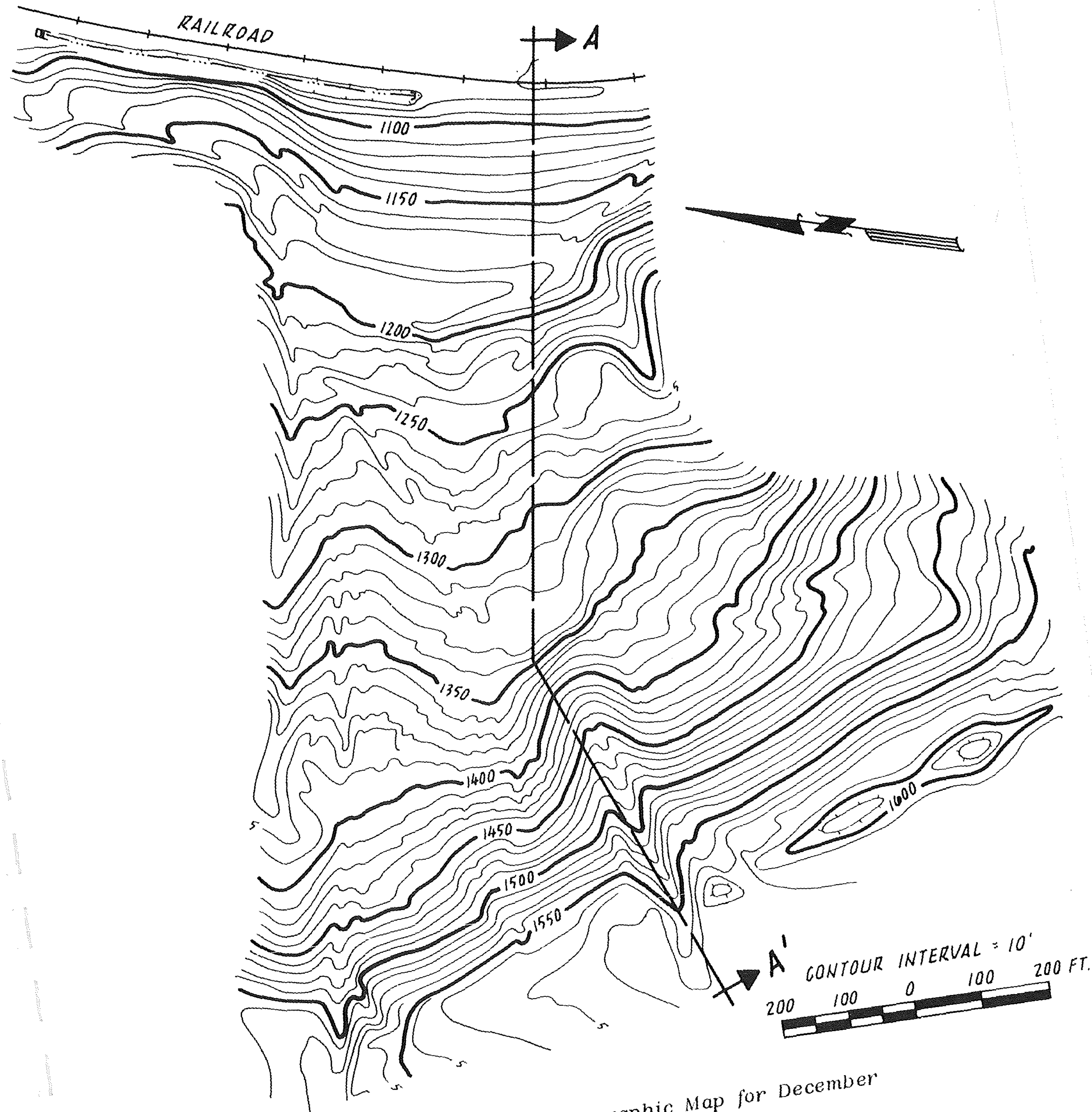


FIGURE 29 - Topographic Map for December

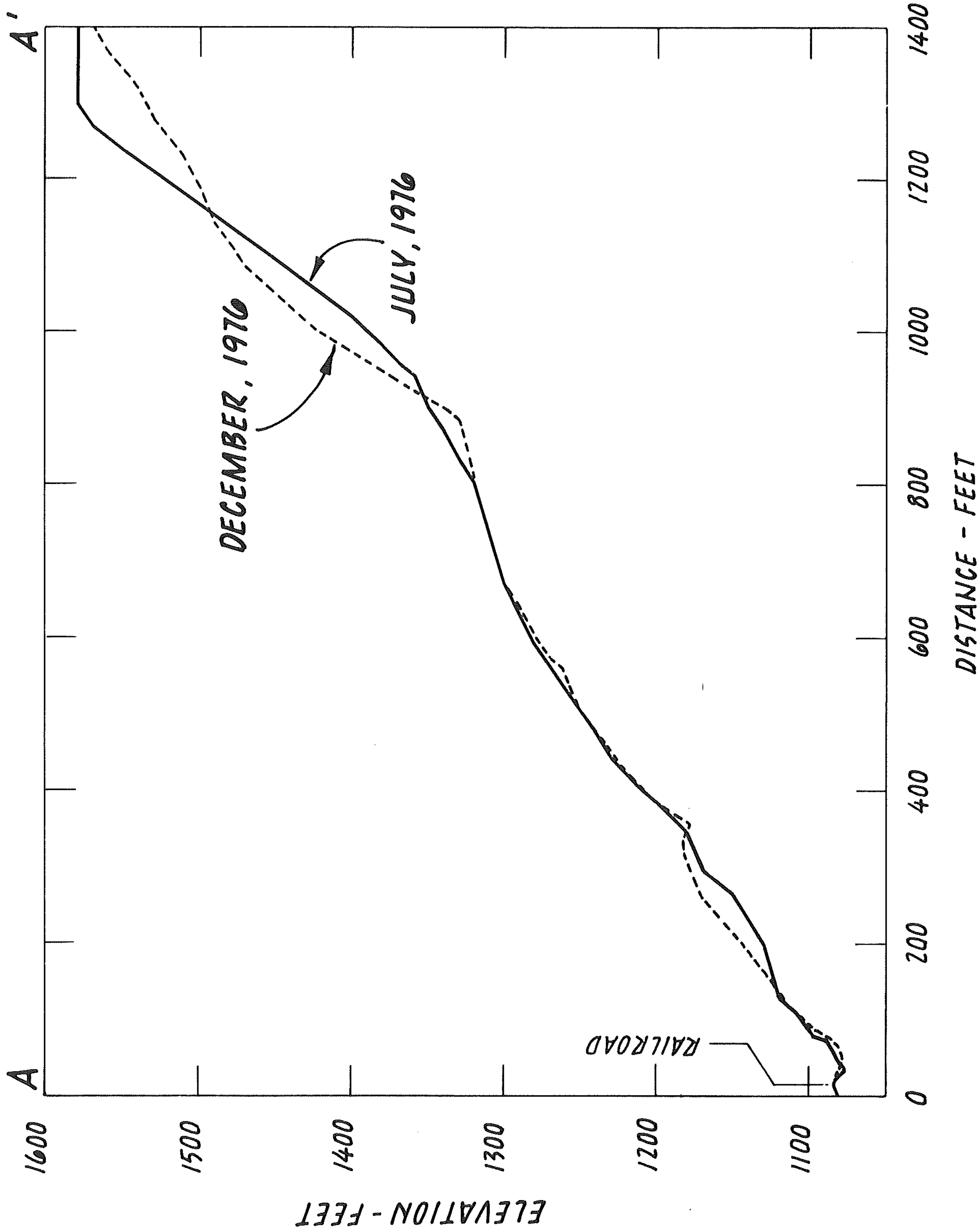
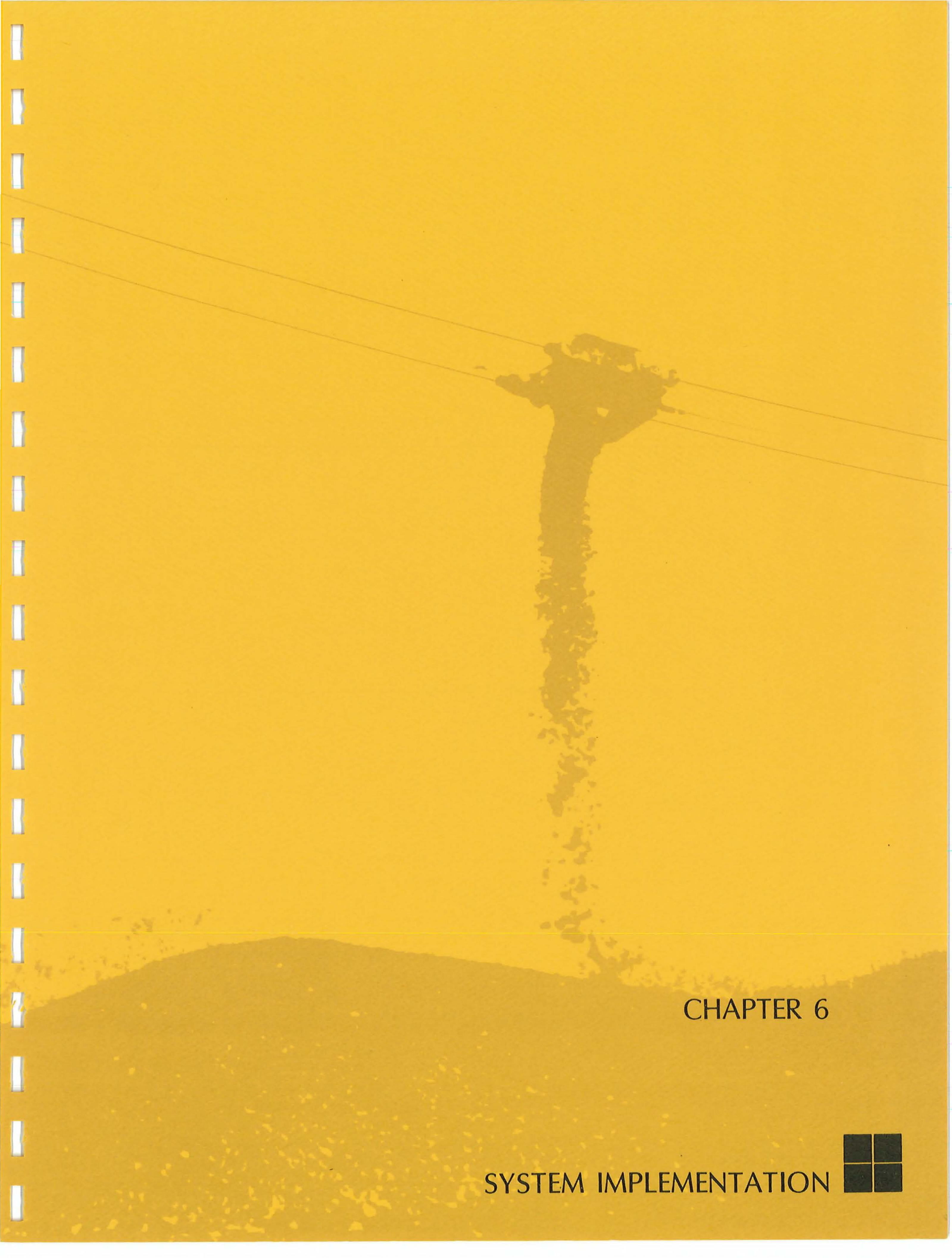


FIGURE 30 - *Cross Section Through Wharton*



CHAPTER 6

SYSTEM IMPLEMENTATION

Chapter 6
SYSTEM IMPLEMENTATION

THE SYSTEM

The rapid monitoring system of aerial photography has proved to be practical for detecting and recording movement of targets on natural slopes and coal refuse embankments. The system is based on existing technology and uses readily available conventional aerial photography cameras with fixed-wing photo aircraft. Convergent photography by intentional aircraft tilt is normally required because most aerial cameras are mounted in a fixed position for vertical photography. More reliable results could be achieved if the mapping camera were mounted to rotate so that convergent photography could be obtained without tilting the aircraft.

A monocomparator is required for measuring on photographs, and data must be analyzed by computer to solve for target coordinates. Copies of computer programs and example input and output formats are shown in the Appendix. One of the computer programs used in data reduction is proprietary; a copy must be purchased through the reference listed in the Appendix.

Targets for the rapid monitoring system are readily available, economic, and easy to install. Other designs or materials could also be used although the actual target face should be painted flat white and should have a minimum diameter of 1/2000 of the flying height above the mean elevation of the embankment to optimize pointing in the monocomparator. Greater lengths of pipe for target bases should be considered where surface materials are loose, or where they are subject to seasonal volume changes. By using common materials, a destroyed target can be readily replaced. Any inspection program using the rapid monitoring system should include a method to account for destroyed or lost targets and their replacements.

Photography for the rapid system should be obtained using film similar to either Kodak Double-X Aerographic 2405 estar base panchromatic (B&W) film or Kodak Aerochrome infrared estar base (CIR) film. Film magazines loaded with each film type are interchangeable in flight. Monocomparator measurements should be made directly on photographic negatives for B&W and on CIR transparencies.

Based on project results, B&W film should probably be selected for mensuration. Although it is not significantly more accurate than CIR, it is easier to use and it is more economic. Either B&W or CIR film can be used for photointerpretation from stereophotographs. Selection of film type for interpretation should be made by the user to suit particular requirements.

The photographs provide a permanent, visual record of embankment conditions. Movement versus time plots should be established and maintained whenever movement is observed. The movement versus time plots should be carefully observed for subtle changes (acceleration or deceleration of movement) that would be indicative of potential stability problems.

PERSONNEL

Implementation of the rapid monitoring system requires personnel with specialized training in two areas: geotechnical engineering and photogrammetry.

Personnel with specialized training in geotechnical engineering (specific experience in design and construction of earth structures) are required to plan and execute inspection programs using the rapid monitoring system. The number and location of targets and correct analysis of data are important to successful use of the rapid monitoring system. Experience at Aberfan and Buffalo Creek shows that mere awareness of movement and signs of instability is not sufficient to prevent failure; the movement and signs of instability must signal the need for further study or corrective action by skilled geotechnical personnel.

Analysis of movement must also be made carefully. It is conceivable that some embankments may be slowly creeping with time, and as long as conditions are relatively constant, corrective actions may not be necessary. On the other hand, it is possible that some embankments may exhibit "brittle" failures where failures occur suddenly with little warning in the form of visual surface movements. In these cases, the embankments must be thoroughly examined for other more subtle indicators of instability. Experienced and knowledgeable personnel must review the data and photographs to assure that unstable conditions are not overlooked or are not misinterpreted.

Personnel with knowledge and experience in photogrammetry and photointerpretation are also required. Flight planning, data reduction, and analysis must be carefully performed. An understanding of the system's limitations as well as the sources and magnitudes of errors are essential. Personnel assigned to mensuration and interpretation tasks must be skilled individuals that are able to identify the sometimes subtle signs of potential safety problems.

SYSTEM SETUP

Careful planning is required before the rapid monitoring system is used on an embankment to ensure that the maximum monitoring potential is achieved. The number and location of targets and control points require careful consideration. Control points should be placed in stable areas outside the area to be monitored. At least four control points are required, and additional points should be considered if there is a possibility that one or more will be inadvertently lost or destroyed. The tentative flight lines should be known before the control points are laid out so that images of the control points will appear as close to the four corners of the photograph as practicable. After the control points have been established, first-order accuracy surveys should be made to determine their X, Y, and Z coordinates. The accuracy of the rapid monitoring system is dependent on the accuracy of the survey for control points. First-order surveys require experienced personnel and precise surveying equipment.

Targets should be placed in areas where movement is likely, or where signs of instability exist. There should be enough targets to adequately cover the embankment and to assure that no gross movements could occur without causing movement of one or more targets. Target layout should be directed by personnel familiar with the behavior of earth structures and with the characteristics of the particular refuse disposal operation. Special considerations for target layout are necessary for embankments that have active operations. The high rate of attrition at Wharton during toe buttress construction demonstrates the vulnerability of targets under certain conditions. Extra targets should be placed where high losses are possible. Targets should be coded for identification and should be catalogued so that inspection forces can keep track of losses and replacements.

The flight lines for the rapid monitoring system are determined by the accuracy requirements for the mathematical computations. Best results are obtained with flight lines arranged so that the airplane flies directly towards the face of the slope or embankment for both the vertical and the convergent photographs. Best results for stereophotography are obtained if the airplane flies parallel to the crest of the embankment. However, flight lines should be carefully planned for each site since the sites differ substantially in size, shape, and vertical relief.

COST

Cost of monitoring is often the most decisive factor in planning the scope of inspection programs. Many factors influence the cost of monitoring: site size and location, vertical relief, accessibility, vegetation, weather, accuracy requirements, frequency, and urgency of monitoring. For the Roseburg landslide, cost of the rapid monitoring system was approximately 40 percent of the cost of conventional ground survey methods for each monitoring. For the Wharton refuse embankment, the cost of the rapid monitoring system was approximately 20 percent of the cost of conventional ground surveys for each monitoring. This percentage reduces to approximately 15 percent when costs for monitoring both Wharton and Stirrat in one air photo mission are compared to ground survey costs.

The rapid monitoring system is not "point-dependent" as ground surveys are. For conventional ground surveys, the time and cost are almost directly dependent on the number of targets. However, it makes very little difference in time and cost for monocomparator measurements and computer analysis of data whether an embankment is instrumented with 10 targets or 100 targets.

Table 4 presents a comparison of possible inspection programs for capability and cost. Information in Table 4 for current inspection methods is based on data obtained from MESA District 4 in Mt. Hope, West Virginia concerning the number of active embankments in their jurisdiction and the approximate cost to administer their inspection program. Costs for conventional ground survey methods and rapid monitoring system are based on costs incurred during this project. The average cost per embankment for the rapid monitoring system includes costs for obtaining five photographs (one vertical, two convergent, and one stereo pair) for four to six embankments per flight. The flight crew is not included in the three-man staff, but their cost is included in the average cost per embankment. The cost for combined inspection is based on using a three-man crew for onsite inspection and the rapid monitoring system. It assumes that two men would make onsite visual inspections and that one man would use the rapid monitoring system.

While the cost for inspection by the rapid monitoring system is about 10-25 percent of the cost for ground surveys, it is about 175-333 percent of the cost of current inspection. However, the rapid monitoring system has been shown to be an effective and powerful monitoring tool. It can accurately detect and monitor movement, and it provides a permanent, visual record. These are valuable features that are not a part of current inspection methods.

If a combination of current inspection methods and the rapid monitoring system were used, the cost per embankment would be 115-220 percent of the cost of current inspection methods. This method would permit detailed investigation of suspect embankments while at the same time permit field forces to more efficiently allocate their inspection time. Embankments that show no apparent signs of instability could be monitored less frequently than those that indicate unstable conditions. Potentially unstable embankments, however, could be monitored both quantitatively and qualitatively by using photogrammetry, photointerpretation, and onsite inspections.

The rapid monitoring system has a high initial cost in comparison to conventional ground survey methods as shown in Table 5.

Table 4
Comparison of Possible Inspection Programs (1975-1976 Costs)

Inspection Program	Capability of 3-Man Staff	Average Cost Per Embankment	Remarks
Current Inspection Methods (based on data from MESA District 4)	60-90 Embankments per Month	$150-$200	1. Inspections are qualitative only. 2. Written descriptions of conditions are recorded on standard forms. 3. Possible unsafe conditions may be overlooked or misinterpreted because of lack of physical measurements or lack of experience of the inspector. 4. Economical.
Conventional Ground Survey Methods	3-5 Embankments per Month	$2,000-$3,500	1. Capable of detecting and monitoring movement. 2. Capable of mapping and determining quantities. 3. Provides written record. 4. Time consuming. 5. Labor intensive. 6. Costly.
Rapid Monitoring System	90-130 Embankments per Month	$350-$500 (using one film type)	1. Capable of detecting and monitoring movement. 2. Capable of mapping and determining quantities. 3. Provides permanent, visual record. 4. Provides qualitative data. 5. Economic in comparison to conventional ground survey. 6. Enables experienced people to view (via photos) many embankments per month.
Combination of Current Inspection Methods and the Rapid Monitoring System	70-100 Embankments per Month	$230-$330	1. Capable of monitoring more embankments than current inspection methods. 2. Provides qualitative information on all embankments and quantitative information on selected embankments. 3. Inspections would allow for better allocation of field inspection resources for suspect embankments. 4. Method would be more economic than rapid monitoring alone.

Table 5
Initial Costs

RAPID MONITORING SYSTEM

	Item	Approximate Cost
1.	Airplane	$ 55,000
2.	Aerial mapping camera	75,000
3.	Monocomparator	30,000
		$160,000

CONVENTIONAL GROUND SURVEY METHODS

	Item	Approximate Cost
1.	2 Theodolites @ $5,000 each	$ 10,000
2.	1 Engineer's level @ $1,500	1,500
3.	Electronic distance measuring equipment	8,000
4.	Miscellaneous equipment	3,500
		$ 23,000

In addition, the rapid monitoring system requires access to a computer with at least 16K memory. This type of computer can cost about $45,000.

By comparison, initial cost for current inspection methods are far less expensive. MESA provides their inspectors with vehicles; required safety equipment (hard hats, etc.); miscellaneous hand equipment (box tapes, hand levels, inexpensive cameras, etc.); necessary inspection forms, manuals, and publications. It is estimated that a MESA inspector can be equipped for current inspection methods for about $8,000-$10,000.

IMPLEMENTATION ALTERNATIVES

For coal refuse embankment monitoring, there are three basic alternative ways to implement the rapid monitoring system. In the first, implementation is by the inspection agency, using its own forces and equipment. In the second, implementation is by the inspection agency through contracts with private firms. The third involves implementation by mine operators.

Actually, the basic alternatives could be combined in many ways to produce any number of inspection packages designed to suit particular needs. Cost of implementation varies widely depending on the alternative or combination of alternatives that is selected.

The second alternative, implementation by an inspection agency through contracts with private firms, probably offers the most advantages. This would avoid the high initial cost of the rapid monitoring system (required in the first alternative) while maintaining the flexibility to use special aircraft or cameras for particular problems. Implementation of the third alternative would require additional legislation and would probably be met by strong opposition from mine operators.

The second alternative provides the most flexibility to the inspection agency. Decisions regarding inspection plans, personnel requirements, and methods to process, analyze, and use data can be made at the local level. These decisions could be based on the urgency of monitoring and the need to suit particular requirements of the local inspection program. Implementation decisions at any level must be based on thorough review of inspection needs to arrive at realistic cost-benefit ratios for use of the rapid monitoring system.

For cost-effective implementation, present inspection methods require modification. The frequency of monitoring by the rapid monitoring system and the frequency of onsite visits by inspection personnel must be coordinated to avoid unnecessary duplication of effort. Because of the quantitative and qualitative data produced by the rapid monitoring system, the frequency and detail of present onsite inspections may be reduced. Proper combination of the two methods may eliminate some unnecessary or unproductive inspection efforts resulting in an overall improvement in cost effectiveness.

SPECIAL CONSIDERATIONS

Implementation recommendations are difficult to make based on the results of this type of research and development effort. For this reason, additional testing of the system is required before realistic cost-benefit ratios can be established. Further testing should be aimed at answering the following questions:

- How useful are the data produced by the rapid monitoring system in an actual long-term inspection program?
- What should be the frequency of monitoring for actual inspection of coal waste embankments?
- Despite the value of quantitative measurement data and qualitative photointerpretation data, can the rapid monitoring system replace the inspector on the ground? Does it merely supplement his activities?
- Although cooperation for use of Wharton and Stirrat was excellent, to what extent will other mine operators cooperate in monitoring programs and target maintenance?
- How do actual costs compare with costs projected from the research and development effort?

- Is the system economic for the benefits achieved?
- How effective are maintenance and replacement programs for lost and destroyed targets?
- Is the system accurate enough for long-term monitoring? Is it too accurate?
- In a given area, how many embankments can be photographed by a single airplane and crew in one day?
- Will mine operators willingly take actions to correct unsafe conditions on the basis of photographic results?
- Which film type is more beneficial in an actual inspection program?
- How does weather affect scheduling for a full-scale monitoring effort?
- What is the most appropriate mix for efforts by the inspection agency and efforts contracted to private firms?
- To what extent will inspection agencies be willing to use the rapid monitoring system or its results in their inspection programs?

Results of this project indicate that the rapid monitoring system has tremendous potential for success as an inspection tool for coal waste embankments. It also has potential for monitoring a wide variety of other types of terrain movement and stability problems. However, these questions should be answered in a full-scale pilot program before final implementation decisions can be made.

In this project, a fast, reliable, and effective method has been developed to assist in coal refuse embankment inspection. The rapid monitoring system meets the objectives of mapping and recording slope conditions while being able to monitor embankment quantities with ease, speed, and reliability. It can provide surveillance of embankment conditions in a fraction of the time required by conventional survey methods, and can be readily integrated with suitable methods for cataloging, evaluating, and analyzing the gathered data.

A significant problem for the rapid monitoring system is its dependence on good weather. Under adverse weather conditions, aerial photography cannot be obtained and the system cannot be used. However, when weather conditions are so severe that low-altitude photography cannot be obtained, conventional field surveys or current inspection procedures would also be difficult.

The rapid monitoring system can only be as effective as the people implementing the program. The inspection agencies must have complete confidence in the data obtained for the system to be successful. The rapid monitoring system could have prevented the Aberfan and Buffalo Creek disasters only if inspection personnel heeded the warnings, however obvious they might have been. As a consequence, future success of the system as an inspection tool rests with the ability and desire of the inspection agency to make use of the data.

APPENDIX

APPENDIX
COMPUTER PROGRAMS

The following programs are used in data reduction to transform photographic image coordinates of targets and control points to ground coordinates. The programs were developed by Dr. Sandor A. Veress, University of Washington. The original versions have been modified for use on CH2M HILL's DECsystem-10 computer. Modifications made were only on input/output statements and devices to facilitate creating input files for succeeding programs and input from CRT terminals in an interactive mode. All input is free format type.

The program for refined image coordinates is not included. This program is one module of a proprietary photogrammetry program package purchased by CH2M HILL from John F. Kenefick, Photogrammetric Consultant, Indiatlantic, Florida.

Sample input and output data are included with Fortran listings for each program.

Program CAMOR

This program computes the X,Y, and Z exposure station coordinates of a camera in the ground coordinate system. The method is based on the principle of equating the cosines of the angles in object space and image space formed by a minimum of three ground control points whose image coordinates have been measured. If more than three control points are used, a least squares solution is performed. The solution is an iterative process and is set up for 10 iterations.

Input

The program as set up on CH2M HILL'S DEC10 computer system reads input data from two separate files and also, from the terminal in an interactive mode.

File 1 - Control point image coordinate data file

Record 1 - STA,XP,YP

where STA = Identification of control point
XP = X-coordinate of measured image point
YP = Y-coordinate of measured image point

Record NCP where NCP = # of control points used

Record NCP+1 9999 0 0 - This record denotes end of image data for photograph.

If more than one photograph is to be processed, records 1 to records NCP+1 are repeated. Note: the number of control points (NCP) can vary from 3 to 20.

File 2 - Ground coordinate data file

Record 1 - SAT,XX,YY,ZZ

where STA = Identification of control point
XX = X-ground coordinate of control point
YY = Y-ground coordinate of control point
ZZ = Z-ground coordinate of control point

Record NCP where NCP = # of control points

Note: The ground coordinate data file requires no sequential order of control points.

Additional input from terminal is an interactive mode as follows:

Each photograph requires -

```
Title
XO,YO,ZO,FL
  where   XO = Approx X-coordinate of exposure Station
          YO = Approx Y-coordinate of Exposure Station
          ZO = Approx Z-coordinate of Exposure Station
          FL = Focal length of camera
```

To end execution, 'END' should be typed in for the title.

Output

Program results are written to two files designated by the user. One file is set up to supply the necessary input for program OMATRI; the other file is a printout of the input data to program CAMOR and the results showing exposure station coordinates and corrections to those coordinates with each iteration.

```
C     SPACE RESECTION (X,Y,Z COORDS OF EXPOSURE STATION)
C     METHOD OF EQUATING COSINES OF ANGLES
C     PROGRAM FROM UNIV. OF WASHINGTON
C
      DIMENSION XGO(20),YGO(20),ZGO(20),CPOINT(20),STA(20)
      DIMENSION XP(30),YP(30),ZP(30),XG(20),YG(20),ZG(20)
      DIMENSION CPX(4),CPY(4),CPZ(4),CGX(4),CGY(4),CGZ(4)
      DIMENSION Q(20,20),R(20,20),S(20,20),AN(30),TITLE(10)
      DIMENSION SP(10),SG(10),CP(20,20),CG(20,20),CONS(20,20),T(40,40)
      DIMENSION PT(100),XX(100),YY(100),ZZ(100)
     COMMON /BLKA/ COEF(60,20),B(60),W(60),D(20,20),V(60),C(20,60)
      DATA PROMPT/"035744020100/
      IN=2
      INN=4
      IOUT=3
      JOUT=8
      CALL SEQIN(IN,'ENTER FILENAME OF CONTROL PT IMAGE COORDS',42)
      CALL SEQIN(INN,'ENTER FILENAME OF GROUND CONTROL COORDS',41)
      CALL SEQOUT(IOUT,'ENTER FILENAME FOR OUTPUT',27)
      CALL SEQOUT(JOUT,'ENTER NAME OF INPUT FILE FOR PROG OMATRI',41)
1     CONTINUE
      NITER=0
      WRITE(5,991)PROMPT
991   FORMAT(/,' ENTER TITLE ',A2,$)
      READ(5,100)TITLE
100   FORMAT(10A4)
      IF(TITLE(1) .EQ. 'END ')GO TO 999
      WRITE(5,992)PROMPT
992   FORMAT(/,1X,'ENTER XO, YO, ZO, FL',A2,$)
      READ(5,*)XO,YO,ZO,FL1
      KNT=1
5     READ(IN,*)STA(KNT),XP(KNT),YP(KNT)
      IF (STA(KNT) .EQ. 9999)GO TO 10
      KNT=KNT+1
      GO TO 5
10    CONTINUE
C     IMAGE PTS NOW READ IN
C
C     READ IN CORRESPONDING GRD. COORDINATES
C
      NCP=KNT-1
      IGSA=1
16    KGSA=1
15    READ(INN,*)PT(KGSA),XX(KGSA),YY(KGSA),ZZ(KGSA)
      IF(STA(IGSA) .EQ. PT(KGSA))GO TO 20
      KGSA=KGSA+1
      GO TO 15
20    XG(IGSA)=XX(KGSA)
      YG(IGSA)=YY(KGSA)
      ZG(IGSA)=ZZ(KGSA)
      IF(IGSA .EQ. NCP) GO TO 30
      IGSA=IGSA+1
      REWIND 4
      GO TO 16
30    CONTINUE
C
      WRITE(IOUT,200)
200   FORMAT(1H1,25X,'*SPACE RESECTION PROGRAM RESULTS*')
      WRITE(IOUT,101)TITLE
101   FORMAT(1X,10A4)
```

```
      WRITE(IOUT,195)
195   FORMAT(13X,12HPHOTO COORDS,13X,14HCONTROL COORDS/,
     15X,3HSTA,6X,1HX,8X,1HY,11X,1HX,11X,1HY,11X,1HZ/)
      DO 47 I=1,NCP
      WRITE(IOUT,196)STA(I),XP(I),YP(I),XG(I),YG(I),ZG(I)
196   FORMAT(3X,F6.0,F10.3,F9.3,F14.2,F12.2,F10.2)
47    CONTINUE
      WRITE(IOUT,201)
201   FORMAT(//,1X,6HNO. OF,10X,21HVALUES OF CORRECTIONS,18X,
     19HCORRECTED,/,1X,10HITERATIONS,12X,14HTO COORDINATES,
     220X,11HCOORDINATES)
48    NITER=NITER+1
      DO 49 I=1,NCP
      XGO(I)=XO-XG(I)
      YGO(I)=YO-YG(I)
      ZGO(I)=ZO-ZG(I)
      SP(I)=SQRT(XP(I)*XP(I)+YP(I)*YP(I)+FL1*FL1)
      SG(I)=SQRT(XGO(I)**2+YGO(I)**2+ZGO(I)**2)
49    CONTINUE
C
      NX=NCP-1
      DO 50 I=1,NX
      K=I+1
      DO 50 J=K,NCP
      CP(I,J)=(XP(I)*XP(J)+YP(I)*YP(J)+FL1*FL1)/(SP(I)*SP(J))
      CG(I,J)=(XGO(I)*XGO(J)+YGO(I)*YGO(J)+ZGO(I)*ZGO(J))/(SG(I)*SG(J))
      CONS(I,J)=CP(I,J)-CG(I,J)
      T(I,J)=(SG(J)-(SG(I)*CP(I,J)))/(SG(I)*SG(J)**2)
      T(J,I)=(SG(I)-(SG(J)*CP(I,J)))/(SG(J)*SG(I)**2)
      Q(I,J)=XGO(I)*T(J,I)+XGO(J)*T(I,J)
      R(I,J)=YGO(I)*T(J,I)+YGO(J)*T(I,J)
      S(I,J)=ZGO(I)*T(J,I)+ZGO(J)*T(I,J)
50    CONTINUE
C
      IROW=(NCP-1)*NCP/2
      DO 51 I=1,IROW
      DO 51 J=1,3
      COEF(I,J)=0.
      B(I)=0.
      W(I)=1.
51    CONTINUE
C
      DO 52 I=1,IROW
      IF(I .GT. 3)GO TO 53
      J=1
      K=I+1
      GO TO 56
53    IF(I .GT. 5)GO TO 54
      J=2
      K=I-1
      GO TO 56
54    IF(I .GT. 7)GO TO 52
      J=3
      K=I-2
56    COEF(I,1)=Q(J,K)
      COEF(I,2)=R(J,K)
      COEF(I,3)=S(J,K)
      B(I)=CONS(J,K)
52    CONTINUE
C
```

```
          M=IROW
          N=3
          CALL LSQR(M,N,AN,VAR)
          XO=XO+AN(1)
          YO=YO+AN(2)
          ZO=ZO+AN(3)
          WRITE(IOUT,202)NITER,(AN(I),I=1,3),XO,YO,ZO
202       FORMAT(/,2X,I2,3X,3(F9.6,1X),3(2X,F12.4))
          IF(NITER-10)48,60,60
60        CONTINUE
          REWIND 4
          WRITE(JOUT,880)TITLE
880       FORMAT(10A4)
          WRITE(JOUT,881)XO,YO,ZO,FL1,NCP
881       FORMAT(3(1X,F16.4),1X,F6.2,1X,I2)
          DO 882 I=1,NCP
          WRITE(JOUT,883)STA(I),XP(I),YP(I)
883       FORMAT(F5.0,1X,F10.5,1X,F10.5)
882       CONTINUE
          DO 884 I=1,NCP
          WRITE(JOUT,885)XG(I),YG(I),ZG(I)
885       FORMAT(3(1X,F14.4))
884       CONTINUE
          GO TO 1
65        STOP
999       END
      SUBROUTINE LSQR (M,N,PAR,ERROR)
      DIMENSION PAR(20)
      COMMON /BLKA/ COEF(60,20),B(60),W(60),D(20,20),V(60),C(20,60)
      DO 1 J = 1, N
      DO 1 I = 1, M
    1 COEF(I,J) = W(I) * COEF(I,J)
      DO 2 J = 1, N
      DO 2 I = 1, N
      D(I,J) = 0.0
      DO 2 K = 1, M
    2 D(I,J) = D(I,J) + COEF(K,I)*COEF(K,J) / W(K)
      CALL MATINV (D,N)
      DO 3 J = 1, M
      DO 3 I = 1, N
      C(I,J) = 0.0
      DO 3 K= 1, N
    3 C(I,J) = C(I,J) + D(I,K)*COEF(J,K)/ W(J)
      DO 4 I = 1, N
      DO 4 J = 1, M
    4 C(I,J) = W(J)*C(I,J)
      DO 5 I = 1, N
      PAR(I) = 0.0
      DO 5 K = 1, M
    5 PAR(I) = PAR(I) + C(I,K)*B(K)
      DO 10 I = 1, M
      SUM = 0.0
      DO 6 J = 1, N
    6 SUM = SUM   + COEF(I,J)*PAR(J)/ W(I)
      V(I) = SUM
   10 CONTINUE
      DO 7 I = 1, M
    7 V(I) = V(I) - B(I)
      ERROR = 0.0
      IF (M .EQ. N ) GO TO 11
```

```
      DO 8 I = 1, M
    8 ERROR = ERROR + V(I)*V(I) * W(I)
      ERROR = ERROR / (FLOAT(M-N))
      DO 9 I = 1, N
      DO 9 J = 1, N
    9 D(I,J) = ERROR*D(I,J)
   11 RETURN
      END
      SUBROUTINE MATINV (A,N)
      DIMENSION A(20,20)
CCC   SUBROUTINE FOR MATRIX INVERSION
CCC   MAXIMUM ELEMENT OF FIRST COLUMN
      AB = 0.0
      DO 1 I=1,N
      AC = ABS(A(I,1))
      AB = AMAX1 (AB,AC)
      IF (AB.GT.AC) GO TO 1
      M = I
    1 CONTINUE
CCC   PERMUTATION OF FIRST AND MTH ROWS
      DO 2 J=1,N
      AA = A(1,J)
      A(1,J) = A(M,J)
      A(M,J) = AA
    2 CONTINUE
CCC   INVERSION OF MATRIX
      NP1 = N + 1
      NM1 = N - 1
      A(1,NP1) = 1.0
      DO 3 I=2,N
    3 A(I,NP1) = 0.0
      DO 6 K=1,N
      DO 4 J=1,N
      JP1 = J + 1
    4 A(NP1,J) = A(1,JP1) / A(1,1)
      DO 5 I=1,NM1
      IP1 = I + 1
      DO 5 J = 1,N
      JP1 = J + 1
    5 A(I,J) = A(IP1,JP1) - A(IP1,1)*A(NP1,J)
      DO 6 J=1,N
    6 A(N,J) = A(NP1,J)
CCC   PERMUTATION OF FIRST AND MTH COLUMNS
      DO 7 I=1,N
      AA = A(I,1)
      A(I,1) = A(I,M)
      A(I,M) = AA
    7 CONTINUE
      RETURN
      END
```

Program OMATR1

This program computes the orientation matrix (9 direction cosines) of a photographic coordinate system using three or more ground points having known ground and photographic coordinates. Also known are the X,Y,Z coordinates of the exposure station in the ground coordinate system. If more than three points are used, a least squares solution is performed.

Input

On CH2M HILL'S DEC10 computer system the input is automatically created in a file upon execution of program CAMOR. The file is set up as follows:

Record 1	Title (40 spaces)
Record 2	XO,YO,ZO,FL1,NCP where XO = X coordinate of exposure station as computed in program CAMOR YO = Y coordinate of exposure station as computed in program CAMOR ZO = Z coordinate of exposure station as computed in program CAMOR FL1 = Focal length of camera (same units as image coords.) NCP = # of control points used.
Record 3 to Record NCP	STA,XP,YP where STA= Identification # of control pt XP = X photograph coordinate YP = Y photograph coordinate Same format as record 3; the total # of records similar to record 3 is equal to NCP.
Record(3+NCP)	XG,YG,ZG where XG = X coordinate of control pt YG = Y coordinate of control pt ZG = Z coordinate of control pt Note: These records must be in same order as photograph coordinate records.
Record(3+NCP)+NCP	Same format as record (3+NCP); the total # of records similar to record (3+NCP) is equal to NCP.

Output

Program results are written to two files designated by the user. One file is a file set up to supply a portion of the necessary input data to program INTER the other file is a printout of the orientation matrix for visual inspection before proceeding with program INTER.

```
C      PROGRAM OMATRIX-ORIENTATION MATRIX OF A PHOTO
C      SOURCE-UNIV OF WASHINGTON
C
       DIMENSION XP(50),YP(50),ZP(50),XG(50),YG(50),ZG(50)
       DIMENSION XGO(20),YGO(20),ZGO(20),STA(50),TITLE(10)
       DIMENSION CPX(20),CPY(20),CPZ(20),CGX(20),CGY(20),CGZ(20)
       DIMENSION SP(50),SG(50),SOL(3,3),AA(6,3),BB(6),AN(30)
       COMMON/BLKA/COEF(60,20),B(60),W(60),D(20,20),V(60),C(20,60)
       IN=8
       IOUT=3
       JOUT=9
       CALL SEQIN(IN,'ENTER INPUT FILENAME FROM PROG RESECT',39)
       CALL SEQOUT(IOUT,'ENTER OUTPUT FILENAME',22)
       CALL SEQOUT(JOUT,'ENTER NAME FOR PROG. INTER INPUT FILE',38)
1      READ(IN,100,END=999)TITLE
100    FORMAT(10A4)
       READ(IN,*)XO,YO,ZO,FL1,NCP
       READ(IN,*)(STA(I),XP(I),YP(I),I=1,NCP)
       READ(IN,*)(XG(I),YG(I),ZG(I),I=1,NCP)
48     NITER=NITER+1
       DO 49 I=1,NCP
       XGO(I)=XO-XG(I)
       YGO(I)=YO-YG(I)
       ZGO(I)=ZO-ZG(I)
       SP(I)=SQRT(XP(I)*XP(I)+YP(I)*YP(I)+FL1*FL1)
       SG(I)=SQRT(XGO(I)**2+YGO(I)**2+ZGO(I)**2)
49     CONTINUE
       DO 80 I=1,NCP
       CPX(I)=-XP(I)/SP(I)
       CPY(I)=-YP(I)/SP(I)
       CPZ(I)=-FL1/SP(I)
       CGX(I)=XGO(I)/SG(I)
       CGY(I)=YGO(I)/SG(I)
       CGZ(I)=ZGO(I)/SG(I)
80     CONTINUE
       WRITE(IOUT,101)TITLE
101    FORMAT(//,' *THE ORIENTATION MATRIX FOR* ',10A4)
       DO 90 K=1,3
       DO 86 I=1,NCP
       DO 86 J=1,3
       COEF(I,J)=0.
       B(I)=0.
       AA(I,J)=0.
       BB(I)=0.
86     CONTINUE
       DO 85 I=1,NCP
       DO 85 J=1,3
       AA(I,1)=CGX(I)
       AA(I,2)=CGY(I)
       AA(I,3)=CGZ(I)
C
C
C
       IF(K-2)82,83,84
82     BB(I)=CPX(I)
       GO TO 81
83     BB(I)=CPY(I)
       GO TO 81
84     BB(I)=CPZ(I)
81     CONTINUE
```

```
            B(I)=BB(I)
            COEF(I,J)=AA(I,J)
            W(I)=1.
85          CONTINUE
            M=NCP
            N=3
            CALL LSQR(M,N,AN,VAR)
            WRITE(IOUT,205)(AN(I),I=1,3)
            WRITE(JOUT,206)(AN(I),I=1,3)
206         FORMAT(1X,3F18.10)
205         FORMAT(/,8X,3F18.10)
90          CONTINUE
            WRITE(JOUT,532)XO,YO,ZO,FL1
532         FORMAT(1X,3(1X,F16.4),1X,F6.2)
            GO TO 1
999         END
      SUBROUTINE LSQR (M,N,PAR,ERROR)
      DIMENSION PAR(20)
      COMMON /BLKA/ COEF(60,20),B(60),W(60),D(20,20),V(60),C(20,60)
      DO 1 J = 1, N
      DO 1 I = 1, M
    1 COEF(I,J) = W(I) * COEF(I,J)
      DO 2 J = 1, N
      DO 2 I = 1, N
      D(I,J) = 0.0
      DO 2 K = 1, M
    2 D(I,J) = D(I,J) + COEF(K,I)*COEF(K,J) / W(K)
      CALL MATINV (D,N)
      DO 3 J = 1, M
      DO 3 I = 1, N
      C(I,J) = 0.0
      DO 3 K= 1, N
    3 C(I,J) = C(I,J) + D(I,K)*COEF(J,K)/ W(J)
      DO 4 I = 1, N
      DO 4 J = 1, M
    4 C(I,J) = W(J)*C(I,J)
      DO 5 I = 1, N
      PAR(I) = 0.0
      DO 5 K = 1, M
    5 PAR(I) = PAR(I) + C(I,K)*B(K)
      DO 10 I = 1, M
      SUM = 0.0
      DO 6 J = 1, N
    6 SUM = SUM   + COEF(I,J)*PAR(J)/ W(I)
      V(I) = SUM
   10 CONTINUE
      DO 7 I = 1, M
    7 V(I) = V(I) - B(I)
      ERROR = 0.0
      IF (M .EQ. N ) GO TO 11
      DO 8 I = 1, M
    8 ERROR = ERROR + V(I)*V(I) * W(I)
      ERROR = ERROR / (FLOAT(M-N))
      DO 9 I = 1, N
      DO 9 J = 1, N
    9 D(I,J) = ERROR*D(I,J)
   11 RETURN
      END
      SUBROUTINE MATINV (A,N)
      DIMENSION A(20,20)
```

```
CCC   SUBROUTINE FOR MATRIX INVERSION
CCC   MAXIMUM ELEMENT OF FIRST COLUMN
      AB = 0.0
      DO 1 I=1,N
      AC = ABS(A(I,1))
      AB = AMAX1 (AB,AC)
      IF (AB.GT.AC) GO TO 1
      M = 1
    1 CONTINUE
CCC   PERMUTATION OF FIRST AND MTH ROWS
      DO 2 J=1,N
      AA = A(1,J)
      A(1,J) = A(M,J)
      A(M,J) = AA
    2 CONTINUE
CCC   INVERSION OF MATRIX
      NP1 = N + 1
      NM1 = N - 1
      A(1,NP1) = 1.0
      DO 3 I=2,N
    3 A(I,NP1) = 0.0
      DO 6 K=1,N
      DO 4 J=1,N
      JP1 = J + 1
    4 A(NP1,J) = A(1,JP1) / A(1,1)
      DO 5 I=1,NM1
      IP1 = I + 1
      DO 5 J = 1,N
      JP1 = J + 1
    5 A(I,J) = A(IP1,JP1) - A(IP1,1)*A(NP1,J)
      DO 6 J=1,N
    6 A(N,J) = A(NP1,J)
CCC   PERMUTATION OF FIRST AND MTH COLUMNS
      DO 7 I=1,N
      AA = A(I,1)
      A(I,1) = A(I,M)
      A(I,M) = AA
    7 CONTINUE
      RETURN
      END
```

Program INTER

This program performs a least squares solution to determine the object space coordinates of observed image points through intersection of homogenous rays in space. The program can be used for two or three cameras, and the intersection of fifty image points maximum.

Input

The program as set up on CH2M HILL DEC10 computer system reads input data from two files.

File 1 - Image Coordinate Data File

Record 1	STA,KI,YI (for first photo)
Record 2	STA,KI,YI (for second photo)
Record 3	STA,XI,YI (for third photo if three are used)

where
STA = Identification number of observed point
XI = Measured X-coordinate
YI = Measured Y-coordinate

Records 1-2 (or 3) are repeated for each pt to be intersected.

File 2 - Camera Orientation File

This file is created automatically upon execution of the program OMATRI and contains the orientation of each photo used for the intersection of observed points. File set-up is as follows:

Record 1	M11,M12,M13
through	M21,M22,M23
Record 3	M31,M32,M33
Record 4	XO,YO,ZO,FL

Where M11-M33 are the values computed in program OMATRI for the orientiation matrix, and XO,YO,ZO are the exposure station coordinates for the camera station computed from program CAMOR, and FL is the focal length of the camera. Records 1-4 are repeated for each photograph.

Output

Two files are created for output data.

File 1 - Long form

Output is written to a file designated by the user. The printout of the file contains the following:

1. Exposure station coordinates for each camera
2. Image coordinates for the point to be intersected
3. Intermediate computation results (Direction cosines, solution matrix)
4. Approximate coordinates
5. Corrections to coordinates
6. Corrected coordinates

File 2 - Short form

Output is written to a file designated by the user. The printout of the file contains a listing of point identification number, and computed X,Y, and Z coordinates.

```
C         SPACE INTERSECTION-2 OR 3 CAMERA STATIONS
C         PROGRAM SOURCE-UNIV OF WASHINGTON
C
          DIMENSION AM(3,3),BM(3,3),CM(3,3),XI(3,50),YI(3,50)
          DIMENSION AA(6,3),R(6),AN(6),AT(3,3),BT(3,3),STA(100)
          DIMENSION XG(100),YG(100),ZG(100),TITLE(10)
        COMMON /BLKA/ COEF(60,20),B(60),W(60),D(20,20),V(60),C(20,60)
          DATA PROMPT/"035744020100/
C
          IC=1
          IN=2
          INN=9
          IOUT=3
          IOUTT=4
          NC=2
          CALL SEQIN(IN,'ENTER IMAGE COORD FILENAME',27)
          CALL SEQIN(INN,'ENTER INPUT FILENAME FROM PROG OMATRI',38)
          CALL SEQOUT(IOUT,'ENTER OUTPUT FILENAME',22)
          CALL SEQOUT(IOUTT,'ENTER S/F OUTPUT FILENAME',28)
          WRITE(5,69)PROMPT
69        FORMAT(/,' ENTER # OF PTS. TO BE INTERSECTED',A2,$)
          READ(5,*)NP
          READ(INN,*)((AM(I,J),J=1,3),I=1,3)
          READ(INN,*)XOA,YOA,ZOA,FL1
          READ(INN,*)((BM(I,J),J=1,3),I=1,3)
          READ(INN,*)XOB,YOB,ZOB,FL2
          READ(INN,*,END=990)((CM(I,J),J=1,3),I=1,3)
          READ(INN,*)XOC,YOC,ZOC,FL3
          NC=3
990       CONTINUE
C
          DO 55 K=1,NP
          WRITE(IOUT,89)
89        FORMAT(1H1,/,20X,'*** SPACE INTERSECTION RESULTS ***',/)
          WRITE(IOUT,888)
888       FORMAT(3X,' EXPOSURE STATIONS COORDINATES',/)
          WRITE(IOUT,87)XOA,YOA,ZOA
87        FORMAT(1X,'PLATE 1',2X,3F14.3)
          WRITE(IOUT,887)XOB,YOB,ZOB
887       FORMAT(1X,'PLATE 2',2X,3F14.3)
          IF(NC .EQ. 2)GO TO 777
          WRITE(IOUT,877)XOC,YOC,ZOC
877       FORMAT(' PLATE 3',2X,3F14.3)
777       CONTINUE
          WRITE(IOUT,88)
88        FORMAT(/,5X,'IMAGE COORDINATES OF THE PT. ',/)
          DO 54 I=1,NC
          READ(IN,*)STA(I),XI(I,K),YI(I,K)
          WRITE(IOUT,90)I,STA(I),XI(I,K),YI(I,K)
90        FORMAT(5X,'PLATE # ',I2,2X,'PT ',F5.0,2F10.4)
54        CONTINUE
          DO 60 I=1,3
          DO 60 J=1,3
          AT(J,I)=AM(I,J)
60        BT(J,I)=BM(I,J)
          PO1=SQRT(XI(1,K)**2+YI(1,K)**2+FL1**2)
          PO2=SQRT(XI(2,K)**2+YI(2,K)**2+FL2**2)
          CX1=-XI(1,K)/PO1
          CY1=-YI(1,K)/PO1
          CZ1=-1*(FL1/PO1)
```

```
      CX2=-XI(2,K)/PO2
      CY2=-YI(2,K)/PO2
      CZ2=FL2/PO2
      CZ2=-CZ2
      DCX1=AT(1,1)*CX1+AT(1,2)*CY1+AT(1,3)*CZ1
      DCY1=AT(2,1)*CX1+AT(2,2)*CY1+AT(2,3)*CZ1
      DCZ1=AT(3,1)*CX1+AT(3,2)*CY1+AT(3,3)*CZ1
      DCX2=BT(1,1)*CX2+BT(1,2)*CY2+BT(1,3)*CZ2
      DCY2=BT(2,1)*CX2+BT(2,2)*CY2+BT(2,3)*CZ2
      WRITE(IOUT,91)DCX1,DCY1,DCZ1,DCX2,DCY2
91    FORMAT(/,5X,'DIRECTION COSINES',/,5X,5(F10.8,2X))
      YGO=(XOB-XOA+YOA*DCX1/DCY1-YOB*DCX2/DCY2)/(DCX1/DCY1
      1-DCX2/DCY2)
      XGO=(YGO-YOA)*DCX1/DCY1+XOA
      ZGO=ZOA+(YGO-YOA)*DCZ1/DCY1
      XP1=XGO-XOA
      YP1=YGO-YOA
      ZP1=ZGO-ZOA
      XP2=XGO-XOB
      YP2=YGO-YOB
      ZP2=ZGO-ZOB
      IF(NC .EQ. 2)GO TO 20
      XP3=XGO-XOC
      YP3=YGO-YOC
      ZP3=ZGO-ZOC
20    CONTINUE
      DEN1=AM(3,1)*XP1+AM(3,2)*YP1+AM(3,3)*ZP1
      DEN2=BM(3,1)*XP2+BM(3,2)*YP2+BM(3,3)*ZP2
      IF(NC .EQ. 2)GO TO 21
      DEN3=CM(3,1)*XP3+CM(3,2)*YP3+CM(3,3)*ZP3
21    CONTINUE
      F1=FL1*(AM(1,1)*XP1+AM(1,2)*YP1+AM(1,3)*ZP1)/DEN1
      F2=FL1*(AM(2,1)*XP1+AM(2,2)*YP1+AM(2,3)*ZP1)/DEN1
      F3=FL2*(BM(1,1)*XP2+BM(1,2)*YP2+BM(1,3)*ZP2)/DEN2
      F4=FL2*(BM(2,1)*XP2+BM(2,2)*YP2+BM(2,3)*ZP2)/DEN2
      IF(NC .EQ. 2)GO TO 22
      F5=FL3*(CM(1,1)*XP3+CM(1,2)*YP3+CM(1,3)*ZP3)/DEN3
      F6=FL3*(CM(2,1)*XP3+CM(2,2)*YP3+CM(2,3)*ZP3)/DEN3
22    CONTINUE
      NCR=NC*2
      DO 50 I=1,NCR
      DO 50 J=1,3
      AA(I,J)=0.
      R(I)=0.
50    CONTINUE
      DO 51 J=1,3
      AA(1,J)=(AM(1,J)*FL1-AM(3,J)*XI(1,K))/DEN1
      AA(2,J)=(AM(2,J)*FL1-AM(3,J)*YI(1,K))/DEN1
      AA(3,J)=(BM(1,J)*FL2-BM(3,J)*XI(2,K))/DEN2
      AA(4,J)=(BM(2,J)*FL2-BM(3,J)*YI(2,K))/DEN2
      IF(NC .EQ. 2)GO TO 51
      AA(5,J)=(CM(1,J)*FL3-CM(3,J)*XI(3,K))/DEN3
      AA(6,J)=(CM(2,J)*FL3-CM(3,J)*YI(3,K))/DEN3
51    CONTINUE
      R(1)=XI(1,K)-F1
      R(2)=YI(1,K)-F2
      R(3)=XI(2,K)-F3
      R(4)=YI(2,K)-F4
      IF(NC .EQ. 2)GO TO 52
      R(5)=XI(3,K)-F5
```

```
       R(6)=Y1(3,K)-F6
52     CONTINUE
       WRITE(IOUT,67)
67     FORMAT(//,5X,' SOLUTION MATRIX ')
       DO 100 I=1,NCR
       WRITE(IOUT,93)((AA(I,J),J=1,3),R(I))
93     FORMAT(/,5X,3F16.9,5X,F16.9)
100    CONTINUE
       WRITE(IOUT,92)XGO,YGO,ZGO
92     FORMAT(//,5X,'APPROXIMATE COORDINATES',/,5X,3(F20.4,2X))
       DO 53 I=1,NCR
       DO 53 J=1,3
       W(I)=1.
       COEF(I,J)=AA(I,J)
       B(I)=R(I)
53     CONTINUE
       M=NCR
       N=3
       CALL LSQR(M,N,AN,VAR)
       WRITE(IOUT,94)(AN(I),I=1,3)
94     FORMAT(//,5X,'CORRECTIONS TO COORDINATES',/,3X,3F16.8)
       XG(K)=XGO+AN(1)
       YG(K)=YGO+AN(2)
       ZG(K)=ZGO+AN(3)
57     WRITE(IOUT,95)STA(1),XG(K),YG(K),ZG(K)
95     FORMAT(//,5X,'CORRECTED COORDINATES ',/,3X,'POINT ',F5.0,3F20.8
       1/)
       WRITE(IOUTT,99)STA(1),XG(K),YG(K),ZG(K)
99     FORMAT(2X,F5.0,3X,F11.3,5X,F11.3,5X,F9.3)
       IC=IC+NC
55     CONTINUE
1000   STOP
999    END
      SUBROUTINE LSQR (M,N,PAR,ERROR)
      DIMENSION PAR(20)
      COMMON /BLKA/ COEF(60,20),B(60),W(60),D(20,20),V(60),C(20,60)
      DO 1 J = 1, N
      DO 1 I = 1, M
    1 COEF(I,J) = W(I) * COEF(I,J)
      DO 2 J = 1, N
      DO 2 I = 1, N
      D(I,J) = 0.0
      DO 2 K = 1, M
    2 D(I,J) = D(I,J) + COEF(K,I)*COEF(K,J) / W(K)
      CALL MATINV (D,N)
      DO 3 J = 1, M
      DO 3 I = 1, N
      C(I,J) = 0.0
      DO 3 K= 1, N
    3 C(I,J) = C(I,J) + D(I,K)*COEF(J,K)/ W(J)
      DO 4 I = 1, N
      DO 4 J = 1, M
    4 C(I,J) = W(J)*C(I,J)
      DO 5 I = 1, N
      PAR(I) = 0.0
      DO 5 K = 1, M
    5 PAR(I) = PAR(I) + C(I,K)*B(K)
      DO 10 I = 1, M
      SUM = 0.0
      DO 6 J = 1, N
```

```
    6 SUM = SUM    + COEF(I,J)*PAR(J)/ W(I)
      V(I) = SUM
   10 CONTINUE
      DO 7 I = 1, M
    7 V(1) = V(I) - B(I)
      ERROR = 0.0
      IF (M .EQ. N ) GO TO 11
      DO 8 I = 1, M
    8 ERROR = ERROR + V(I)*V(I) * W(I)
      ERROR = ERROR / (FLOAT(M-N))
      DO 9 I = 1, N
      DO 9 J = 1, N
    9 D(I,J) = ERROR*D(I,J)
   11 RETURN
      END
      SUBROUTINE MATINV (A,N)
      DIMENSION A(20,20)
CCC   SUBROUTINE FOR MATRIX INVERSION
CCC   MAXIMUM ELEMENT OF FIRST COLUMN
      AB = 0.0
      DO 1 I=1,N
      AC = ABS(A(I,1))
      AB = AMAX1 (AB,AC)
      IF (AB.GT.AC) GO TO 1
      M = I
    1 CONTINUE
CCC   PERMUTATION OF FIRST AND MTH ROWS
      DO 2 J=1,N
      AA = A(1,J)
      A(1,J) = A(M,J)
      A(M,J) = AA
    2 CONTINUE
CCC   INVERSION OF MATRIX
      NP1 = N + 1
      NM1 = N - 1
      A(1,NP1) = 1.0
      DO 3 I=2,N
    3 A(I,NP1) = 0.0
      DO 6 K=1,N
      DO 4 J=1,N
      JP1 = J + 1
    4 A(NP1,J) = A(1,JP1) / A(1,1)
      DO 5 I=1,NM1
      IP1 = I + 1
      DO 5 J = 1,N
      JP1 = J + 1
    5 A(I,J) = A(IP1,JP1) - A(IP1,1)*A(NP1,J)
      DO 6 J=1,N
    6 A(N,J) = A(NP1,J)
CCC   PERMUTATION OF FIRST AND MTH COLUMNS
      DO 7 I=1,N
      AA = A(I,1)
      A(I,1) = A(1,M)
      A(I,M) = AA
    7 CONTINUE
      RETURN
      END
```

REFINED IMAGE COORDINATE DATA FILE

1.	-54.0336	-8.9595
2.	-56.0768	-15.4850
3.	-45.9028	-19.1515
4.	-41.8631	-8.2426
5.	-24.5798	-9.4498
6.	-24.6408	-13.0448
7.	-24.6731	-18.3398
8.	-16.8305	-17.6127
9.	-16.6183	-14.8826
10.	-16.2017	-10.7761
11.	-13.7717	-8.7484
12.	-11.9717	-13.5929
13.	-9.8053	-19.0191
14.	-2.5407	-20.5287
15.	-2.0276	-10.8062
16.	-3.8302	-6.2231
17.	3.9586	-2.5526
18.	18.2670	-27.2440
19.	16.7148	-32.1366
20.	26.6198	-34.2099
21.	28.8320	-32.7138
22.	30.3612	-35.2383
103.	38.4200	-41.9848
9001.	-68.2536	-2.0887
9002.	-52.3601	-6.4580
102.	0.6171	-17.3318
105.	13.9384	-41.1011
1.	-48.6446	17.4720
2.	-50.2378	12.0010
3.	-40.9430	7.8216
4.	-37.9034	16.7852
5.	-22.2694	14.4756
6.	-22.0138	11.4696
7.	-21.6006	7.1431
8.	-14.3808	7.2175
9.	-14.4559	9.5521
10.	-14.4919	12.8980
11.	-12.4595	14.3559
12.	-10.3128	10.5007
13.	-7.6709	5.8202
14.	-0.7154	4.7363
15.	-1.4447	12.6556
16.	-3.6407	16.2362
17.	3.0811	18.7652
18.	20.1817	-1.1667
19.	19.5635	-5.7648
20.	29.7490	-7.8535
21.	31.6485	-6.4998
22.	33.6853	-8.8190
103.	43.1315	-14.5038
9001.	-61.0875	21.1428
9002.	-47.2620	19.6379
102.	1.7947	7.6814
105.	18.4425	-14.3044
1.	-46.4642	-18.3077
2.	-46.9192	-23.6038
3.	-37.5761	-23.9230
4.	-36.0451	-14.6219
5.	-20.4964	-11.4377
6.	-20.0093	-14.3352

7.	-19.2616	-18.6697
8.	-12.3842	-16.3312
9.	-12.5592	-14.0820
10.	-12.7390	-10.6093
11.	-10.7925	-8.3065
12.	-8.5233	-12.0950
13.	-5.8943	-16.0513
14.	0.8276	-16.1031
15.	0.2539	-7.7842
16.	-1.9171	-4.0854
17.	5.0257	1.0125
18.	20.3732	-17.7972
19.	19.3014	-21.8404
20.	28.4687	-21.6562
21.	30.4378	-20.0728
22.	31.9485	-21.8149
103.	39.4986	-26.1383
9001.	-60.2215	-14.1409
9002.	-45.5104	-16.1488
102.	3.3500	-13.0608
105.	17.4424	-29.0935

```
102 21045.0226 9686.0755 959.141
103 21756.7029 9160.4999 753.606
105 21274.8727 9229.6512 859.71
9001 20000.00 10000.00 1308.29
9002 20234.9127 9923.7811 1308.399
```

PROGRAM CAMOR

INPUT DATA FILE 2

```
 103.     38.4200    -41.9848
9001.    -68.2536     -2.0887
9002.    -52.3601     -6.4580
 102.      0.6171    -17.3318
 105.     13.9384    -41.1011
9999.  0.  0.  0.
 103.     43.1315    -14.5038
9001.    -61.0875     21.1428
9002.    -47.2620     19.6379
 102.      1.7947      7.6814
 105.     18.4425    -14.3044
9999.  0.  0.  0.
 103.     39.4986    -26.1383
9001.    -60.2215    -14.1409
9002.    -45.5104    -16.1488
 102.      3.3500    -13.0608
 105.     17.4424    -29.0935
9999.  0.  0.  0.
```

PROGRAM CAMOR

INPUT DATA FILE 1

SPACE RESECTION PROGRAM RESULTS

LEFT CONVERGENT CIR FEB FLT

	PHOTO COORDS		CONTROL COORDS		
STA	X	Y	X	Y	Z
103.	38.420	-41.985	21756.70	9160.50	753.61
9001.	-68.254	-2.089	20000.00	10000.00	1308.29
9002.	-52.360	-6.458	20234.91	9923.78	1308.40
102.	0.617	-17.332	21045.02	9686.08	959.14
105.	13.938	-41.101	21274.87	9229.65	859.71

NO. OF ITERATIONS	VALUES OF CORRECTIONS TO COORDINATES			CORRECTED COORDINATES		
1	44.499929	17.654123	5.662040	20944.5000	9967.6542	3655.6620
2	0.142381	0.674462	-0.758593	20944.6423	9968.3286	3654.9034
3	0.001391	0.001986	-0.000434	20944.6438	9968.3306	3654.9030
4	-0.001163	-0.001164	0.000134	20944.6426	9968.3293	3654.9031
5	0.001240	0.002009	-0.000319	20944.6438	9968.3313	3654.9028
6	-0.000510	-0.000848	0.000178	20944.6433	9968.3304	3654.9030
7	0.000272	0.000801	-0.000165	20944.6436	9968.3313	3654.9029
8	-0.000188	-0.000545	0.000045	20944.6433	9968.3308	3654.9029
9	-0.000330	-0.001025	0.000170	20944.6431	9968.3298	3654.9031
10	0.000200	0.000425	-0.000093	20944.6433	9968.3302	3654.9030

PROGRAM CAMOR

SAMPLE OUTPUT

SPACE RESECTION PROGRAM RESULTS

VERTICAL CIR FEB FLT

STA	PHOTO COORDS X	PHOTO COORDS Y	CONTROL COORDS X	CONTROL COORDS Y	CONTROL COORDS Z
103.	43.131	-14.504	21756.70	9160.50	753.61
9001.	-61.088	21.143	20000.00	10000.00	1308.29
9002.	-47.262	19.638	20234.91	9923.78	1308.40
102.	1.795	7.681	21045.02	9686.08	959.14
105.	18.443	-14.304	21274.87	9229.65	859.71

NO. OF ITERATIONS	VALUES OF CORRECTIONS TO COORDINATES			CORRECTED COORDINATES		
1	*********	-4.311804	1.537719	20876.9817	8585.6882	3651.5377
2	0.100945	0.322436	-0.036796	20877.0825	8586.0106	3651.5009
3	0.001601	0.001514	0.000598	20877.0842	8586.0121	3651.5015
4	-0.001622	-0.001139	-0.000575	20877.0825	8586.0110	3651.5009
5	-0.000708	-0.001257	-0.000434	20877.0818	8586.0098	3651.5005
6	0.000746	0.001263	0.000472	20877.0825	8586.0110	3651.5010
7	-0.000537	-0.001442	-0.000554	20877.0820	8586.0095	3651.5004
8	0.000999	0.002063	0.000763	20877.0830	8586.0116	3651.5012
9	-0.000423	-0.000721	-0.000262	20877.0825	8586.0109	3651.5009
10	0.000800	0.001047	0.000458	20877.0833	8586.0120	3651.5014

```
LEFT CONVERGENT  CIR  FEB FLT
       20944.6433        9968.3302         3654.9030 152.67  5
 103.    38.42000  -41.98480
9001.   -68.25360   -2.08870
9002.   -52.36010   -6.45800
 102.     0.61710  -17.33180
 105.    13.93840  -41.10110
     21756.7029      9160.4999      753.6060
     20000.0000     10000.0000     1308.2900
     20234.9126      9923.7811     1308.3990
     21045.0227      9686.0754      959.1410
     21274.8728      9229.6512      859.7100
VERTICAL  CIR  FEB FLT
       20877.0833        8586.0120         3651.5014 152.67  5
 103.    43.13150  -14.50380
9001.   -61.08750   21.14280
9002.   -47.26200   19.63790
 102.     1.79470    7.68140
 105.    18.44250  -14.30440
     21756.7029      9160.4999      753.6060
     20000.0000     10000.0000     1308.2900
     20234.9126      9923.7811     1308.3990
     21045.0227      9686.0754      959.1410
     21274.8728      9229.6512      859.7100
RIGHT CONVERGENT  CIR  FEB FLT
       21170.4360       10922.7057         3653.0597 152.67  5
 103.    39.49860  -26.13830
9001.   -60.22150  -14.14090
9002.   -45.51040  -16.14880
 102.     3.35000  -13.06080
 105.    17.44240  -29.09350
     21756.7029      9160.4999      753.6060
     20000.0000     10000.0000     1308.2900
     20234.9126      9923.7811     1308.3990
     21045.0227      9686.0754      959.1410
     21274.8728      9229.6512      859.7100
```

PROGRAM CAMOR

OUTPUT FILE

ALSO INPUT FILE FOR PROGRAM OMATRI

```
*THE ORIENTATION MATRIX FOR* LEFT CONVERGENT  CIR  FEB FLT

             0.9984878450     -0.0413690880      0.0374741089
             0.0411004499      0.9990602810      0.0103980694
             0.0378954113      0.0088423491     -0.9992440940

*THE ORIENTATION MATRIX FOR* VERTICAL  CIR  FEB FLT

             0.9832310530     -0.1810773610     -0.0253968611
             0.1793114130      0.9251521830      0.3347511400
             0.0371295810      0.3336762790     -0.9419564900

*THE ORIENTATION MATRIX FOR* RIGHT CONVERGENT  CIR  FEB FLT

             0.9870708590     -0.1601863210      0.0035047755
             0.1518576520      0.9285110090     -0.3394401710
            -0.0511133969     -0.3354856970     -0.9406568710
```

PROGRAM OMATRI

SAMPLE OUTPUT

0.9984878450	-0.0413690880	0.0374741089	
0.0411004499	0.9990602810	0.0103980694	
0.0378954113	0.0088423491	-0.9992440940	
20944.6433	9968.3302	3654.9030	152.67
0.9832310530	-0.1810773610	-0.0253968611	
0.1793114130	0.9251521830	0.3347511400	
0.0371295810	0.3336762790	-0.9419564900	
20877.0833	8586.0120	3651.5014	152.67
0.9870708590	-0.1601863210	0.0035047755	
0.1518576520	0.9285110090	-0.3394401710	
-0.0511133969	-0.3354856970	-0.9406568710	
21170.4360	10922.7057	3653.0597	152.67

PROGRAM INTER

INPUT DATA FILE 2

1.	-54.0336	-8.9595
1.	-48.6446	17.4720
1.	-46.4642	-18.3077
2.	-56.0768	-15.4850
2.	-50.2378	12.0010
2.	-46.9192	-23.6038
3.	-45.9028	-19.1515
3.	-40.9430	7.8216
3.	-37.5761	-23.9230
4.	-41.8631	-8.2426
4.	-37.9034	16.7852
4.	-36.0451	-14.6219
5.	-24.5798	-9.4498
5.	-22.2694	14.4756
5.	-20.4964	-11.4377
6.	-24.6408	-13.0448
6.	-22.0138	11.4696
6.	-20.0093	-14.3352
7.	-24.6731	-18.3398
7.	-21.6006	7.1431
7.	-19.2616	-18.6697
8.	-16.8305	-17.6127
8.	-14.3808	7.2175
8.	-12.3842	-16.3312
9.	-16.6183	-14.8826
9.	-14.4559	9.5521
9.	-12.5592	-14.0820
10.	-16.2017	-10.7761
10.	-14.4919	12.8980
10.	-12.7390	-10.6093
11.	-13.7717	-8.7484
11.	-12.4595	14.3559
11.	-10.7925	-8.3065
12.	-11.9717	-13.5929
12.	-10.3128	10.5007
12.	-8.5233	-12.0950
13.	-9.8053	-19.0191
13.	-7.6709	5.8202
13.	-5.8943	-16.0513
14.	-2.5407	-20.5287
14.	-0.7154	4.7363
14.	0.8276	-16.1031
15.	-2.0276	-10.8062
15.	-1.4447	12.6556
15.	0.2539	-7.7842
16.	-3.8302	-6.2231
16.	-3.6407	16.2362
16.	-1.9171	-4.0854
17.	3.9586	-2.5526
17.	3.0811	18.7652
17.	5.0257	1.0125
18.	18.2670	-27.2440
18.	20.1817	-1.1667
18.	20.3732	-17.7972
19.	16.7148	-32.1366
19.	19.5635	-5.7648
19.	19.3014	-21.8404
20.	26.6198	-34.2099
20.	29.7490	-7.8535
20.	28.4687	-21.6562

PROGRAM INTER

INPUT DATA FILE I

21.	28.8320	-32.7138
21.	31.6485	-6.4998
21.	30.4378	-20.0728
22.	30.3612	-35.2383
22.	33.6853	-8.8190
22.	31.9485	-21.8149
103.	38.4200	-41.9848
103.	43.1315	-14.5038
103.	39.4986	-26.1383
9001.	-68.2536	-2.0887
9001.	-61.0875	21.1428
9001.	-60.2215	-14.1409
9002.	-52.3601	-6.4580
9002.	-47.2620	19.6379
9002.	-45.5104	-16.1488
102.	0.6171	-17.3318
102.	1.7947	7.6814
102.	3.3500	-13.0608
105.	13.9384	-41.1011
105.	18.4425	-14.3044
105.	17.4424	-29.0935

*** SPACE INTERSECTION RESULTS ***

EXPOSURE STATIONS COORDINATES

PLATE 1	20944.643	9968.330	3654.903
PLATE 2	20877.083	8586.012	3651.501
PLATE 3	21170.436	10922.706	3653.060

IMAGE COORDINATES OF THE PT.

PLATE #	1	PT	1.	-54.0336	-8.9595
PLATE #	2	PT	1.	-48.6446	17.4720
PLATE #	3	PT	1.	-46.4642	-18.3077

DIRECTION COSINES
.29923172 .03308188 .95360663 .24213209 -.47098910

SOLUTION MATRIX

0.066697340	-0.002520484	-0.020840531	0.002232075
0.002855637	0.065885243	-0.003179838	0.004405856
0.058061365	-0.004362181	-0.018994433	-0.002767086
0.010214796	0.051754002	0.025822663	0.012712240
0.056995919	-0.015387748	-0.016589784	0.000205517
0.008549451	0.052112815	-0.026531636	-0.007756948

APPROXIMATE COORDINATES
20208.2944 9886.9224 1308.2693

CORRECTIONS TO COORDINATES
0.12301869 0.05126238 0.38158379

CORRECTED COORDINATES
POINT 1. 20208.41750000 9886.97363000 1308.65089000

PROGRAM INTER

SAMPLE OUTPUT

*** SPACE INTERSECTION RESULTS ***

EXPOSURE STATIONS COORDINATES

PLATE 1	20944.643	9968.330	3654.903
PLATE 2	20877.083	8586.012	3651.501
PLATE 3	21170.436	10922.706	3653.060

IMAGE COORDINATES OF THE PT.

PLATE #	1	PT	2.	-56.0768	-15.4850
PLATE #	2	PT	2.	-50.2378	12.0010
PLATE #	3	PT	2.	-46.9192	-23.6038

DIRECTION COSINES
.31119739 .07222887 .94759759 .25795557 -.44140805

SOLUTION MATRIX

0.066778062	-0.002514465	-0.021737380	0.003099442
0.002964499	0.065956865	-0.005999244	0.004124403
0.058833098	-0.004212641	-0.019820374	-0.009497166
0.010425177	0.053128198	0.024160688	0.023504734
0.056231359	-0.015241593	-0.016532098	-0.004992962
0.008333445	0.050748110	-0.028068833	-0.013118744

APPROXIMATE COORDINATES
20173.8196 9789.4221 1307.7408

CORRECTIONS TO COORDINATES
0.17402857 0.10808371 0.68645919

CORRECTED COORDINATES
POINT 2. 20173.99370000 9789.53015000 1308.42722000

1.	20208.417	9886.974	1308.651
2.	20173.994	9789.530	1308.427
3.	20303.935	9718.999	1231.027
4.	20370.038	9886.870	1217.437
5.	20625.100	9850.223	1092.378
6.	20621.396	9790.308	1089.745
7.	20617.696	9702.361	1092.848
8.	20744.055	9702.743	1036.447
9.	20749.635	9749.295	1036.730
10.	20759.188	9818.644	1033.358
11.	20800.903	9850.587	1013.426
12.	20828.356	9765.563	1009.635
13.	20861.452	9668.597	994.127
14.	20986.907	9633.109	966.059
15.	21003.149	9802.580	953.123
16.	20974.657	9885.023	955.110
17.	21118.878	9943.490	893.982
18.	21365.818	9478.444	856.134
19.	21333.434	9390.080	855.699
20.	21527.630	9329.184	793.684
21.	21573.689	9352.398	780.620
22.	21602.750	9301.336	771.932
103.	21756.695	9160.650	753.887
9001.	19999.992	10000.022	1308.231
9002.	20234.990	9923.801	1308.616
102.	21044.984	9685.992	958.900
105.	21274.854	9229.557	859.521

PROGRAM INTER

SAMPLE OUTPUT
(SHORT FORM)