The BSC Group

BALL MOUNTAIN DAM
JAMAICA, VERMONT

FINAL REPORT ON THE SURFACE DEFORMATIONS

(JULY 1986 - SEPTEMBER 1987)

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TABLE OF CONTENTS

VOLUME 1

PAGE

VOLUME II

VOLUME III

APPENDIX III C
Horizontal Deformation Analysis:
Epoch 4 vs. Epoch 5

APPENDIX III D
Horizontal Deformation Analysis:
Epoch 5 vs. Epoch 6

APPENDIX III E
Vertical Deformation Analysis:
Epoch 1 vs. Epoch 6

APPENDIX III F
Vertical Deformation Analysis:
Epoch 3 vs. Epoch 4

APPENDIX III G
Vertical Deformation Analysis:
Epoch 4 vs. Epoch 5

APPENDIX III H
Vertical Deformation Analysis:
Epoch 5 vs. Epoch 6

LIST OF FIGURES

LIST OF TABLES

LIST OF PLANS

EXECUTIVE SUMMARY

This report describes the design, execution and findings of the first and final four campaigns of Boston Survey Consultants' deformation monitoring program at Ball Mountain Dam, Jamaica, Vermont. (See report dated January 1987 for interim analysis.)

The design of the monitoring scheme was completed in early 1986. The installation of the monitoring stations was undertaken during the period of May 7 through June 7, 1986. The first series of measurements was completed in July, 1986 while the remaining five campaigns took place between September, 1986 and September, 1987.

A detailed analysis of the observation data over this period has revealed small horizontal movements at most of the monitored points. A number of stations situated on or near the crest edge has undergone horizontal downstream displacement of a few millimeters (1mm - 7mm) while movements of similar magnitude have been detected at several other locations. No significant vertical movements have been identified.

1. INTRODUCTION

This report describes the design, measurement, adjustment and deformation analysis phases of four of the six epochs of the geodetic monitoring scheme. It has been arranged in three parts. This volume includes the written report, Volume II contains the single epoch adjustment results and Volume III includes the deformation analyses. Nine plans accompany the report. The first shows the topography of the dam site as well as the location of the referenced and object points. The remaining plans relate to the deformation analysis.

These four epoch comparisons consist of campaigns one, three, four, five and six. Comparisons involving campaign two may be found in the interim report covering campaigns one, two and three (Report on Ball Mountain Dam, May, 1987).

Network adjustments were performed using the Geodetic Network Adjustment (GNA) program while the Localization and Analysis of Deformations (LAD) software was employed for the deformation analysis. Both are products of the Intergraph Corporation. All the statistical tests in the deformation analysis have been performed at the 95% level of confidence. Thus a horizontal displacement is "statistically significant at the 95% level of confidence" if the displacement vector extends beyond the perimeter of the 95% confidence region (ellipse). Similarly, a vertical displacement is significant at the 95% level of confidence if the vector extends beyond the vertical 95% confidence interval.

2. NETWORK DESIGN AND PRE-ANALYSIS

The network design and pre-analysis are interdependent undertakings. The pre-analysis is concerned with the network configuration, the type, number and quality of the observables, the computational requirements and the specification of equipment and observing procedures.

In the case of Ball Mountain Dam, the network configuration is severely constrained by the nature of the site which is characterized by extremely rugged terrain and extensive forest within a narrow valley. The final reference network consists of five pillars, a Corps of Engineers disk set in the abutment of the spillway and an additional reference station situated on top of the intake tower. (see Plan #1). The disk (P6) and tower (1218) stations are treated as object points during the deformation analyses.

In the pre-analysis, consideration was given to the detection of single point displacement both on the dam structure (object points) and in the reference network (reference points). Note that the reference points are presumed to be unstable from one campaign to the next (In the first step of each deformation analysis they are tested for stability at the 95% level of confidence).

A tolerance limit of 3mm at the 95% level of confidence was employed in the pre-analysis. Thus, any single point displacement exceeding 3mm in either the horizontal (x,y) or vertical (z) should be detected as significant at the 95% level of confidence. The pre-analysis was undertaken by a team from the University of New Brunswick led by Dr. Adam Chrzanowski, (Chrzanowski et al., 1985). The following two sections summarize the salient features of the pre-analysis.

2.1 THE HORIZONTAL MONITORING SCHEME

In the final design, all possible directions were to be measured from stations P1, P2, P3, P4 and P5. At the time of the first campaign, it was decided to take additional observations from P6. Four distances were to be measured from P4 to P2, P3, P5 and P6.

The accuracy requirements for the observables are:

- directions: std. dev. = +/- 0.5"
- distances: std. dev. = +/- 5mm +/- 5ppm

Figure 2.1 shows the results of the horizontal pre-analysis. The directions are to be measured in 4 sets using an electronic theodolite such as the Wild T2000 or Kern E2. As Chrzanowski et al., (1985) point out this accuracy can be attained only if certain observing precautions are adhered to. These include shading the theodolite from direct sunlight, using mechanical forced centering for the theodolite and targets, using specifically designed targets, and measuring the tilt of the vertical axis. The distances are required to be measured using a suitable electro-optical distance measuring instrument (EODMI). This should be calibrated for zero error and scale and, if necessary, for cyclic error. Appropriate equipment must be employed for measuring the dry bulb temperature and atmospheric pressure.

Ordinary Wild traversing targets are used on the 27 object points and at P6. Special conical, omni-directional targets (Figure 2.2) are employed on the tower and at points P1 through P5. These were designed and produced under contract by the Dept. of Surveying Engineering at the University of New Brunswick.

2.2 THE VERTICAL MONITORING SCHEME

The vertical monitoring program requires that all zenith angles from stations P1 through P5 be measured to a standard deviation of 0.7". This can be achieved if 4 sets are observed and if the same precautions are adhered to as those listed in Section 2.1 above. Theodolite and target heights must be measured to an accuracy of at least 1mm.

2.3 REFRACTION

Chrzanowski et al., (1985) have emphasized that the ability of the monitoring scheme to detect vertical displacements may be severely degraded by changes in the coefficient of refraction from one campaign to the next. At their suggestion, temperature profile measurements were taken during each of the six campaigns. A preliminary analysis of these data attests to the severity of this problem (see Appendix IC).

2.4 MONUMENTATION

Three kinds of monumentation were planned (Figure 2.3, 2.4 and 2.5). In the case of the reference pillars, the design reflects the need for a stable observing platform. Note the forced-centering socket which ensures precise horizontal relocation of the theodolite. The benchmark provides a reference point for the vertical network. During each campaign, the pillars are wrapped in 5cm thick foam rubber in order to minimize the distortions which may be induced by temperature imbalances.

The slope and crest monuments are designed in such a way that they will adequately represent local movements in their vicinity. To ensure that they are visible from the reference points, the slope monuments protrude approximately 1m above the rockfill slope. For the same reason, removable 0.5m extension rods are inserted in the crest monuments during the observing process. In order to ensure precise forced-centering, Wild GRT10 stems were grouted into the tops of these monuments. These match the removable Wild traversing targets, and extension rods.

The substratum associated with each pillar and monument is listed in Table 2.1.

TABLE 2.1

Summary of Pillar and Monument Installations

POINT	SUBSTRATUM
P1	bedrock
P2	bedrock
P3	glacial till
P4	bedrock
P5	bedrock
P6	concrete retaining wall
11, 12, 13 21, 22, 23 31, 32, 33	gravel fill on dam crest
14-19, 24-29, 34-39	rock fill on downstream slope
1218	on top of concrete intake tower

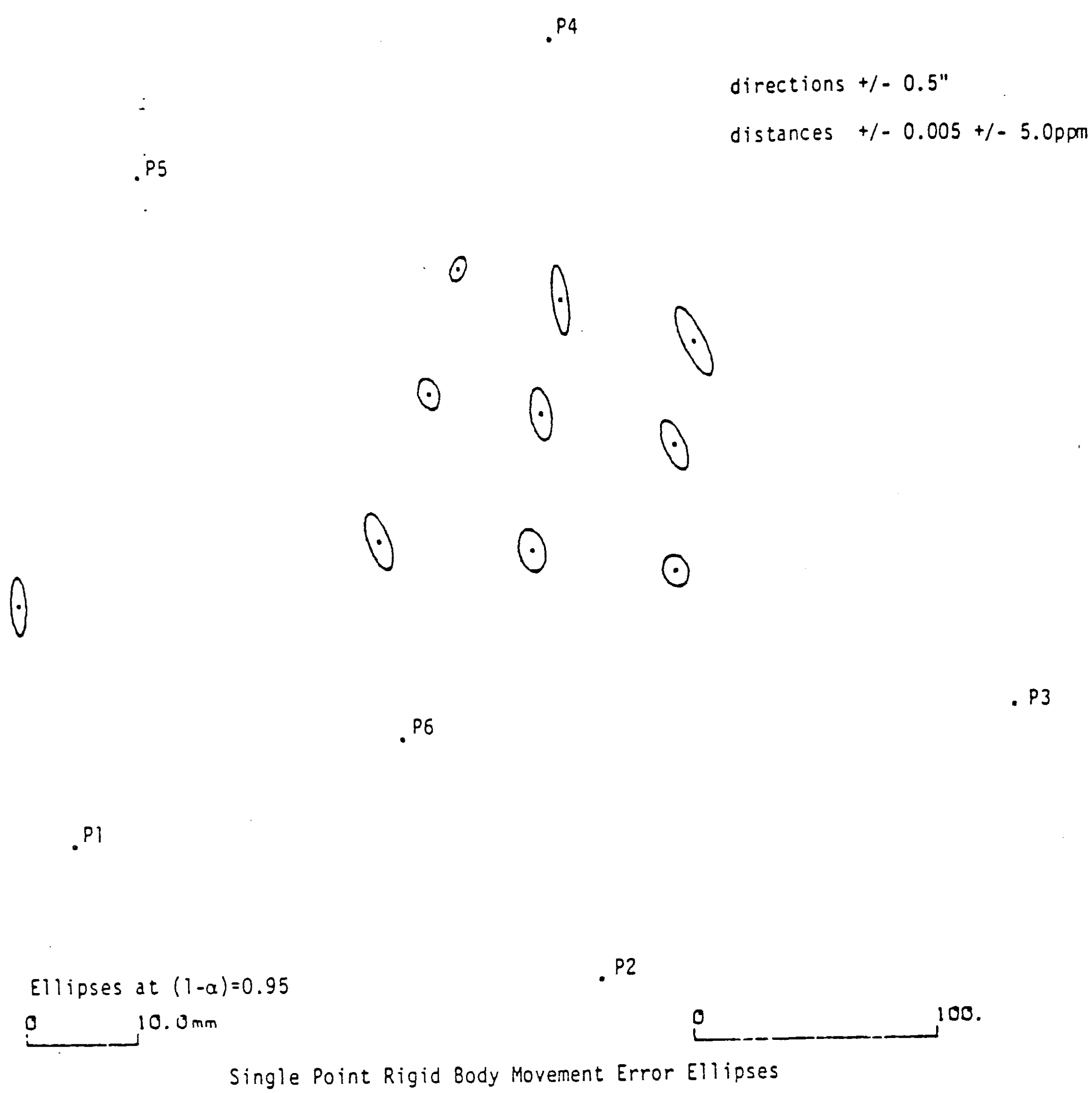


Figure 2.1 Horizontal pre-analysis after Chrzanowski et al. (1985) Note that the final position of P3 differs slightly from that shown here (see Plan #1).

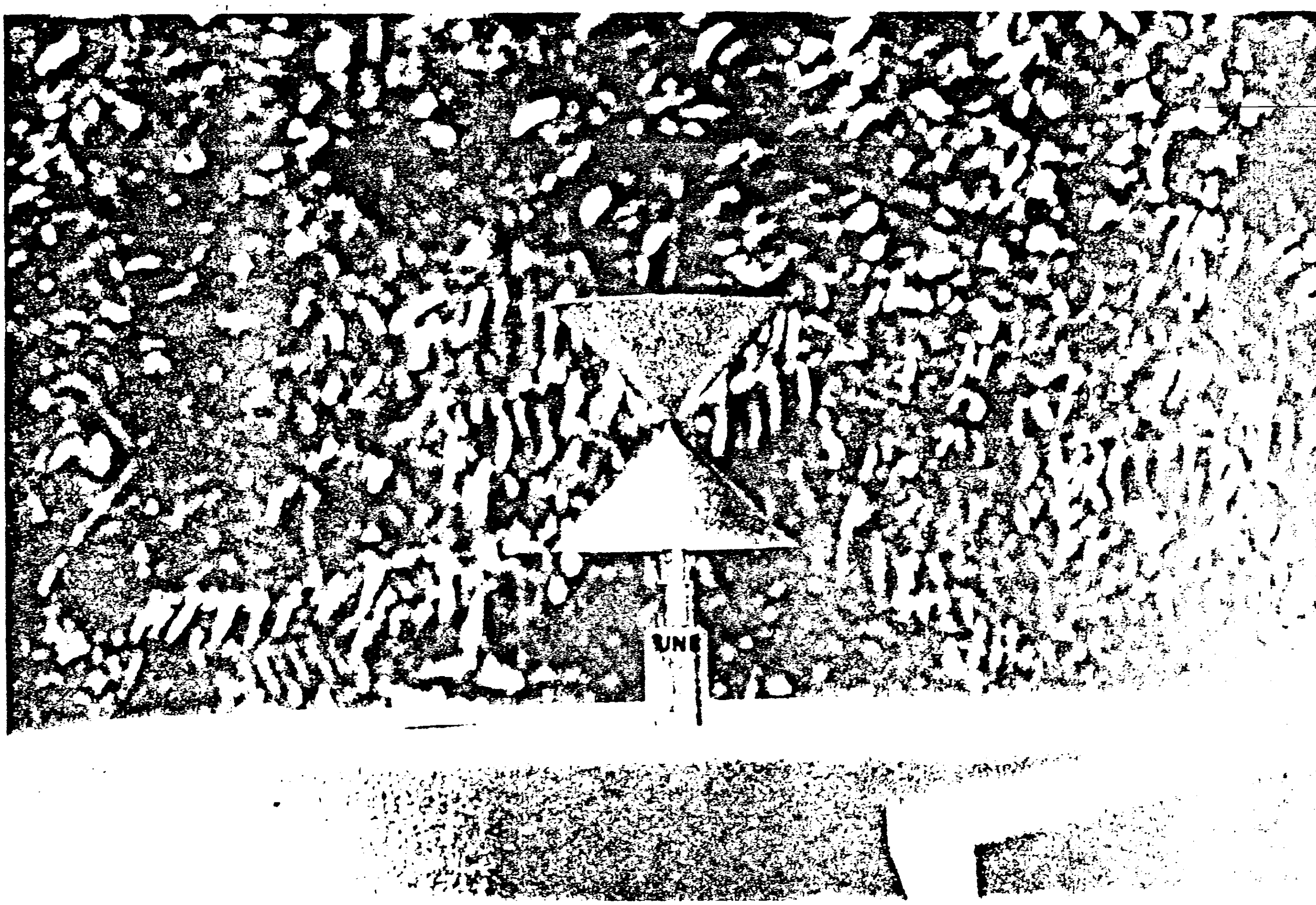
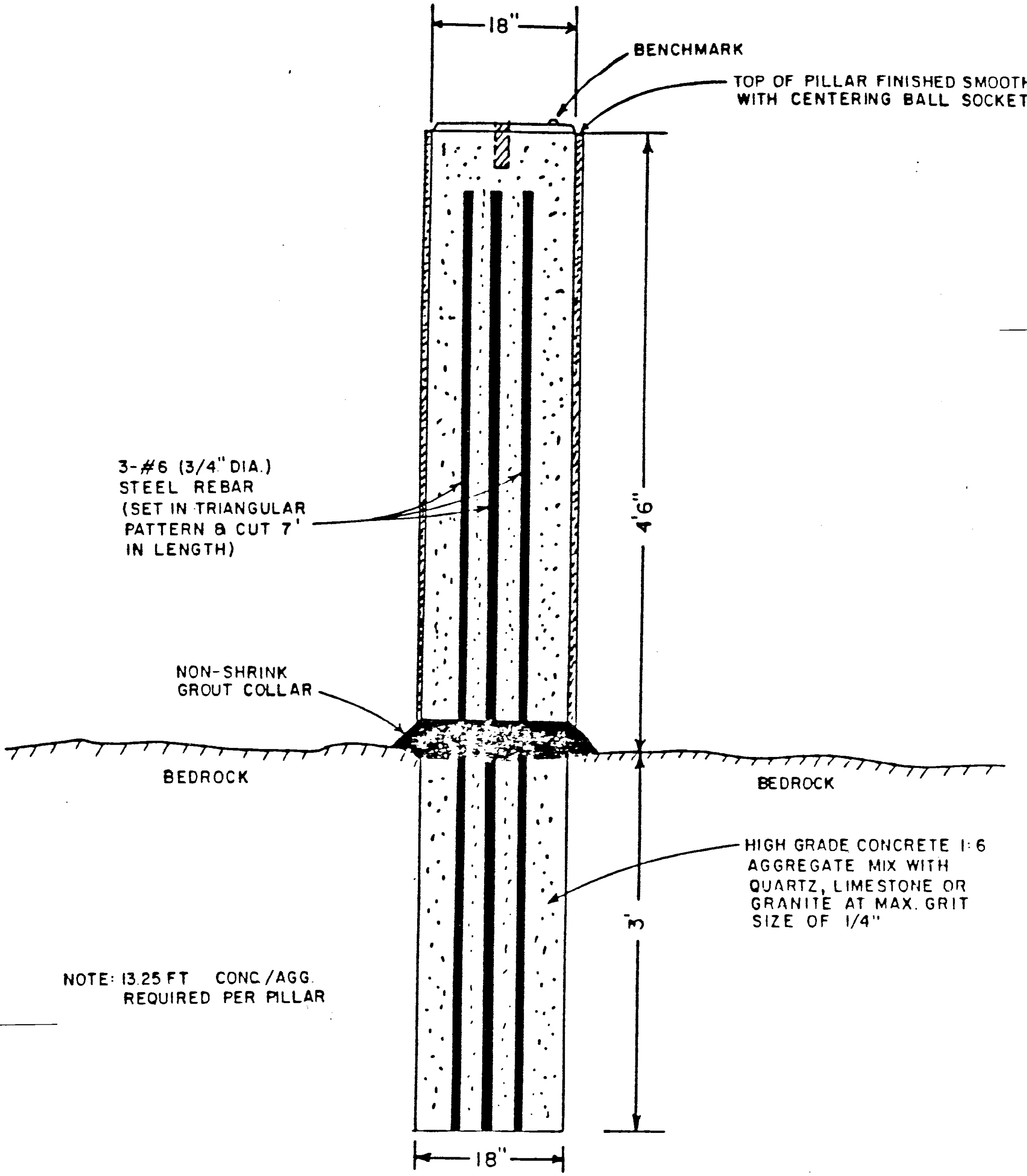
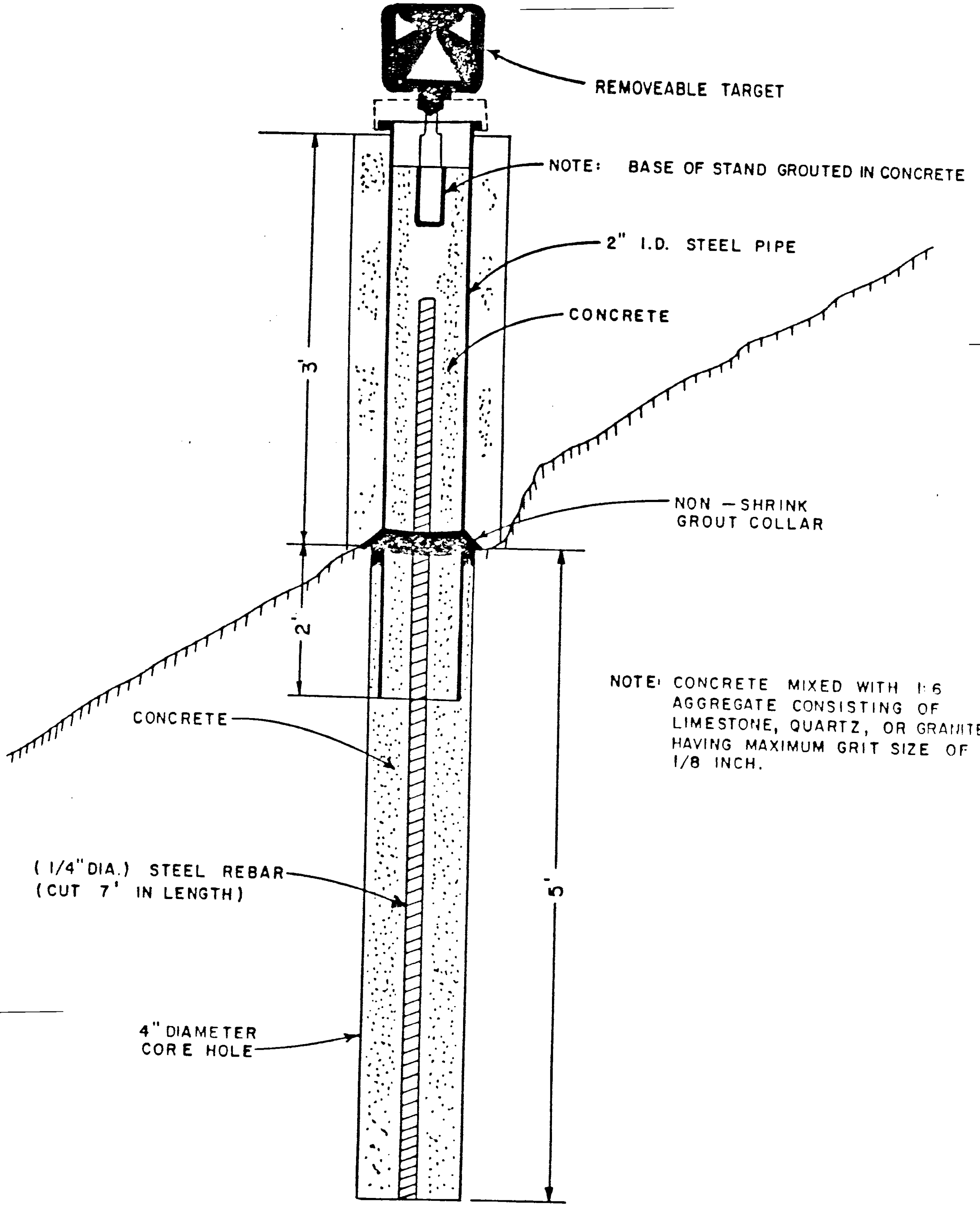


Figure 2.2 The UNB target design.



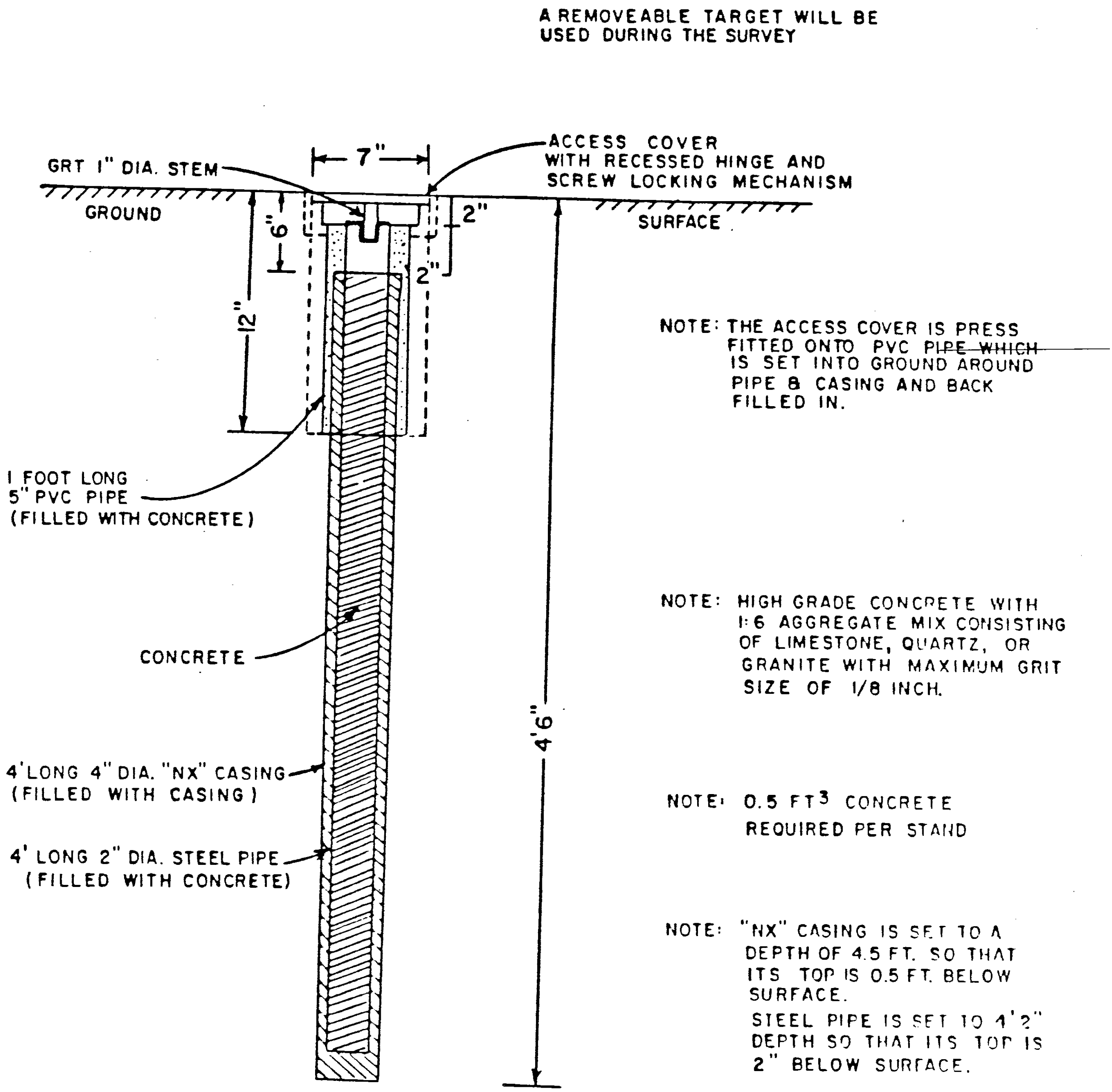
BSC	REFERENCE PILLAR DESIGN
PROJECT NO. 1-1654.00	
NOVEMBER, 1985	

Figure 2.3



BSC	SLOPE MONUMENT DESIGN
PROJECT NO. 1-1654.00	
NOVEMBER, 1985	

Figure 2.4



BSC	CREST MONUMENT DESIGN
PROJECT NO. 1-1654.00	
NOVEMBER, 1985	

Figure 2.5

3.0 OBSERVATION, ADJUSTMENT AND ANALYSIS

The dates of the six epochs are listed in Table 3.1 which also summarizes the prevailing weather conditions.

In the first two campaigns, Wild T2000 and DI4L instruments were used for the angle and distance measurements respectively, while A Kern E2/DM502 combination was employed in the remaining campaigns. The two electronic theodolites yield comparable results and satisfied the specifications. However, the Kern E2 is more appropriate for this kind of work since it can provide precise vertical axis tilt measurements. The Kern DM502 proved to be slightly more precise than the Wild DI4L. This can be ascribed to the availability of high quality calibration data for the former instrument.

Observation data were manually recorded and checked in the evenings during the first three campaigns. Prior to the fourth campaign in May of 1987 software written for the Hewlett Packard 71B handheld computer was completed. The software along with the necessary memory and peripheral enhancements allows for real time data logging, data validation and on-site station adjustments. This greatly improved both field and office productivity.

Temperature profile measurements were taken near the theodolite while the angular observations were being made at P3, P4 and P6. Several profiles from the first and second epochs have been analyzed (see Appendix IC). The results confirm the concern expressed in the pre-analysis regarding the severity of the refraction problem.

The horizontal and vertical network adjustments were performed in the office using the GNA software. The salient features of these computations are abstracted in Appendix ID.

3.1 THE HORIZONTAL NETWORK

The GNA results for the four relevant campaigns may be found in Volume II of this report. The "Summary Reports" from each campaign are reproduced in Tables 3.2 to 3.6.

In each case the standard deviation of unit weight corroborates the weighting scheme employed in the adjustment. The a priori standard deviation (0.6") used for (campaigns prior to epoch 4) the directions differs only slightly from the value (0.5") called for in the pre-analysis. In addition, the a priori distance standard deviations (+/- 3mm +/- 4.6 ppm for Epochs 1 and +/- 2mm +/- 3ppm for Epoch 3 through 6) are slightly better than the +/- 5mm +/- 5ppm specified in the pre-analysis. Campaigns four through six utilized an a priori standard deviation derived from individual station adjustments not a global value as in the first three campaigns. These values are not significantly different from the 0.5" required by the pre-analysis.

The relative error ellipses (95% confidence level) indicate that all five epochs have satisfied the specification that the monitoring scheme be capable of detecting a 3mm horizontal movement at the 95% level of confidence in the downstream direction.

3.2 THE VERTICAL NETWORK

The GNA results for the five vertical adjustments are contained in Volume II of this report. The "Summary Reports" for each campaign are reproduced in Tables 3.7 to 3.11.

Once again the values of the standard deviation of unit weight confirm the a priori weighting scheme. In the first epoch a standard deviation of 0.5" was used for weighting the zenith angles. A value of 0.6" was employed for the third adjustment. All remaining adjustments utilized values obtained from the station adjustments.

The absolute 95% confidence intervals vary from 1.4 mm to 3.2 mm. Unfortunately, GNA did not provide the required relative confidence regions. However, reference to the LAD results (Volume III) reveals that the relative 95% confidence intervals for the inter-epoch comparisons varied from 1.7mm to 2.8mm. These results satisfy the specifications.

TABLE 3.1

Synopsis of the Campaigns

Epoch	Dates	Temperature °F	Weather Conditions
I	July 14, '86	75 - 80	clear
	15	75 - 80	clear, gusting winds
	16	75 - 80	clear, haze
	17	---	---
	18	75 - 85	clear, calm
	19	65 - 75	overcast, windy
	20	65 - 75	light rain, windy
II	Sept 23, '86	65	overcast, drizzle
	24	70	clear
	25	70	clear, windy in p.m.
	26	70	clear, calm
	27	70	clear
	28	60	overcast
III	Nov. 18, '86	40	overcast, calm
	19	20	clear, windy
	20	28	overcast, windy
	21	35	rain, windy
	22	28	clear, windy
	23	35	clear, light wind
	24	38	partly cloudy, windy
IV	May 4, '87	45	overcast, drizzle
	5	45	overcast, drizzle, calm
	6	50	overcast, windy
	7	65	clear in a.m., showers in p.m.
	8	65	calm a.m., gusting winds p.m. clear

V	July 20, '87	78	partly cloudy, humid, calm
	21	82	partly cloudy, calm
	22	72	partly cloudy, windy
	23	83	clear, calm
	24	82	clear, light wind
VI	Sept 28, '87	60	clear, light wind
	29	80	partly cloudy, windy
	30	60	overcast, humid
	1	45	rain, windy
	2	50	clear, calm

TABLE 3.2

Summary Report: Epoch 1 - Horizontal

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	150	0.659136D+02	0.741045D+02	0.94312
AZIMUTHS	1	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	5	0.123737D+01	0.389550D+01	0.56360
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
HEIGHT DIFFERENCE	0	0.000000D+00	0.000000D+00	1.00000
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	156	0.671510D+02	78	0.92785

STATIONS:		
	FIXED	1
	FREE	32
	WEIGHTED	0
	TOTAL	33

TABLE 3.3

Summary Report: Epoch 3 - Horizontal

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	135	0.885519D+02	0.651182D+02	1.16613
AZIMUTHS	1	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	3	0.297731D+01	0.188182D+01	1.25783
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
HEIGHT DIFFERENCE	0	0.000000D+00	0.000000D+00	1.00000
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	139	0.915292D+02	67	1.16881

STATIONS:		
	FIXED	1
	FREE	33
	WEIGHTED	0
	TOTAL	34

TABLE 3.4

Summary Report: Epoch 4 - Horizontal

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	125	0.675242D+02	0.521082D+02	1.13835
AZIMUTHS	1	0.000000D+00	-.444565D-16	1.00000
HORIZONTAL DISTANCE	5	0.360539D+01	0.389181D+01	0.96250
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
HEIGHT DIFFERENCE	0	0.000000D+00	0.000000D+00	1.00000
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	131	0.711296D+02	56	1.12702

STATIONS:		
	FIXED	1
	FREE	33
	WEIGHTED	0
	TOTAL	34

TABLE 3.5

Summary Report: Epoch 5 - Horizontal

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	121	0.778614D+02	0.500804D+02	1.24689
AZIMUTHS	1	0.000000D+00	-.444565D-16	1.00000
HORIZONTAL DISTANCE	5	0.751923D+00	0.391964D+01	0.43799
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
HEIGHT DIFFERENCE	0	0.000000D+00	0.000000D+00	1.00000
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	127	0.786134D+02	54	1.20657

STATIONS:		
	FIXED	1
	FREE	32
	WEIGHTED	0
	TOTAL	33

TABLE 3.6

Summary Report: Epoch 6 - Horizontal

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	128	0.855704D+02	0.560252D+02	1.23586
AZIMUTHS	1	0.000000D+00	-.111141D-15	1.00000
HORIZONTAL DISTANCE	4	0.345664D+01	0.297480D+01	1.07795
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
HEIGHT DIFFERENCE	0	0.000000D+00	0.000000D+00	1.00000
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	133	0.890271D+02	59	1.22839

STATIONS:		
	FIXED	1
	FREE	33
	WEIGHTED	0
	TOTAL	34

TABLE 3.7

Summary Report: Epoch 1 - Vertical

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	0	0.000000D+00	0.000000D+00	1.00000
AZIMUTHS	0	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	132	0.109791D+03	0.919897D+02	1.09248
HEIGHT DIFFERENCE	13	0.337395D+01	0.401033D+01	0.91723
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	145	0.113165D+03	96	1.08572

STATIONS:		
	FIXED	1
	FREE	48
	WEIGHTED	0
	TOTAL	49

TABLE 3.8

Summary Report: Epoch 3 - Vertical

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	0	0.000000D+00	0.000000D+00	1.00000
AZIMUTHS	0	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	120	0.945190D+02	0.800372D+02	1.08671
HEIGHT DIFFERENCE	10	0.834129D+00	0.962835D+00	0.93077
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	130	0.953531D+02	81	1.08499

STATIONS:		
	FIXED	1
	FREE	50
	WEIGHTED	0
	TOTAL	51

TABLE 3.9

Summary Report: Epoch 4 - Vertical

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	0	0.000000D+00	0.000000D+00	1.00000
AZIMUTHS	0	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	149	0.200982D+03	0.106049D+03	1.37665
HEIGHT DIFFERENCE	8	0.488249D+01	0.195075D+01	1.58205
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	157	0.205865D+03	108	1.38064

STATIONS:		
	FIXED	1
	FREE	48
	WEIGHTED	0
	TOTAL	49

TABLE 3.10

Summary Report: Epoch 5 - Vertical

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	0	0.000000D+00	0.000000D+00	1.00000
AZIMUTHS	0	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	129	0.115919D+03	0.894143D+02	1.13860
HEIGHT DIFFERENCE	12	0.136895D+02	0.558569D+01	1.56551
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	141	0.129608D+03	95	1.16803

STATIONS:		
	FIXED	1
	FREE	45
	WEIGHTED	0
	TOTAL	46

TABLE 3.11

Summary Report: Epoch 6 - Vertical

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	0	0.000000D+00	0.000000D+00	1.00000
AZIMUTHS	0	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	126	0.125671D+03	0.851854D+02	1.21460
HEIGHT DIFFERENCE	8	0.140768D+01	0.181456D+01	0.88078
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	134	0.127079D+03	87	1.20858

STATIONS:		
	FIXED	1
	FREE	46
	WEIGHTED	0
	TOTAL	47

4.0 DEFORMATION ANALYSIS

4.1 HORIZONTAL ANALYSIS

4.1.1 EPOCH 1 VS. EPOCH 6

The results for this inter-epoch comparison may be found in Appendix III A. Plan #2 depicts the displacement vectors and their attendant 95% confidence ellipses.

The analysis of the reference stations reveals that points P2 and P5 are unstable. P2 is found to have a displacement of 2.4mm in a northeasterly direction while P5 has been displaced 1.2mm in a southeasterly direction. The remaining reference points P1, P3 and P4 are considered to be stable thereby providing a suitable reference base for the subsequent deformation analysis.

All of the 26 object points (point 19 or C9 has been destroyed) have significant displacements. Three blocks of points were tested for group movement (Table 4.1). The first block assumes all object points act as one rigid body and shows significant displacements in x y and rotation parameters. The second and third blocks break the first block into two groups based on differing trends. Block two contains only the crest and first row (#4) of the slope monuments. Again significant displacement of the block has occurred in x, y and rotation parameters similar to the results for all points taken together. The final block containing only the slope monuments shows significant x and y displacements; however, the y displacement is one-fifth the magnitude of that obtained for the crest monuments.

4.1.2 EPOCH 3 VS. EPOCH 4

This comparison spans the longest consecutive time frame and the most severe environmental influences which are exemplified by the extremely high head pond water levels and subsequent flooding in the Spring of 1987.

The computations and analysis for this epoch comparison are contained in Appendix III B. The corresponding displacement vectors and their associated 95% confidence regions are presented on plan #4. The stable base points are P2, P4 and P5. This illustrates how LAD selects the reference base independently for each comparison since P2 and P5 appeared to lose their stability between epochs 1 and 6. The remaining reference points P1 and P3 have been displaced 5mm in a southwesterly direction and 3.3mm in a northerly direction respectively. Of the remaining thirty-one points twenty-six show some significant movement ranging from 2 to 8 mm.

The worst cases are points 32, 33, 23, 24, 34, 13 all of which are located on or near the crest of the dam. One block containing all points was analyzed, see Table 4.2. Plan #3 shows the downstream trend for all vectors on the dam. Block two contains all of the crest points as well as the fourth row of monuments because of their similarities in the magnitudes and direction of their displacements. For similar reasons, the remaining group was included in block three.

4.1.3 EPOCH 4 VS. EPOCH 5

The results for this comparison may be found in Appendix III C. The displacement vectors and their associated 95% confidence ellipses are shown on Plan #4.

Again, the reference base for this analysis changes from the earlier results. The stable points are P2, P3 and P5 with P1 and P4 showing significant movements of 6.7mm in a slightly easterly direction and 4mm in a northerly direction respectively.

Of the remaining object points (27 in all) all but one, (39/A9) have significant movement. Displacement is much less severe in the positive X direction between these two epochs with an average displacement of approximately 1.5mm upstream and 1.6mm downstream for 13 and 14 points respectively. Most of the upstream movement is found in the points at or near the crest. Unlike the previous analysis, however, there appears to be a significant movement across the dam towards the north. This apparent movement averages 2.7mm with an extreme value of 7mm.

The resulting analysis of individual blocks consists of three groupings. Group 1 contains all the points on the dam and manifests a small significant (downstream) displacement of 1.2mm and a small rotation. The second group consists of the first 4 points of each row. However, only the across-stream deformation and small rotation are significant. The final block containing A4-A8, B5 to B9 and C4 to C9 shows a small significant displacement downstream of 1.2mm and a slightly larger movement to the north of 2.1mm.

4.1.4 Epoch 5 vs. Epoch 6

The tabulated results for the comparison of epochs 5 and 6 can be found in Appendix III D. The 95% confidence ellipses and associated point displacement vectors are shown on Plan #8.

The reference base for this comparison consists of P1, P2, P3 and P4 with P5 showing a significant displacement of 1.4mm in a northerly direction.

Of the observation points only 32 (A2 in the corps numbering scheme) shows no significant movement. All the other points are displaced by amounts varying from between .2mm to 3.7mm with an average magnitude of 1.5mm. Unlike campaigns 4 and 5 movement appears to be in the downstream direction for most points but like the previous analysis significant movement in a northerly direction can be seen along the crest and line C.

Group movements consisted of three separate blocks of points. The first block contains all the crest and slope monument. This group displays movements in the upstream and northerly directions of almost equal magnitude (.7mm). Removal of the group parameters results in small displacements in a downstream and across stream direction. The second block of points consists of points A1 to A3, B1 to B3 and C1 to C3. No significant x component is defined in this group but a significant positive y displacement exists of about 1mm. The final group consists of all remaining points and the slope monuments show a significant downstream and across stream displacement is a rigid body. Removal of these group parameters results in individual points moving slight downstream with magnitudes up to 1.8mm. Again most points illustrate perpendicular cross-stream movement in the positive y direction of between .2mm and .3mm.

4.1.5 Summary

It is apparent from the foregoing analysis that most of the deformation activity seems to have occurred during the interval covered by campaigns 3 and 4, i.e., between the November 1986 and May 1987 campaigns. In summary, the following comments may be made with regard to the horizontal deformation analysis:

1. Downstream movement of "several millimeters" (5mm - 7.5mm) is manifest in the upper part of line A. This extends from the crest center-line (point 32) down to points 35 and 36 which lie on the bulge.

2. Downstream movement of "several millimeters" (2mm - 7mm) seems to have occurred in the upper part of line B. This deformation is consistent throughout the line beginning at point 22 but is most significant for points 23-29..

3. Some upstream motion can be seen in points 11, 12 and 21 along the upstream crest.

4. Some downstream displacement is evident below the bulge in line A (points 38 and 39).

5. There seems to be a general downstream trend throughout the set of object points. This "movement" has been flag as significant at the 95% level of confidence. There is a possibility that this trend is influenced by changes in lateral refraction from one campaign to the next.

6. Except for small displacements of individual pillars the reference network is stable and relatively consistent. The inconsistent movement of P2, P1, P3 and P5 over (P2 and P1) may be ascribed to geological factors (e.g., deformation of the exposed bedrock) or to distortion of the pillar (e.g., concrete shrinkage) over time.

TABLE 4.1

Epoch 1 versus Epoch 6

Summary of the group movement analyses - horizontal
(Refer to Appendix III A)

Group #1	1	2	3
Stations	All	A1 - A4 B1 - B4 C1 - C4	A5 - A8 B5 - B9 C5 - C9
X displacement[1]	4.9mm	7.0mm	5.0mm
Y displacement[2]	2.2mm	5.8mm	1.1mm
Rotation[3]	-3.3 sec	NO	NO

1. Positive to the east (downstream)
2. Positive to the north
3. Positive clockwise from north
4. Displacement vectors in mm.

TABLE 4.2

Epoch 3 versus Epoch 4

Summary of the group movement analyses - horizontal
(Refer to Appendix III B)

Group #	1	2	3
Stations	All		
X displacement[1]	3mm		
Y displacement[2]	NO		
Rotation[3]	-4 arc sec		

1. Positive to the east (downstream)
2. Positive to the north
3. Positive clockwise from north
4. Displacement vectors in mm.

TABLE 4.3

Epoch 4 versus Epoch 5

Summary of the group movement analyses - horizontal
(Refer to Appendix III B)

Group #	1	2	3
Stations	All	A1-A4 B1-B4 C1-C4	A5-A8 B5-B9 C5-C9
X displacement[1]	1.2mm	NO	1.2mm
Y displacement[2]	NO	2mm	2.2mm
Rotation[3]	-1 arc sec	2 arc sec	NO

1. Positive to the east (downstream)
2. Positive to the north
3. Positive clockwise from north
4. Displacement vectors in mm.

TABLE 4.4

Epoch 5 versus Epoch 6

Summary of the group movement analyses - horizontal
(Refer to Appendix III D)

Group #	1	2	3
Stations	All	A1-A3 B1-B3 C1-C3	A4-A8 B4-B9 C4-C9
X displacement[1]	-.7mm	NO	NO
Y displacement[2]	.7mm	.8mm	-.8mm
Rotation[3]	1 arc sec	1 arc sec	NO

1. Positive to the east (downstream)
2. Positive to the north
3. Positive clockwise from north
4. Displacement vectors in mm.

4.2 VERTICAL ANALYSIS

4.2.1 EPOCH 1 vs. EPOCH 6

The results for this comparison may be found in Appendix IIIE. Plan #3 shows the displacement vectors.

All five reference points (P1 through P5) pass the stability test at the 95% level of confidence. They form a suitable base for the subsequent deformation analysis.

All but seven of the 26 object points have negative displacement vectors (Table 4.5). This indicates an apparent downward movement of the points in the Epoch 1 - Epoch 6 interval. The vectors are small, varying in length from 0.01mm to 7.3mm with a mean of 2.6mm. The analysis reveals that only 8 of these displacements are significant at the 95% level of confidence.

4.2.2 EPOCH 3 vs EPOCH 4

The results for this analysis are included in Appendix IIIF. The corresponding displacement vectors are shown on Plan #5.

Examination of the base points (P1 through P5) indicates that there is no significant movement of the reference network.

All the object points appear to have undergone substantial negative (downward) vertical displacements (Table 4.4). The movements vary from 1mm to 7.7mm with a mean value of 4.5mm. Nineteen (70%) of the 27 displacements are significant. An attempt was made to model the object point movement. Considered together as a single group, the 27 points have a negative translation of 8.7mm.

4.2.3 EPOCH 4 vs. EPOCH 5

The results for this comparison may be found in Appendix IIIG. Plan #7 shows the displacement vectors. The stable point analysis reveals no significant movement of the reference points. All 27 object points manifest negative (downward) displacements (except 39) which vary from 0.1mm to 1.2mm with a mean of 1.9mm (Table 4.4). Only one of the displacements is significant. The group analysis, which includes all object points, reveals a negative downward translation of 1.6mm which is not significant.

4.2.4 EPOCH 5 vs. EPOCH 6

The LAD output for the analysis of these two campaigns can be found in Appendix IIIH. The graphic representation of the analysis is shown on Plan #9.

As with all previous analyses all five reference points pass the stability test at the 95% confidence level and therefore form the basis for object point comparison.

All object points show an apparent positive movement as seen on Plan 9 and summarized in Table 4. The vectors are small, varying in length from .2mm to 3.8mm with a mean upward displacement of 1.6mm. The analysis, however, shows that only five of the 26 included points (19%) have a significant displacement and these are marginal in most cases. A group analysis including all points produces a non-significant vertical (positive) displacement of 1.2mm.

4.2.5 SUMMARY

The inter-epoch comparisons reveal very obvious trends in the displacement vectors (Table 4.5). These may be explained by the effect of changes in the coefficient of refraction from one campaign to the next. This problem is addressed in some depth in Appendix IC. At present - considering the 14 month interval between Epochs 1 and 6 - the expected size of the point displacements is of the same order of magnitude as the systematic refraction error. Therefore, it is not possible to discriminate between real vertical movements and the apparent displacements caused by refraction, except between epochs 3 and 4 where movement is quite significant and beyond the noise level.

Owing to the fact that the rays linking the reference stations have ample ground clearances, they are less affected by changes in refraction than are the rays between the reference and object points which generally graze close to the surface. This is borne out by the results of the base point analyses which reveal that all five reference stations have remained stable at the 95% level of confidence.

TABLE 4.5

Single Point Displacements
(vertical network analysis)
(in mm)

Point	Epoch 1 to Epoch 6	Epoch 3 to Epoch 4	Epoch 4 to Epoch 5	Epoch 5 to Epoch 6
P1	-2.3	.8	-2.4	0.2
P2	1.3	.2	1.6	-1.1
P3	0.3	0	.3	-0.1
P4	-0.9	.6	1.4	-0.1
P5	1.5	.4	-0.9	1.1
P6				
31	0.8	-2.4	-1.4	1.0
32	-0.1	-2.3	-2.0	1.5
33	-6.0*	-7.1*	-1.4	1.0
34	-5.9*	-6.4*	-1.1	.6
35	-2.8*	-4.1*	- .1	.5
36	-2.5	-4.0*	- .5	1.2
37	-0.01	-3.8*	- .4	1.5
38	-0.6	-3.8	- .2	1.2
39	-2.8	-3.9*	0.7	.2
21	1.0	-1.0	-1.3	.8
22	0.8	-1.2	-1.5	.6
23	-2.2	5.7*	-11.2*	1.2
24	-7.3*	-7.8*	-1.2	.6
25	-3.9*	-5.3*	-1.3	1.4
26	-3.1*	-6.3*	-3.3	2.6
27	-1.4	-4.6*	-1.6	2.8
28	-1.6	-4.2*	-1.7	3.6*
29	-1.3	-6.6*	-2.7	3.8*

11	-0.7	-1.7	-1.3	.4
12	1.6	-1.7	-1.8	1.8
13	-4.1*	-6.0*	-1.0	1.0
14	-6.5*	-6.4*	-1.1	.8
15	-2.4	-4.5*	-1.0	2.2
16	-2.2	-4.4*	-2.2	3.1*
17	-1.8	-4.6*	-2.7	3.3*
18	-1.6	-4.5*	-1.8	3.7*
19		-1.5		

* - Displacement is significant at the 95% level of confidence (significance level = 0.05)

TABLE 4.6

Epoch 1 versus Epoch 6

Summary of the group movement analyses - vertical
(Refer to Appendix III E)

Group #	1	2	3
Stations	All		
z translation	NO		

1. Positive is upward

TABLE 4.7

Epoch 3 versus Epoch 4

Summary of the group movement analyses - vertical
(Refer to Appendix III F)

Group #	1	2	3
Stations	All		
Z displacement[1]	-8.7mm		

1. Positive is upward

TABLE 4.8

Epoch 4 versus Epoch 5

Summary of the group movement analyses - vertical
(Refer to Appendix III G)

Group #	1	2	3
Stations	All		
Z displacement[1]	NO		

1. Positive is upward

TABLE 4.9

Epoch 5 versus Epoch 6

Summary of the group movement analyses - vertical
(Refer to Appendix III H)

Group #	1	2	3
Stations	All		
Z translations[1]	NO		

1. Positive is upward

5. CONCLUSIONS

In general, the outcome has confirmed the importance and relevance of the pre-analysis when doing a project of this kind. The horizontal deformation results are very pleasing, since they generally confirm the expected trend established in our initial hypothesis, which was that downstream motion was occurring at Ball Mountain Dam. It is not easily determined from the analysis, however, if movement of up to 7mm for a single point and 5mm for all points over a fourteen month time period may be significant enough to warrant action. Most of this deformation first appears after the spring floods of 1987 and while the movement is significant the analyses after this time period suggest some rebounding after the abatement of the floodwaters leaving a residual downstream deformation at the marginal level of detectability for epochs 5 and 6. With regard to the vertical analysis it appears that the flooding influenced a significant change in the dam's downstream face and crest. This change is large enough to be beyond the expected influence of refraction.

In summary, it should be pointed out that from a statistical point of view, while they are significant, the horizontal and vertical displacements are approaching the level of marginal detectability of the monitoring system.

RECOMMENDATIONS

BSC would like to recommend that observations be carried out twice a year at this structure during the periods of October and May (times of minimal and maximum water levels). Such a scheme would enable the detection of long term trends in the displacements. It is also suggested that the monumentation be maintained at Ball Mountain Dam.

6. BIBLIOGRAPHY

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"Localization and Analysis of Deformations User's Guide" (Preliminary)

APPENDIX IA

Summary of
Daily Activities

The following tabulations have been abstracted from Boston Survey Consultants' "Daily Chief Reports":

IA.1 Epoch 1

DATE	WEATHER	ACTIVITY
7/14/86	clear 75°F - 80°F	travel to site, cut lines wrapped pillars, set targets
7/15/86	clear, windy, 75°F - 80°F	direction obs. at P1,P4 and P5
7/16/86	clear, hazy, 75°F - 80°F	direction obs at P4 distance obs P6 to P1,P2,P4 and P5
7/17/86	-----	direction obs at P3
7/18/86	clear, 75°F - 85°F	direction obs at P2
7/19/86	overcast, windy, 65°F - 75°F	direction obs at P6
7/20/86	windy, light rain 65°F - 75°F	repeated some dir obs at P3 repeated some dir obs at P6 measured distance P6-P3 travel to Boston.

IA.2 Epoch 2

DATE	WEATHER	ACTIVITY
9/23/86	drizzle 65°F	travel to site, prepare targets, install bolts at two pillars
9/24/86	fog a.m. clear p.m. 70°F	installed two pillar bolts, placed PVC on slope monuments, dir obs from P6
9/25/86	clear, windy p.m. 70°F	direction obs. at P2 and P1 install last pillar bolt
9/26/86	clear, calm 70°F	direction observations from P3 and P5, adjusted level
9/27/86	clear, 70°F	direction obs at P4 and P6 (reobserved)
9/28/86	overcast 60°F	reobserve direction obs at P6, levl NGVD disc to P1, distance measurements P4, to P1, P3, P5, P6, P2. Dismantle and winterize site drive to Boston.

IA.3 Epoch 3

DATE	WEATHER	ACTIVITY
11/18/86	overcast -5°C	travel to site, direction obs. at P1 and P5, set out crest targets and tripod at P6.
11/19/86	windy -6°C	prepared all pillars, P6 and slope monuments, dir obs from P4
11/20/86	overcast, windy -2°C	direction obs. at P6 and P3
11/21/86	rain, snow, wind 2°C	no field work owing to severe weather conditions, some data reductions done.
11/22/86	clear,windy -2°C	direction obs at P3 and P2
11/23/86	clear,windy 3°C	direction obs. at P2 and P5, distance measurements P4, to P1, P3, P5, P6.
11/24/86	fog, windy 3°C	direction obs. at P6, distance measurements P6 to P1,P2, travel to Boston

IA.4 Epoch 4

DATE	WEATHER	ACTIVITY
5/4/87	overcast, drizzle, 45°F	mobilize, prepare site, observe P1
5/5/87	overcast, drizzle, calm, 45°F	observed from P1, P4 P5, distances monuments, dir obs from P4
5/6/87	overcast, windy 50°F	observed from P6 and P3
5/7/87	clear A.M., showers P.M., 65°F	observed from P6, P2
5/8/87	calm, A.M., gusty winds P.M., clear 65°F	demobilize, observe P6

IA.5 Epoch 5

DATE	WEATHER	ACTIVITY
7/20/87	partly cloudy, humid, calm, 78°F	Mobilization
7/21/87	partly cloudy, calm, 82°F	observed from P1, P5, P4
7/22/87	partly cloudy, windy, 72°F	observed from P2 and P3
7/23/87	clear, calm, 83°F	observed from P6
7/24/87	clear, light wind 82°F	demobilization

IA.6 Epoch 6

DATE	WEATHER	ACTIVITY
9/28/87	clear, light wind, 60°F	mobilization
9/28/87	partly cloudy, windy, 80°F	observed from P1, observed heights
9/30/87	overcast, humid 60°F	observed from P4 and P6 distances
10/1/87	rain, windy 45°F	observed from P3, P2
10/2/87	clear,calm, 50°F	demobilize, observe P5

APPENDIX IB

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: July 14, 1986
Time: 08:00 hours

Safety meeting was held this date for the following BSC Group personnel:

Clark R. Donkin
Mark W. Rohde
L. Jeff Lowell

Conducted by: Kevin Hanley

Subjects discussed included:

Accident Prevention
Individual Protective Equipment
Prevention of Falls

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: July 14, 1986
Time: 08:00 hours

Total on-site exposure hours for BSC Group personnel:

July 14, through July 20, 1986:

Clark R. Donkin	81.0 manhours
Mark W. Rohde	81.0 manhours
L. Jeff Lowell	81.0 manhours

Signature: [signature]
The BSC Group / Division Manager

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: August 25, 1986
Time: 11:00 hours

Safety meeting was held this date for the following BSC Group personnel:

Clark R. Donkin
Mark W. Rohde
L. Jeff Lowell
W.J. Trevor Greening

Conducted by: Kevin Hanley

Subjects discussed included:

Accident Prevention
Individual Protective Equipment
Prevention of Falls

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: August 25, 1986
Time: 11:00 hours

Total on-site exposure hours for BSC Group personnel:

September 23, through September 28, 1986:

Clark R. Donkin	53.0 manhours
Mark W. Rohde	53.0 manhours
L. Jeff Lowell	53.0 manhours
W.J. Trevor Greening	32.5 manhours
Kevin Hanley	5.0 manhours

Signature: Kevin Hanley
The BSC Group / Division Manager

THE BSC GROUP

SAFETY MEETING AT BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: November 18, 1986
Time: 08:30 hours

Safety meeting was held this date for the following BSC Group personnel:

Clark R. Donkin
Mark W. Rohde
L. Jeff Lowell
W.J. Trevor Greening

Conducted by: Kevin Hanley

Subjects discussed included:

Accident Prevention
Individual Protective Equipment
Prevention of Falls

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: November 18, 1986
Time: 08:30 hours

Total on-site exposure hours for BSC Group personnel:

July 14, through July 20, 1986:

Clark R. Donkin	52.0 manhours
Mark W. Rohde	52.0 manhours
L. Jeff Lowell	26.5 manhours
W.J. Trevor Greening	26.5 manhours

Signature: Kevin Hanley
The BSC Group / Division Manager

APPENDIX IC

Ball Mountain Dam
An Assessment of the Effects
of Atmospheric Refraction

INTRODUCTION

In the Preanalysis of the monitoring survey it was pointed out that changes in the coefficient of refraction may adversely affect the results of the trigonometric levelling at Ball Mountain Dam. It was suggested that the problem might be ameliorated by measuring vertical temperature gradients/profiles during each campaign. Accordingly, several trial profile measurements were undertaken during the July 1986 and September 1986 epochs. A preliminary analysis of these data indicates that the influence of refraction requires further and continued attention.

THEORETICAL BACKGROUND

Kukkamaki (1938, 1939a, 1939b) proposed that vertical temperature gradients and hence refraction corrections could be estimated from observed vertical temperature profiles by means of a simple mathematical model:

$$T = a + bh^c \qquad (1)$$

where a, b and c are constants for a particular profile. T is the mean temperature at height h above the ground. By measuring several (at least 3) temperatures at different heights it is possible to solve for the values of a, b and c. If redundant measurements are made then estimates can be obtained using a least squares adjustment.

The mean vertical temperature gradient is obtained by differentiation of equation (1):

$$\frac{dT}{dh} = bch^{c-1} \qquad (2)$$

In accordance with the free convection theory, many authors (e.g. Fraser, 1977; Holdahl, 1982) set c = -1/3. This assumption is valid during typical unstable daytime conditions.

The coefficient of refraction may be computed using the expression (see e.g., Greening, 1985):

$$k = 78.83 \frac{PR}{T^2} [0.0342 + \frac{dT}{dh}] 10^{-6} \qquad (3)$$

where P is the atmospheric pressure [mb],
R is the radius of curvature of the earth [m], and
T is the mean atmospheric temperature [K].

In equation (3), the gradient dT/dh is the dominant term. The value of k is rather insensitive to assumptions made with regard to the atmospheric pressure (P) and temperature (T).

Finally, the total refraction error in a particular sighting can be evaluated by numerical integration along the optical path (Angus-Leppan, 1971; 1979):

$$\text{Ref} = \frac{1}{R} \{\frac{s_1}{2} (k^1 S + k_2 [S-s_1])$$

$$+ \frac{s_2}{2} (k_2 [S-s_1] + k_3 [S-s_1-s_2])$$

$$+ \ldots\ldots + \frac{sn}{2} (k_n [S-s_1-\ldots\ldots-s_n -_1\} + 0))\} \qquad (4)$$

R is the radius of curvature of the earth, s_1, s_2, ..., s_n are successive subsections of the total distance S and k_1, k_2, ..., k_n are the corresponding coefficients of refraction.

The use of equation (4) pre-supposes a fairly detailed knowledge of the terrain profile and temperature stratification along the line of sight. In the following section, equations (1) through (4) are employed to evaluate the significance of the refraction error in the heighting of one of the object points on the dam wall. These computations have been made to assess the seriousness of the refraction phenomenon. They are not intended for the application of corrections.

RESULTS

Table 1 shows the temperature measurements for four profiles taken from the July and September campaigns. For each data set, a least squares adjustment provided estimates of the coefficients a and b (Table 2). the value of $c = -1/3$ was held fixed. Graphs of the computed profiles appear in Figure 1 through 4. Equations (2) and (3) were used for computing the vertical temperature gradients and corresponding values of k (Figures 5 through 8).

When $dT/dh < 0.0342\ Cm^{-1}$, then $k < 0$ and the curvature of the optical path is convex to the ground. In this case the object points will appear to be lower than their true positions (Figure 11). If $dT/dh > 0.0342\ Cm^{-1}$, then $k > 0$ and points will appear higher than their true locations. The former situation can be expected to occur during typical warm summer days when the heat flux is upward out of the ground. In winter months and/or at night the latter may occur.

In order to assess the problem, refraction errors were computed for the height differences P3-28 and P6-28. Figure 9 shows the horizontal positions of these stations. The terrain profiles are presented in Figure 10 and the refraction error computations are summarized in Table 3.

It is somewhat surprising that the computed refraction errors agree so well. In general, variations of "several millimeters" may be expected to occur. However, the outcome does emphasize the systematic nature of the phenomenon. During any particular campaign, a trend may occur throughout the set of object points. Unfortunately this systematic effect may change seasonally. For example, in summertime, when strong negative temperature gradients predominate, the average refraction error may lie in the range -10mm to -3mm. On the other hand, during winter the near surface gradients may be positive in which case the refraction error is positive. This seasonal variation would be manifest as an apparent upward movement of the object points from summer to winter. The opposite would occur in the winter - summer interval.

CONCLUSIONS AND RECOMMENDATIONS

It is clear that the refraction problem requires further attention. If the effect is ignored, it may be extremely difficult to discriminate between spurious refraction induced displacements and the real vertical motions of the object points.

The following recommendations are made:

1. The process of collecting vertical temperature profile information should be fully implemented.

2. Resources should be allocated to the analysis of the temperature data.

3. Resources should be made available for precise geometric levelling between certain network points as a means of verifying the systematic refraction error component.

With regard to recommendation 3 above, it is suggested that the following loop be measured: P4 - 31 - 21 - 11 - P6 - 15 - 25 - 35 - P4. This will entail the observation, under very difficult conditions, of approximately 35-40 setups. The levelling would require one extra field day per epoch while the analysis of the temperature profile and levelling data will necessitate a further 4 days' office work.

TABLE 1
SUMMARY OF TEMPERATURE
PROFILE MEASUREMENTS

#	DATE	TIME	A	B	C	D	E	F	REMARKS
1	1986 - 0715	13:00	22.5	22.8	23.5	24.5	25.1	26.0	middle of crest, clear, sunny, 15 mph winds, P1 and P5 occupied
2	1986 - 0717	11:30	24.7	25.6	25.4	26.2	26.2	26.2	P3 occupied gradients in bush clowdy / calm
3	1986 - 0727	11:30	15.2	16.9	16.8	18.7	20.8	21.0	P3 occupied, clowdy / calm
4	1986 - 0924	14:00	22.1	22.5	22.9	23.2	24.4	25.2	P6 occupied, Sunny / calm

PROBE HEIGHTS
A 4.0
B 3.0
C 2.0
D 1.2
E 0.6
F 0.3

WTGTAB1.20

TABLE 2

SUMMARY

LEAST SQUARES SOLUTION FOR COEFFICIENTS
OF THE TEMPERATURE PROFILE

	1	2	3	4
a	20.188	24.739	11.829	19.968
b	4.057	0.935	6.697	3.571
	1.30	2.10	3.52	0.61
	1.772	2.85	4.79	0.83
	1.767	2.84	4.78	0.83
	-0.95	-0.95	-0.95	-0.95
RESIDUALS:				
v	0.24	0.63	0.85	0.12
v	0.20	-0.21	-0.43	-0.06
v	-0.09	0.08	0.34	-0.10
v	-0.50	-0.58	-0.57	0.13
v	-0.10	-0.35	-1.03	-0.20
v	0.25	0.44	0.83	0.10

TABLE 3

SUMMARY OF REFRACTION ERROR COMPUTATIONS

LINE P3 - B8

SEGMENT #	1	2	3	4	
SEGMENT LENGTH	50m	47	33	32	
ACCUMULATED DISTANCE	50m	97	130	162	
RAY CLEARANCE	1.8m	11.5	22.3	11.0	from figure
POINT VALUE OF k	-5.8	-0.3	-0.01	-0.3	from figure
REFRACTION ERROR	-3.82mm	-0.13	-0.03	-0.02	
					TOTAL: -4.0mm

LINE P6 - B8

SEGMENT #	1	2	3	4	
SEGMENT LENGTH	35m	35	35	36	
ACCUMULATED DISTANCE	35	70	105	141	
RAY CLEARANCE	1.5m	2.1	2.7	1.8	from figure
POINT OF VALUE OF k	-3.8	-2.3	-1.6	-2.9	from figure
REFRACTION ERROR	-2.14mm	-0.98	-0.60	-0.29	
					TOTAL: -4.0mm

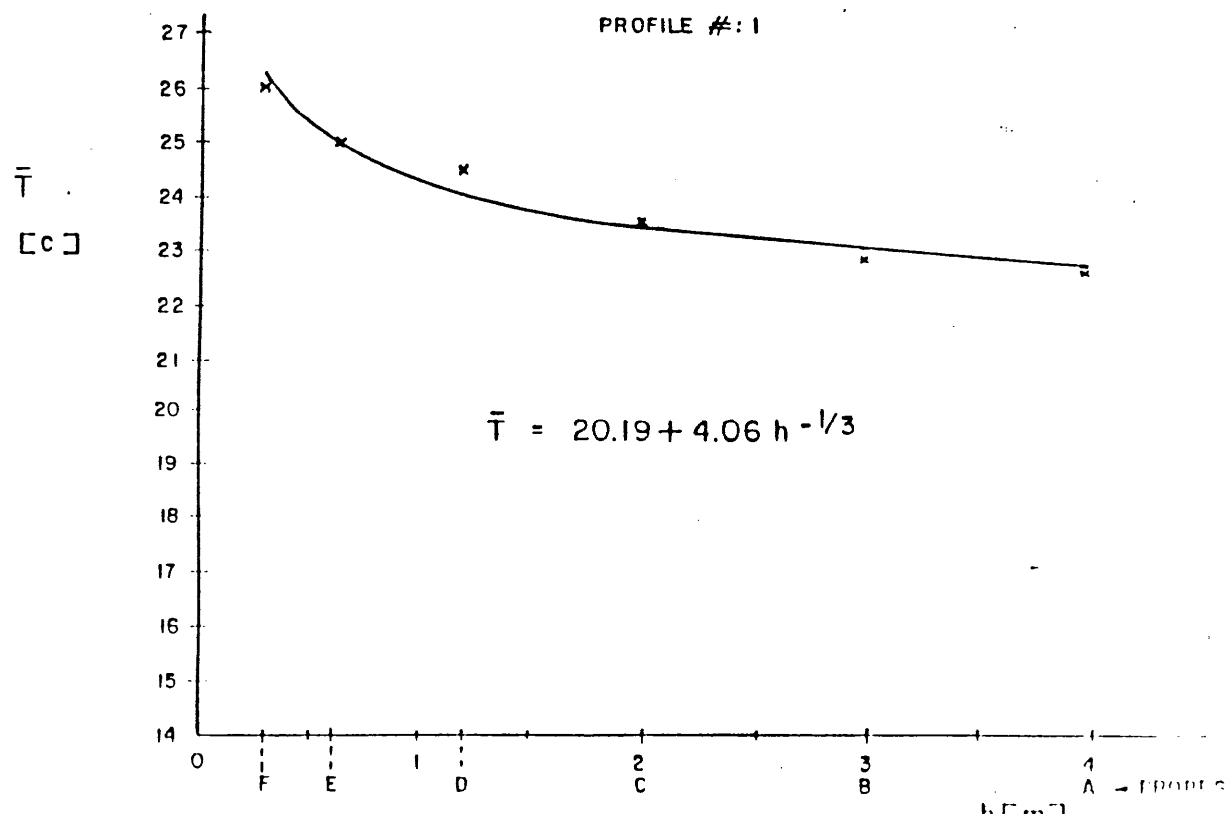


FIGURE 1

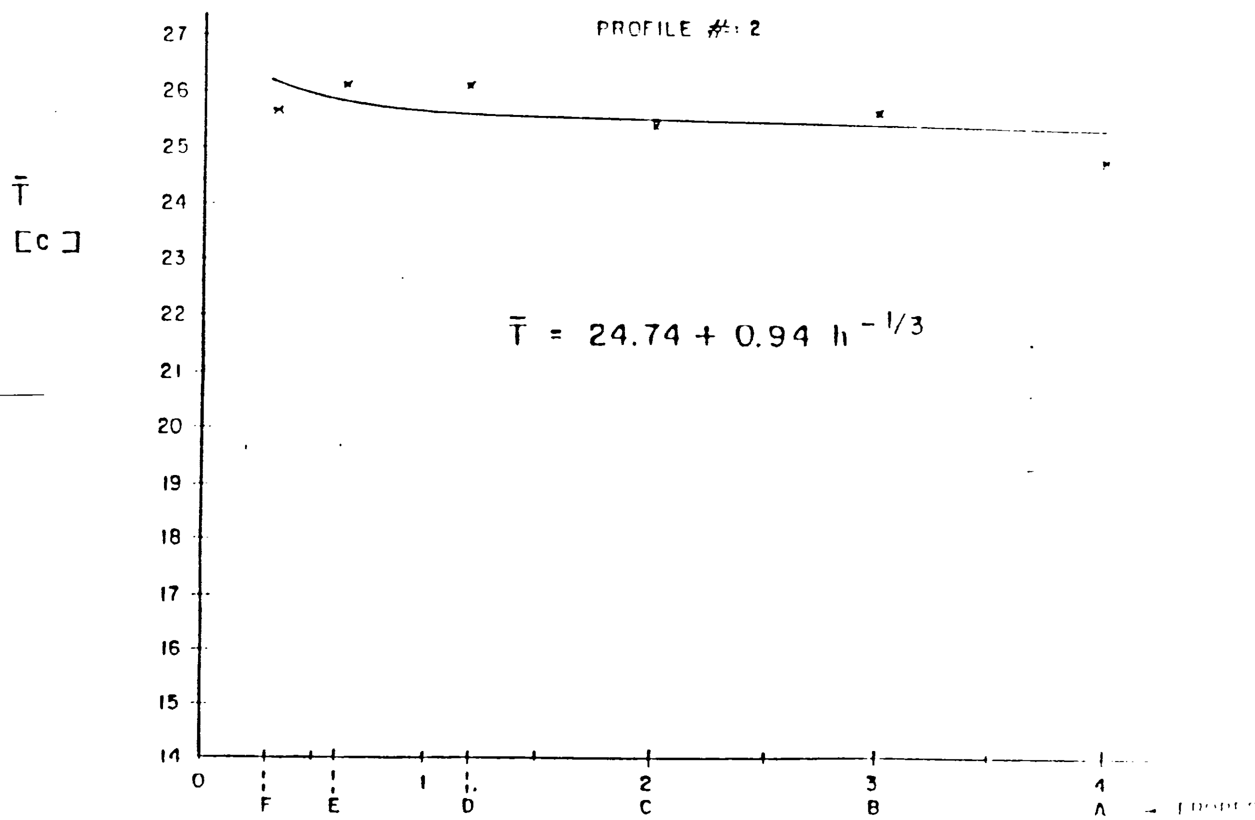


FIGURE 2

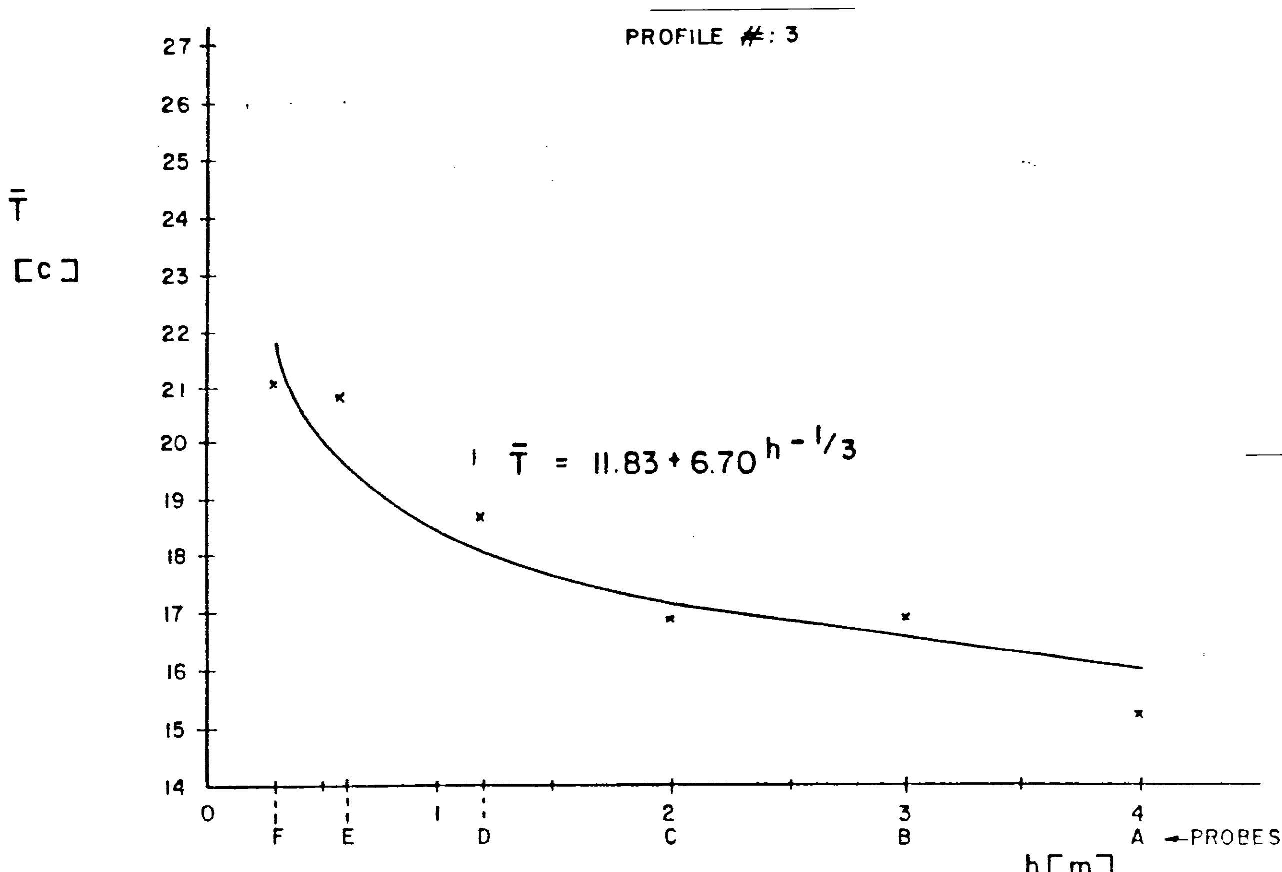


FIGURE 3

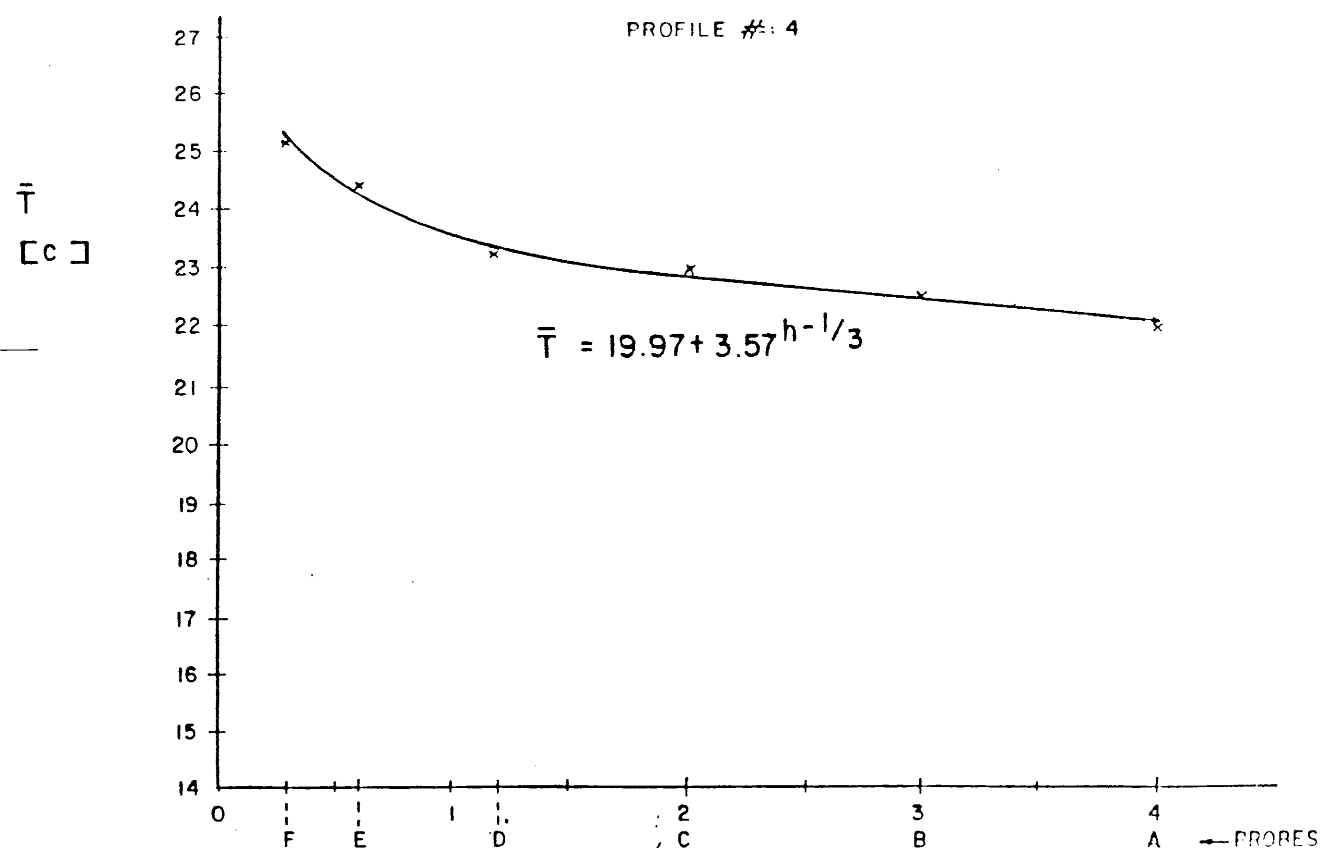


FIGURE 4

PROFILE # : 1

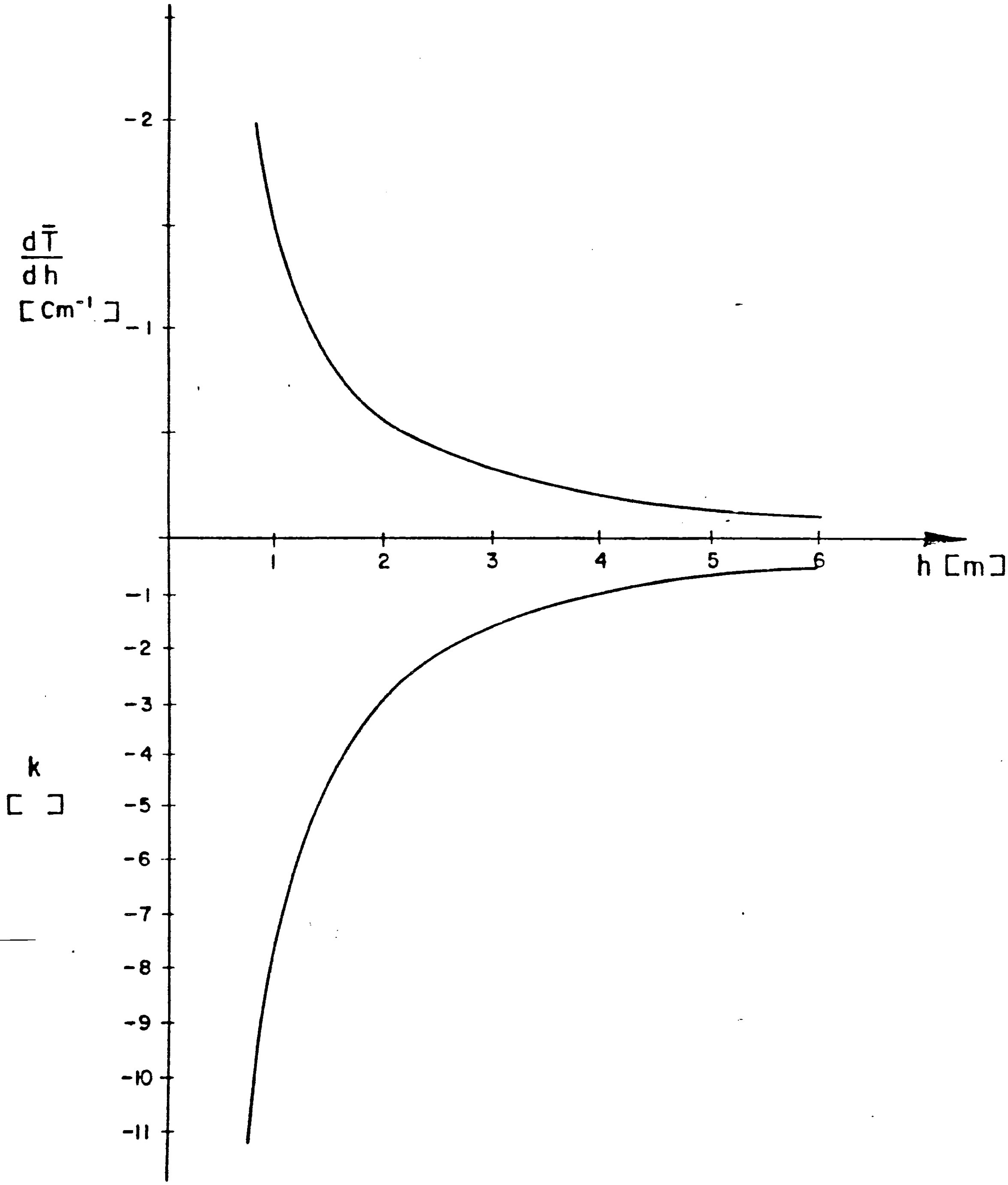


FIGURE 5

PROFILE # : 2

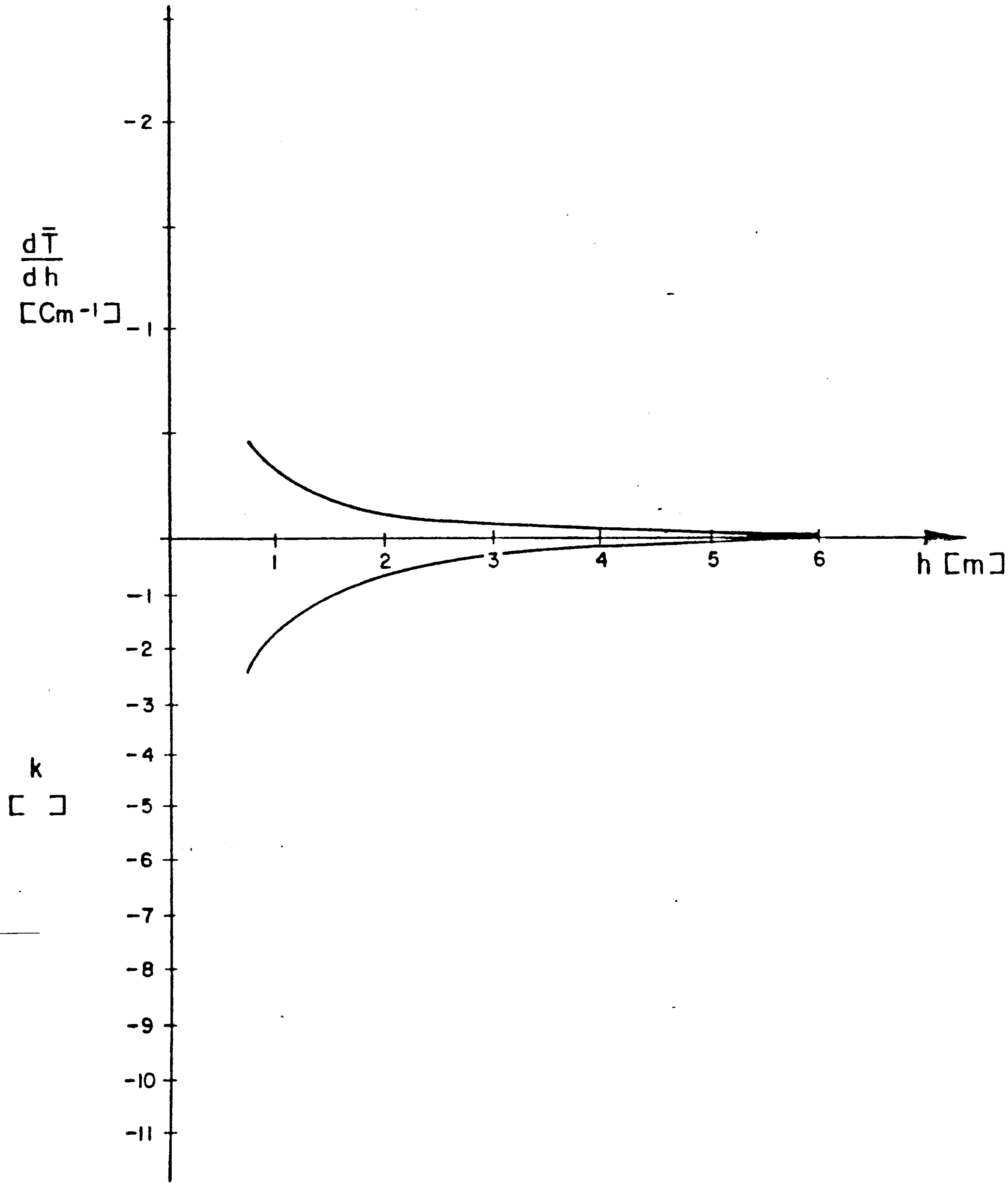


FIGURE 6

PROFILE #: 3

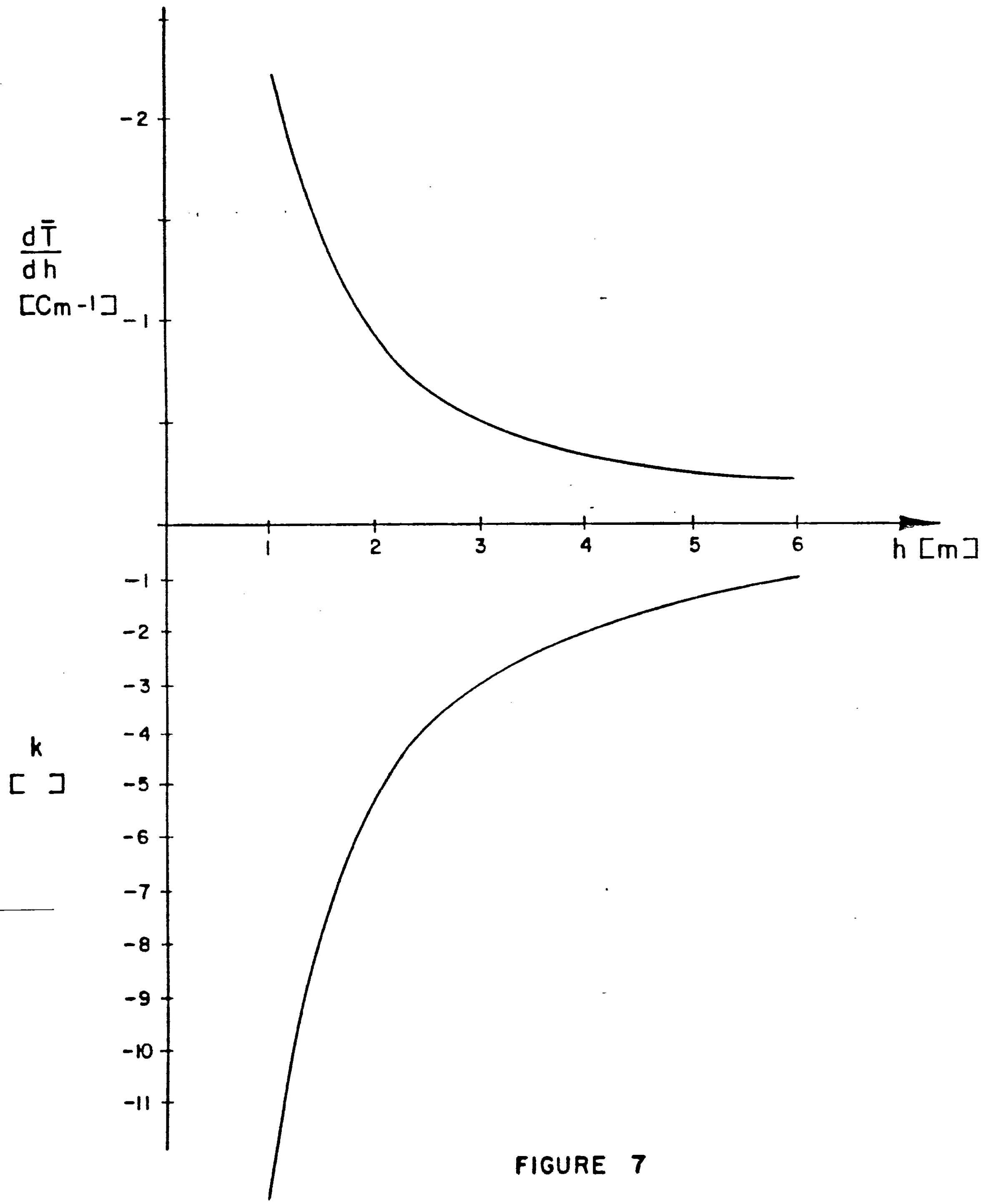


FIGURE 7

PROFILE # : 4

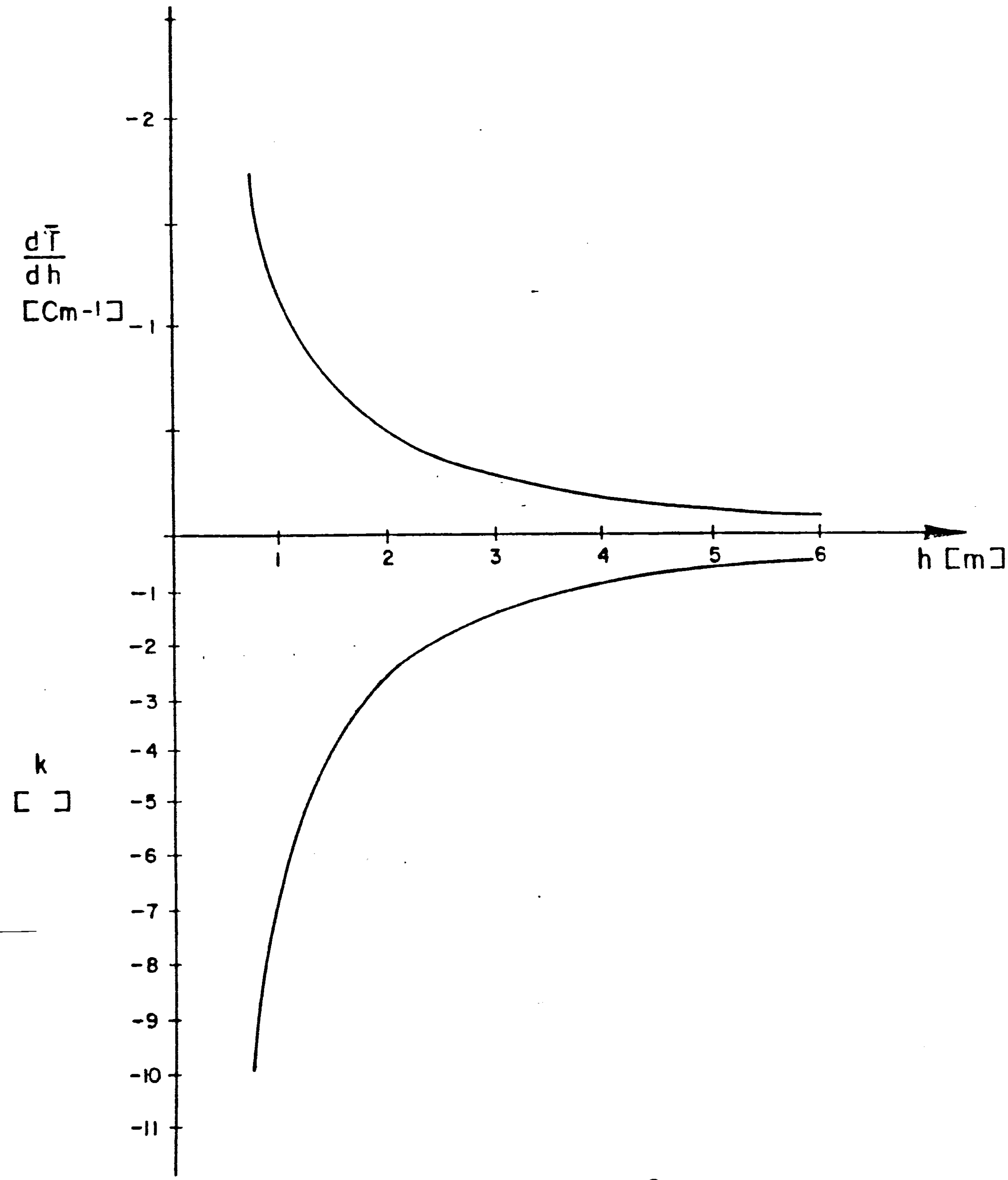


FIGURE 8

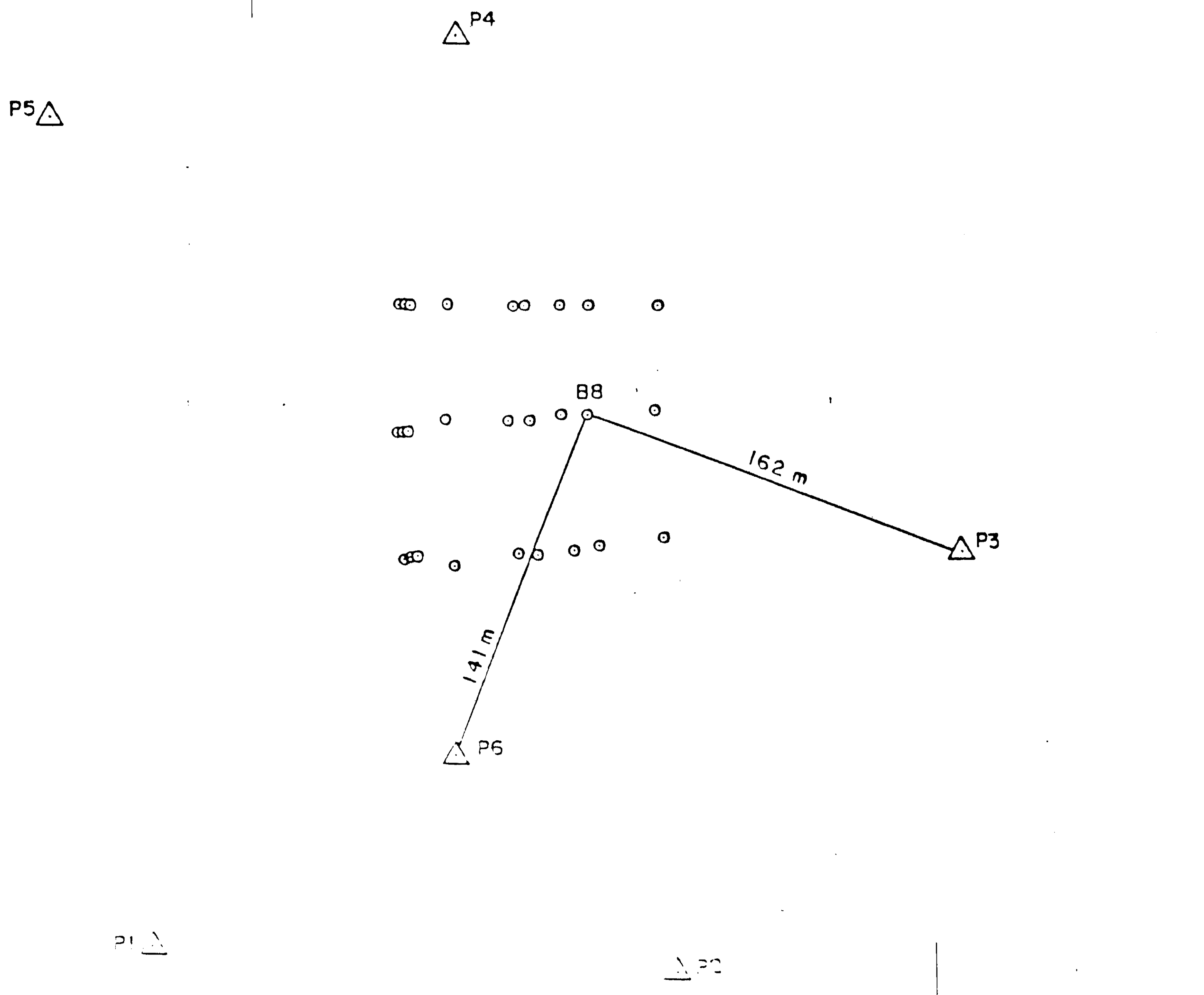
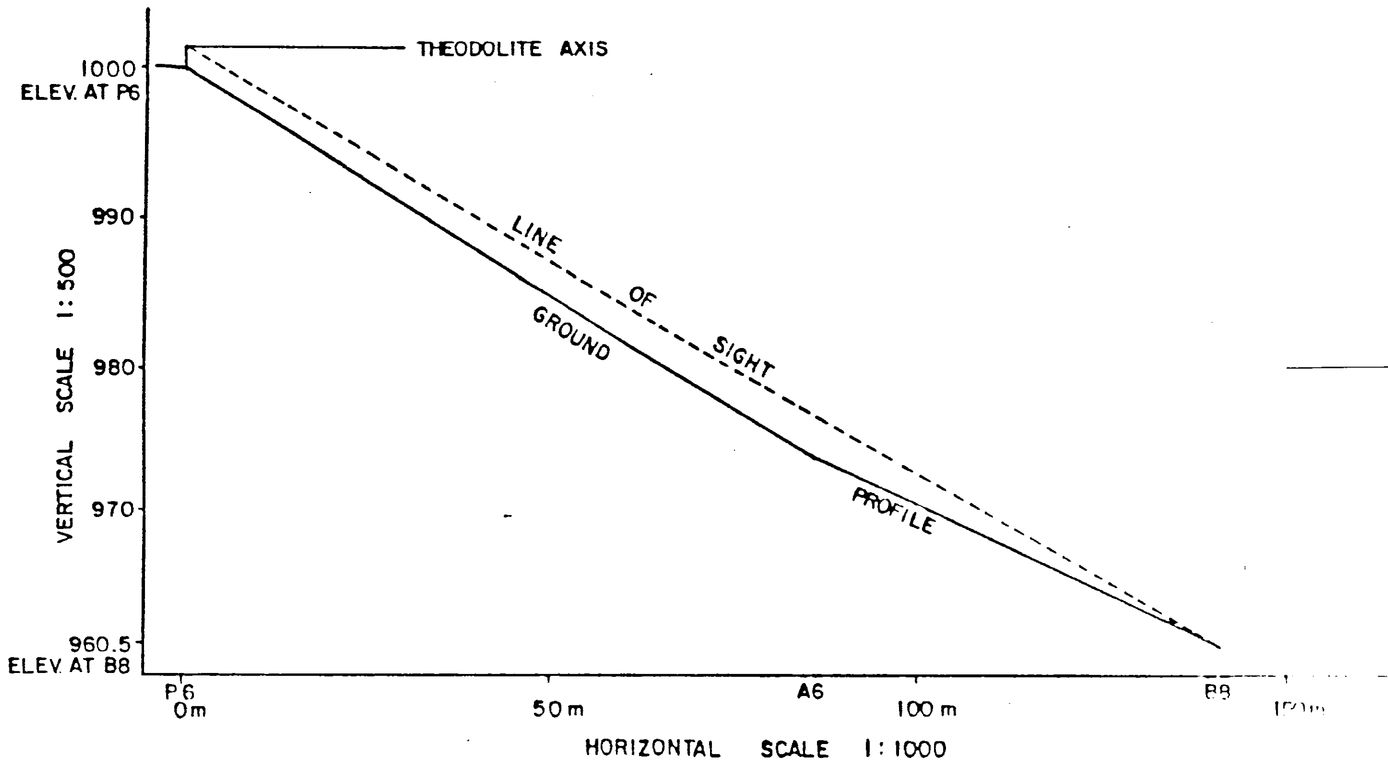
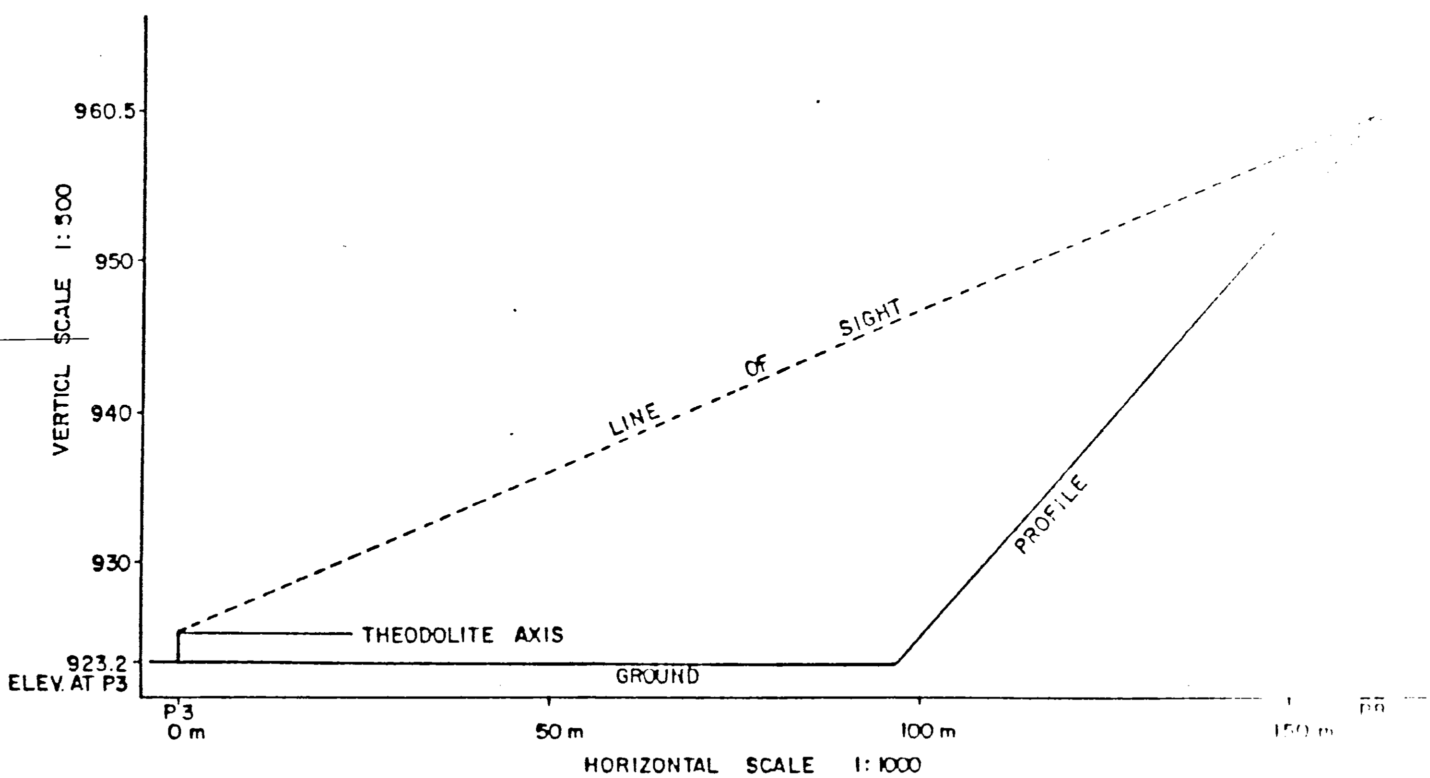


FIGURE 9

P6 TO B8



P3 TO B8



FIQURE 10

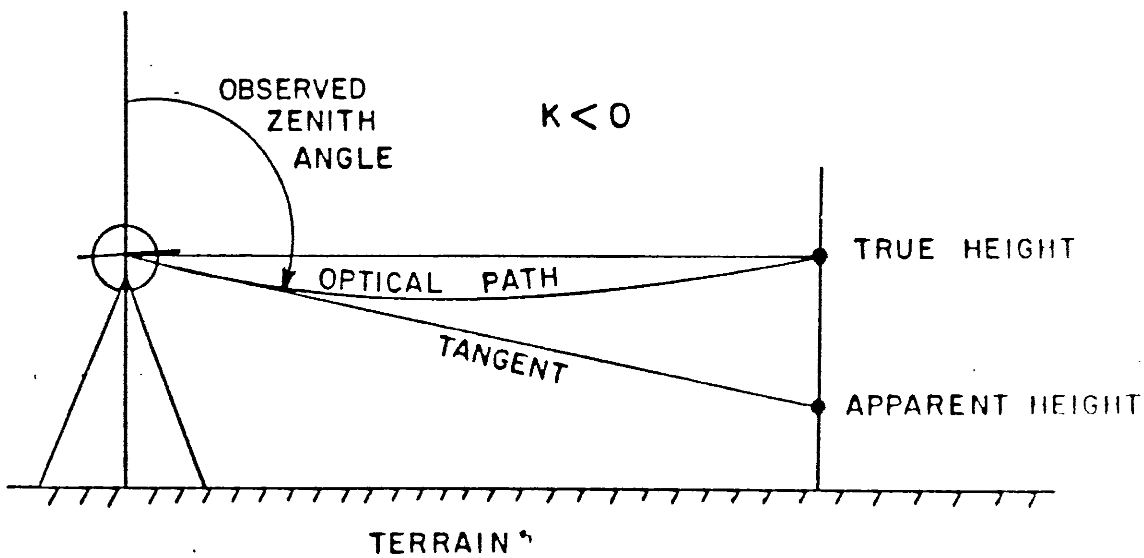


FIGURE 11

THE EFFECT OF A NEGATIVE
COEFFICIENT OF REFRACTION

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APPENDIX ID

GNA Methodology
(from Intergraph Corporation, 1986)

ID.1 Lease-Squares Adjustment

Least-square adjustment is a specific method, fully rigorous, which adjusts observations to remove inconsistency in redundant or overdetermined systems. In addition, the least-squares method offers several useful properties:

- a unique, unbiased estimate of the coordinate results
- maximum likelihood values for coordinates, assuming normally distributed residuals
- unbiased estimated residuals
- an available estimate of coordinate precisions
- minimum variance associated with the coordinates

ID.2 Pre-Analysis

The least-squares process, which produces precision estimates, can be used without actual observations to estimate the precision of point coordinates. Therefore, it is possible to assess or pre-analyze proposed networks using the least-squares algorithm.

Pre-analysis exploits the fact that estimates of parameter precisions (how accurately coordinates are determined) are represented by the parameter covariance matrix. The covariance matrix is a function of network geometry and observation precision. A priori knowledge of the standard deviations of proposed observations network in conjunction with a preliminary configuration makes it possible to assess the probable accuracy attainable from a proposed design prior to entering the field to gather observations.

The use of pre-analysis also ensures an optimal or efficient design by enabling the minimization of the number of stations and observations to meet design criteria.

ID.3 Reliability

GNA allows not only for precision or accuracy design but also for reliability design. In general, reliability measures yield a means of defining the sensitivity of a network solution to the presence of outliers or undetected blunders in the data.

Internal reliability indicates the magnitude that a blunder in an observation must reach before the examination of residuals from an adjustment detects it. In pre-analysis mode, GNA outputs the minimally detectable blunder for each observation.

Since the coordinates, not the actual observations, are of primary interest, the effect of undetected blunders on the coordinates is expressed as the external reliability. GNA outputs a global external reliability value for each observation. This value indicates how an undetected blunder in a single observation affects estimated coordinate values. As a general rule of thumb, near constant values of global external reliability indicate a well designed network.

APPENDIX IE

Lad Methodology
(Quoted from Integraph Corporation, 1986)

LAD utilizes a method whereby the coordinates of "same" points are compared to determine any displacements and to further analyze these to check for deformations. The concept is best exploited within an absolute deformation network i.e. one in which a stable base of reference points in both epochs is used to compare coordinating of non-stable points. Such a network is utilized at Ball Mountain Dam.

"The localization procedure in LAD involves the determination, by statistical testing, of point and/or groups of point displacement parameters. Localization is first applied to those points defining the assumed stable reference system. Any reference points whose movement is statistically significant are removed from the reference system. The statistical significance is primarily a function of the other base points and the quality or precision of the coordinates as expressed in the covariance matrix.

After determination of a suitable reference frame LAD transforms both sets or coordinates and their respective covariance matrix to a common datum as defined by the remaining stable reference points. This allows the user to compare coordinates from adjustments using different minimum constraint solutions. In addition erroneous deformation results may ensue without the transformation to the common coordinate system.

LAD then tests all points NOT belonging to the base for statistically significant movement with respect to the reference network. The magnitude and coordinate components i.e. horizontal/vertical are derived.

LAD also allows for the determination and statistical testing of any group of points suspected of common deformation i.e. scale, rotation and/or translation. The statistical testing of these group parameters ensures that only significant deformation parameters are obtained". (Intergraph Corporation, 1986).

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