Dam Deformation Surveys

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Introduction

More than 170 major dams have been constructed in NSW and new dams continue to be constructed. The waters retained by these large reservoirs have enormous potential energy which, if released in an uncontrolled fashion by dam failure, could cause extensive loss of life and damage to the environment over and above the consequences of the loss of the dam.

Each year there is at least one significant dam failure somewhere in the world and many more near failures have occurred. Australia has an enviable safety record in this regard with only one major dam failure, which occurred in Tasmania over 50 years ago and resulted in 14 people being killed. Accordingly, the proper functioning of dams under all conditions is an important matter of public welfare and safety.

With these factors in mind the NSW Government constituted the NSW Dams Safety Committee (DSC) in 1979 to adopt an ongoing watchdog role to ensure the integrity of the State's dams and their stored waters. Prior to the formation of the DSC, and in fact dating back some 63 years, Metropolitan Water Sewerage and Drainage Board (now known as Sydney Water) surveyors have undertaken monitoring surveys of their dams. Since its formation AWT SURVEY has undertaken the monitoring surveys for Sydney Water.

Functions of the Dam Safety Committee

The DSC has statutory functions under the Dams Safety Act 1978 and the Coal Mining Act. Its main objective is to ensure that all 'prescribed dams' (see definition below) are in a safe condition. This is achieved by requiring all dam owners to arrange regular surveillance, monitoring and assessment of the behaviour of their dams.

The committee also ensures that coal mining activities do not endanger the safety of any dam or reservoir. Recommendations are made to Government on the nature and extent of coal mining which should be permitted near dams and reservoirs.

The DSC requires owners of all 'prescribed dams' to prepare and submit to the Committee Surveillance Reports in respect of their dams at intervals not exceeding 5 years.

Hazard Rating of Dams

Along with dam safety authorities world-wide the DSC classifies dams according to the extent of development downstream from them, and the potential loss of life and destruction of property in the hypothetical event of dam failure. This classification is defined as the dam's 'Hazard Rating'. It does not involve any assessment of the risk of

failure of the dam. Thus a dam which meets the highest safety standards can have a **HIGH** hazard rating. Because the DSC is concerned with the safety of the public, a dam with only limited downstream development may fall in the 'High Hazard' category because of downstream residents whose lives would be directly threatened in the event of dam failure, even though this may be a most unlikely event.

Hazard rating is used to determine the amount and frequency of the surveillance of the dam to ensure its continuing safety and to set priorities for, and determine the extent of upgrading or repair work where the surveillance results indicate such needs.

The hazard rating system adopted in NSW is summarised as follows:

* LOW — No habitation or significant facilities in the alley downstream, no loss of life expected, minimal economic loss (i.e. farm buildings, minor roads, crops etc.)

* SIGNIFICANT — No urban development and only a small number of habitable structures downstream of dam, loss of a few lives expected, appreciable economic loss (i.e. public utilities, secondary roads, minor railways, agricultural facilities etc.)

* HIGH — Extensive development downstream, loss of more than a few lives expected, excessive economic loss (i.e. damage to communities, industrial and commercial facilities, highways and important public facilities.)

Prescribed Dams

A 'prescribed' dam is one listed in Schedule 1 of the Dams Safety Act 1978 (Appendix 2). This schedule is amended from time to time by additions and deletions on the recommendations of the DSC. This is usually based on the size, hazard rating and to some extent the storage capacity of the dam in the following manner:

* All high hazard dams are prescribed.
* All dams above 15 metres in height are prescribed.
* Significant hazard rating dams between 5 and 10 metres in height with a storage capacity in excess of 50ml are prescribed.
* Significant hazard rating dams between 10 and 15 metres in height with a storage capacity in excess of 20ml are prescribed.

Sydney Water currently has 32 prescribed dams. Of these 15 have a high hazard rating (10 of which are monitored with survey), 9 a significant rating (3 monitored with survey) and 8 a low rating (4 monitored with survey).

Monitoring and Surveillance Requirements

The DSC endorses the recommendations contained in the publication 'Guidelines for Operation, Maintenance and Surveillance of Dams' which has been prepared by the Australian National Committee on Large Dams (ANCOLD).

ANCOLD comprises the principal Australian, State and Local Government instrumentalities and private organisations which own, build or manage dams in Australia and its Territories. Its membership also includes consulting engineers, contractors and others concerned with dams. This document was reviewed in 1994, resulting in a general lessening in the monitoring required for dams.

Some of the forms of monitoring recommended in the ANCOLD Guidelines include:

* Reservoir water levels which provide a record of the loadings on the dam.
* Seepage which may be measured at any point on the dam, abutments, or reservoir rim or even well downstream of the dam.
* Pore-water pressure and water table levels which may be related to seepage, reservoir level and rainfall.
* Surface and internal movements.
* Stresses which may be measured in embankments or structural concrete.
* Spillway performance and condition.
* Seismic events which may be measured on a regional or local basis.
* Rainfall which may relate to the amount of seepage.

The recommended frequency, as listed in the ANCOLD guidelines, for monitoring surveys is as shown in the table below. With only a few exceptions, where the surveys are carried out on a more frequent basis, Sydney Water has adopted this timetable for the surveys of its dams.

Guide for 'In Service' Monitoring Frequency

	SMALL <15m high			LARGE >15m high		
	LOW	SIG	HIGH	LOW	SIG	HIGH
CONTROL SURVEY	-	ADVIS	5 YRS	ADVIS	5 YRS	3 YRS
NORMAL SURVEY	-	-	YEARLY	-	2 YRS	YEARLY
INTERNAL DISPLACEMENT	-	-	YEARLY	-	2 YRS	YEARLY

Note 1: These frequencies may need to be varied according to the conditions at and the type of dam and applies to instrumentation already installed at the dam.

Note 2: A control survey uses monuments which are remote from the dam site to check the location of the major monuments at the dam site.

General Principals

The deformation behaviour of a dam and its abutments is responsive to the age of the dam, geographical conditions of the area, fluctuations in the stored water level and seasonal (temperature) change. Displacement behaviour at typical locations in a dam can be monitored by internal instrumentation (eg. Inclinometers, Clinometers etc.) however for a broad monitoring coverage of deformation behaviour providing a register of absolute movement of the dam and abutments, precise survey methods are utilised.

Surface displacements of a dam are monitored by a precise survey system generally based on a triangulation network which is established with a high degree of accuracy. The network is usually based on a local grid in a measurement plane near the level of the crest of the dam. There may be reasons for relating the primary stations to the Integrated Survey Grid, but this should be an independent exercise as, for the purpose of monitoring, it is not essential.

Survey Systems

Normal Survey:

Figure 1 shows the monitoring station layout for Woronora Dam. This layout is typical for the large, high hazard rating concrete dams monitored by AWT SURVEY. The following *italic* print indicates a reference to Figure 1 within the general comments on normal surveys.

EDM distances are measured from the centre of the crest of the dam (*station CT5*) to the upstream and downstream orientation stations (*WO6 and WO5 respectively*). This gives an immediate indication of the crest location to within +/-1.5mm.

Resections are read at between two and three stations on the crest of the dam (*W1 and W4*), relative to stations established in the near vicinity of the dam, which are assumed to be stationary. Directions are observed to selected points on the crest of the dam (*CT1, CT2, CT3, CT4, CT5, CT6, CT7 and CT8*). EDM distances are also observed to these selected stations from the resection stations.

Levels are observed at all stations on the crest of the dam, being connected to bench marks located outside the zone of influence of the dam.

This system provides a quick check on the movement of the crest of the dam in relation to previous series, from which seasonal, or any unusual movements can be defined.

After an initial two year period of conducting these surveys at a three monthly interval, to determine seasonal movements, they were measured at a six monthly frequency to coincide with the dams maximum upstream and downstream location. Since 1994 the frequency has been adjusted generally to twelve monthly, with only two exceptions, in order to comply with the new ANCOLD guidelines.

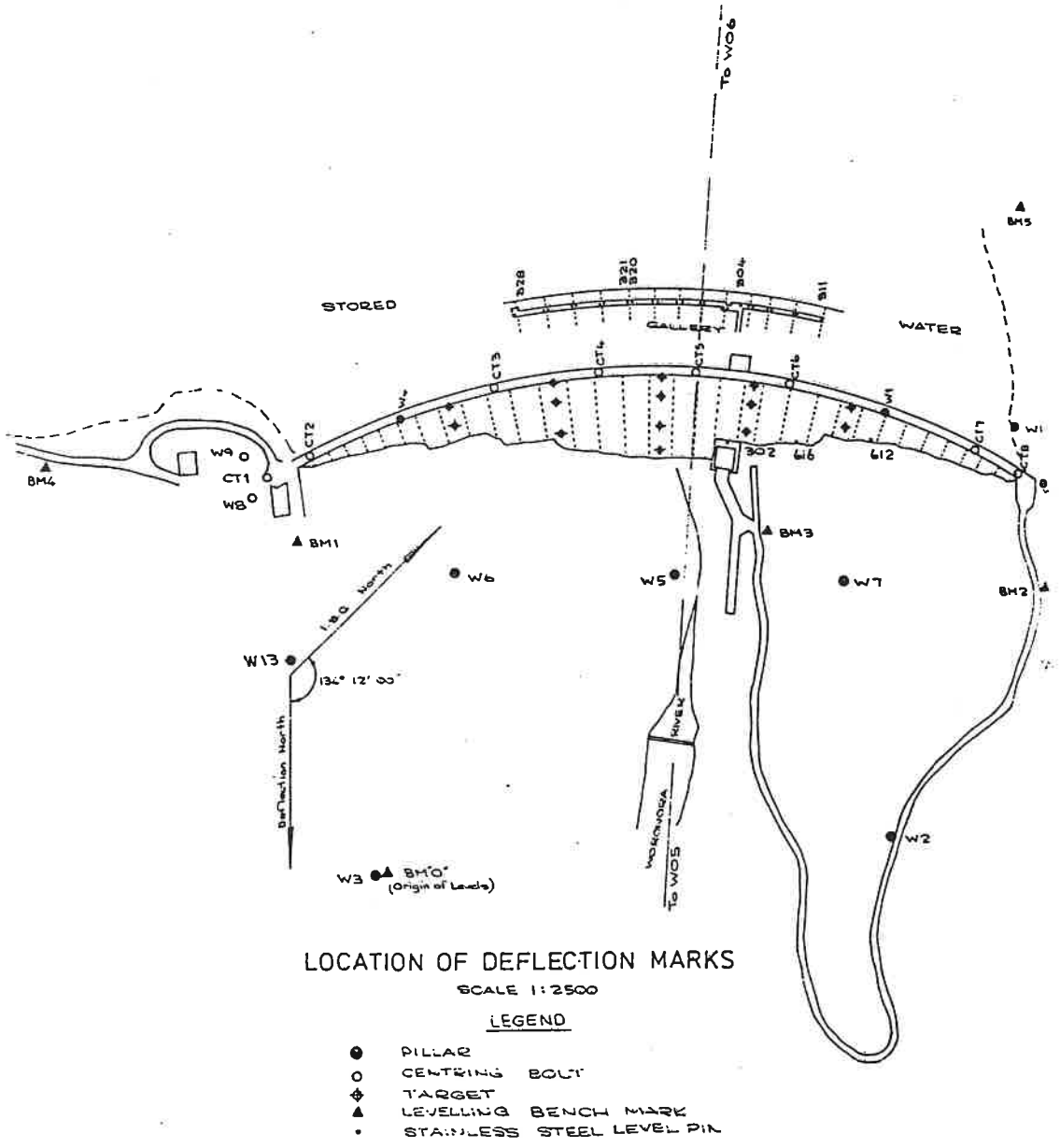

Figure 1:- Woronora Dam control network layout.

Control Survey:

The normal survey is connected to the control stations surrounding, and outside the zone of influence of, the dam. All control stations are occupied, with observations being taken to all other stations. Observations are also made to targets on the downstream face of the dam from survey stations located immediately downstream of the dam.

Relative movements between reference stations as small as 0.5mm are of interest and in order to record such movements a high standard of survey work is required.

Levels are observed on the crest stations, on selected stations on the abutments and within the galleries. If access exists a vertical invar wire chainage is observed from the crest to the gallery to strengthen the levelling adjustment.

The normal and control surveys require an accuracy standard, as set down by the surveillance engineers, of better than +/-2mm both horizontally and vertically. Typically an accuracy of +/-1mm at the dam stations is achieved.

For both normal and control surveys, if the dam has galleries, tilts of the dam are measured utilising Huggenburger Clinometers at selected locations.

With high hazard rating earth fill embankment dams a combination trilateration/triangulation survey is utilised. Control stations are established on the crest of the dam from observations to and from a minimum of 4 fixed control stations surrounding the dam. From these crest control stations observations are made to selected points on the crest and downstream face of the dam.

Levels are observed on the survey stations/marks on the crest and downstream face of the dam, connected to benchmarks located outside the zone of influence of the dam.

The accuracy standard for these earth fill embankment dams is not required to be as high and is requested, by the surveillance engineers, to be of the order of better than +/-5mm, both horizontally and vertically. The accuracy achieved is typically +/-2mm.

For significant and low hazard rating dams the horizontal deflections are determined by reading direct offsets from a line joining control stations, located on the abutments of the dam, to a limited number of stations located on the dam structure.

The levelling is as surveyed in the normal survey.

Setting Out

Horizontal Control:

Observation pillars are normally placed immediately downstream of the dam and founded on solid rock if possible. Additional pillars are placed downstream, with at least one upstream, away from the zone of influence of the dam in order that one or more may be

used to provide an origin for co-ordination of the system and appropriate figure adjustment based on accepted geodetic methods.

The survey pillars are fitted with centring bolts set in a vertical position. This type of bolt allows the interchange of both the theodolite and targets used for observation.

The baseline used for the establishment of a standard geodetic figure is located along the crest of the dam. In the past this line was measured with a pair of standardised invar wires. This procedure was discontinued with the arrival of high precision short range EDM. The invar wires did, however, necessitate the location of traverse stations at intervals consistent with the curvature of the dam and the available invar wire length. This interval was either 25 metres or 50 metres.

These traverse stations are the selected stations observed coincident with the resections on the crest of the dam and consist of the same centring bolts as installed in the control pillars. Care must be taken that these bolts are attached to the concrete of the dam proper, as distinct from parapets and wearing slabs (eg. roadways).

Targets are placed in horizontal and vertical rows at critical locations on the downstream face of the dam.

Vertical Control:

Levelling points are placed across the crest of the dam adjacent to the traverse stations and block joints, in the roof of galleries, on abutment rock and any relevant geological feature.

One or more bench marks are placed outside the zone of influence of the dam to provide an origin for the vertical control survey. If practicable all control pillars should be levelled to add an additional check on their stability.

Internal Displacement:

Internal displacements are measured utilising a Huggenburger Clinometer. These measurements were taken at selected stations monthly prior to the release of the new ANCOLD guidelines. The frequency has been adjusted to yearly since 1994 in order to coincide with these new guidelines.

Clinometer stations are placed within the galleries of the dam, across contraction joints and at other specific locations which require monitoring.

The measurement points are precise stainless steel setting balls, placed 1000mm apart and embedded in mortar within the wall.

Method of Measurement

Direction (Angle) Measurement:

All directions are observed with a first order theodolite. In the case of AWT SURVEY this is a Wild T2000 electronic theodolite.

For both the control and normal surveys four sets of observations are made at each station. The standard deviation for the four sets of observations is generally less than 0.5 seconds. These observations are undertaken at night in order to minimise atmospheric effects. The observations for the earth fill dams and lower hazard dams are undertaken during normal daylight shifts.

Software developed within AWT SURVEY allows the previous survey series results to be loaded into the Wild GRE3 or Wild GRE4 data recorder prior to commencement of the current survey. On site the surveyor identifies his location and is prompted with the reference object followed by the name and direction of every station to be observed in turn.

A course check is done by the GRE3/GRE4 as each observation is read to determine if it is within preset parameters, when compared to the previous result, to eliminate blunders.

Distance observations are also recorded in the GRE3/GRE4 along with atmospheric conditions at either end of the line observed, height of instrument and target.

Height Displacement Measurement:

All differences in height are determined by the precise levelling method utilising a first order level and standardised invar staves. The staves are fitted with supporting legs and are generally not hand held.

The levelling accuracy aimed for is that the rise or fall between any two consecutive pins on the forward and return runs should agree to within 0.0002m.

Observations are either recorded directly by the instrument (NA3000) or in a HP41 used as a data recorder with programs developed within AWT SURVEY.

Clinometers:

Clinometer readings to one second of arc are made utilising either a horizontal or vertical Huggenburger Clinometer. These consist of a precise spirit bubble attached to an invar frame which sits (horizontal) or hangs (vertical) on the measurement balls 1000mm apart.

As major temperature changes are encountered from inside the gallery to the outside of

the dam wall, care has to be taken to allow the clinometer bubble to stabilise within the gallery prior to the commencement of readings.

Computations

Following the down loading of the distance and direction data from the GRE3/GRE4 into a PC, the observations are reduced with software developed within AWT SURVEY.

The direction reduction checks for outlying observations and prompts the surveyor for decisions on which way to proceed if they occur. A print out of the reductions is supplied (Fig. 2) with outlying observations underlined.

WORONORA DAM 08-09-1993

Station Name W4

W.D.LAWTHER

Individual Sets

Rejected Directions Shown Underlined

Set 1				Set 2				Set 3				Set 4			
To				To				To				To			
W03	0°	0'	0.00"	W03	0°	0'	0.00"	W03	0°	0'	0.00"	W03	0°	0'	0.00"
W15	8°	51'	28.40"	W15	8°	51'	29.25"	W15	8°	51'	28.35"	W15	8°	51'	26.95"
W3	22°	0'	11.70"	W3	22°	0'	16.35"	W3	22°	0'	16.80"	W3	22°	0'	13.90"
W13	44°	31'	48.75"	W13	44°	31'	53.05"	W13	44°	31'	52.45"	W13	44°	31'	51.90"
W8	82°	18'	0.35"	W8	82°	18'	1.10"	W8	82°	18'	1.35"	W8	82°	17'	59.40"
CT1	86°	15'	4.55"	CT1	86°	15'	6.05"	CT1	86°	15'	4.85"	CT1	86°	15'	3.85"
CT2	87°	32'	29.50"	CT2	87°	32'	30.90"	CT2	87°	32'	31.75"	CT2	87°	32'	30.00"
W9	96°	50'	36.80"	W9	96°	50'	36.30"	W9	96°	50'	36.75"	W9	96°	50'	34.35"
W14	185°	52'	11.55"	W14	185°	52'	5.25"	W14	185°	52'	12.90"	W14	185°	52'	11.50"
W16	220°	52'	14.00"	W16	220°	52'	9.00"	W16	220°	52'	15.95"	W16	220°	52'	15.85"
CT3	269°	19'	22.10"	CT3	269°	19'	18.40"	CT3	269°	19'	24.35"	CT3	269°	19'	22.50"
CT4	274°	50'	3.50"	CT4	274°	49'	57.90"	CT4	274°	50'	4.55"	CT4	274°	50'	4.45"
CT5	279°	18'	34.05"	CT5	279°	18'	28.55"	CT5	279°	18'	36.80"	CT5	279°	18'	33.60"
W1	288°	14'	40.30"	W1	288°	14'	36.50"	W1	288°	14'	43.30"	W1	288°	14'	42.50"
W11	289°	7'	25.50"	W11	289°	7'	19.00"	W11	289°	7'	26.40"	W11	289°	7'	27.25"
W10	293°	49'	59.40"	W10	293°	49'	54.70"	W10	293°	50'	2.10"	W10	293°	50'	0.05"
W12	308°	52'	40.00"	W12	308°	52'	33.15"	W12	308°	52'	42.10"	W12	308°	52'	40.05"
W2	329°	25'	31.10"	W2	329°	25'	25.60"	W2	329°	25'	33.75"	W2	329°	25'	31.35"

MEAN

To			
W03	0°	0'	0.00"
W15	8°	51'	28.24"
W3	22°	0'	14.69"
W13	44°	31'	51.54"
W8	82°	18'	0.55"
CT1	86°	15'	4.83"
CT2	87°	32'	30.54"
W9	96°	50'	36.05"
W14	185°	52'	10.30"
W16	220°	52'	13.70"
CT3	269°	19'	21.84"
CT4	274°	50'	2.60"
CT5	279°	18'	33.25"
W1	288°	14'	40.65"
W11	289°	7'	24.54"
W10	293°	49'	59.06"
W12	308°	52'	38.83"
W2	329°	25'	30.45"

AMENDED MEAN

Shown Underlined

To			
W03	0°	0'	0.00"
W15	8°	51'	28.24"
W3	22°	0'	14.69"
W13	44°	31'	51.54"
W8	82°	18'	0.55"
CT1	86°	15'	4.83"
CT2	87°	32'	30.54"
W9	96°	50'	36.05"
W14	185°	52'	11.98"
W16	220°	52'	13.70"
CT3	269°	19'	21.84"
CT4	274°	50'	2.60"
CT5	279°	18'	33.25"
W1	288°	14'	40.65"
W11	289°	7'	26.38"
W10	293°	49'	59.06"
W12	308°	52'	40.72"
W2	329°	25'	30.45"

Standard Deviation = 1.36 Seconds

Figure 2:- Print-out of reduced directions from GRE3/GRE4 - Woronora Dam crest station W4.

The distances are reduced, using previously loaded heights of all stations observed, for differences in instrument and target elevation and to a specified plane for each dam. This plane is usually at or near the crest level of the dam. A print out of the reduction is supplied (Fig. 3).

DISTANCE MEASURING SHEET

Location : WORO Series : 19C Observer : LAWTHER

Instrument : DI2000 Computed : Fri Aug 26 08:15:12 1994

Station	EDM CT2	Reflector CT1
Altitude	170.338	170.407
Instrument Height	1.560	0.240
Instrument Altitude	171.898	170.647
	Temp Celsius	Press mmHg
Instrument Atmospherics	14.0	758.3
Target Atmospherics	14.0	0.0
Mean Atmospherics	14.0	758.3
	OBSERVED	DISTANCES
	25.0247	25.0247
	25.0247	25.0245
	25.0246	25.0246
	25.0246	25.0245
	25.0246	25.0244
Reflector Constant	-0.00200	
Mean Distance	25.02259	
Slope Distance	25.02266	
Horizontal Distance	24.99136	
Plane Distance (H : 152.0)	24.99129	**********

Station	EDM CT2	Reflector W8
Altitude	170.338	179.337
Instrument Height	1.560	0.238
Instrument Altitude	171.898	179.575
	Temp Celsius	Press mmHg
Instrument Atmospherics	14.0	758.3
Target Atmospherics	14.0	0.0
Mean Atmospherics	14.0	757.9
	OBSERVED	DISTANCES
	36.6947	36.6939
	36.6936	36.6939
	36.6935	36.6937
	36.6935	36.6938
	36.6938	36.6934
Reflector Constant	-0.00200	
Mean Distance	36.69178	
Slope Distance	36.69188	
Horizontal Distance	35.87977	
Plane Distance (H : 152.0)	35.87964	**********

Figure 3:- Print-out of reduced distances from GRE3/GRE4 - Woronora Dam crest distances CT2 to CT1 and CT2 to W8.

Once the surveyor is satisfied with the raw data the software will input the reduced directions and distances directly into the least squares adjustment package COMPNET, which has been written by one of the surveyors from AWT SURVEY and is commercially available.

Primary triangulation figures for each survey are adjusted by the method of least squares, oriented from points located outside the zone of influence of the dam structure, and coordinated by latitudes and departures using adjusted bearings and the measured base line.

Specified remote pillars are used as a stationary origin for the co-ordinate calculations.

Level field data is similarly down loaded into a PC where it is manipulated by software developed within AWT SURVEY for input into the COMPNET least squares adjustment software.

Presentation of Results

Horizontal Deflections (See Fig. 4):

The magnitude and direction of crest and target movements are shown graphically by plotting the computed rectangular co-ordinates of the marks at an exaggerated scale of 4:1.

Co-ordinates of the targets obtained during the first, or base, series of measurements are used as a plotting origin and all subsequent variations are related to these base co-ordinates.

Vertical Deflections (See Fig. 5):

Vertical deflections are shown by longitudinal sections of levelling runs, presenting movements of all significant marks and pillars. These are also plotted at an exaggerated scale of 4:1.

Levels observed in the first, or base, series of measurements are used as a plotting origin and are represented as a horizontal datum line. All subsequent movements are related to this base level.

On the same plan are shown location details, date of measurement and stored water level details.

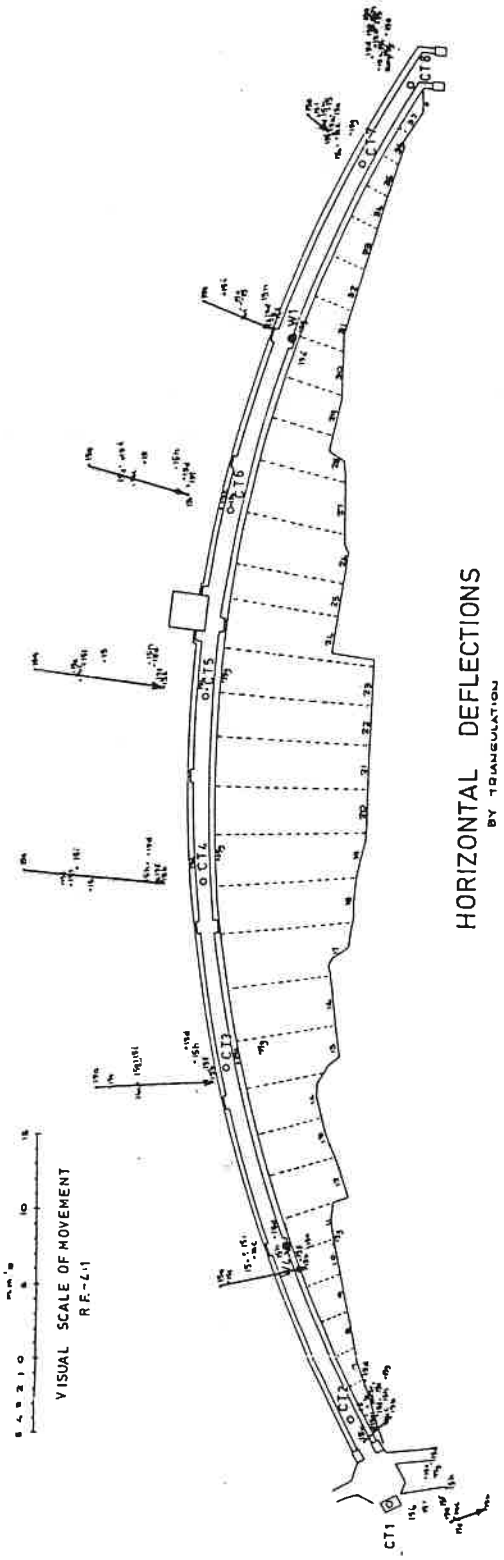

Figure 4:- Sample horizontal deflection plot - Woronora Dam Normal Survey. Typical vectors of movement are shown.

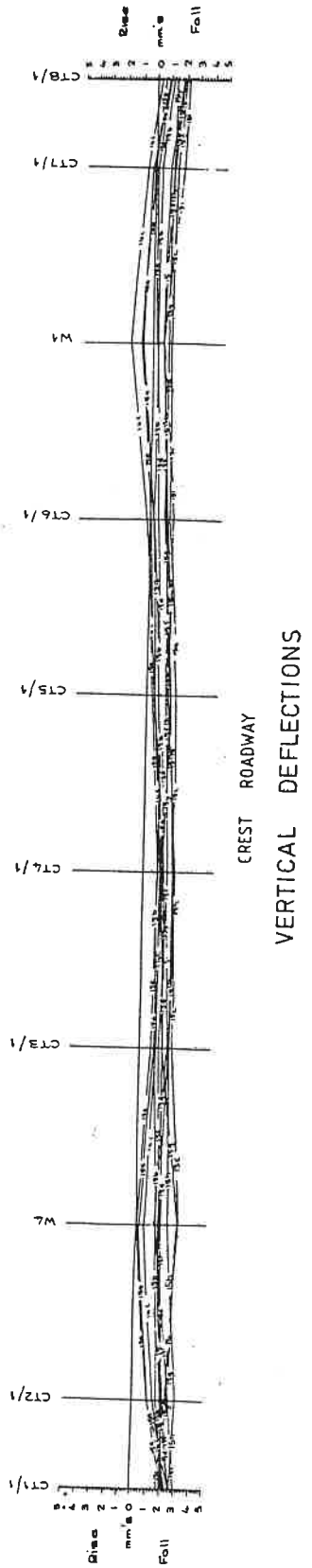

Figure 5:- Sample vertical deflection plot - Woronora Dam Normal Survey.

Clinometers (See Fig. 6):

Previously monthly, now yearly, readings are plotted over a period of time from which movements of +/-2 seconds of arc can be determined. A graph is plotted, for each station, of seconds of arc against time.

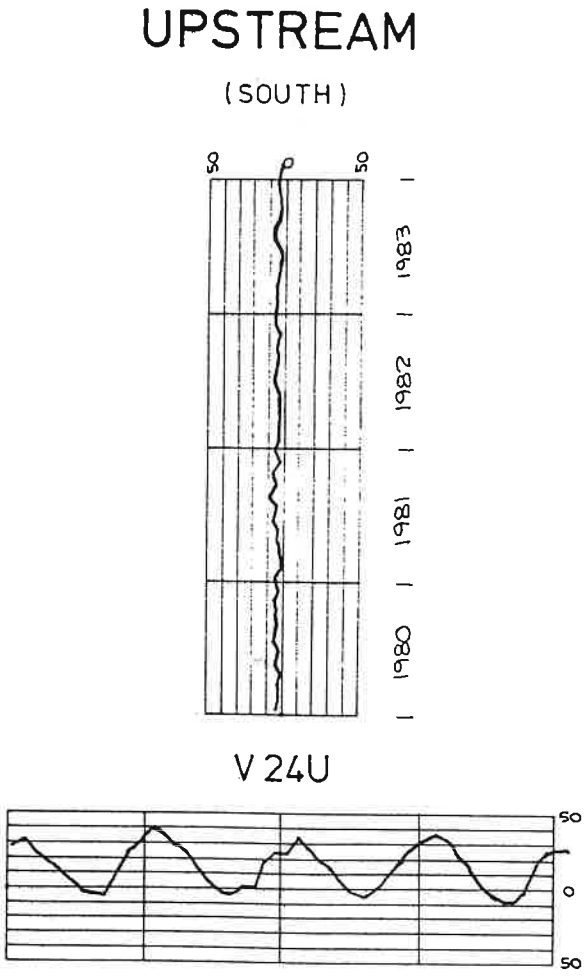

Figure 6:- Sample clinometer tilt plot - Woronora Dam vertical clinometer station V24U. The seasonal pattern is evident.

Equipment

Wild T2000 Theodolite:

An electronic theodolite with a claimed standard deviation of the mean of face left and face right of 0.5 seconds, the T2000 combines the advantages of electronic horizontal/vertical display with the precision of a Wild T3, which it replaced.

The precision of this instrument derives from its unique angle measurement system. A rotating glass arch divided into equally spaced intervals is scanned by two pairs of diametrically opposed light barriers which are equivalent to the zero and telescope positions of a conventional theodolite. The phase difference between the light barriers is measured 512 times per single angle measurement taking 0.9 seconds. It is claimed that the result is largely free of eccentricity and graduation errors, thus eliminating the need to set different zeroes.

Display of vertical axis dislevellment and two speed drives to aid pointing are further features.

Wild GRE3 Data Terminal:

Features of the version in use are:

Magnetic Bubble memory: Advantages claimed for this are high data security, particularly in the presence of magnetic influences, a small volume for large data storage capacity and non volatility (no power required for data retention).

128K data storage capacity.

9.5K BASIC program module permitting a flexible format and two way communication with the T2000 and DI2000.

Wild DI 2000 EDM:

Compatibility with T2000/GRE3 has dictated the choice of a Wild EDM. Deformation and other requirements prompted adoption of the Wild T2000 with its ease of use and 1mm + 1ppm accuracy.

Levels:

An array of levels including Wild N3, Wild NA2, Zeiss NI1 and Leica NA3000 are utilised on the deformation surveys for different applications. All are used with standardised invar staves and with the optical levels a parallel plate micrometer.