MONITORING OF FACE DAMS

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INTRODUCTION

The term Face Dam is used to mean a fill dam having an impervious membrane on the upstream face. The membrane may be of reinforced concrete, bituminous concrete, timber, steel or any other suitable material.

The overall performance of this type of dam depends almost entirely on the compressibility of the embankment material and the ability of the membrane and its joints to withstand the deformation to which they are subjected. The fill material will normally be non-cohesive and relatively pervious and may be a sandy gravel or, more commonly, a quarried rockfill. If the fill is highly compressible large deflections of the membrane will result leading to large strains in the membrane and the likelihood, in the case of a high dam, of rupture and consequent leakage. This is what occurred at such dams as Dix River (275 ft. - 1925), Salt Springs (328 ft. - 1931), Paradela (355 ft. - 1958), Wishon (290 ft. - 1958) and Courtright (310 ft. - 1959). Leakage flow at these dams has been in the range 20 to 130 cusecs. All were constructed of quarried rockfill placed by dumping it in high lifts.

In recent years the trend has been towards improving the deformation properties of the fill and this has been achieved by placing rockfill in thin layers and compacting with heavy vibratory rollers.

This paper presents details of various types of instrumentation used to monitor the behaviour of several rolled rockfill face dams recently completed by the Hydro-Electric Commission, Tasmania. Measurements from different types of instrument are compared and the results of some observations are given.

DATA ON FACE DAMS COMPLETED

The Commission has completed the construction of 5 face dams in the last 3 years. A sixth dam, Scotts Peak, is also very nearly complete, the final phase consisting of the construction of a 12 ft. high wave wall along the 3500 ft. length of crest. The dams are listed in Table 1 below together with other relevant details.

In all cases the membrane was constructed after the rockfill had reached virtual crest level this being done to preclude deformation of the membrane due to construction settlement. The reinforced concrete membranes were constructed by slipforming 40 ft. wide slabs from toe to crest. Horizontal contraction joints were almost entirely eliminated.

Table 1 DETAILS OF FACE DAMS

Name of Dam	Ht (ft)	Lgth (ft)	Vol. of Fill 10^6 yds^3	Type of Membrane	Rockfill Details			
					Type of Rock	Zone 2	Zone 3A	Zone 3B
Wilmot	110	450	0.160	r.c.	Greywacke	1'-6"* -9"**	4'-6" -24"	4'-6" -24"
Cethana	360	700	1.800	r.c.	Quartzite	1'-6" -9"	3'-0" -36"	4'-6" -54"
Paloona	130	560	0.180	r.c.	Chert and Argillaceous Chert	1'-6" -9"	2'-0" and -24"	4'-6" -24"
Serpentine	130	430	0.170	r.c.	Quartzite and schist	thin layer on face -6"	3'-0" -36"	3'-0" -36"
Mackenzie	50	3200	0.230	b.c.	Dolerite	thin layer on face -4"	4'-6" -54"	4'-6" -54"
Scotts Peak	150	3500	0.765	b.c.	Argillite	gravel 1'-6" -3"	3'-0" -36"	3'-0" -36"

r.c. = reinforced concrete

b.c. = bituminous concrete

* layer thickness

** maximum particle size

Information of the design, instrumentation and performance of some of these dams has already been published - ref (1), (2) and (3). Two companion papers on Cethana Dam have been submitted to the 1973 ICOLD Congress in Madrid - ref (4) and (5).

INSTRUMENTATION

Measurement is made of:-

a) vertical settlement within the embankment

b) deflection in 3 co-ordinate directions of crest and downstream face targets

c) deflection of the membrane in the vertical, slope and normal directions

d) movement between the membrane and the plinth in the plane of the membrane and normal to it

e) opening and closing movement of joints in the slope direction above full supply level
f) strain in the membrane
g) leakage

Not all of these measurements have been carried out on each of the dams. The most comprehensive instrumentation system was provided at Cethana Dam as it is a high dam and one of the first of its type and size to be constructed of rolled rockfill. The general arrangement of Cethana instrumentation is shown in fig 1. Instrumentation of the other dams is shown in fig 2 - Wilmot; fig 3 - Paloona; fig 4 - Serpentine; and fig 5 - Scotts Peak. There are no embedded instruments in Mackenzie Dam on which monitoring is minimal and limited to settlement observations on a few crest targets and leakage measurement.

METHODS OF MEASUREMENT AND INSTRUMENT DETAILS

a) General

The operation of the reservoir behind each of the dams is such that the level is controlled close to full supply level at all times. Measurements on the upstream face therefore are carried out under water.

Where possible 2 different methods of measurement are made to provide a check on the results of observations.

b) Measurement of Vertical Settlement

The hydrostatic settlement cell is the instrument used to measure settlement at points within the rockfill.

The conventional vertical cross-arm settlement installation is not particularly suitable in rockfill because of the difficulty of digging back each time a vertical extension is required. Cross-arms were installed in Rowallan Dam (6) without digging back but were unsuccessful due to disturbance from vibratory roller compaction.

The settlement cell used is similar to that developed by Russel (7) and contains 2 independent weirs connected by $\frac{1}{2}$ in. dia. rigid polyvinyl chloride tubing to a gauge board at the downstream toe. In addition to the 2 levelling tubes there is an air tube to maintain atmospheric pressure in the cell and a fourth tube to drain off excess water. The accuracy of measurement is $\pm$ 0.01 ft.

Conventional survey methods are used to measure settlement and deflection of crest and downstream face targets.

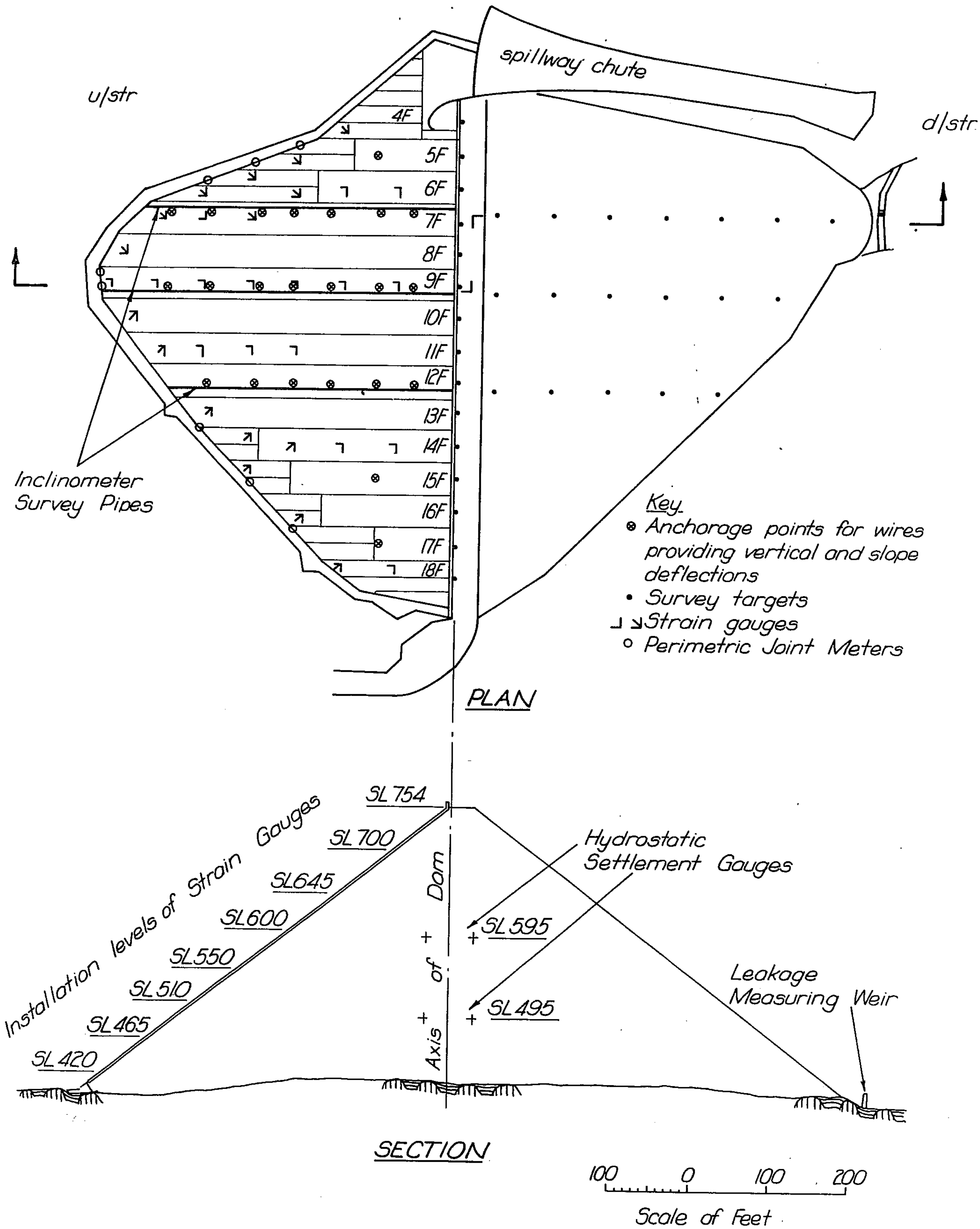


Fig. 1. CETHANA DAM - GENERAL ARRANGEMENT OF INSTRUMENTATION

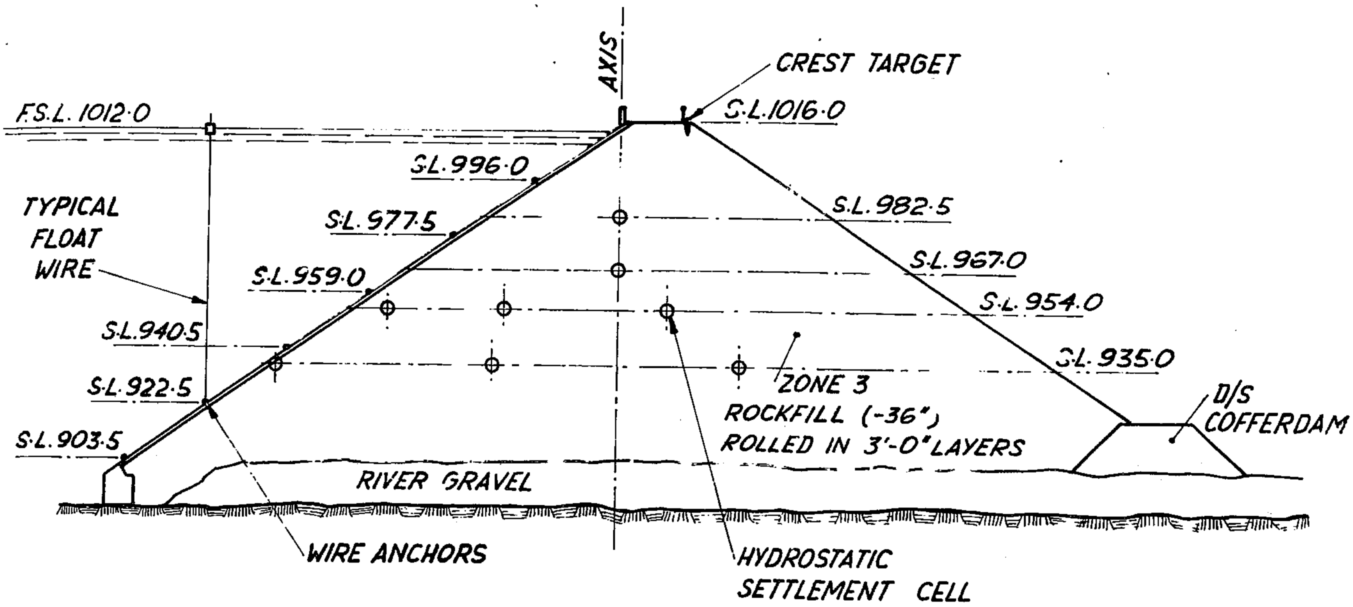


FIG.4 SERPENTINE DAM - INSTRUMENTATION

0 40 80
SCALE OF FEET

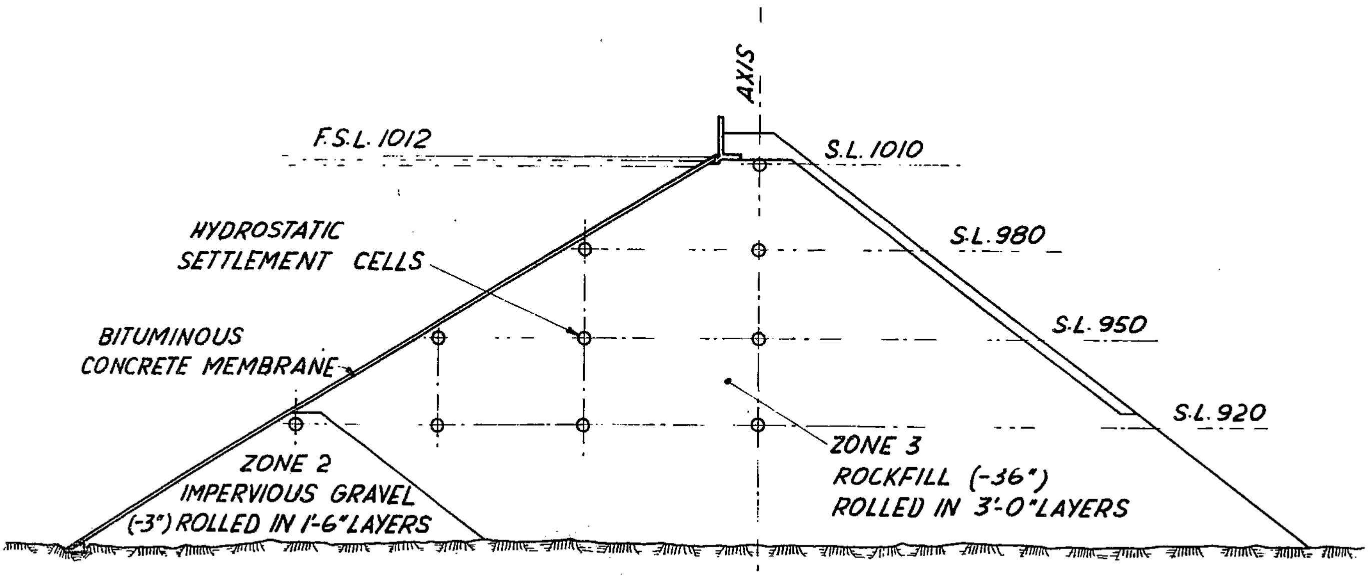


FIG. 5 SCOTTS PEAK DAM - INSTRUMENTATION

0 40 80
SCALE OF FEET

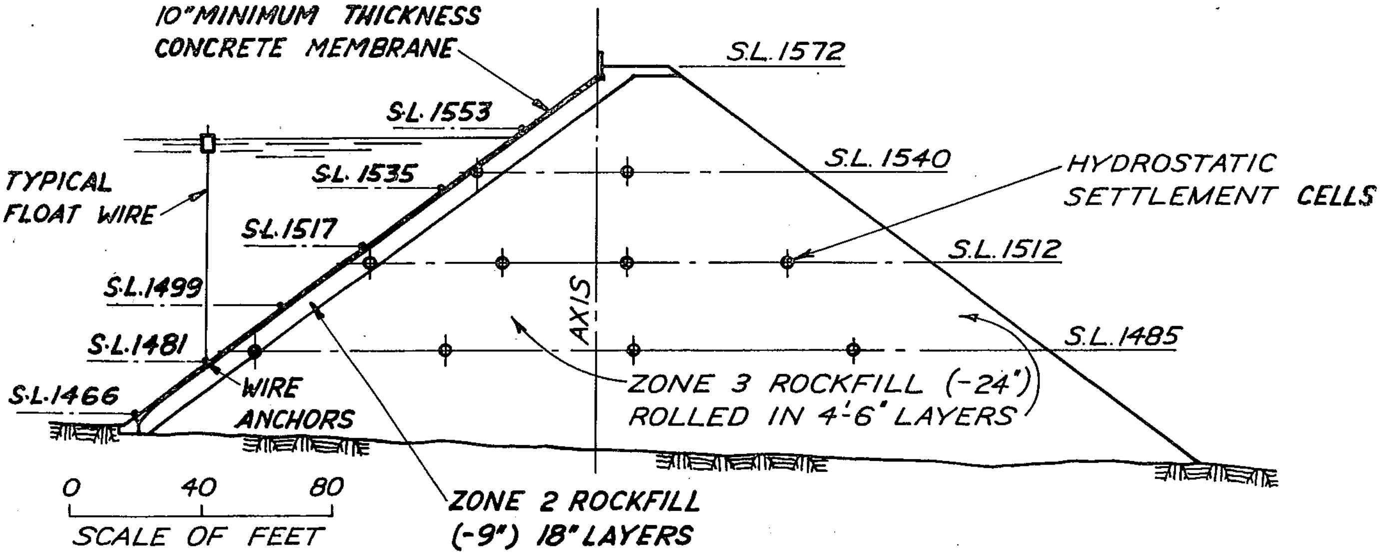


FIG. 2 WILMOT DAM - INSTRUMENTATION

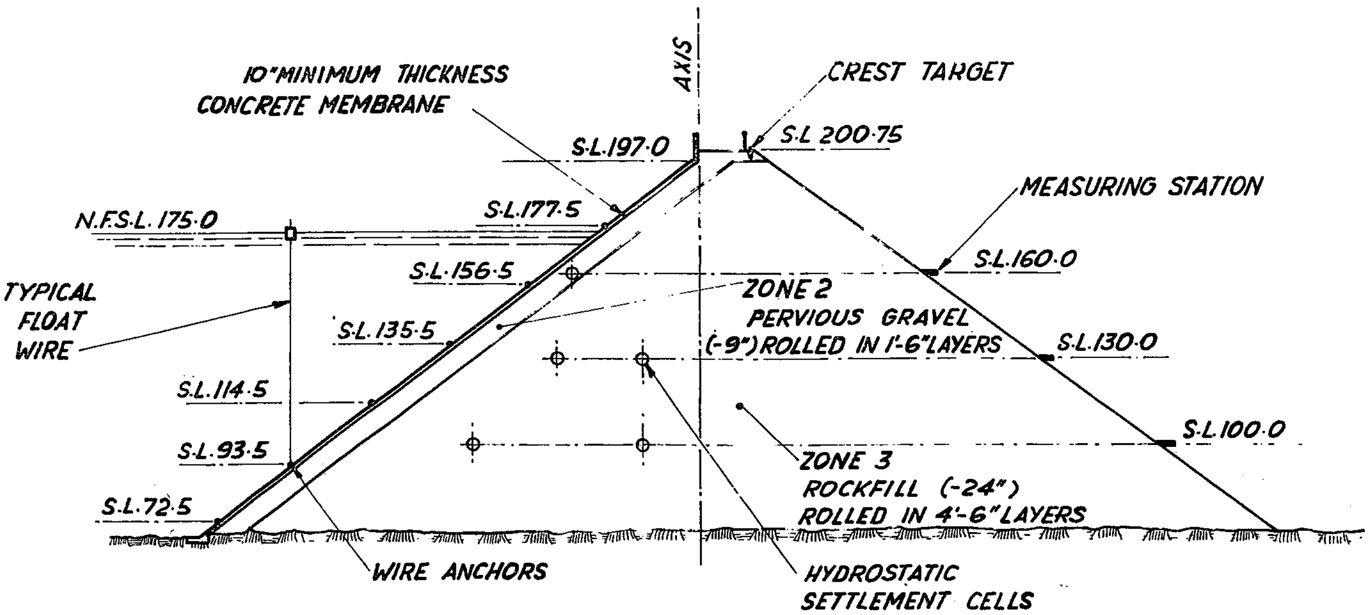


FIG. 3 PALOONA DAM - INSTRUMENTATION

0 40 80
SCALE OF FEET

c) Measurement of Membrane Deflection

Above lake level vertical and horizontal deflection is measured by conventional survey methods.

Vertical deflection is measured below water level by what is termed a float wire system and by hydrostatic settlement cells installed in the rockfill just beneath the membrane.

Slope deflection (that is, deflection up or down the slope of the face) is measured by a system of fixed wires from points on the face to the crest. When strain meters are installed the slope deflections are calculated by integration of strain. At the upstream toe the slope deflection of the membrane relative to the plinth is measured by a Carlson type joint meter.

Normal deflection is measured by surveying along the inside of a 3 in. dia. pipe attached to the membrane using a portable inclinometer which is a bore hole survey type of instrument. At the upstream toe the normal deflection of the membrane relative to the plinth is also measured by a joint meter. Instrument details are as follows:-

(i) Float Wire System

At each point where measurement of vertical deflection is required, a stainless steel non-fouling swivel anchor was fixed to the membrane and its elevation determined. A single strand stainless steel wire, 1 mm diameter and graduated with tags at 5 ft. intervals, is attached to the anchor and extended up the slope to the crest. When a measurement is to be made, the wire is detached from the crest and taken by boat to a position above the anchor. A special float carrying a survey staff is then attached to the wire and the immersion of the float is adjusted to obtain a specified tension in the wire. The float brings the wire to a vertical position in the same manner as an inverted plumb bob. The new elevation of the anchor on the membrane is determined by reading the survey staff with a level from the reservoir bank and measuring from the staff reading to the closest wire graduation. This work has to be carried out in very calm conditions. Corrections are made for the effect of tension and temperature on the wire.

(ii) Fixed Wire System

At each point where measurement of slope deflection is required, a single strand stainless steel wire 1 mm diameter is attached to an anchor and extended up the membrane, through nylon guides at 40 ft. spacing, to a fixing on the parapet wall.

The wire passes over a datum consisting of a scribed line on a metal plate fixed to the parapet wall. Measurement of slope deflection is made by tensioning the wire and measuring the distance between a tag graduation attached to the wire and the scribed line. The measurement is corrected for movement of the datum and for the effect of tension and temperature on the wire.

(iii) Inclinometer

The instrument was designed and constructed by Mr. P.A. Watt of the University of Tasmania and is called the Watt Inclinometer. It comprises a multi-wheeled $2\frac{1}{2}$ in diameter by 5 ft long probe, a power supply and digital display unit - fig 8. The probe contains two force balanced servo - accelerometers and associated electronic equipment. The mounting containing the accelerometers is automatically rotated so that the axis of one of the accelerometers is maintained normal to a vertical plane through the probe. This accelerometer measures the inclination of the probe axis and its output is digitised and telemetered to the display unit at the crest of the dam. The probe is lowered down the pipe by 5 ft long steel rods and readings are taken at rod length intervals.

The instrument accuracy of the inclinometer over the measuring range of $37^\circ \pm 11\frac{1}{2}^\circ$ is $\pm$ 5 seconds of arc. The accuracy of a closed survey on a 500 ft long pipe is $\pm \frac{1}{2}$ in. at the mid point.

The pipe extends from a hinged mounting on the plinth to the crest and is attached to the face by galvanized steel brackets providing full restraint normal to the pipe axis and no restraint in the axial direction. To minimise corrosion, galvanized pipes coated externally with high density polyethylene, and filled with a 0.2% solution of calcium hydroxide giving a pH of 12, were used.

In use the procedure adopted is as follows:-

The inclinometer is traversed down the pipe in a constant orientation and readings taken at 5 ft intervals. At the bottom it is turned through 180° and traversed up the pipe again with a constant orientation and readings at 5 ft intervals.

The two readings for each 5 ft interval are averaged and the change in inclination from the datum position determined.

The normal deflection at the crest is found from conventional survey measurements and the pipe hinge point on the plinth is assumed to be fixed.

Uncorrected normal deflections and the misclose at the hinge point are calculated by summation of the angular change times the distance traversed (5 ft). The adopted deflections are obtained by a linear correction for the misclose.

(iv) Joint Meters

The instrument used to measure deflection of the membrane relative to the plinth is a 360 mm long Carlson type joint meter (Kyowa CJ-40G). The meter is attached to an anchor on the membrane and is connected to an anchor on the plinth by a 2 ft long by $\frac{1}{4}$ in. dia. stainless steel rod. This arrangement, shown in fig 6, was designed to avoid shear on the meter due to movement normal to its axis.

d) Measurement of Strain and Temperature in the Membrane

The strain meters were designed and manufactured by the Hydro-Electric Commission and consist of a 5 mm range Carlson type joint meter (Kyowa Model CJ-5G), an extension rod, a thin walled steel tube 2 in. dia., and two end flanges $2\frac{3}{4}$ in. dia. The 260 mm long joint meter is fixed to one end flange and is connected to the other end flange by the extension rod which is held centrally in the tube by blocks of polyurethane foam. The tube is filled with grease. Each strain meter was adjusted to half the total extension of the joint meter so that equal tensile and compressive strains could be measured. The long gauge length was chosen to minimise any local affects caused by reinforcement or tensile cracking.

The strain meters are installed in 45° and 90° rosettes in the centre of the membrane and mid-way between contraction joints in the slope direction. All electrical conductors are embedded in the membrane and routed to the terminal installation in the crest parapet.

In addition to providing strain readings the meters also provide temperature readings.

RESULTS OF MEASUREMENTS

a) Crest Settlement with Time

Crest settlement since the end of construction of 7 dams is shown in fig 7. Settlement is expressed as a percentage of the height of the dam. Two central core dams, Rowallan and Parangana, have been included because they are representative of rolled fill construction.

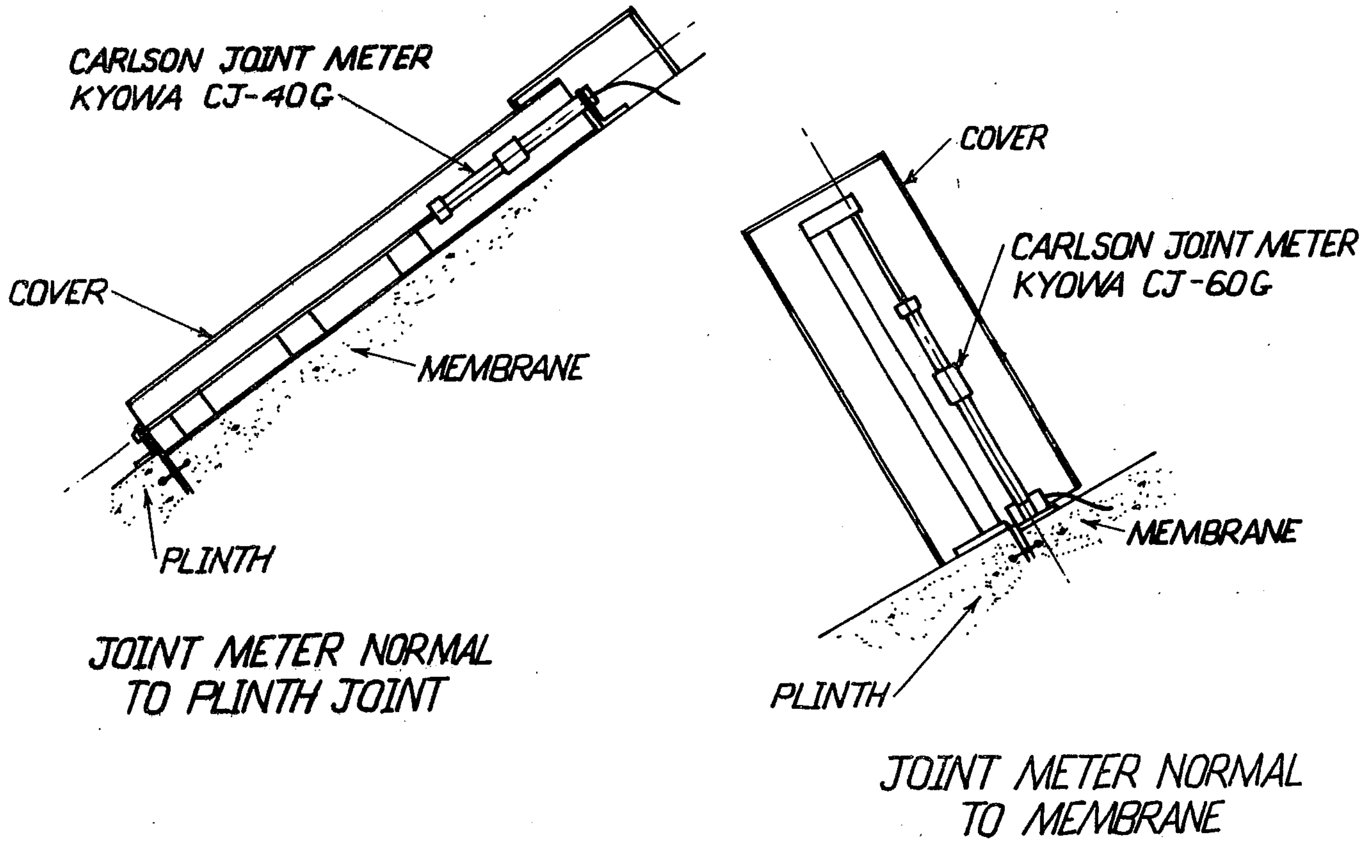


FIG 6 - JOINT METER INSTALLATION

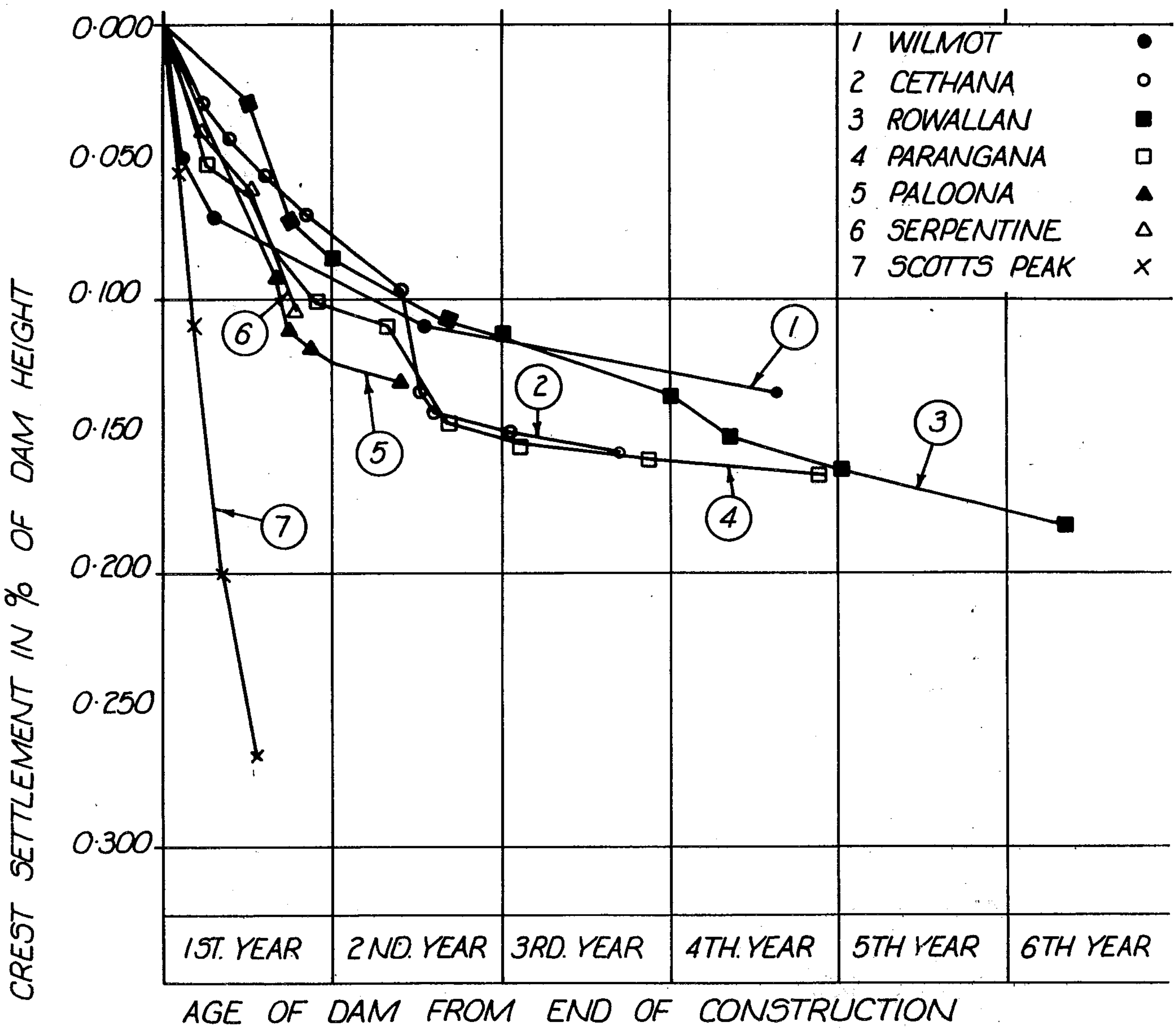
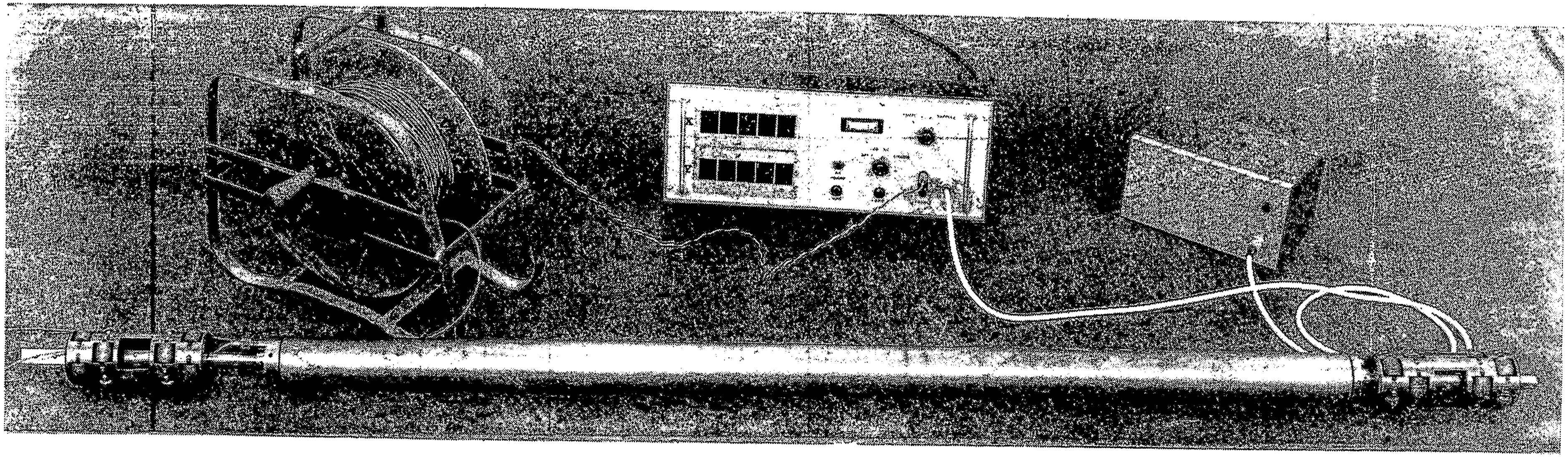
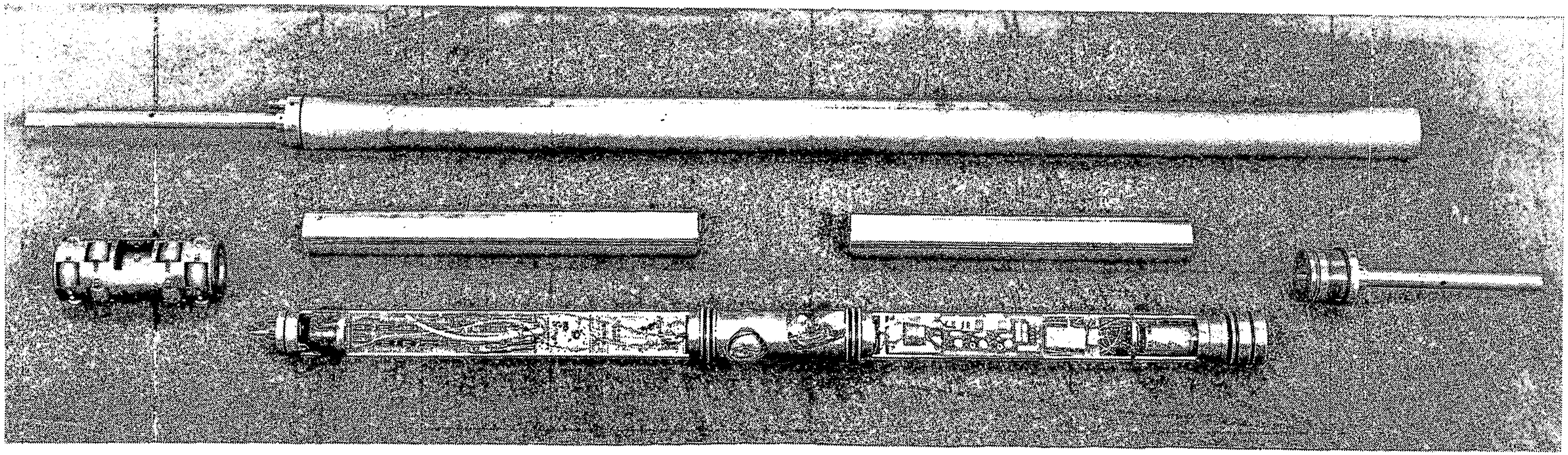


FIG.7- LONG TERM SETTLEMENT





above: - probe, cable drum, digital display unit and power supply
below: - probe disassembled

FIG 8 - WATT INCLINOMETER

The cores of both dams are composed of non-plastic material - a well graded glacial till in the core of Rowallan and a decomposed granodiorite at Parangana - and the rockfill zones were placed and compacted in layers.

As the results are from the end of construction the reservoir filling period is included. In the case of Cethana this took place midway through the 2nd year and is the reason for the increased rate measured at that time.

It is too early yet to obtain any indication of the rate of long term settlement at Serpentine and Scotts Peak. The indicated rate of long term settlement for the other 5 dams varies from 0.006% per year for Parangana to 0.015% per year for Rowallan. This is to be compared with the long term settlement of dumped rockfill which has been measured at Dix River and Salt Spring Dams for over 30 years and has averaged 0.033% per year - ref (7). In addition the primary settlement occurring in the first year is only about one quarter of that for dumped rockfill. The rather larger settlement at Scotts Peak is due to the relatively weak argillite used as rockfill.

b) <u>Membrane Deflections</u>

(i) <u>Cethana Dam</u>

The slope deflections at Cethana are measured by conventional survey at the crest, by fixed wire survey and integrated strains for points on the membrane and by joint meters at the toe. The results for 3 slabs are shown in fig 9 where it may be seen that the wire survey and integrated strain methods are not even in approximate agreement.

There is reasonable agreement, however, between the total shortening of the slab from strain integration and the total change in length as measured at the crest and toe of the slab. For this reason it is considered that the fixed wire survey is the more likely to be in error.

The vertical deflections at Cethana are measured by conventional survey at the crest and by float wire survey for points on the membrane. Where the slope deflection is small compared with the vertical deflection, as is the case at Cethana, the normal deflection is obtained with quite acceptable accuracy from the vertical deflection by neglecting the slope deflection. The normal deflections calculated from the float wire survey are shown in fig 10.

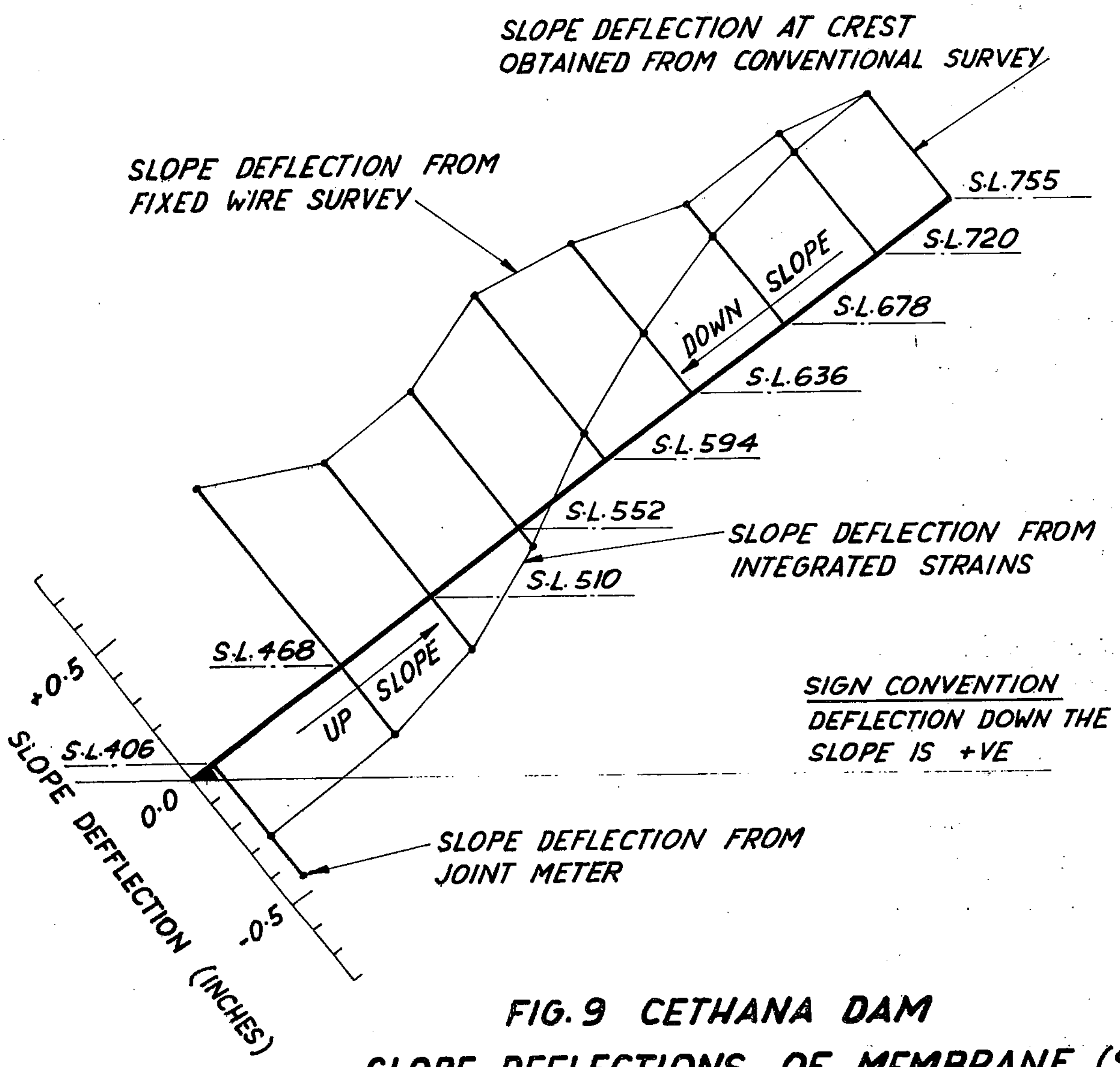


FIG. 9 CETHANA DAM

SLOPE DEFLECTIONS OF MEMBRANE (SLAB 9F)

(8-12-71)

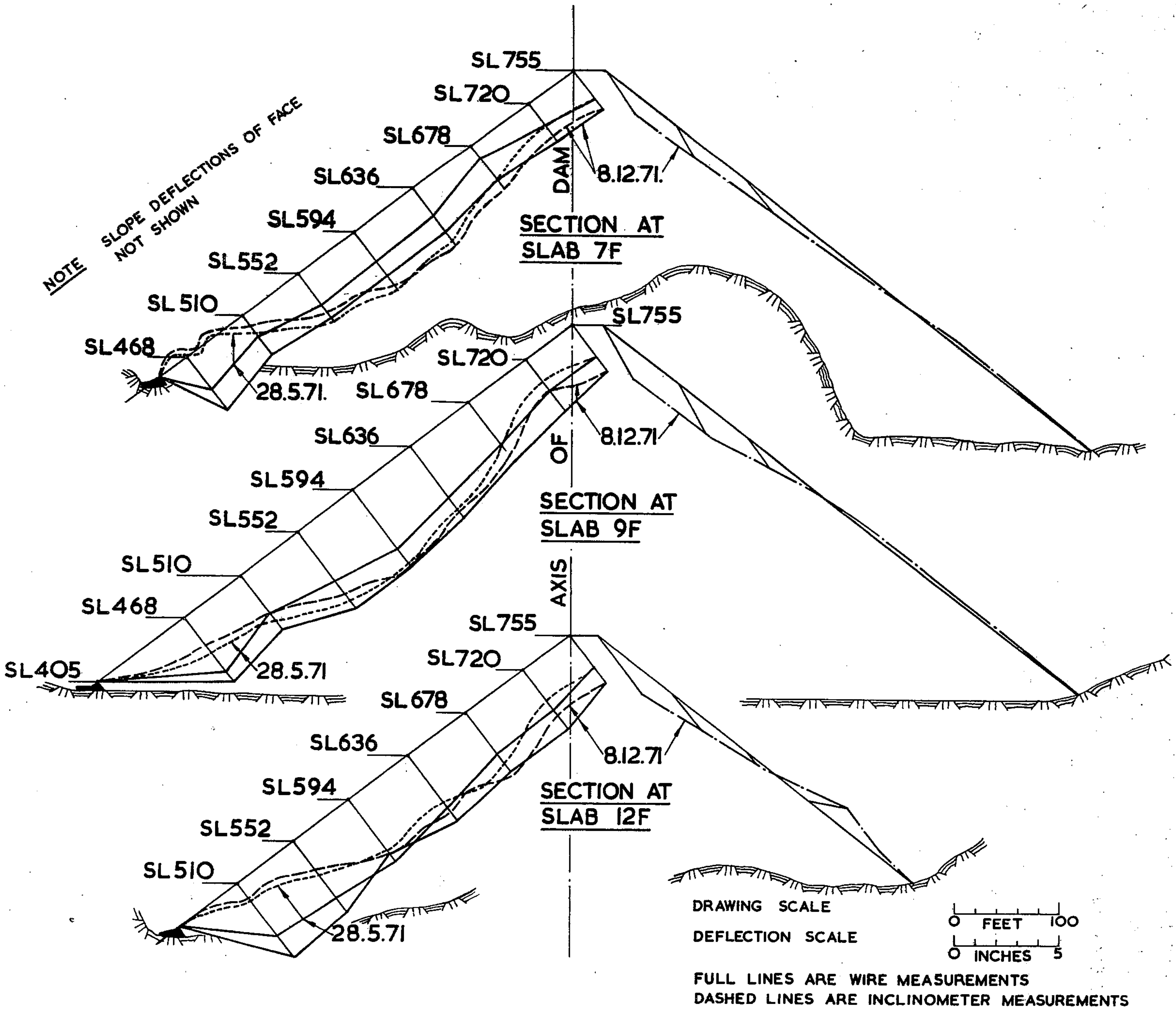


FIG. 10 NORMAL DEFLECTIONS OF UPSTREAM FACE AND DEFLECTIONS OF DOWNSTREAM FACE

Also shown in fig 10 are the normal deflections obtained from the inclinometer survey. While in reasonable agreement over the upper two thirds of the membrane there is considerable disagreement in the lower one-third. The float wire survey shows the greater deflections in the lower region.

The maximum normal deflection at the centre of Slab 9F is about 4.5 in. by both methods.

(ii) Wilmot

Slope deflections from the fixed wire survey are all less than $\frac{1}{8}$ in. and have been neglected in calculating the normal deflections.

Vertical deflections are measured by float wire survey and by hydrostatic settlement cells. The normal deflections calculated from the two sets of vertical deflection measurements are shown in fig 11.

There is quite a significant difference in the results from the two methods, the wire survey indicating the larger deflections, with a maximum of less than 1 inch. The hydrostatic cells are not located directly on the underside of the membrane but within the rockfill at a depth of 3 or 4 ft from the face. Some of the difference is therefore due to the compression of this small depth of fill but it is considered likely that this could account for only a small fraction of the difference.

(iii) Paloona

Fig 12a shows the normal deflections of the central section of the membrane as calculated from the float wire survey. The one hydrostatic cell very close to the underside of the membrane at SL 160 is in good agreement. However, at the toe the wire surveys give quite a different result from that measured by the joint meters - see fig 12b.

(iv) Comments on Methods of Deflection Measurement

The results presented above show that the deflections obtained from the float and fixed wire systems are generally greater than those obtained by the other methods.

There is not a great deal of evidence on which to base a judgement but it is considered by the author that the wire measurements are likely to be the less reliable. This view is based mainly on the proven realiability, both in the laboratory and in the field, of hydrostatic settlement cells and electrical resistance joint meters.

If the wire measurements are in error the reasons for this are not easy to ascertain or determine and as yet no answer has been found. The system is a simple one but does rely on corrections for temperature and tension for accuracy.

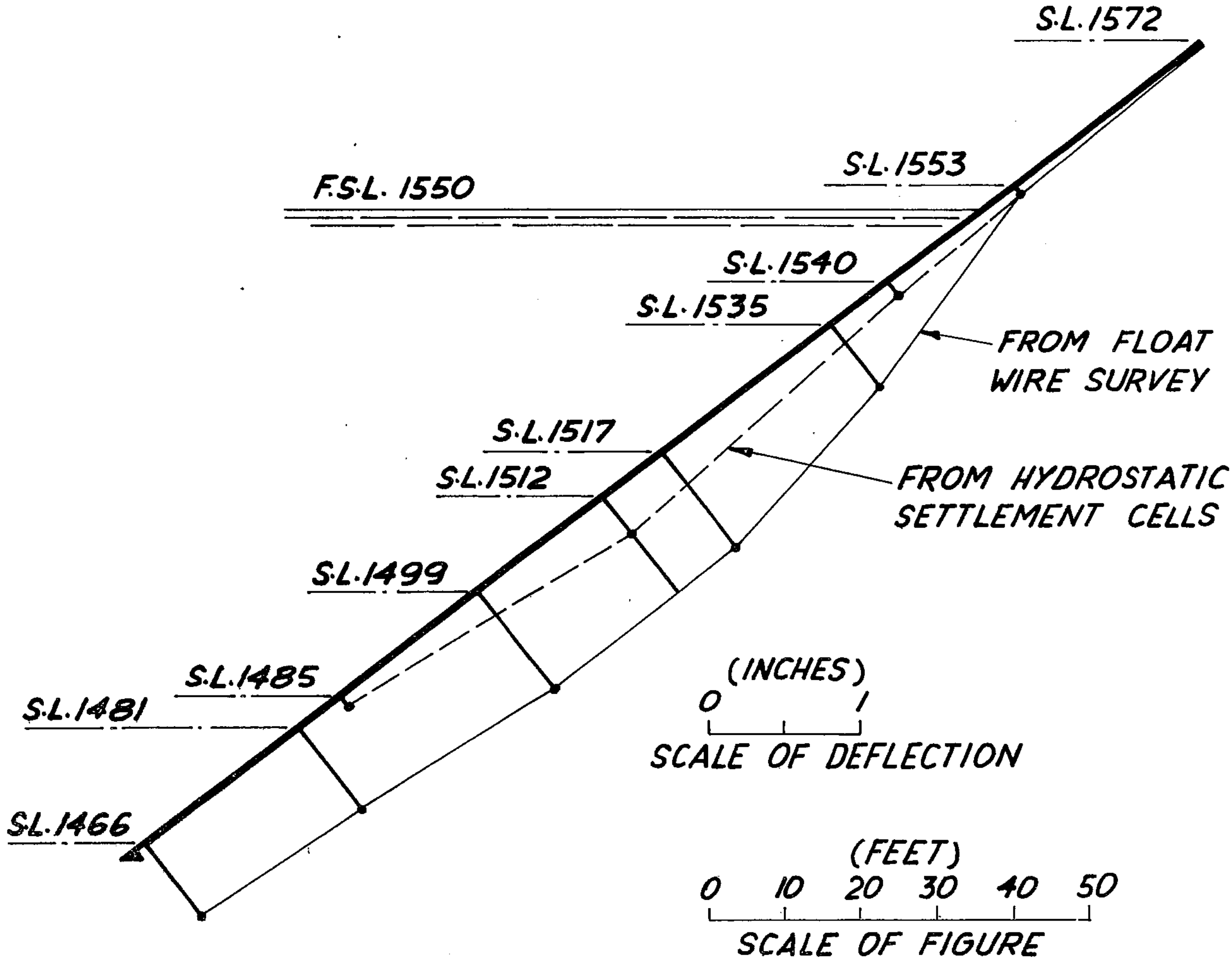


FIG.11 WILMOT DAM - NORMAL MEMBRANE DEFLECTION

(24-4-70)

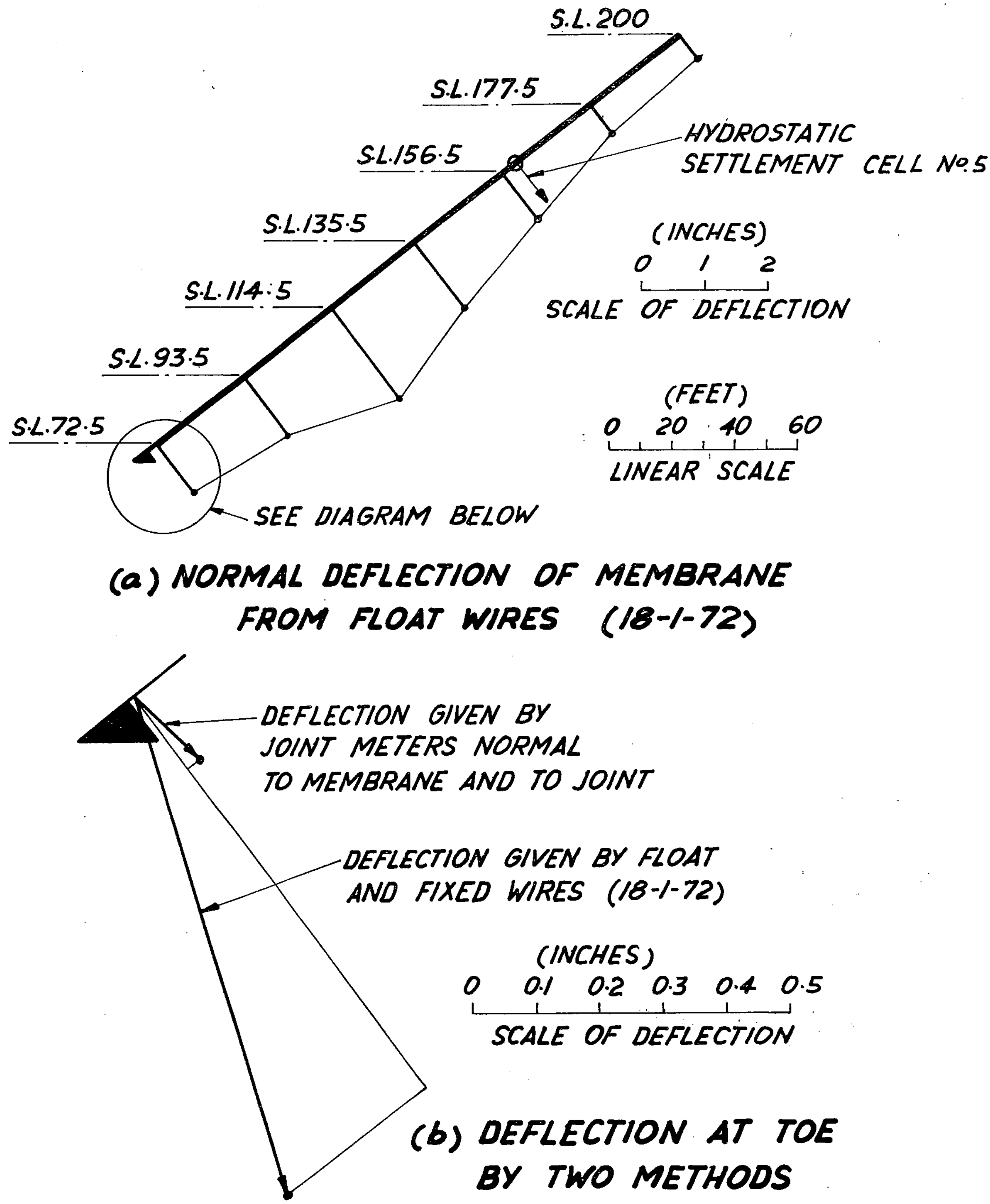


FIG.12 PALOONA DAM - MEMBRANE DEFLECTION (18-1-72)

In order for the corrections to be accurate the coefficient of linear expansion and Young's modulus must be unfiorm and the changes in temperature and tension must be measured with little error.

With regard to the fixed wires it is thought that the assessment of temperature distribution along the wire, firstly in air at the time of datum measurements and subsequently in water and air at the time of each survey, has not been sufficiently accurate to calculate the true temperature correction which is equal to or larger than the measurement itself. In retrospect this could have been overcome by having two wires of different coefficients of linear expansion attached to each point and using the two readings to calculate the temperature change.

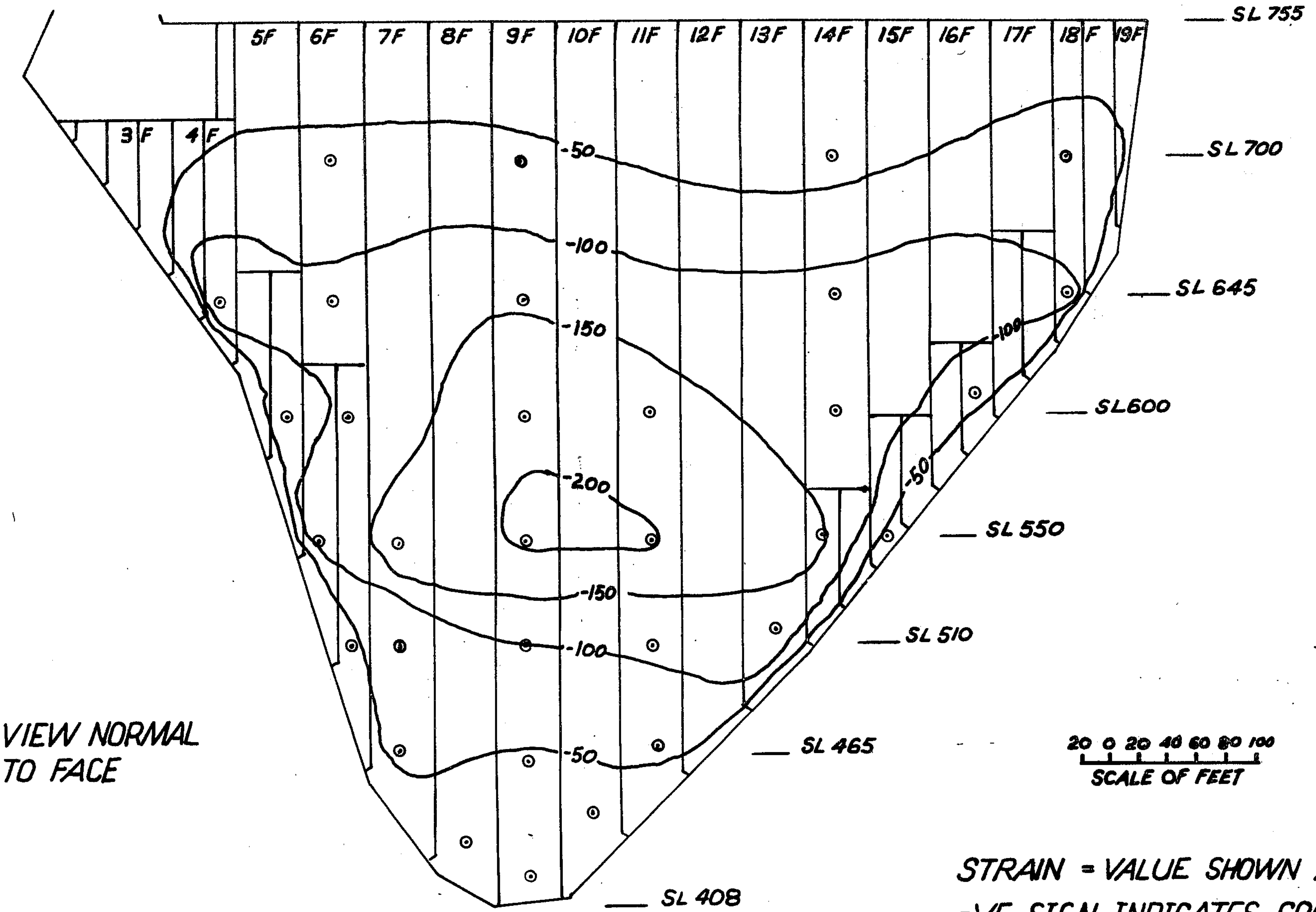
For the float wire measurements the temperature corrections are small compared with the deflections measured so that a small error in the correction could not account for the apparent discrepancies. That the wire is vertical when the measurement is made has been checked by triangulation on the float which was found to be well within any significant radius of error. A remote possibility is that the non-fouling swivel correction to the membrane may not be fool proof. What has not been done, and in hindsight should have been done, is a proper check on the validity of the method by anchoring a wire onto the plinth which could be considered to have negligible movement.

STRAIN AND STRESS IN CETHANA MEMBRANE

Cethana Dam is the only one in which membrane strains have been measured. The patterns of strain and stress developed in the membrane between the start of reservoir filling, 4th February 1971, and the 8th December 1971 are shown in figs 13, 14, 15 and 16.

The pattern of strain in the slope direction, fig 13, is reasonably symmetrical about slabs 9F and 10F in the centre of the membrane. Over a fairly large area the strain is greater than 150×10^{-6} units and in a much smaller region within this central area it is a little greater than 200×10^{-6} units.

Stress in the slope direction, fig 14, reflects the strain pattern with maximum stress in the central region being about 350 lb/in^2. Tensile stresses exist in the lower one third of the membrane, in a narrow region up each abutment and across the top portion of the membrane. The maximum tension is 250 lb/in^2 near the toe in slab 9F.



VIEW NORMAL TO FACE

STRAIN = VALUE SHOWN × 10^{-6}

-VE SIGN INDICATES COMPRESSION

FIG 13. CETHANA DAM CONTOURS OF STRAIN IN MEMBRANE IN SLOPE DIRECTION. (4-2-71 to 8-12-71)

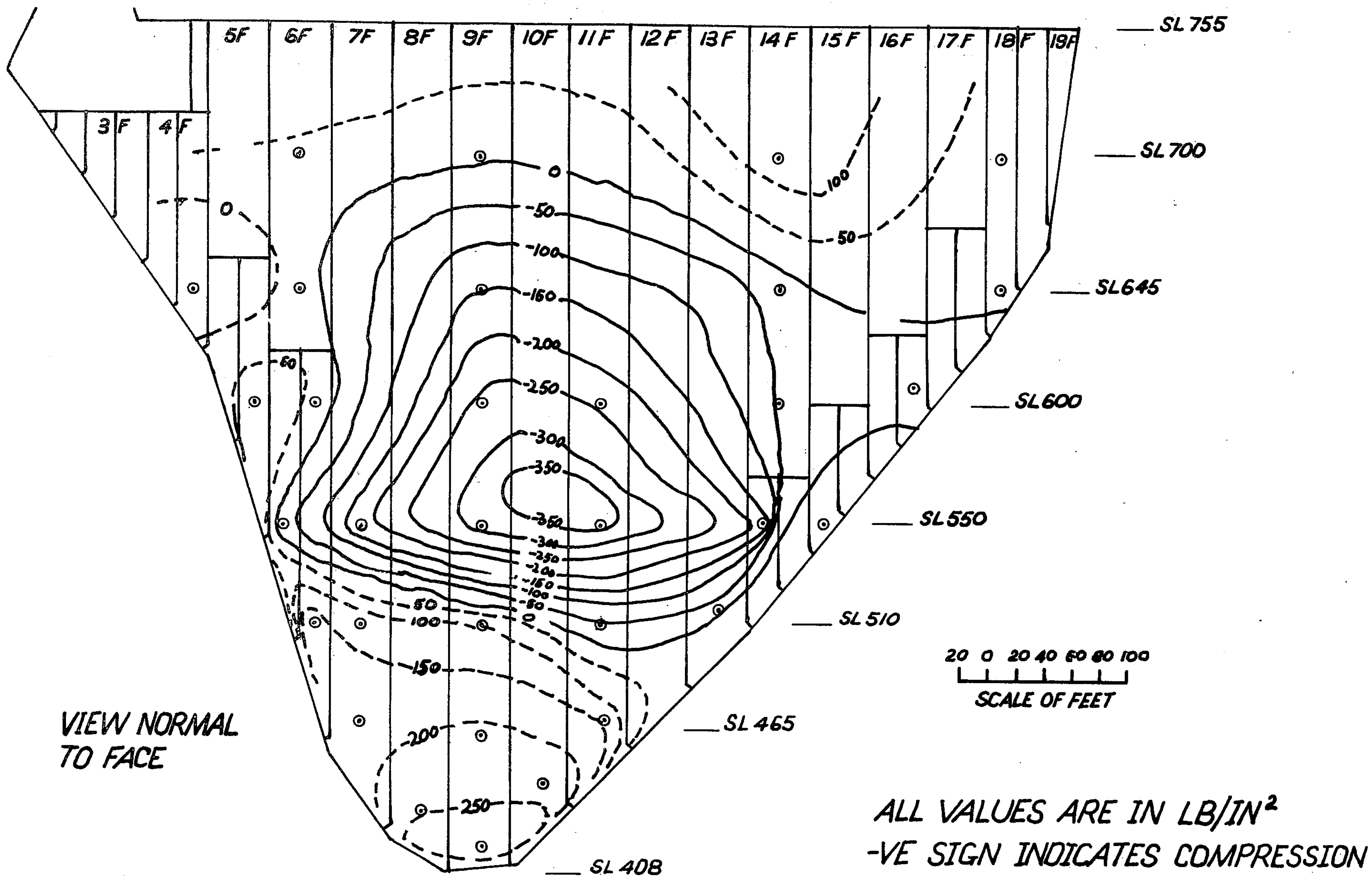


FIG 14. CETHANA DAM CONTOURS OF STRESS IN MEMBRANE IN SLOPE DIRECTION. (4-2-71 to 8-12-71)

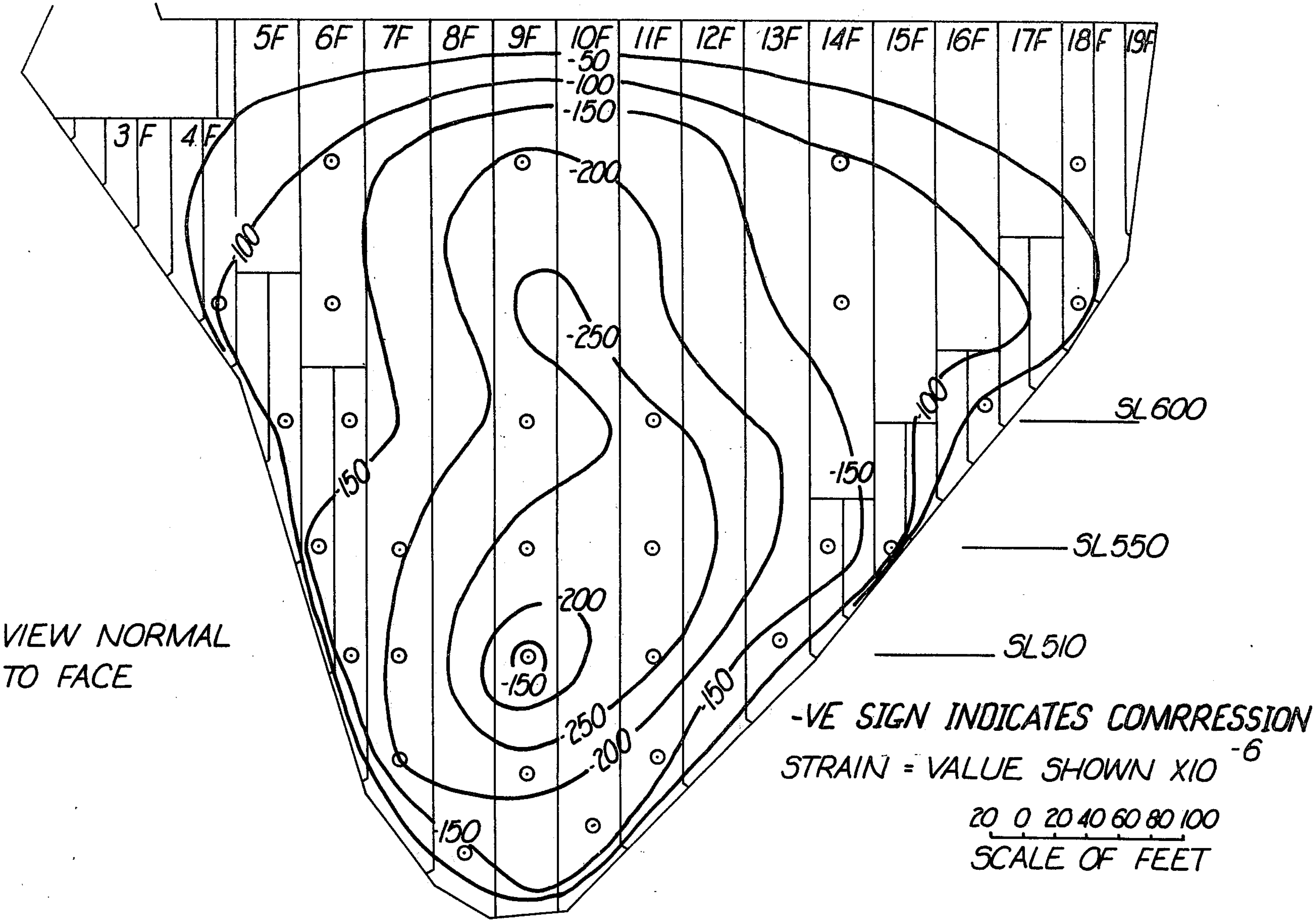


FIG.15 CETHANA DAM - CONTOURS OF STRAIN IN MEMBRANE IN HORIZONTAL DIRECTION

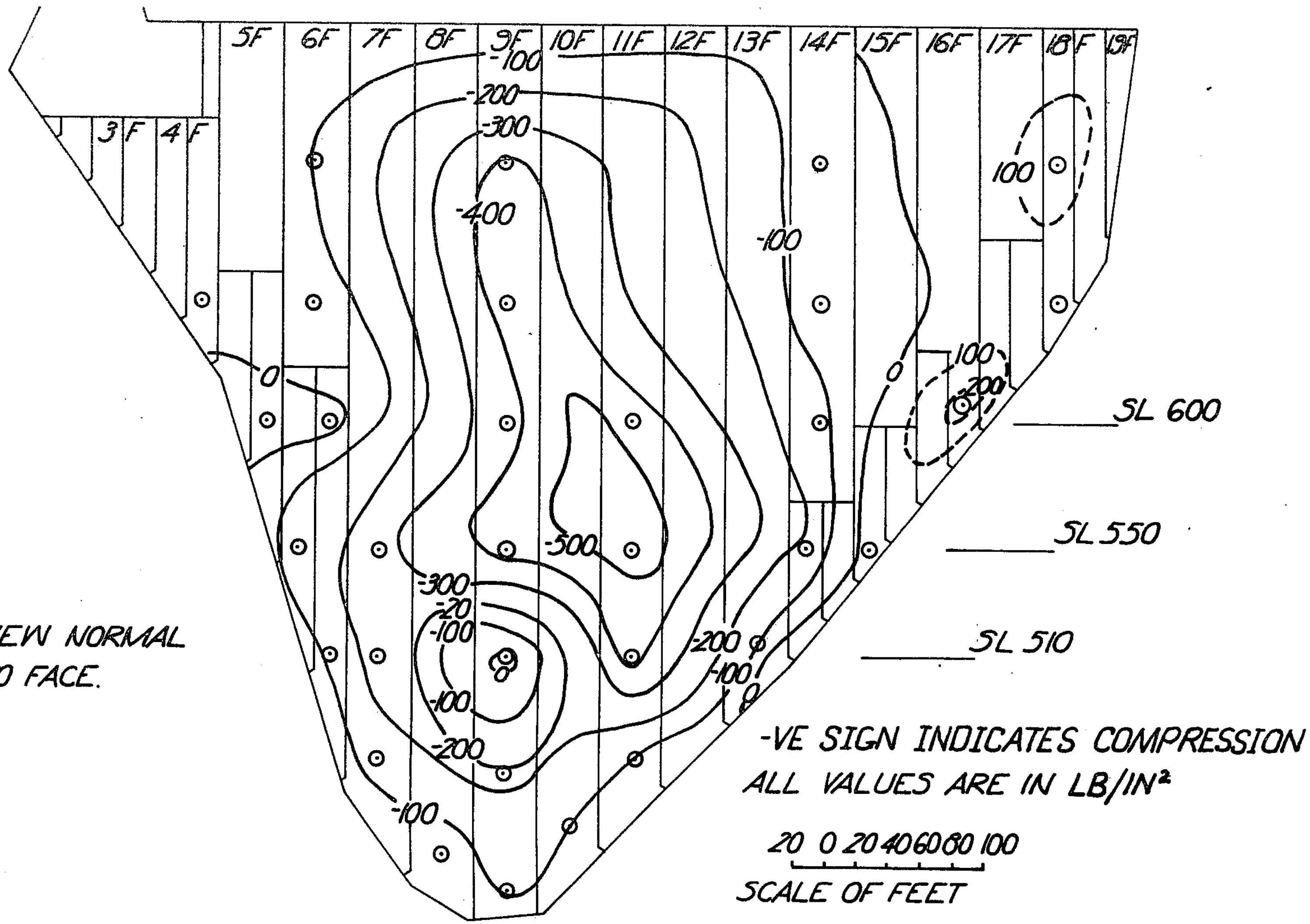


FIG 16. CETHANA DAM — CONTOURS OF STRESS IN MEMBRANE IN HORIZONTAL DIRECTION (4·2·71–8·12·71)

Stresses were calculated using values of the elastic constants of 3×10^6 lb/in^2 for Young's Modulus and 0.2 for Poisson Ratio.

Strain in the horizontal direction, fig 15, appears to reflect the influence of the boundary shape of the left abutment. About one third of the way up slab 9F there is a local depression in the strain pattern where the magnitude drops to 150×10^{-6} units in an area which is generally above 250×10^{-6} units. This appears a little anomalous.

The corresponding stress pattern in the horizontal direction, fig 16, shows this anomalous looking result more clearly. Maximum compressive stress is 500 lb/in^2 in the central region.

The overall pattern of stress and strain is indeed very satisfactory and reflects the uniformity of loading and support of the membrane. The maximum compressions of 350 lb/in^2 (slope direction) and 500 lb/in^2 (horizontal) are very moderate.

It may be shown that under the action of the normal water load the friction on the underside of the membrane is quite sufficient to provide full restraint against membrane movement relative to the rockfill except close to a free boundary. Conversely, the strain in the membrane will be that imposed on it by the movement of the rockfill. As the strains developed in the Cethana membrane due to water load are all compressive there is little doubt that the tensile stresses are due to the temperature drop of 20 to 25°F that occurred during and after filling.

LEAKAGE

The discharge measured at the downstream toe of a face dam includes seepage through the membrane and joints in the membrane, seepage through the foundation rock beneath the plinth, and local run-off from the dam and the abutments between the dam crest and the measuring weir.

At Cethana the discharge increased as the reservoir level rose during the initial filling. After the reservoir level reached full supply level in April, 1971 the weir discharge remained reasonably constant at 1.7 cusecs throughout the winter. Fluctuations above this occurred during periods of high rainfall. After March, 1972 the discharge reduced slowly to just under one cusec at which it has remained constant for several months.

The leakage at Paloona Dam is 0.1 cusecs. No figure is available for Wilmot as the measuring weir was covered with eroded bed material during spillway discharge which occurred straight after filling.

CONCLUSIONS

Monitoring of several face dams constructed of rolled rockfill has been carried out to check their performance and to obtain data on which studies of behaviour could be based.

That this type of dam is highly successful has been shown by the small magnitude of the deflections and the leakage.

The importance of duplicating the measurements where possible with different types of instrumentation has also been demonstrated.

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