CHAPTER 2

2. RCC CONSTRUCTION, RCC MIXES, RCC INSTRUMENTATION & RCC DAMS STUDIED

2.1. INTRODUCTION

The research and investigations addressed in this Thesis relate entirely to the behaviour and performance of Roller Compacted Concrete in dams. In view of the fact that many of the observations made and the hypotheses presented relate to the nature of RCC as a material and the methods applied for construction, it is considered appropriate to provide the reader with some background on RCC in these areas. Consequently, Chapter 2 presents a background for RCC construction, describing the typical composition of RCC, isolating specifically the "high-paste" RCC that is of particular interest, the methods applied for construction and their influence on instrumentation readings and the instruments installed.

Each of the five dams whose instrumentation data are investigated during the course of this study is subsequently introduced.

2.2. RCC DAM CONSTRUCTION

2.2.1 BACKGROUND

The following description of RCC is partly extracted from *Fulton's Concrete Technology*. (Ninth Edition). 2009(1), Chapter 24, RCC for Dams, which was written by the author of this Thesis.

The term Roller Compacted Concrete (RCC) is used to describe a concrete used in the construction of dams (and pavements), which combines the economical and rapid placement techniques used for fill dams with the strength and durability of concrete. As a consequence of the application of high capacity plant and equipment, it is most suited to use in large-scale construction and for mass concrete works. Since the early 1980s, RCC has gained general acceptance as an appropriate material and method for the construction of dams and by the end of 2009, more than 350 large RCC dams had been completed worldwide.

In the early days, RCC was perceived as a low quality, low strength mass material. It has since become possible to produce a range of concrete qualities by roller compaction, with the most common product being a dense, high quality and relatively high strength concrete.

In principle, RCC is placed and compacted in 300 mm deep horizontal layers, at rates often exceeding 3000 m^3 per day, allowing construction progress commonly of around 10 m in height per month. The main benefits of RCC for dam construction are increased economy and more rapid implementation.

To minimise cementitious materials contents and to take advantage of the fact that the critical zones of a large dam do not generally experience load for an extended period after placement, characteristic strengths for RCC are specified at ages of up to 1 year, and commonly not less than 90 days age.

2.2.2 MODERN RCCS

Modern RCCs are primarily designed in accordance with two different approaches(2):

- The "overall" approach, which relies on the dam body for water-tightness through high quality concrete and treatment to ensure well-bonded layer and lift joints.
- The "separate" approach, which relies on an independent impervious barrier, which is usually placed on the upstream face.

The majority of RCC dams contain mineral admixtures, most commonly fly ash, as an active constituent of the concrete.

Beyond the basic requirements of strength, a modern RCC mix is defined by the paste/mortar (p/m) and the sand/aggregate (s/a) ratios, the maximum size aggregate (MSA) and the modified Vebe time. These parameters essentially relate to the achievable density (and impermeability), the achievable compaction ratio and the tendency of the constituent materials to segregate during handling. Under construction conditions, the aforementioned properties determine workability and the difference between permeable, stoney RCC, with planes of weakness and a cohesive, seamless watertight and dense RCC. For the "overall" approach, mixes are designed for maximum density, with a paste/mortar ratio of at least 0.37 being required to achieve a density of 98.5% of the theoretical maximum solid density.

In modern RCC practice, a tendency to use a MSA of 37.5, or 40 mm has developed, as larger sizes demonstrate a tendency to segregate in an RCC mix during handling operations. While early RCC testing suggested that a lower sand/aggregate ratio was optimal for RCC, compared to conventional vibrated concrete (CVC), practical experience in the interim has demonstrated that quality control and the maintenance of RCC consistency is much more realistically achieved in an RCC with a sand/aggregate ratio exceeding 0.35.

The workability of RCC is determined by testing with the Vebe apparatus, which is modified to include a surcharge mass of 19.1 kg. For workable RCC, the modified Vebe time should lie between 10 and 20 seconds. For high-workability RCC, a modified vebe time of 8 to 15 seconds is usually specified. In the case of lean RCC, the modified Vebe time generally exceeds 30 seconds.

With a very significant number of approaches attempted during the early years of development, three primary concepts emerged for the design and construction of RCC dams:

- The lean RCC dam; for which the cementitious materials content is < 100 kg/m³. For such mixes, often only Portland cement is used without mineral admixtures, or pozzolanic material.
- The RCD method (roller compacted dam) unique to Japan; for which the cementitious materials content is generally 125 kg/m³, but only the hearting zone of the dam is RCC.
- The high-paste RCC dam; for which the cementitious materials content is > 150 kg/m³.

In the case of high-paste RCC, the RCC material itself provides the watertight barrier and must be designed for an in-situ permeability equivalent to that of traditional dam mass concrete. The RCC and the associated construction methods must further be designed to ensure effective bond between layers. Various facing systems are applied for high-paste RCC dams, but with the simple objective of creating a good and durable surface finish. Transverse joints are induced at pre-determined intervals, which are generally wider than is the case on a conventional vibrated mass concrete dam.

In early RCC dam construction, a particular problem was recognised as low bond between successive placement layers. Whilst a relatively high shear friction angle could generally be assured between layers under all circumstances, low cohesion and tensile strengths were compounded by high permeability when a new layer was placed on an excessively mature existing layer. Development in the interim has included the use of set retarding admixtures and the use of sloped and non-continuous layer placement methods to ensure the freshness of the underlying RCC layer when the subsequent layer is placed. While such practices are only implemented where required as part of the dam design, the result is a seamless bond between successive RCC placement layers, with joint properties equivalent to the parent RCC properties.

2.2.3 RCC MIX COMPOSITION

In the case of lean RCC, the material itself is not designed for impermeability and consequently the requirements for aggregate gradings are not necessarily as prescriptive as would be the case for CVC, although density is always important in the case of a dam.

Lean RCC is also often referred to as a dry consistency mix RCC. With similar water contents to high-paste RCC, i.e. 100 – 125 litres/m³, aggregate contents are obviously relatively high. To ensure consistency and ease of compaction under construction conditions, lean mix RCC often contains a high proportion of aggregate fines (often around 8% of the total aggregate content)(3) that form part of the paste fraction.

A typical lean RCC comprises the following materials proportions:

Constituents	Portland Cement	Fly Ash	Water	Coarse Aggregate	Fine Aggregate	Air
By Mass (kg/m³)	60 - 70	0 - 40	100 - 125	1500	825	0
By Volume (litres/m³)	21	9	113	545	300	12

Ignoring the aggregate fines, the typical lean mix above would contain approximately 140 litres of paste per m³ of concrete. Including 8% fines in the aggregates, the total paste would be of the order of 200 litres.

In view of the fact that high-paste RCC is designed for impermeability, maximum density is important and consequently a continuous aggregate grading is applied. For the latest high-workability RCC mixes, more restrictive aggregate specifications than required for CVC are applied, with lower compacted void ratios and tighter restrictions in respect of aggregate shaping and flakiness. For all high-paste RCC, aggregates of suitable quality for use in a 30 MPa concrete are required.

A typical high-paste RCC comprises the following materials proportions:

Constituents	Portland Cement	Fly Ash	Water	Coarse Aggregate	Fine Aggregate	Retarder
By Mass (kg/m³)	60 - 70	140 - 150	100 - 125	1400	800	3
By Volume (litres/m³)	21	63	113	510	290	3

While it is common to allow relatively high percentages of sand fines in RCC to increase the paste volume, ignoring this component, a high paste RCC will comprise approximately 200 litres of paste and 800 litres of aggregates per m³ of concrete.

2.2.4 RCC CONSTRUCTION

A number of different approaches exist for RCC placement, but the essential principle is to place and compact 300 mm (compacted) layers as rapidly as practically possible, creating a monolithic mass either by placing successive layers before the first set of the previous layer, or by binding layers together with a bedding mortar, or concrete. RCC is generally placed continuously between upstream and downstream formwork and the abutments, with no expansion joints and with induced joints at predetermined intervals to accommodate long-term shrinkage and creep and thermal contraction due to temperature drop loads.

While it is optimal to place RCC as continuously as possible, without interruptions, practical circumstances and breakdowns often necessitate breaks, when a “cold’ joint is formed and the compacted RCC surface must be “green-cut” and treated with mortar, or grout before placement above is resumed.

Plate 2.1: RCC Construction- Dumping, Spreading & Compaction

Plate 2.2: RCC Compaction

Compaction is achieved with 10 to 15 tonne, single-drum vibratory rollers generally applying 4 passes in either direction to achieve the target compaction. The behaviour of lean RCC and high-paste RCC under vibratory compaction are quite different; with the former consolidating to form a hard and flat surface and the latter producing a "live" surface, particularly when the set is retarded, into which the passage of trucks, etc, can make an impression. While lean, or dry consistency mix RCC simply consolidates in the same manner as a fill under compaction, consolidation causes paste to be squeezed through the aggregate structure and to rise to the surface in high-paste (and particularly high-workability) RCC.

Plate 2.3: High Workability RCC

2.2.5 INDUCED JOINTS IN RCC

Joints are induced in RCC at specific cross-sections by de-bonding placement by between 25 and 100% and thereby creating a localized weakness that will concentrate cracking consequential to long term temperature drop shrinkage at a pre-determined location, where it can be isolated with a waterstop. While South African practice has to date inserted a de-bonding mechanism in every fourth layer (see **Figure 2.1**), international practice generally applies de-bonding in every layer. The early practice of inserting de-bonding systems into the RCC during placement (see **Plate 2.4** and **Figure 2.2**), but before compaction, has almost universally been replaced by driving de-bonding systems into compacted RCC (see **Figure 2.3** and **Plate 2.5**).

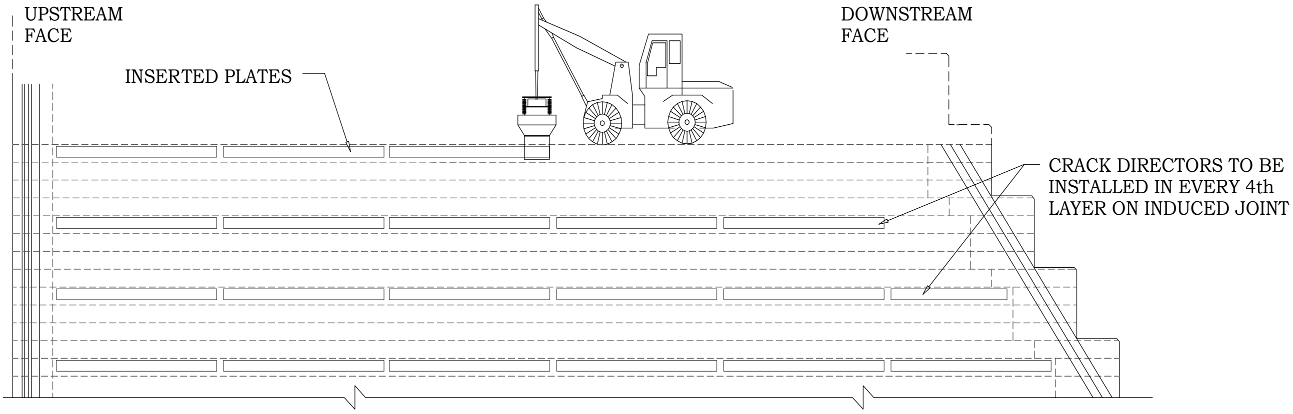

Figure 2.1: Induced Joints Cut into RCC every 4th Layer

Plate 2.4: Induced Joints Inserted into RCC with Placement(3)

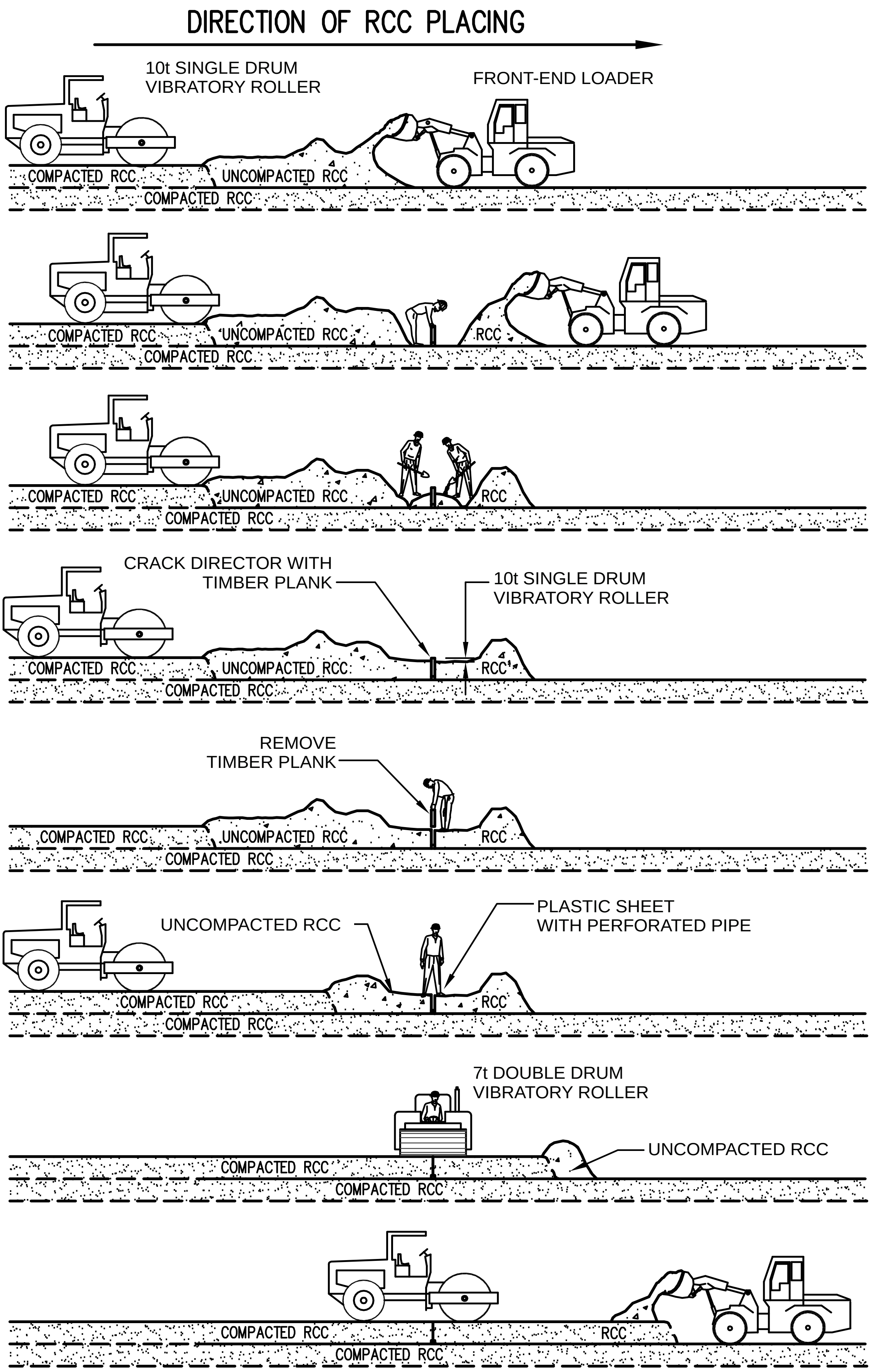

Figure 2.2: Induced Joint Inserted with RCC Placement[3]

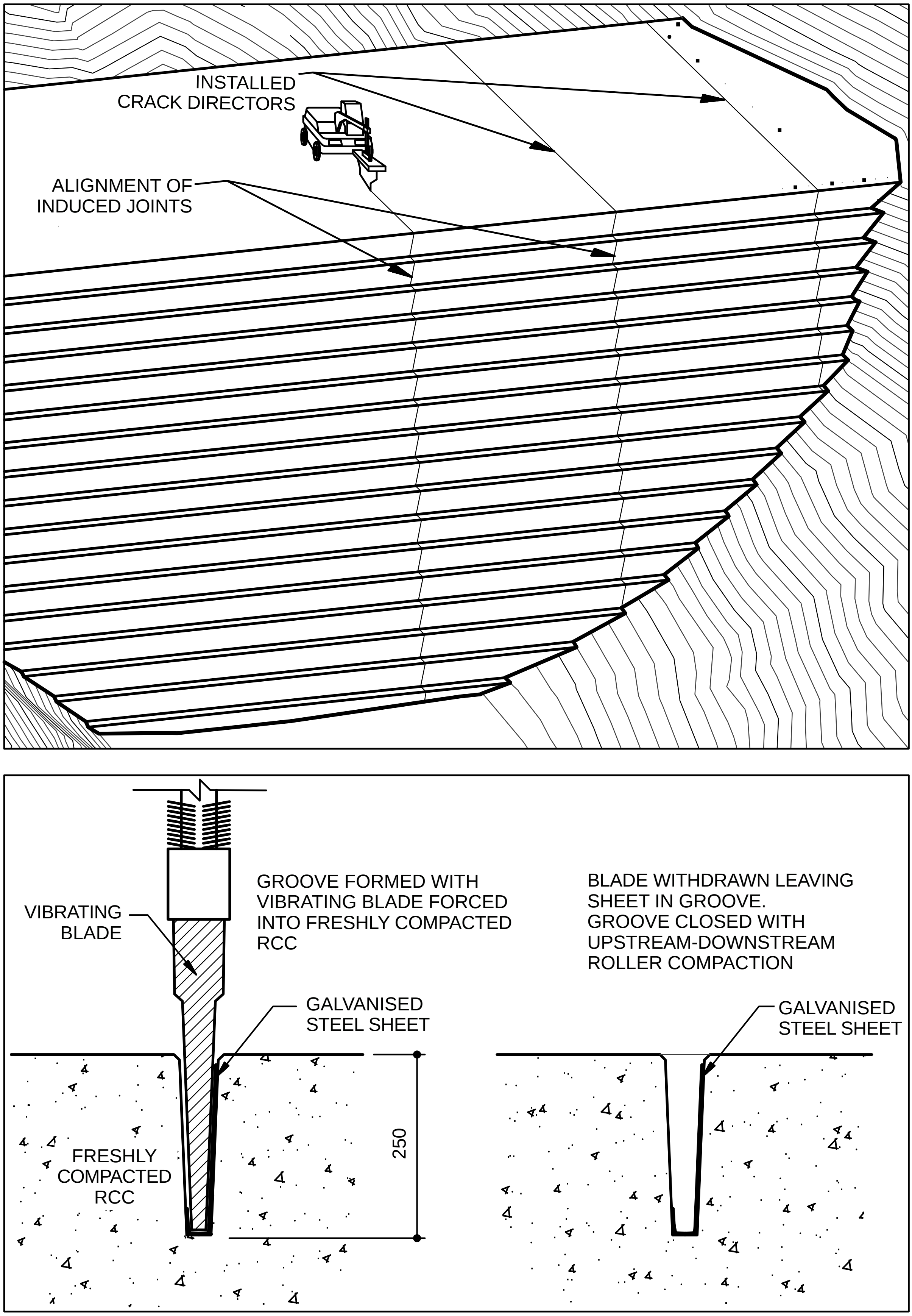

Figure 2.3: Induced Joint Inserted into Compacted RCC

Plate 2.5: Induced Joint Inserted into Compacted RCC

Although several methods and systems are used for de-bonding RCC to create an "induced joint", all result in an increased compressibility on the induced joint, compared to the adjacent RCC. While the construction process causes a disturbance of the RCC on either side of the induced joint, the insertion of folded plastic sheeting, geotextile material, or a folded galvanized steel sheet, implies that the aggregate-to-aggregate contact within the RCC is broken. As the presence of the de-bonding system implies that the RCC structure cannot be as effectively redeveloped during the subsequent re-compaction, the increased compressibility is undoubtedly not only the consequence of a compressible joint filler, but also a slightly more open structure within the concrete on either side.

A consequence of the evident compressibility of the de-bonded areas of the induced joints is local exaggerated movement/closure during thermal expansion of the RCC. As the temperature of the RCC rises with the evolution of hydration heat, it will experience expansion, which will be restrained by the continuity of the placement in a direction parallel to the dam axis (left to right bank direction). Due to the fact that joint inducers are only installed in every second, or fourth layer in the dams investigated as part of this study, their presence will not reduce the overall resistance of the RCC mass to thermal expansion, nor will it cause any perceptible increase in the overall compressibility of the full joint, but it will undoubtedly give rise to increased local compression across the actual de-bonded section of the joint

2.3. RCC INSTRUMENTATION

2.3.1 GENERAL

The instrumentation installed in the dams addressed in this study was designed to fulfil two specific purposes; to monitor the overall performance of the dam structure with a view to ensuring continued dam safety and to monitor the behaviour of the constituent RCC. The dam safety instrumentation comprised pendulums, displacement survey systems, load cells, pore pressure meters and seepage measurement weirs, while the RCC-specific instrumentation comprised long-base-strain-gauge-temperature-meters (LBSGTMs), strain gauges, temperature gauges and thermocouples.

Instrumentation installed in RCC was generally developed for use in soils and for monitoring geotechnical structures, etc. Accordingly, it is of a robust construction and only instruments and measurement systems that have proved accurate and reliable in conditions in which heavy equipment operates are installed in RCC dams.

2.3.1 THE INSTRUMENTS

The Long-Base-Strain-Gauge-Temperature-Meters (LBSGTMs) and the strain gauges installed at all of the dams addressed in this study were vibrating-wire type gauges, a system that is acknowledged for its long-term stability and accuracy(5).

A long-base-strain-gauge-temperature-meter is essentially a long strain, or deformation gauge that is installed across (perpendicular to) the alignment of an induced joint. These instruments are correspondingly aligned parallel to the axis of the dam structure. The LBSGTM was developed by Geokon for use in RCC dam construction on the request of the South African Department of Water Affairs (DWA). The gauge is a vibrating wire meter that measures deformation across a distance of between 600 mm and 1 m. The long-base was considered necessary to ensure that the crack on the induced joint passes between the flanged end plates of the gauge. Initially, a gauge length of 1 m was considered necessary, but it has since become evident that 600 – 700 mm is quite adequate. The Geokon Model 4430 gauge is specified for a measurement sensitivity of 0.01 mm and an accuracy of ± 0.05 mm. The gauge measures temperature, as well as deformation, and the indicated deformations must be adjusted for temperature.

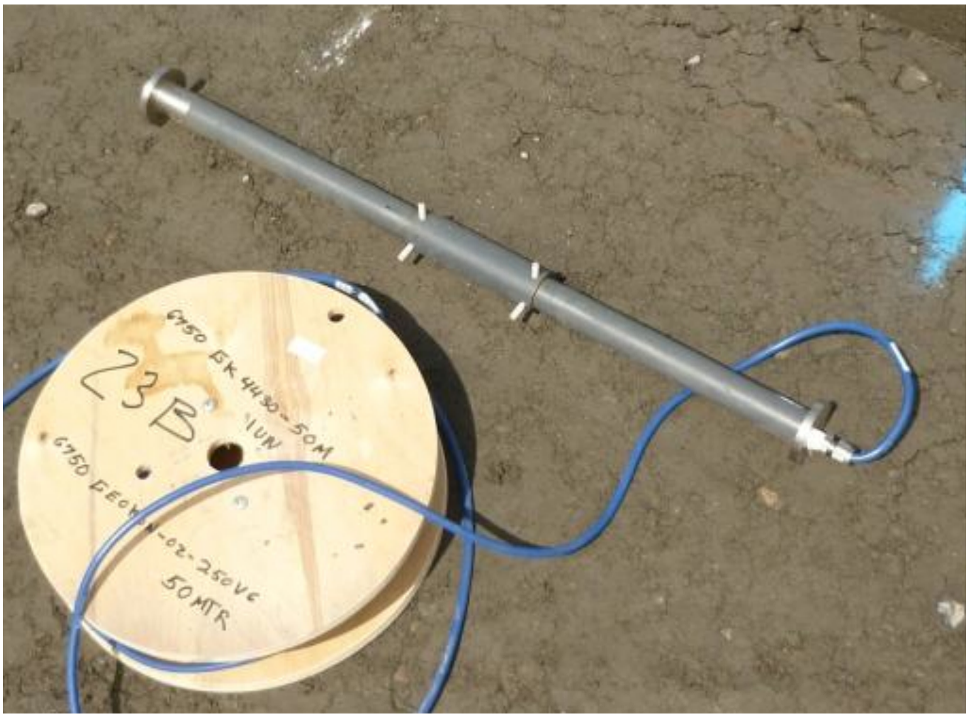

Plate 2.6: Long-Base-Strain-Gauge- Temperature-Meter (LGSGTM)

The first gauges used by DWA were tested under the direct action of a 10 tonne vibratory roller(6) and were demonstrated to remain operational and to continue providing accurate measurement no matter how roughly they were treated. The continued operation of the vast majority of these gauges at Wolwedans Dam after some 20 years is testament to their robustness.

The Geokon Model 4210 gauge used for measuring strain is a particularly robust, all-stainless steel-cased instrument that is designed for direct installation into concrete with large aggregate and indicates a measurement sensitivity of 0.4 microstrain and an accuracy of ± 1%. The gauge also measures temperature and the gauge readings must be adjusted to indicate actual concrete strain.

Plate 2.7: Strain Gauge

2.3.2 INSTRUMENT INSTALLATION

For simplicity and to ensure minimum interruption to RCC placement, instrumentation to monitor RCC behaviour is generally installed at a number of specific elevations over the height of an RCC dam, ideally when planned stoppages will anyway occur for galleries, etc. Stoppages generally correspond with "cold" lift joints, where the RCC is allowed to set fully. A number of methods have been used to create trenches and slots in the RCC surface for the instrumentation and associated cabling and this has sometimes been done by excavation after completion of the layer and other times by cutting slots with a vibrating blade during the process of completing the layer surface. In either case, the cabling is laid out, the instruments are installed and the trenches and slots are backfilled with a structural concrete. Resumption of RCC placement above can often be delayed for a further number of days, but critical data collection starts as soon as the respective gauge is covered with a layer of RCC.

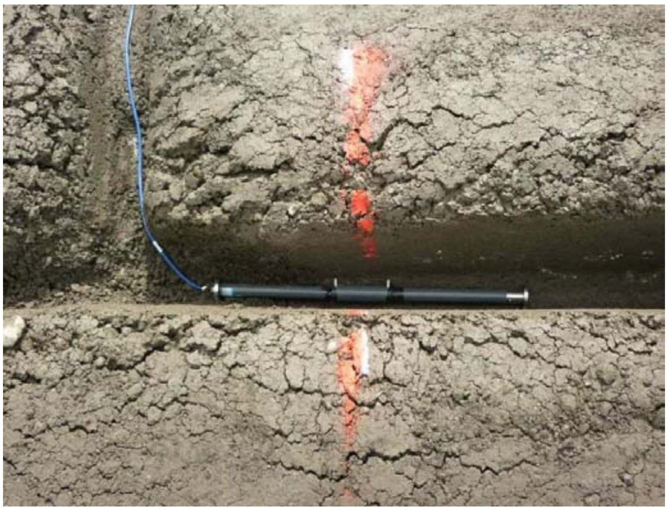

Plate 2.8: LBSGTM in Slot

Plate 2.9: Instrumentation Cable Trench

LBSGTMs are installed in, or immediately above, the layer in which the induced joint de-bonding medium is installed, to ensure that the crack occurs relatively centrally on the gauge.

As a consequence of locating the LGSTMs immediately above an induced joint de-bonding mechanism, the initial deformation readings during the build up in temperature due to hydration reflect the compressibility of the joint inducer system installed. While this will result in a distortion and will not provide a true representation of the actual strain within the continuous RCC in compression above and below the de-bonding system while the temperatures are elevated, the related impact will dissipate once the joint experiences any tension and/or cracking.

2.4. THE RCC DAMS STUDIED

The central focus of the work presented in this Thesis is the data recovered from instrumentation installed in the Wolwedans and Knellpoort Dams in South Africa, Çine Dam in Turkey and Wadi Dayqah Dam in Oman. On the basis of the interpretation of this data, the behaviour of the constituent RCC is observed over periods varying from several months to several years. Behavioural observations from Changuinola 1 Dam, currently under construction in Panama, are also addressed herein.

2.5. WOLWEDANS DAM

2.5.1. INTRODUCTION

Wolwedans Dam was completed in early 1990 and was the first RCC dam in the world to rely fully on three-dimensional arch action for stability. The dam is 70 m high, has a crest length of 270 m, an upstream face arch radius of 135 m and comprises approximately 200 000 m^3 of concrete. The dam was constructed with induced joints at 10 m spacings, de-bonding every 4th layer with inducers installed during placement and the RCC was placed in October and November of 1988 and between May and November of 1989. The first season involved the placement of the bottom 15 m of the dam, while the second encompassed the placement of the remaining 55 m. RCC placement for Wolwedans was achieved over a total period of approximately 7.5 months, with a peak daily rate of 2994 m^3 (7).

The dam first filled to capacity during 1992 and the induced joints were grouted during late winter in 1993. With a full storage volume of 64% of the Mean Annual Runoff (MAR), a high supply assurance requirement and a relatively high catchment rainfall, Wolwedans Dam is subject to consistently high water levels. The dam has spilt on several occasions to date and discharged a relatively large flood just two years after completion.

The composition of the high-paste Wolwedans RCC mix was as follows(7):

Constituents	Portland Cement	Fly Ash	Water	Coarse Aggregate	Fine Aggregate	Air
By Mass (kg/m^3)	58	136	100	1510	625	0
By Volume ($litres/m^3$)	18.5	63.5	100	565	240	13

Ignoring aggregate fines, the Wolwedans RCC comprised 182 litres of paste and 805 litres of aggregates. The blend of 75% crusher and 25% pit sand contained only 1.3% of fines and accordingly, the paste volume was only increased by 3 litres/m^3. With a low sand/aggregate ratio of just 0.3, the paste/mortar ratio was correspondingly high, at almost 0.44.

A basic layout of Wolwedans Dam is provided in **Figure 2.4**.

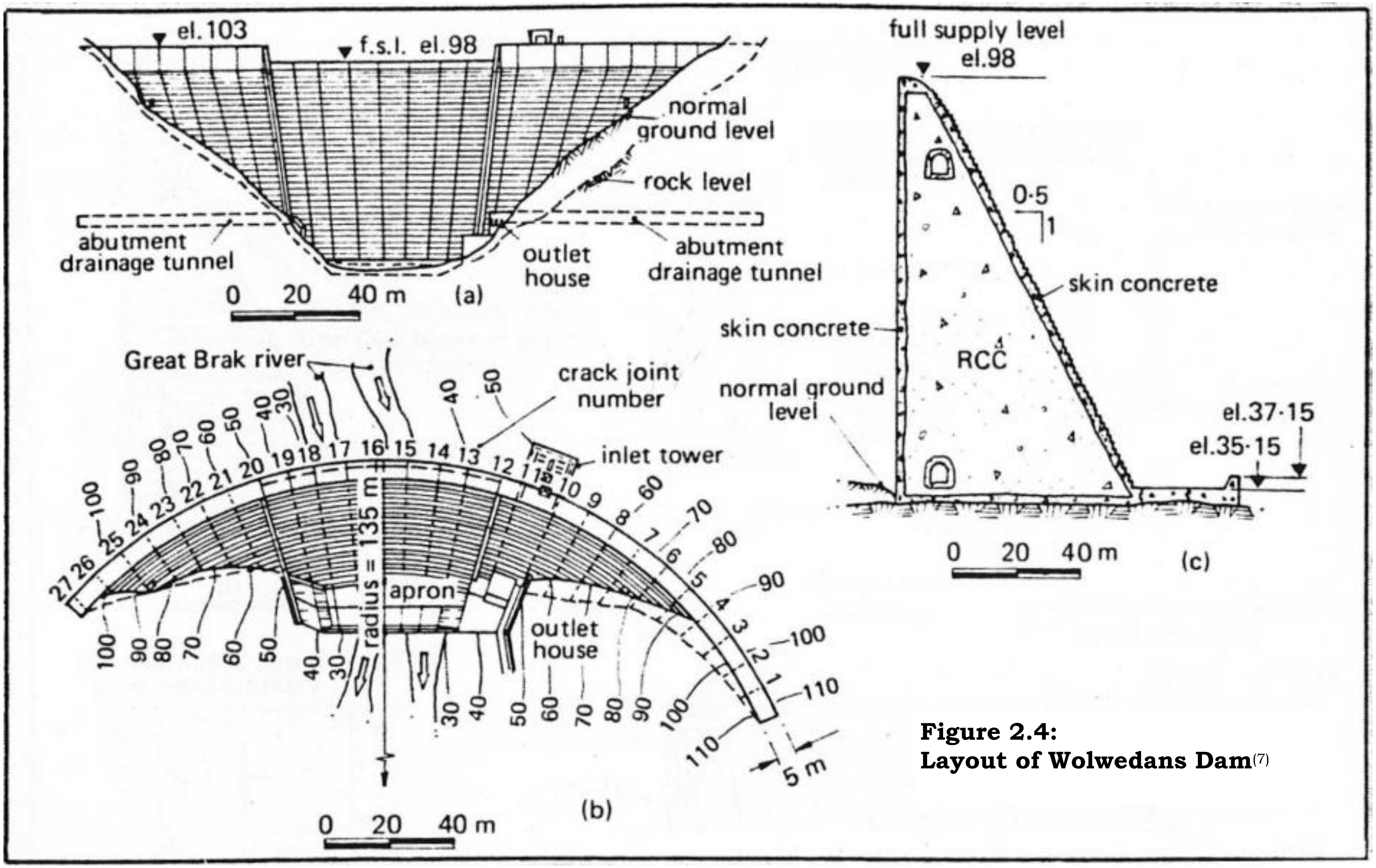

Figure 2.4:
Layout of Wolwedans Dam(7)

2.5.2. WOLWEDANS INSTRUMENTATION

Being one of the first two structures of its type and dependent on arching for stability, a very comprehensive network of structural and thermal monitoring instrumentation was installed within the body of Wolwedans Dam (see **Figure 2.11** at the end of this Chapter and **Figures C1** to **C4** in **Appendix C**). Virtually all of the instrumentation installed during construction is still functional and a central, remotely interrogated control system allows real-time monitoring of the dam's performance and behaviour.

LBSGTMs were installed across all induced joints at four different levels and these instruments formed the core of the system for monitoring the thermal/structural behaviour of the dam structure. With a lowest foundation elevation of RL 33 m and a NOC elevation of RL 103 m, instrumentation was installed at elevations RL 40.25 m, RL 52.25 m, RL 66.25 m and RL 84.25 m.

The lowest level of instrumentation was installed approximately at mid-height of the first RCC cast during October and November 1988. The second level of instrumentation was installed just 4.25 m above the bottom level of the RCC placed during 1989. The third level of instrumentation was installed at approximately mid height, 33 m above lowest foundation level. The top level of instrumentation was installed at the level of the top gallery, implying that instruments were installed 2 m from an external surface on one side and 2.75 m from the gallery on the other.

Plate 2.10: Wolwedans Dam

2.5.3. IMPORTANT INFLUENCES ON RECORDED BEHAVIOUR

In view of the fact that the dam structure at Wolwedans was constructed in two distinct parts(7), separated by a substantial break, it is not considered that the full structure behaves entirely monolithically with respect to temperature and hydration heat dissipation. Two specific issues are considered of importance in this regard; construction of the first part during the summer months and initiation of the latter part in winter and the fact that the instrumentation installed at elevation RL 40.25 m suggests that almost all of the hydration heat from the bottom section had been dissipated by the time that the construction of the upper section was initiated. Correspondingly, the instrumentation data at elevations RL 40.25 m and RL 52.25 m are likely to have been influenced significantly by the extended interruption in construction that occurred at RL 48 m.

With only 2 rows of LBSGTMs and surface cover of just 2 m to the outside and 2.75 m to the gallery, it is considered that the readings in the highest level of instrumentation (RL 84.25 m) will substantially reflect surface zone temperatures and effects. In the third level of instrumentation (RL 66.25 m), however, foundation restraint will not be a significant influence, while the dam wall thickness is approximately 21 m, which the instrumentation records demonstrated to be sufficient to limit the core temperature variation over a typical annual cycle to approximately 2°C, while still allowing all of the hydration heat to be dissipated within 2 years after dam completion.

The induced joints at Wolwedans Dam were grouted in two phases, between July and November 1993. With the impounded water level dropped by 8 m during the latter part of the period, grouting to mid dam height (RL 66.25 m) was completed over the winter months of June to August. With the dam filled to capacity once more, the top half of the structure was subsequently grouted over the Spring and early Summer months of September to November. It is significant to note that while a net upstream crest movement of the order of 2.5 mm was recorded when the water level was drawn down, equivalent displacements in the upper gallery were of the order of only 0.5 mm and no associated movement was really apparent on any of the induced joint instruments. At the time that the induced joints were grouted, it is apparent from the displacement data records that the dam crest was displaced downstream by a maximum of well over 10 mm, indicating that the structure was already subject to a significant temperature drop and that the grouting merely filled open joints and did not serve a significant purpose in alleviating the impact of long-term temperature-related loading.

2.6. KNELLPOORT DAM

2.6.1. INTRODUCTION

Knellpoort Dam is also in South Africa and was designed in parallel with Wolwedans, but construction was initiated earlier and completed over a shorter period, as concrete volumes were relatively small. Although this 50 m high dam is defined as an arch/gravity structure, arching is only incurred under extreme loading conditions and, as an off-channel storage dam, with a large capacity compared to the natural catchment inflow, hydrostatic loadings are generally low.

The main part of the dam is aligned on a circular arch and has a vertical upstream face and a downstream face sloped at 0.6 horizontal to 1 vertical. The left flank comprises a straight conventional gravity structure. The combined crest length measures 200 m.

The 60 000 m^3 of concrete comprising Knellpoort Dam was placed over a single winter season during 1988. Induced joints were aligned radially at a 10 m spacing on the upstream face, de-bonding every 4th layer with inducers installed during RCC placement.

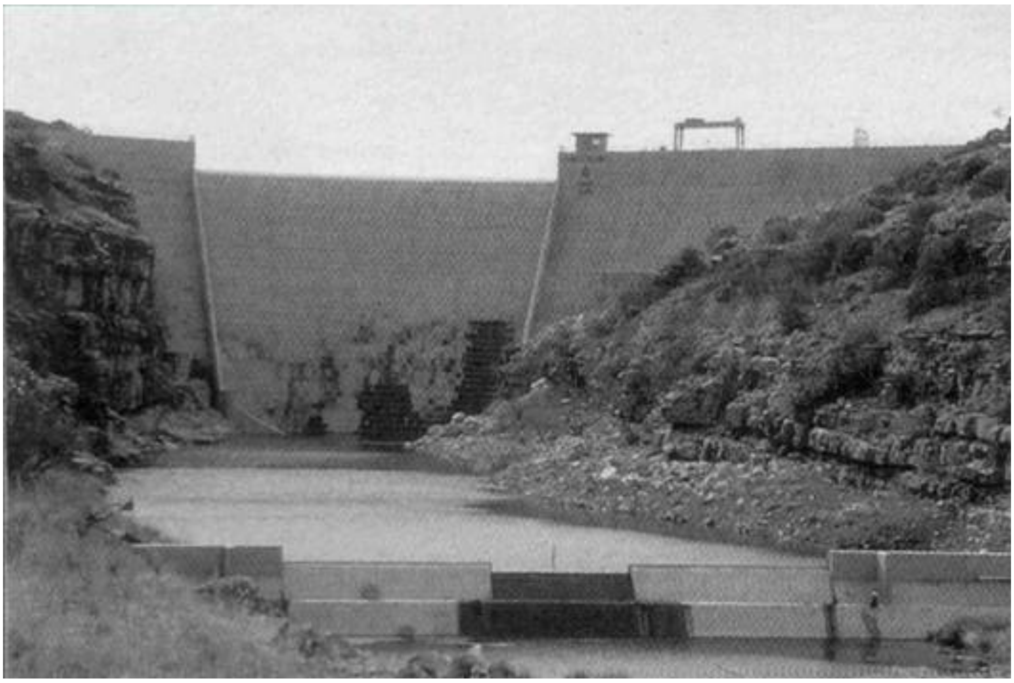

Plate 2.11: Knellpoort Dam(8)

The composition of the RCC mix placed at Knellpoort Dam was as follows(8):

Constituents	Portland Cement	Fly Ash	Water	Coarse Aggregate	Fine Aggregate	Air
By Mass (kg/m^3)	61	142	108	1610	685	0
By Volume ($litres/m^3$)	19.5	66	108	555	245	6.5

Ignoring aggregate fines, the Knellpoort RCC comprised approximately 195 litres of paste and 800 litres of aggregates. Again, a low sand/aggregate ratio of just 0.3 gives rise to a high paste/mortar ratio of 0.44.

A basic layout of Knellpoort Dam is provided in **Figure 2.5**.

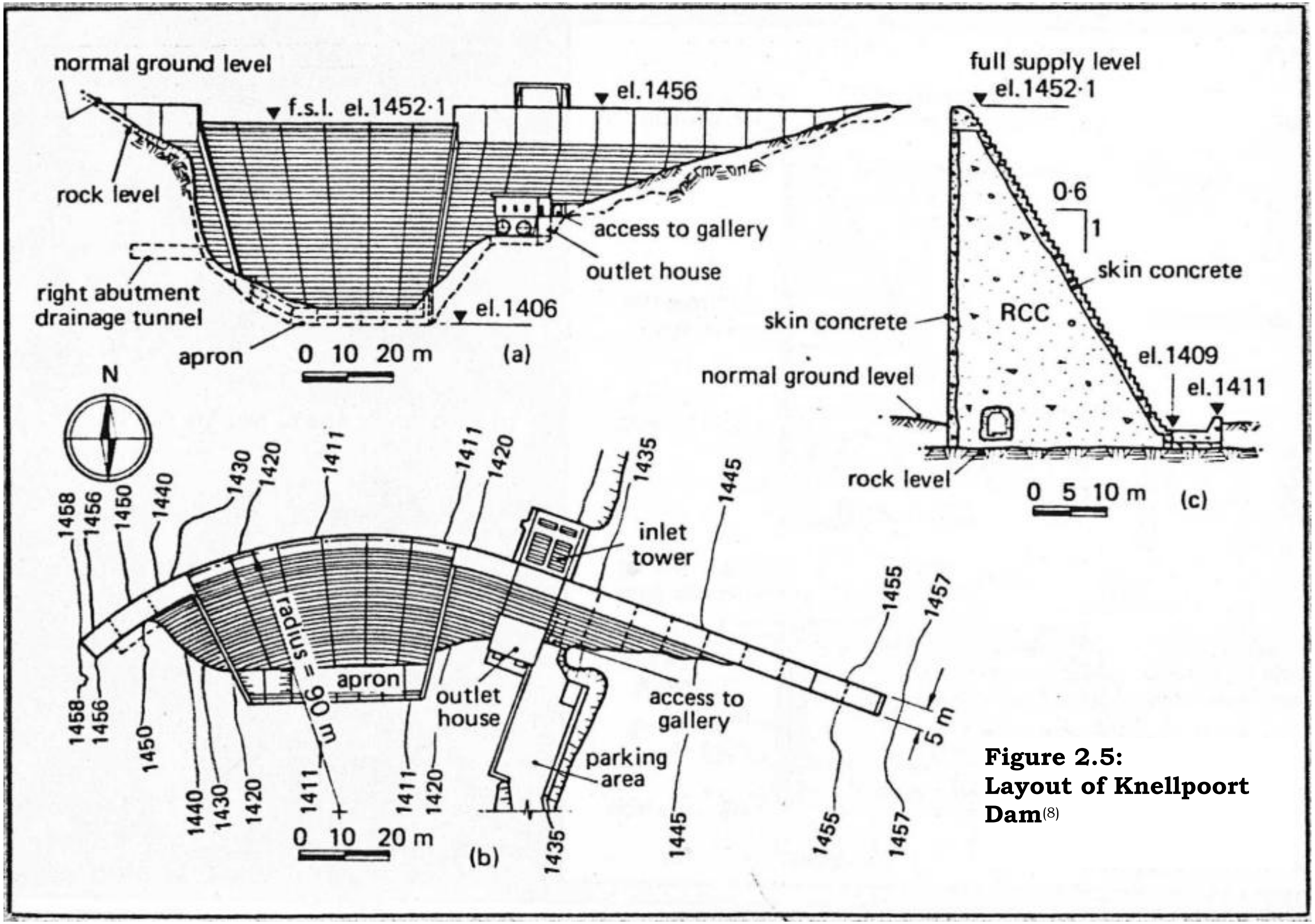

Figure 2.5: Layout of Knellpoort Dam(8)

2.6.2. KNELLPOORT INSTRUMENTATION

The instrumentation installed at Knellpoort Dam was essentially identical to that installed at Wolwedans. Despite the lower dam height, the reduced dependence on arching and the inclusion of only a single gallery, instrumentation was installed on four separate levels. However, unlike Wolwedans Dam, Knellpoort was constructed largely during a particularly cold winter, with built-in temperatures frequently below 15°C.

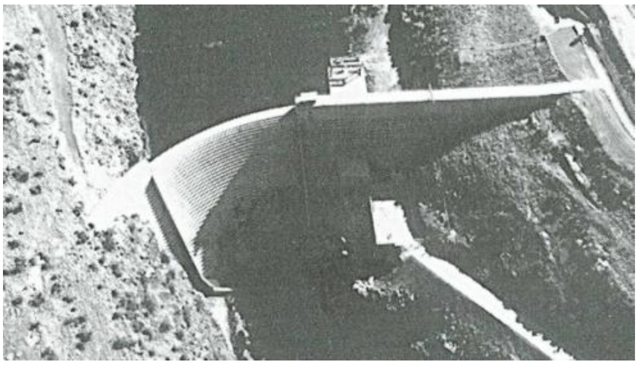

Plate 2.12: Knellpoort Dam(9)

2.6.3. IMPORTANT INFLUENCES ON RECORDED BEHAVIOUR

Knellpoort Dam was constructed primarily over a particularly cold winter in 1988. The temperature at which the RCC at any particular location in the dam body was placed, or effectively insulated by RCC placed above, was frequently below 15°C. In view of the fact that the long-term temperature at the core of the dam structure varies seasonally between 13 and 16°C, the difference between the average long-term core temperature and the average "built-in" temperature is minimal, as indicated in **Figure 2.6**.

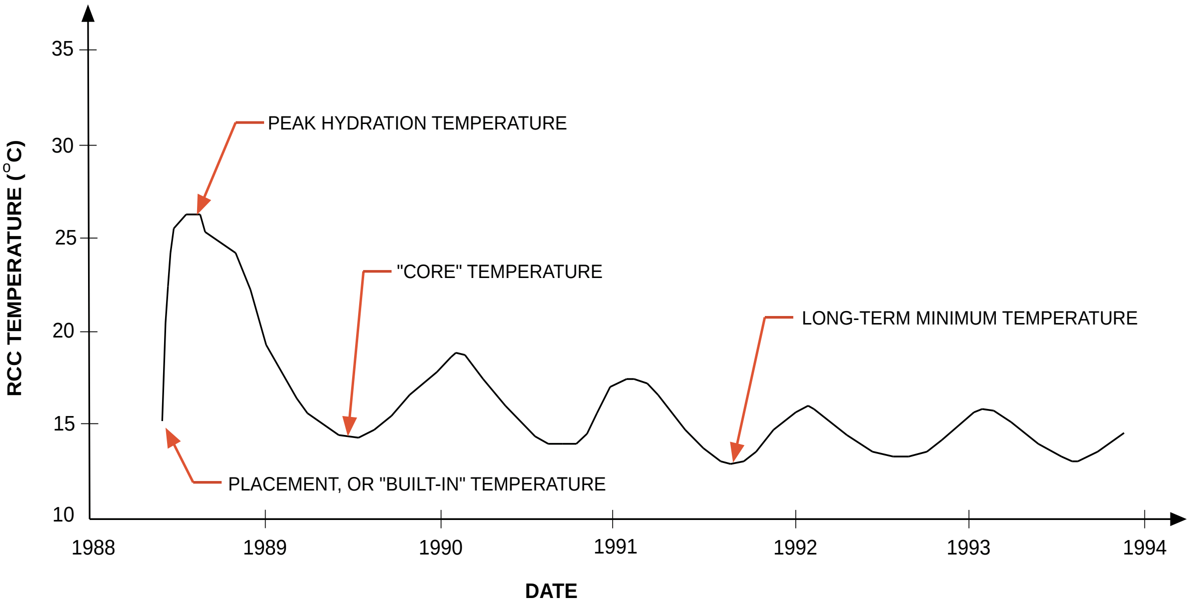

Figure 2.6: Typical RCC Temperature History for Knellpoort Dam(8)

2.7. ÇINE DAM

2.7.1. INTRODUCTION

Plate 2.13: Çine Dam

Çine Dam is currently under construction in south-western Turkey. Placement of RCC is restricted to the winter months of the year and limited each year on the basis of available State fund allocations. By April 2009, almost 1.4 million m³ of the required total of 1.65 million m³ of RCC had been placed. The dam is a gravity structure with a maximum height of 136.5 m and a crest length of approximately 300 m. While the topography could accommodate an arch structure, the foundation rockmass conditions were not considered suitable. As a consequence of the dam's location in an area of relatively high seismic risk, the structure has a wide base and the RCC strength characteristics are determined by the related requirements under seismic loading.

Induced joints at Çine Dam were installed in the compacted RCC at intervals of 24 m along the length of the main body of the wall, de-bonding every 4th layer. On the extremes of the flanks, where the dam height reduces, a closer joint spacing was applied. The RCC for Çine Dam is zoned, with the an upstream "impermeable" zone containing 85 kg/m³ cement and 105 kg/m³ fly ash and the remaining bulk of the wall structure containing 75 kg/m³ cement and 95 kg/m³ fly ash.

The compositions of the two RCC mixes placed at Çine Dam were as follows(10):

Constituents	Portland Cement	Fly Ash	Water	Coarse Aggregate	Fine Aggregate	Air
D10 Mix						
By Mass (kg/m³)	85	105	115	1406	791	0
By Volume (litres/m³)	27	46	115	516	290	6

Net Paste (l/m³)	Fines (l/m³)	Aggregate (l/m³)	Paste/ Mortar	Sand/ Aggregate
193	49	806	0.40	0.36

Constituents	Portland Cement	Fly Ash	Water	Coarse Aggregate	Fine Aggregate	Air
D05 Mix						
By Mass (kg/m^3)	75	95	120	1590	586	0
By Volume (litres/m^3)	24	41	120	586	218	11
Net Paste (l/m^3)	Fines (l/m^3)	Aggregate (l/m^3)	Paste/ Mortar	Sand/ Aggregate		
185	36	804	0.46	0.27		

A basic plan layout of Çine Dam is provided in **Figure 2.7**.

2.7.2. ÇINE INSTRUMENTATION

A comprehensive network of monitoring instrumentation was installed in Çine Dam, including 200 LBSGTMs, 50 separate temperature gauges, 3 pendulum lines, 30 strain gauges, 30 surface crack meters, 13 piezometers and 6 seepage measurement sites. The dam contains 3 separate, horizontal galleries at elevations 147.5 mASL, 185 mASL and 232 mASL and instrumentation was installed at each of these levels, as well as at elevation 210 mASL.

For the purposes of evaluating the thermal performance of the RCC at Çine Dam, data from the LBSGTMs, the strain gauges and the various temperature meters were analysed. The LBSGTMs were ascribed an SGT designation, while the strain gauges were ascribed an SGA designation. **Figure 2.12** at the end of this Chapter and **Figures C5** to **C7** illustrate the basic layout of the installed instrumentation on a typical induced joint. The SGA strain gauges installed at Çine Dam were aligned in an array in an upstream-downstream direction to measure strain perpendicular to the dam axis.

2.7.3. IMPORTANT INFLUENCES ON RECORDED BEHAVIOUR

As previously mentioned, the RCC for Çine Dam was placed between October and April of each year from 2004. Each season saw the placement of approximately 300 000 m^3 of RCC, with the levels listed in **Table 2.1** being achieved at the end of each placement in April. The surface of the RCC at this level was subsequently exposed to the elements, until placement resumed the following October.

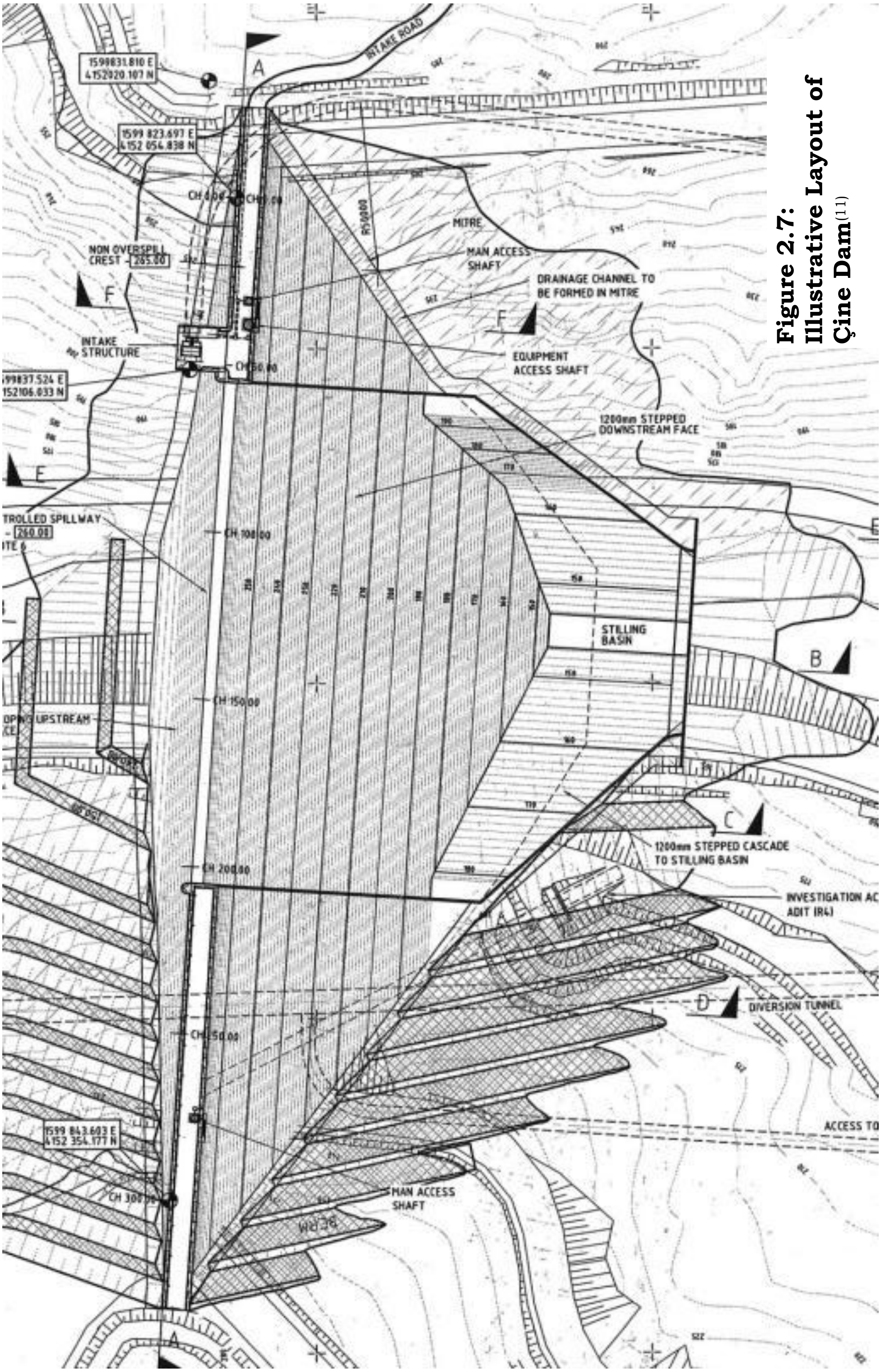

Figure 2.7: Illustrative Layout of Çine Dam(11)

The dam structure, constructed in accordance with the actual construction programme, was consequently the subject of a detailed thermal analysis, undertaken to establish whether any consequential deleterious thermal stresses might be developed and to establish whether any RCC cooling and/or thermal insulation may be required.

This thermal analysis will not be addressed in detail in this study, as the related results have no specific relevance. However, it is important to note that a very good correlation was evident between the temperatures within the dam predicted by the finite element thermal model and those measured on the prototype structure and this is illustrated in Chapter 4.

Table 2.1: RCC Progress at Çine Dam

Placement Period		**Level Achieved** (m ASL)
1	October 2004 – April 2005	147.50
2	October 2005 – April 2006	166
3	October 2006 – April 2007	187
4	October 2007 – April 2008	208.25
5	October 2008 – April 2009	232
6	October 2009 – October 2010	265 (completed)

Figure 2.8: Çine Dam Construction Progress

April 2007

April 2008

February 2010

Figure 2.8: Çine Dam Construction Progress *continued*

2.8. WADI DAYQAH DAM

2.8.1. INTRODUCTION

Construction of Wadi Dayqah Dam in Oman was recently completed (2009). The dam comprises an 80 m high RCC gravity structure and a 40 m high rockfill saddle embankment. With a crest length of a little under 400 m, the RCC structure comprises a total concrete quantity of approximately 650 000 m^3 and the RCC was essentially placed between February and December 2008. The dam is aligned on a curve, with a radius of 500 m to the upstream face and induced joints are arranged radially, generally at a spacing of 15 m measured on the upstream face. Induced joints were installed in every 2nd layer of RCC after compaction.

Plate 2.14: Wadi Dayqah Dam

The RCC for Wadi Dayqah Dam was zoned, with an upstream "impermeable" 15 MPa RCC zone containing 126 kg/m^3 cement and 54 kg/m^3 ground Limestone and the remaining bulk of the wall structure (12 MPa RCC) containing 112 kg/m^3 cement and 48 kg/m^3 ground Limestone.

The compositions of the two RCC mixes placed at Wadi Dayqah were as follows(12):

Constituents	Portland Cement	Ground Limestone	Water*	Coarse Aggregate	Fine Aggregate	Retarder
Zone 1 - 15 MPa Mix						
By Mass (kg/m^3)	126	54	137	1200	944	1.76
By Volume (litres/m^3)	41	21	103	455	378	1.5
Net Paste (*l*/m^3)	Fines (*l*/m^3)	Aggregate (*l*/m^3)	Paste/ Mortar**	Sand/ Aggregate		
166.5	51	833	0.31	0.45		

* - the free water content was 103 litres/m^3, but an additional quantity of 34 litres was required due to aggregate absorption.

** - including aggregate fines increases the paste to 217.5 litres/m^3 and the p/m to 0.40.

Constituents	Portland Cement	Ground Limestone	Water*	Coarse Aggregate	Fine Aggregate	Retarder
Zone 2 – 12 MPa Mix						
By Mass (kg/m³)	112	48	131	1227	960	1.76
By Volume (litres/m³)	37	19	96	463	384	1.5
Net Paste (l/m³)	Fines (l/m³)	Aggregate (l/m³)	Paste/ Mortar**	Sand/ Aggregate		
153.5	52	847	0.29	0.45		

* - the free water content was 96 litres/m³, but an additional quantity of 35 litres was required due to aggregate absorption.

** - including aggregate fines increases the paste to 205.5 litres/m³ and the p/m to 0.38.

2.8.2. WADI DAYQAH INSTRUMENTATION

The instrumentation installed in Wadi Dayqah RCC gravity dam in Oman was less comprehensive than was the case for the previous examples. With the same types of instruments, only a single LBSGTM was installed across each of the induced joints in the centre of the section at two elevations, namely 135 mASL and 150 mASL. Five levels of concrete temperature meters and external temperature gauges were also installed on three specific cross sections; one in the spillway section and one on the non-overspill section on either flank. The typical layouts of the temperature meters and the LBSGTMs are illustrated on **Figures 2.13** and **2.14** at the end of this Chapter.

2.8.3. IMPORTANT INFLUENCES ON RECORDED BEHAVIOUR

Placement of the RCC for Wadi Dayqah Dam took place between February 2008 and July 2009 in temperatures varying between 25 and 45°C. However, as a consequence of the dam having a spillway with Robert's crest splitters, a substantial slowing in the pace of construction occurred once the base of the spillway crest was reached in November 2008. The vast majority of the RCC comprising the dam was accordingly placed in just 10 months.

With a better picture of the behaviour expectations of the RCC and a relatively small budget for instrumentation, it was considered most appropriate to install a single LBSGTM across all joints in the centre of the dam section at two levels. With this configuration, it was understood that only the behaviour of the "core" zone RCC would be monitored.

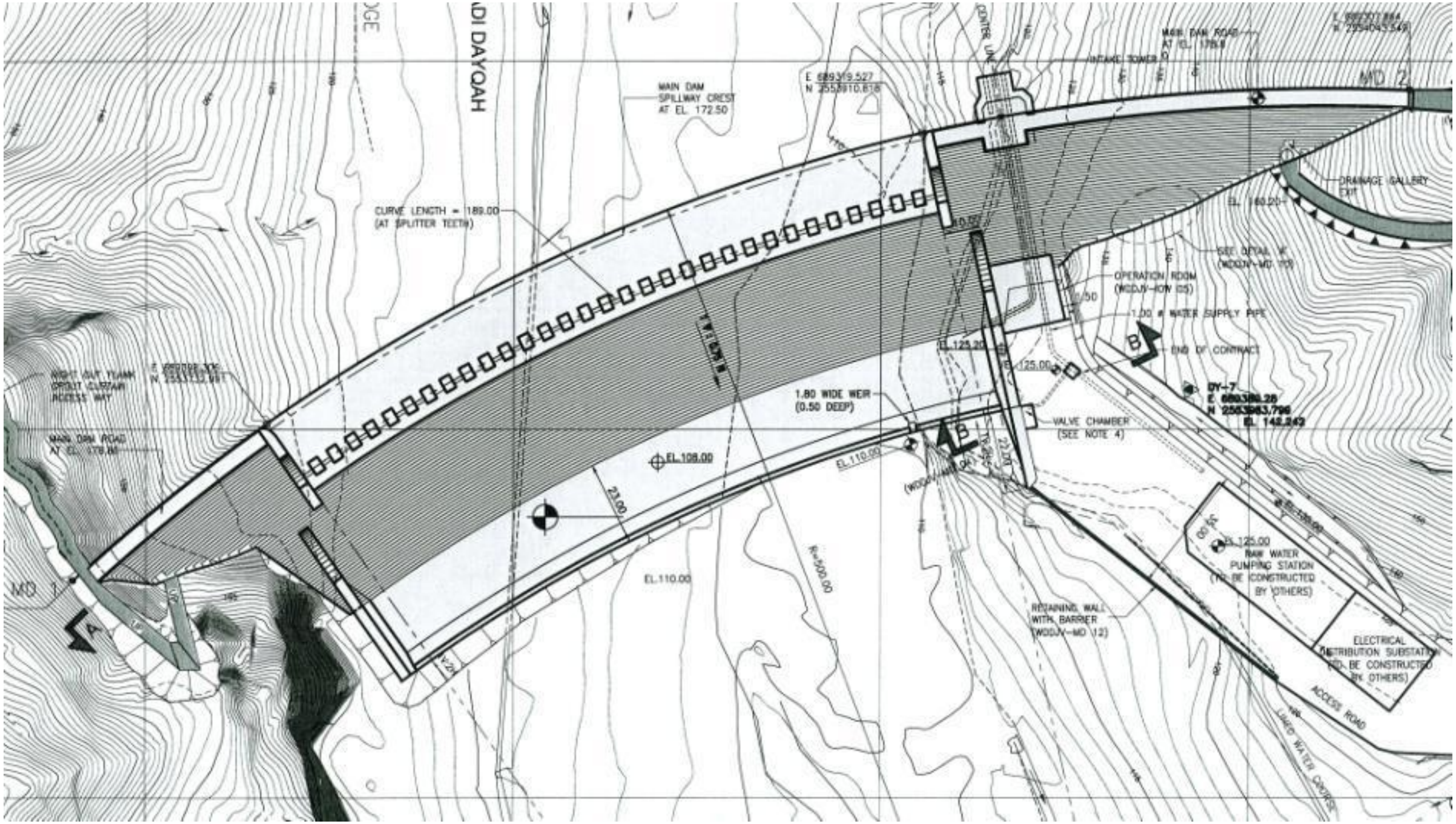

Figure 2.9: Illustrative Layout of Wadi Dayqah Dam(13)

Whereas all of the other dams for which instrumentation data were reviewed contain high-paste RCC for which a relatively high proportion of fly ash was used, the RCC of Wadi Dayqah comprised a relatively low cement content (112 kg/m^3) in combination with a ground limestone filler (48 kg/m^3) and a 0.44 sand/aggregate ratio. Furthermore, 34% of the sand fraction comprised crushed limestone. As a consequence, the final RCC contained over 13% fines.

Three further factors are considered of importance in respect of the measured behaviour of the RCC at Wadi Dayqah Dam and these are the rounded particle shape of the natural gravel coarse aggregate, the high water absorption characteristics of the aggregates (approximately 35 litres/m^3) and the fact that the RCC temperature was artificially cooled by approximately 15°C before placement.

Plate 2.15: Wadi Dayqah Dam January 2009

2.9. CHANGUINOLA 1 DAM

2.9.1. INTRODUCTION

Placement of the RCC for Changuinola 1 Dam in Panama commenced in December 2009, with completion scheduled for February/March 2011. The dam is a 105 m arch/gravity structure comprising approximately 890 000 m^3 of RCC. The upstream face arch radius is 525 m, the induced joints are spaced at 20 m intervals, with inducers installed in every 2nd layer after compaction and the downstream face slope varies from 0.5 H to 1 V in the centre to 0.7 H to 1 V on the flanks.

For Changuinola 1, a high-workability RCC is being applied, with a first set retarded typically to 20 hours. The mix strength requirements are determined primarily by a target direct vertical tensile strength of 1.2 MPa and peak RCC placement rates should exceed 120 000 m^3 per month.

The composition of the high-workability RCC mix applied for Changuinola 1 is follows:

Constituents	Portland Cement	Fly Ash	Water	Coarse Aggregate	Fine Aggregate	Retarder
By Mass (kg/m^3)	70	145	119	1282	888	3.44
By Volume (litres/m^3)	22	60	119	462	334	3
Net Paste (l/m^3)	Fines (l/m^3)	Aggregate (l/m^3)	Paste/ Mortar	Sand/ Aggregate		
201	35	799	0.375	0.42		

Including the aggregate fines within the paste increases the p/m to 0.44.

2.9.2. CHANGUINOLA 1 INSTRUMENTATION

The instrumentation to be installed in Changuinola 1 Dam is very similar to the arrangements described above. At the time of writing, however, only one level of instruments had been installed and the while these were indicating the same patterns as for Wolwedans and Knellpoort, the record was of not of adequate length to be used for the purposes of the work addressed herein.

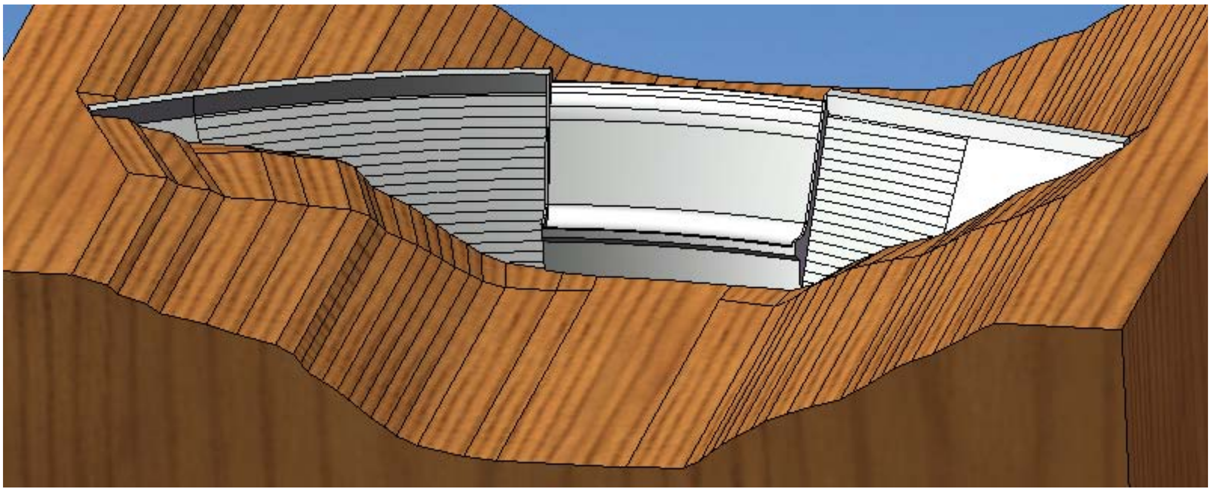

Figure 2.10: Changuinola FE Model Illustrating Final Layout

2.9.3. IMPORTANT INFLUENCES ON RECORDED BEHAVIOUR

With almost 3 m of rainfall per annum on site and a wet month containing 25 days of rain and a dry month 16 days, the weather conditions on site represent a very significant factor in relation to the construction of Changuinola 1 Dam. While RCC dam construction offered very significant advantages in respect of the river diversion, compared to other dam types, the final programme and the shear size of the river implied that the structure was constructed to approximately 40 m height in two sections, with a formed joint in between (see **Plate 2.16**). Another factor of specific relevance in the case of Changuinola 1 Dam is the temperate climatic conditions, with average monthly temperatures varying only by 4°C year-round.

Plate 2.16: Construction Progress at Changuinola 1 Dam on 25th June 2010

2.10. INSTRUMENTATION LAYOUTS

2.10.1. WOLWEDANS DAM

Figure 2.11 illustrates the typical layout of the instrumentation installed in Wolwedans Dam. Additional plan layouts of each of the instrumentation levels are provided for illustration on **Appendix C**.

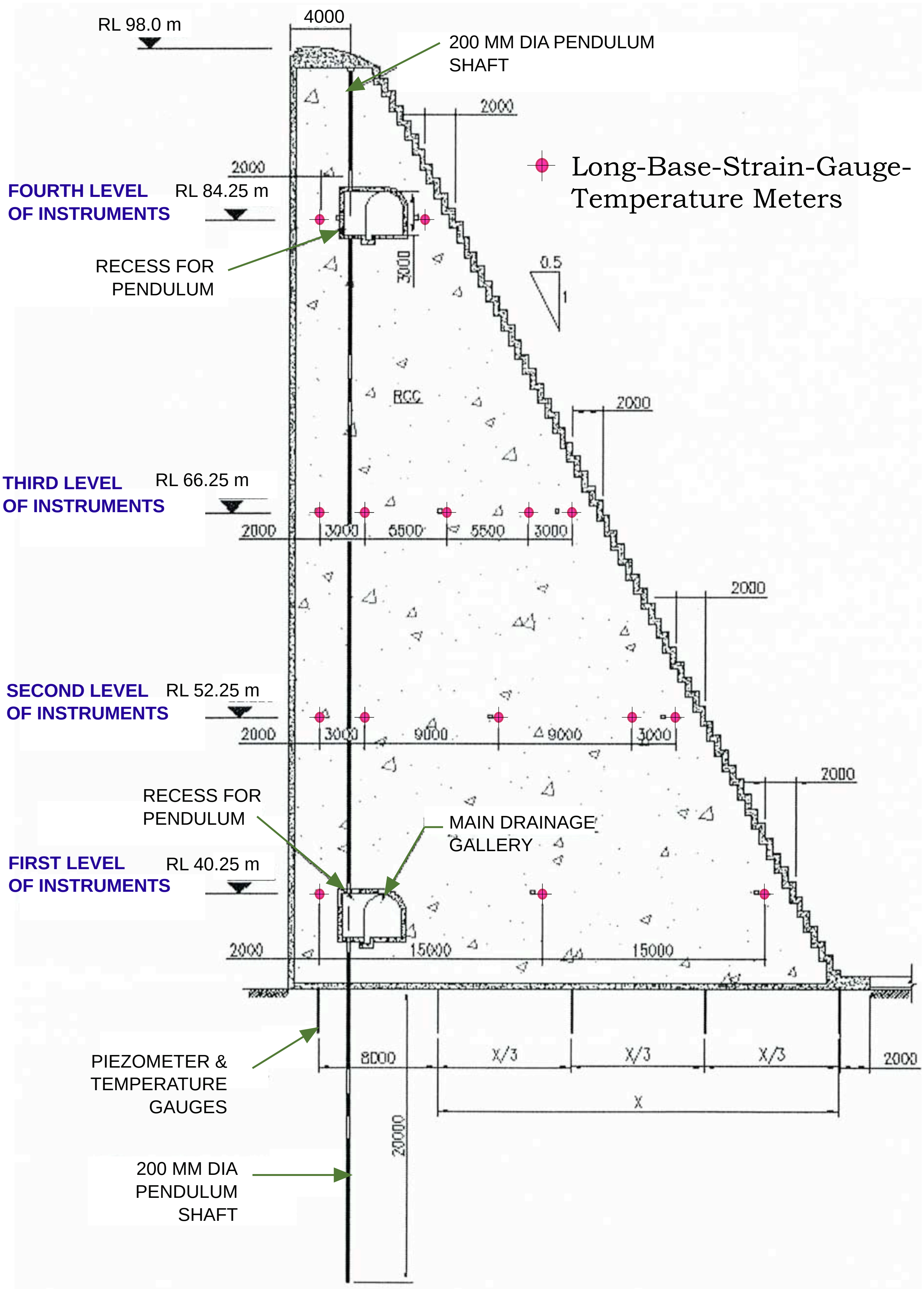

Figure 2.11: Illustrative Section Indicating Instrumentation(7)
(from 1987/88 Hand Drawn Plan)

2.10.2. ÇINE DAM

Figure 2.12 illustrates the typical instrumentation installed in Çine Dam. The layouts for the instrumentation at El 147.5 mASL, El 184.25 mASL & El 208.5 mASL are included in **Appendix C**.

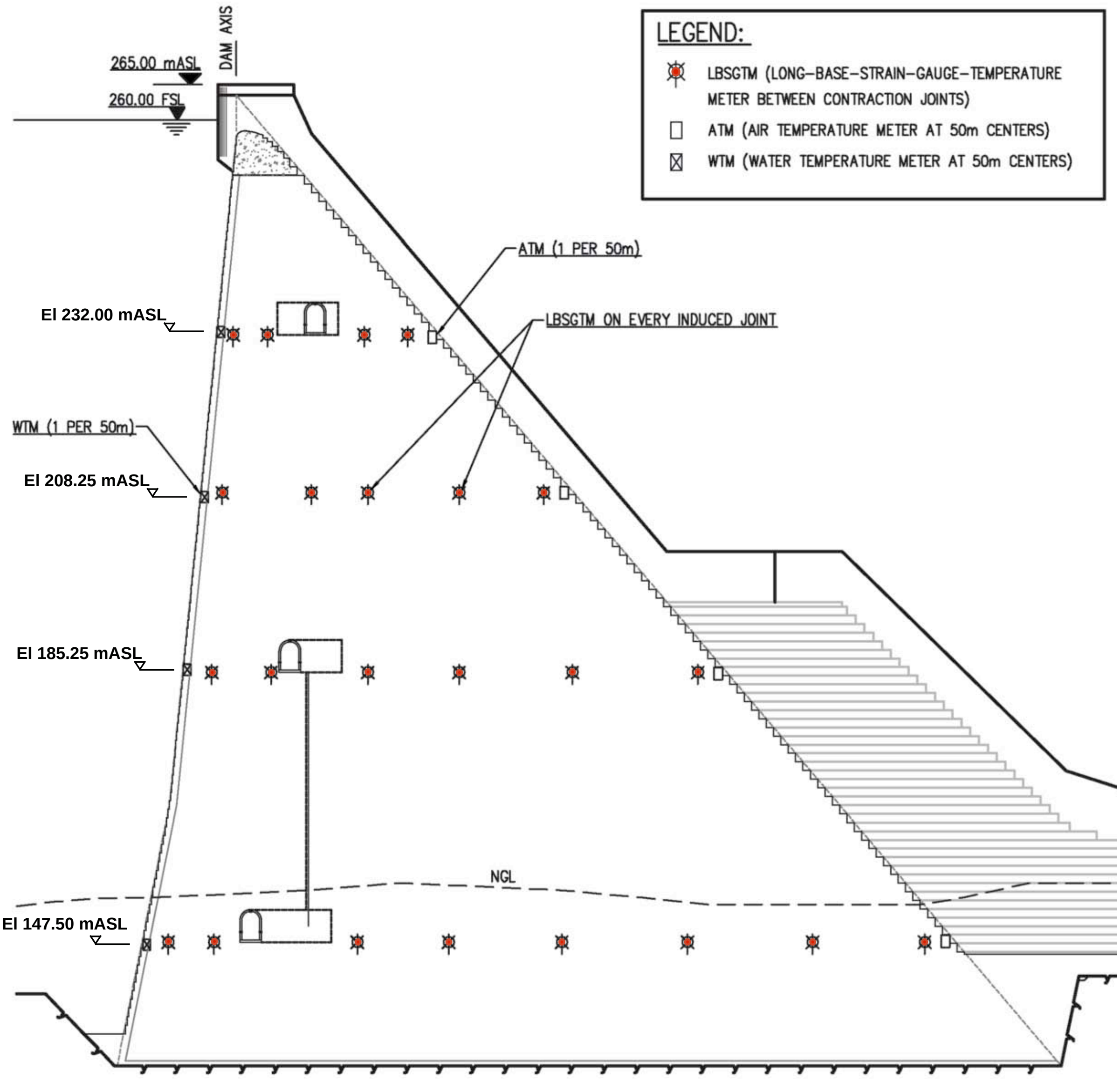

FIGURE 2.12: Typical Instrumentation Installed in Çine Dam(11)

2.10.3. WADI DAYQAH DAM

Figures 2.12 and **2.14** illustrate the typical instrumentation installed in Wadi Dayqah Dam.

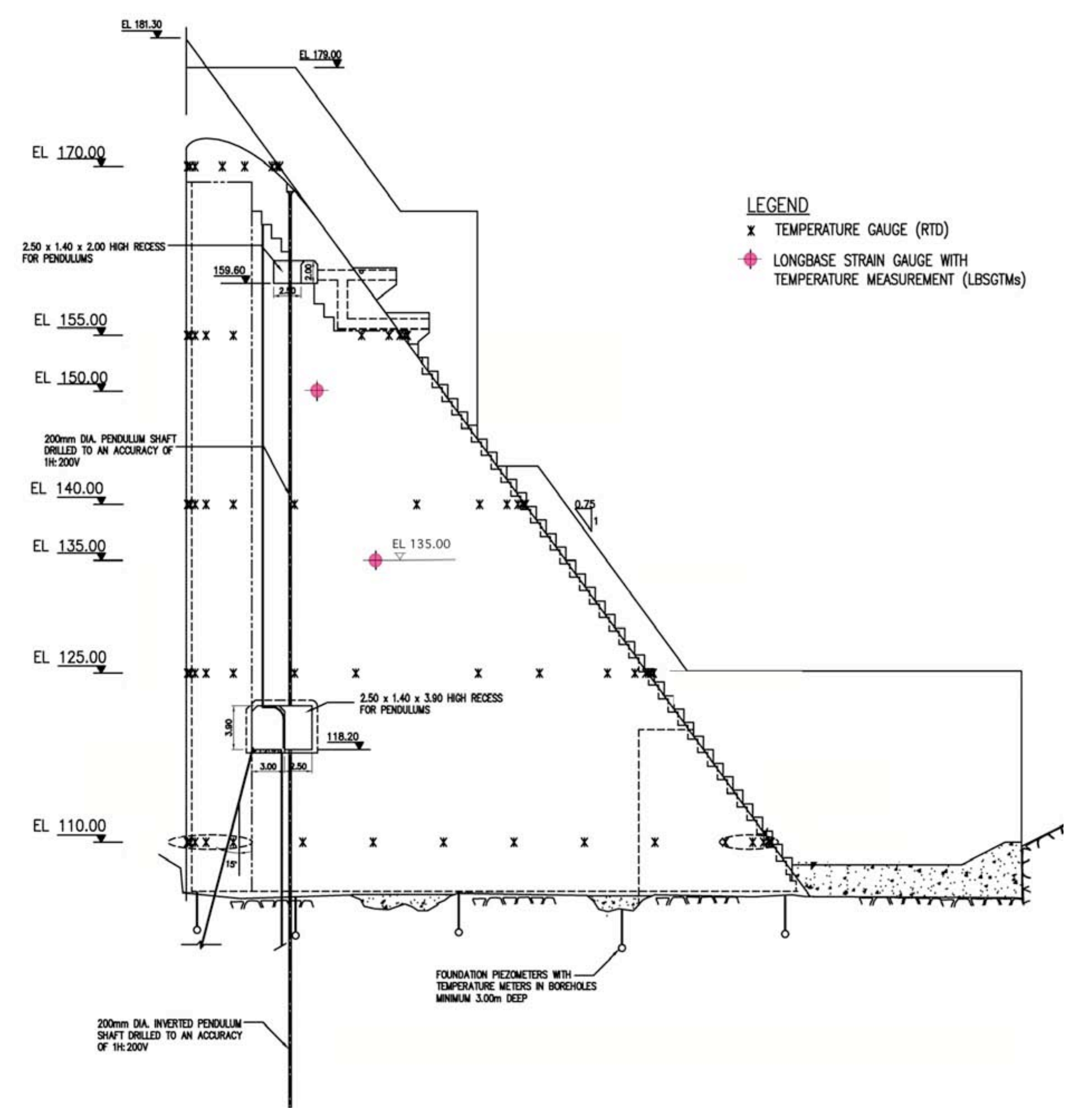

Figure 2.13: Typical Instrumentation - Spillway Section – Wadi Dayqah Dam(13)

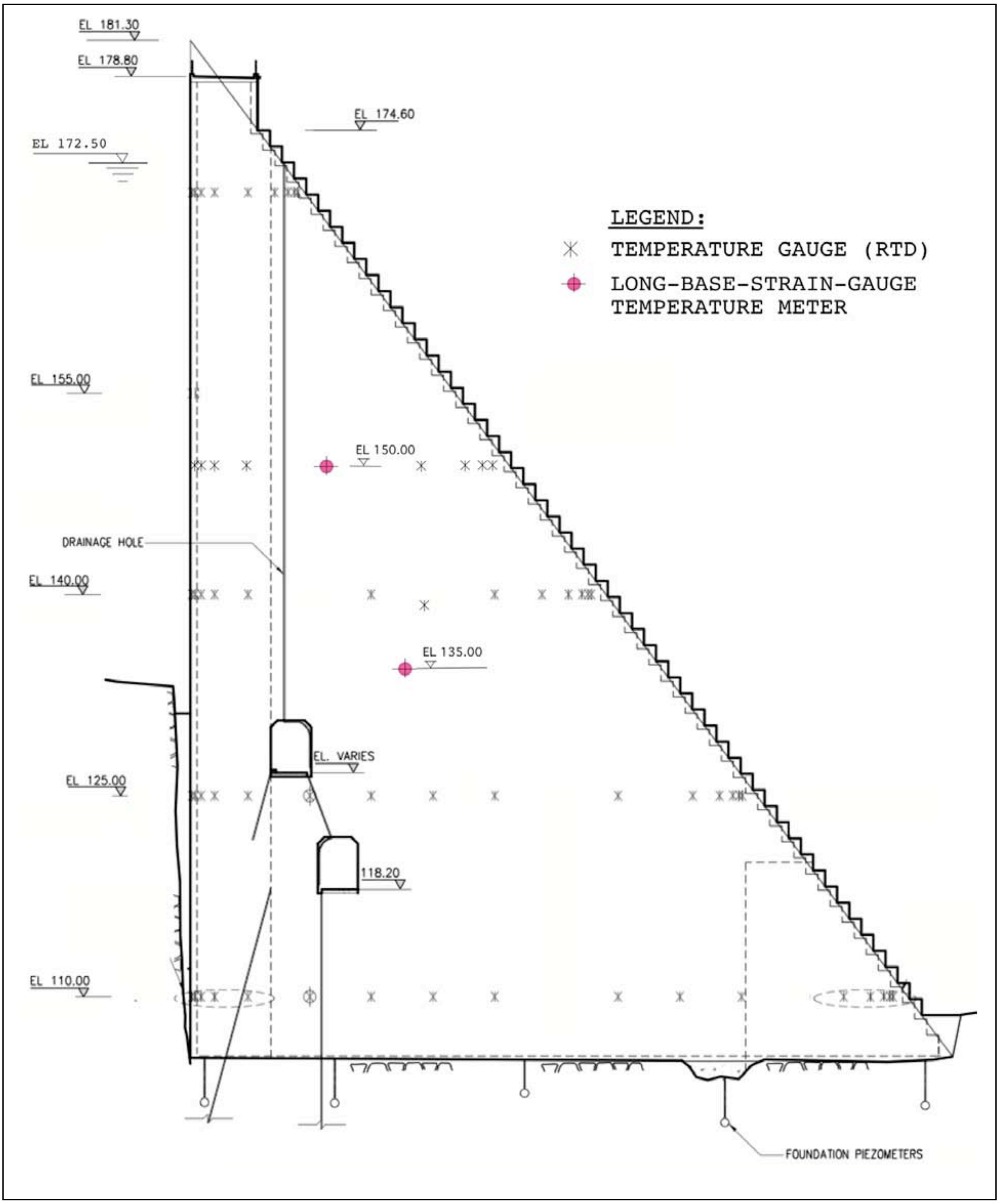

Figure 2.14: Typical Instrumentation - NOC Section – Wadi Dayqah Dam(13)

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