Wadi Dayqah Dams: design modifications in the wake of Cyclone Gonu

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SYNOPSIS: A contract for the construction of a 75m high x 400m long RCC Main Dam on Wadi Dayqah in Oman commenced in June 2006. During foundation excavation Oman was hit by a major cyclone with extensive flood damage to the infrastructure of the region. The unprecedented rainfall (almost one metre in 24hrs at one gauge) called for a review of the design floods which resulted in the 1 in 10,000 year flood being increased from 7,000 to 13,500 m^3/s. Following a study of options it was found possible to design modifications to the dam to accommodate this major increase in design flood with only minor additional cost and without any hold-up of the on-going construction. Hydraulic spreadsheets were used to optimise the design modifications, coupled together with re-assessment of the potential impact on dam stability taking advantage of the "as constructed" strength parameters as measured during the construction.

INTRODUCTION

The Sultanate of Oman is an arid country with few permanent surface water resources. Wadi Dayqah is unique in Oman in that there is some flow throughout the year and studies pursued by the Ministry of Regional Municipalities and Water Resources (MRMWR) in the early 1970s identified Wadi Dayqah as a potential water source. Its catchment area to the sea is almost 2,000 km^2 and average annual rainfall within the catchment is 148 mm. Much of this rain comes from thunderstorms that can give rise to flash floods. Occasionally the region is affected by tropical cyclones that originate in the Indian Ocean but track further north than normal and enter the Arabian Sea. Oman is most likely to be affected during the months of May to November inclusive with June having the highest cyclone frequency.

The Wadi Dayqah project comprises two dams, a water treatment works, pumping station and water transfer pipelines for potable water supply to local towns and to supplement the supply to the capital Muscat. The contract for detail design, preparation of procurement documentation and construction supervision of the dams and water supply scheme was awarded in early 2005 to a Joint Venture led by Black & Veatch International (UK) with NESPAK (Pakistan) and Su Yapi (Turkey).

A hydrological assessment of the available data was carried out as part of the design of the dams. Two key parameters derived from this study were a Probable Maximum Flood (PMF) of 18,400 m^3/s and a 1 in 10,000-yr flood of some 7,000 m^3/s. The spillway on the Main Dam was designed to contain this 1 in 10,000-yr flood within the width of the ogee crest whilst the PMF would be accommodated with overspill over the full width of the dam.

PRINCIPAL RESERVOIR CONSTRUCTION FEATURES (FIG 1)

The Main Dam is 75m high and some 400m overall crest length, designed as a gravity dam and constructed of some 600,000m^3 of roller compacted concrete. The dam is founded within the narrow limestone gorge through which the wadi flows and the foundation rock here is sound and appropriate for this form of construction. An ungated Roberts Type spillway with ogee crest and splitter teeth[1] extends over 200m of the central half of the dam crest. Physical model tests were carried out to confirm the configuration and dimensions of the spillway crest and downstream apron with scaled discharge rates of up to 90 $m^3/s/m$ with a depth of over 10.5m over the crest. The Saddle Dam is nearly 50m high from base of core trench to crest, with a crest length of some 360m. The abutments and foundations of the dams are sealed with a 2.1 km long grout curtain. A fuller description of the construction has been published elsewhere[2].

Excavation of the Central Area between the Main Dam and Saddle Dam started three months into the contract. By June 2007 preparation of the rock foundation for temporary culverts was going well when Oman was hit by a tropical cyclone. Cyclone Gonu brought unprecedented rainfall, widespread flooding and damage to infrastructure throughout the region. At Wadi Dayqah the cofferdams were washed away and the excavation filled with coarse alluvium. The peak flow at the Wadi Dayqah dams site during Cyclone Gonu was estimated to be of the order of 10,000 m^3/s. Such a flow is 40% greater than the original 1 in 10,000-year Design Flood of some 7,000 m^3/s. The unprecedented event clearly merited a review of the hydrology.

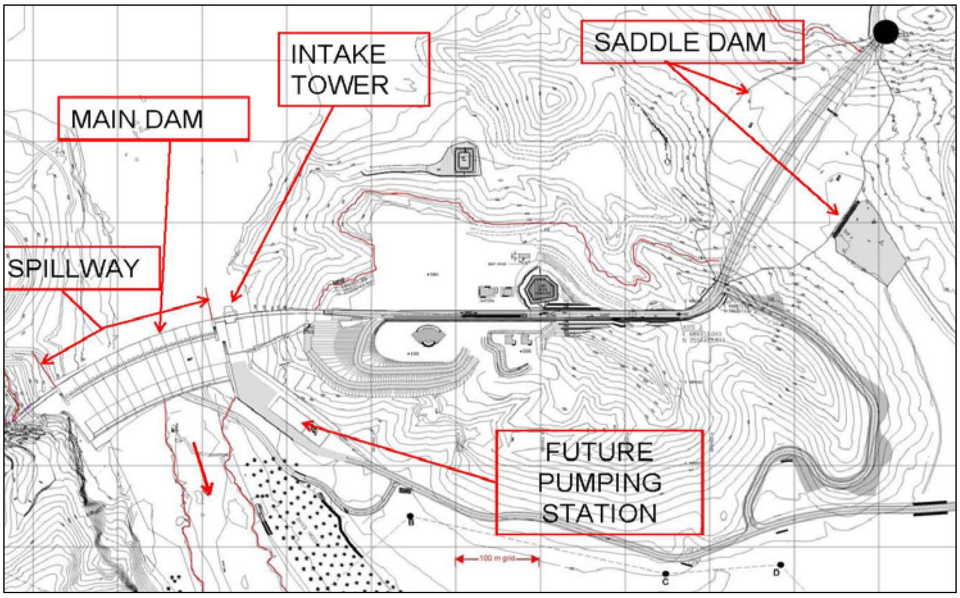

Figure 1. General Layout

POST-CYCLONE GONU HYDROLOGICAL REVIEW

<u>Observed rainfall during Cyclone Gonu</u>

In the immediate aftermath of Cyclone Gonu, reports were received of daily rainfalls of 613 mm at Hayfadh and 515 mm at Taba. Both of these stations are in the Wadi Majlis catchment, immediately to the north of Wadi Dayqah. There were also reports of 848 mm although the location and duration of this rainfall were unclear. Although these were all point measurements they are of the same order, or even exceed, the value of 550 mm in 24 hours used in design flood calculations to represent the PMP (Probable Maximum Precipitation) on the 1688 km^2 catchment to the dam site. Efforts were made to obtain other observations of rainfall during Cyclone Gonu to determine the spatial extent of these high rainfall values.

There are at least 25 raingauges in the Muscat/Wadi Dayqah region of north east Oman although nine raingauges within the dam catchment were apparently damaged or destroyed during the event. Nevertheless, the available data clearly indicate that the storm moved northwards across the region with the highest recorded totals occurring over the Wadi Dayqah catchment or just to the north.

Records are available from three tipping bucket raingauges within the Wadi Dayqah catchment. Two of these (Jabal Al Asfar and Jabal Abyadh East) are on the edge of the catchment, apparently at high elevations. They recorded the highest daily (midnight to midnight) event totals in the region: 736 and 634 mm respectively. Rolling 24 hour totals were even higher. At Jabal Asfar the maximum 30 hour total was 956 mm, 935 mm of which fell in 24 hours. This is over twice the previous highest 24-hr total for Oman, whilst the 12-hr total (725mm) was over five times the highest previously recorded amount. Figure 2 illustrates the storm profile recorded at Jabal Al Asfer. The third functioning gauge in the catchment was at Mazara, just downstream of the dam site. This recorded a much lower daily total of 322 mm which illustrates the uneven distribution of rainfall and the wide variation in storm totals over relatively short distances.

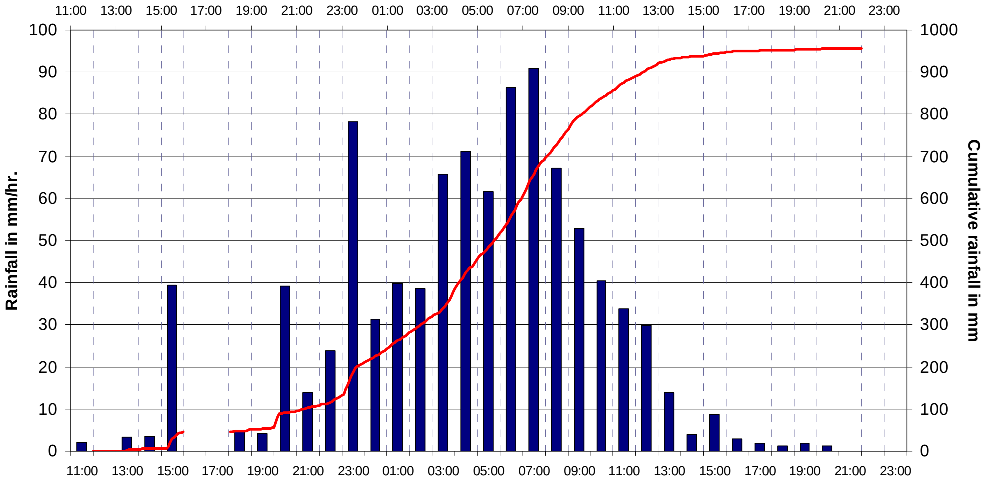

Figure 2. Storm profile recorded at Jabal Al Asfer on 5th/6th June, 2007

<u>Peak discharges observed during Cyclone Gonu</u>

Analysis of peak discharge data for 12 wadis in and around the Muscat/Wadi Dayqah region showed that in 9 of the 12 wadis, the highest recorded discharge occurred during Cyclone Gonu. The data are presented on a plot of maximum discharge versus catchment area (Figure 3) which also includes the various flood estimates for the Wadi Dayqah dam site as well as the Creager and Rodier envelope curves for the World maximum recorded floods. The nearest permanent gauging station to the Wadi Dayqah dam site is at Mazara, approximately 1.5 km downstream of the dam. MRMWR records for this gauge show a peak discharge of 8160 m^3/s during the Cyclone Gonu event. This is presumed to be derived from the maximum recorded water level and the current stage/discharge relationship for the site.

A preliminary estimate by the Chief Resident Engineer immediately after the event assessed the peak discharge at the dam site as being approximately 8,500 m^3/s. This estimate was derived using the Manning formula and the observed hydraulic characteristics of the river channel in the vicinity of the dam site. The calculation assumed that the river carried very large quantities of sediment as bedload, thereby reducing effective depth and the overall fluvial flow. Without this assumed sediment load peak discharge at the dam site would have been of the order of 10,500 m^3/s, possibly greater. Attempts were made subsequently to improve the initial peak discharge estimates by developing a 1-dimensional river model capable of carrying out steady state and transient flow simulations using the available topographical data for a 11 km length of wadi either side of the dam site. The water surface profile for the peak of the flood was defined by water level observations made or estimated at three locations upstream and downstream of the dam. The results of these analyses confirmed the earlier conclusion that the flood at the dam site was of the order of 8,000 to 10,000 m^3/s. For the purposes of flood frequency analysis a value of 10,000 m^3/s was adopted for the peak flood discharge at the dam site during Cyclone Gonu.

Flood frequency analysis of Wadi Dayqah flows

One of the biggest problems for flood estimation in arid zones like Oman is the erratic and infrequent nature of flood discharges. Little or no flow occurs in a number of years while extreme events are several orders of magnitude higher than the average. This leads to very steep flood growth curves (at least for short return period floods) and a difficulty in defining the mean annual flood precisely as this may be greatly influenced by a single extreme event, especially where the record length is short. Large historic events such as Cyclone Gonu therefore have to be included in the analysis with care.

Peak flood discharges and water levels have been recorded continuously on Wadi Dayqah since 1975 with occasional reports of extreme discharges before that (Table 1). The events of 2007 and 1927 stand out as notable extremes but there are other large floods in the record such as 1965. Any frequency analysis based on this one record alone would depend heavily on the weighting given to these extreme events. To avoid the bias introduced by single-station outliers it is necessary to pool all the available data from a large number of stations throughout the region.

Such a regional flood frequency analysis has been carried out by MRMWR and the results presented in their Design Flood Manual for Oman. Their recommended approach for catchments greater than 10 km^2 is to compute an index flood (the mean annual flood or MAF) and apply regional growth curves to obtain estimates of floods of varying return period. The results in relation to the Wadi Dayqah dam site are presented in Table 2.

Table 1: Annual maximum floods recorded in the Wadi Dayqah at Mazara gauging station

Year	**Peak discharge (m^3/s)**	**Year**	**Peak discharge (m^3/s)**
Historic events:			
1927	9950	1965	7750
Recent record:			
1975	3,000	1993	235
1976	2,300	1994	149
1977	1,700	1995	1,740
1978	650	1996	1,430
1979	76	1997	2,160
1980	313	1998	630
1981	0	1999	104
1982	5,190	2000	574
1983	580	2001	72
1984	23	2002	35
1985	18	2003	696
1986	392	2004	29
1987	776	2005	1,830
1988	338	2006	792
1989	0	2007	10,000
1990	776		
1991	218	Mean	1130
1992	530	Median	575

Notes:
1. Source of data – MRMWR, except 2007 (Consultant's estimate)
2. The mean and median values are computed from the recent record only (including Cyclone Gonu but excluding 1927 and 1965).

Table 2. Estimated floods of varying return period at Wadi Dayqah dam site

Return Period (years)	Flood Peak (m^3/s)
25	5,100
100	7,000
1,000	10,200
5,000	12,500
10,000	13,500
PMF	18,400

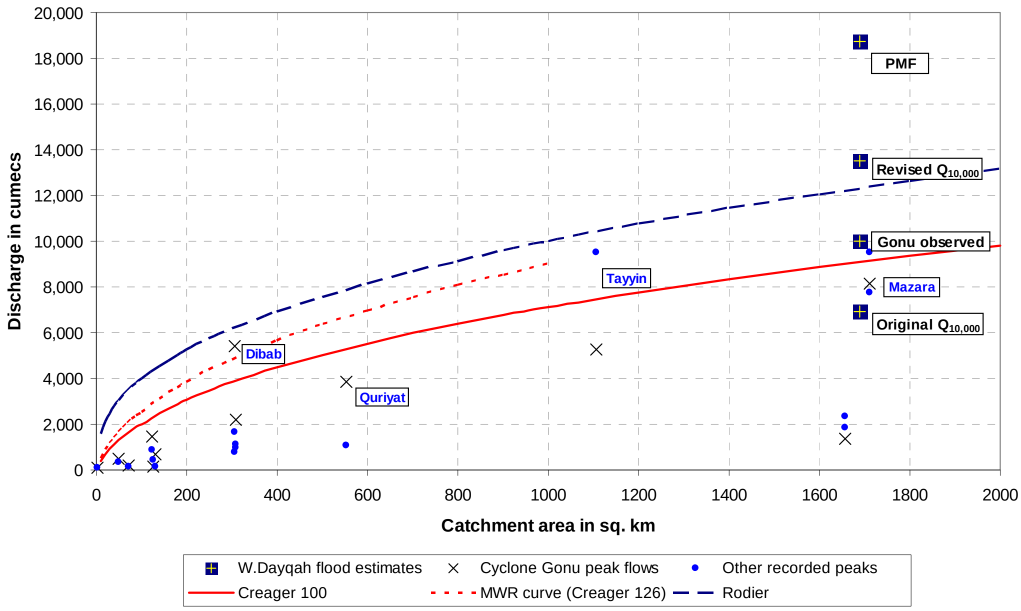

Figure 3. Relationship between peak discharge and catchment area for Cyclone Gonu floods and others

The flood growth curve plots as a straight line on semi-logarithmic paper and reflects a steep rise at lower return periods but a flatter section at high return periods where extreme cyclone events dominate. The peak observed discharge at the Wadi Dayqah dam site during Cyclone Gonu (circa 10,000 m^3/s) equates to an estimated return period of 1000 years and the revised estimate of the 1 in 10,000 year Design Flood is 13,500 m^3/s.

Estimation of the Probable Maximum Flood

To the best of our knowledge, a detailed national study of Probable Maximum Precipitation (PMP) over Oman has not as yet been carried out. Without this, simple statistical methods have to be relied on.

The original design flood calculations for Wadi Dayqah dam used the standard Hershfield approach presented in the WMO manual for PMP estimation and recommended in the Design Flood Manual for Oman. The method employs the mean annual maximum 1-day rainfall recorded in the region and produced a 24-hour PMP rainfall of 550 mm for the 1700 km^2 Wadi Dayqah catchment. This in turn produced an estimated peak discharge of 18,400 m^3/s at the dam site.

It is clear that point values of 24-hour rainfall considerably greater than 550 mm occurred in and around the Wadi Dayqah catchment during

Cyclone Gonu. However, rainfall over the catchment as a whole is not known. The ratios of point to areal rainfall are poorly understood in Oman, as elsewhere, and the Design Flood Manual for Oman gives an aerial reduction factor (ARF) of 60% for a 1-hour rainfall rising to 91% for a 24-hour total over the 1,700 km^2 catchment. The spatial variation in rainfall observed during Cyclone Gonu was greater than this and the use of larger reduction factors would seem justified.

The review looked at the PMF estimate in a wider context. Whilst it is true that PMP rainfall does not look large relative to the highest Cyclone Gonu point totals, the computed PMF peak discharge does look large compared to envelope curves of world maximum floods. The PMF peak of 18,400 m^3/s is 200% of the Creager 100 value for the corresponding area[3] and 150% of the value from the Rodier curve[4] (Figure 3).

Flood Design Criteria

The design flood selection followed general UK practice for dams as this has historically been the norm in Oman, making the dam Category A. The spillway works were therefore designed such that floods up to the 1 in 10,000 year flood would be accommodated by the Main Dam spillway and floods in excess of the 1 in 10,000 flood and up to the PMF, will also spill over the dam roadway crest. Some damage will be accepted for PMF conditions, provided the works remained stable and without major failure. Without any design changes the increase in the 1:10,000 year flood resulting from the re-assessment of the hydrology would result in spilling over the dam roadway on more frequent occasions (1 in 100 year flood), thus failing to meet the original design criteria.

The model tests on the 196m long central overspill indicated good hydraulic performances up to a unit discharge of 72.5 $m^3/m/s$ and with an unstable, but acceptable, performance up to the maximum unit flow tested of 84.2 $m^3/m/s$. These corresponded to discharges over the central spillway section of 14,200 m^3/s and 16,500 m^3/s respectively. The latter case was the 18,400 m^3/s PMF event with additional water passing over the dam road crest.

OPTIONS REVIEW

Options were reviewed to identify practical modifications which would accommodate the revised design floods, meet design criteria acceptable to MRMWR and be initiated at the current stage of construction with least implications on project cost and programme.

The principal means available for increasing spillway capacity were:

(a) increasing depth over the spillway by raising the crest roads on either side.

(b) increasing depth over the spillway by lowering the crest of the spillway

(c) lengthening of the spillway crest

(d) re-introducing an auxiliary spillway (part of the original tender design).

(e) introduction of gates, fuse gates or fuse plugs to cater for extreme events.

Design Checks were carried out to establish the combined effects of spillway widening and dam crest raising. Reducing the crest level of the spillway would reduce the storage capacity of the reservoir which was unacceptable to the Ministry.

Whilst these investigations were being carried out, construction continued, including the casting of the spillway apron and the start of placement of the Roller Compacted Concrete for the Main Dam.

Following an initial review the Ministry opted to follow a recommendation from their Panel of Experts for the Main Spillway to be modified to accommodate a flood of similar size to that experienced in Cyclone Gonu and for greater floods to over top the full width of the dam.

Effects of over-topping

In addition to the potential operational inconvenience of an increased probability of over-topping of the crest road, a more significant consideration is the increase in the probability and severity of damage to the unprotected abutments and to the installations at the left bank toe of the dam. On inspection, the scale of works required to contain the energy resulting from 350 m^3/s of water cascading down the dam would be considerable. After considering various options the Panel of Experts suggested the addition of a sacrificial pre-cast parapet in place of the upstream hand railing on the raised crest of the dam. The design was to contain the 1 in 10,000 year flood but not to impede a PMF flow and thus not increase the ultimate loading on the dam in the PMF. The concept of fused gates had been considered previously but was not at that time favoured by the client. The Panel's suggestion was developed into a counterbalanced pre-cast parapet which replaced the handrailing on the upstream side; could be accommodated within the limited width of the original crest; provided a practical and inexpensive means of containing the

1 in 10,000 year flood and thus met the designers' intended safety criteria in line with internationally established dams safety practice.

The final modifications comprised:

- Lengthening Main Spillway crest and apron by 6m towards Right Abutment
- Raising Main Dam Crest Roads by 1.65m
- Providing pre-cast parapet wall in place of upstream hand railing
- Adjusting curvature of spillway crest to accommodate increased maximum expected depth
- Raising Intake Tower so that top access floor level is at 180.45m to match revised road crest.
- Providing solid concrete parapet on top of Left Abutment apron wall in place of hand railing
- Raising crest of Saddle Dam by 0.31m to maintain freeboard in PMF

DESIGN CHECKS

Hydraulics

The arrangement of splitter teeth as originally designed was shown to give a reasonable flow separation for the range of flows investigated in the original model tests. In the situation where design changes were being proposed during construction one aim was, if possible, to keep the hydraulic characteristics of the spillway discharge within the range of conditions investigated by the original model tests. This proved to be achievable. Design checks using data from Tropical Cyclone Gonu indicated that in practice tailwater levels in extreme floods are likely to be higher than were assumed at the time of the model tests, hence performance of the apron is expected to be better than recorded in the model tests at the higher unit flows.

Main Spillway Discharge & Reservoir Levels

Various combinations and permutations of spillway arrangements were investigated by hydraulic spreadsheet in reviewing options.

Spillway Crest Discharge Coefficient

The design check on the hydraulic spreadsheet included a review of the discharge coefficient in relation to increased depths. The depth v. discharge coefficient relationship was confirmed as valid for the range of depths relating to the proposed modifications.

Spillway Crest – Cavitation

The increases in depth over the spillway at peak flow are relatively modest but sufficient to push the ratio of "design flow depth / expected maximum flow depth" into the region in which there is the potential for cavitation[5]. Minor adjustment to the curvature of the upstream side of the crest kept the ratio within published guidelines at minimal cost.

Validity of original Model Test results

The spillway model tests carried out for the original design investigated discharges rates of up to 84.2 m3/m/s and concluded that the design provided adequate performance in the context of a PMF. The calculated PMF discharge rate for the Design Modifications is 84.5 m3/m/s, at a depth over the crest of 11m.

Main Dam Stability

An increase in water level in the reservoir increases the loading on the dam. Initial analyses using the same parameters as used at the time of the original design indicated little scope for accommodating an increase in water load. Although the factors of safety were acceptable for normal operating conditions and for the 1 in 1000 years flood events for the extreme case of the PMF the factors of safety for overturning stability fell below the acceptable target value of 1.20. In the case of a PMF flood level of 183.41m retained within the reservoir by a raising of the roadway section of the dam the factor of safety against sliding fell below unity.

Assumptions, such as concrete characteristics, made at the time of design are necessarily conservative, so the opportunity was there to look at these again. With construction well under way it was possible to use the concrete characteristics as measured for the material as placed and to recognise the quality of construction being achieved. Check stability analyses for the Design Modifications therefore adopted an increased concrete density of 2.5 tonnes/m^3 with an internal friction angle of 45^o and cohesion of 600kPa, and a residual effective cohesion for the concrete in sliding of 100 kPa. Separate analyses carried out for the Crest Road cross section and for the Spillway overflow cross section showed that the cross sections proposed in the Design Modifications met the original design criteria for factors of safety under the various defined load conditions.

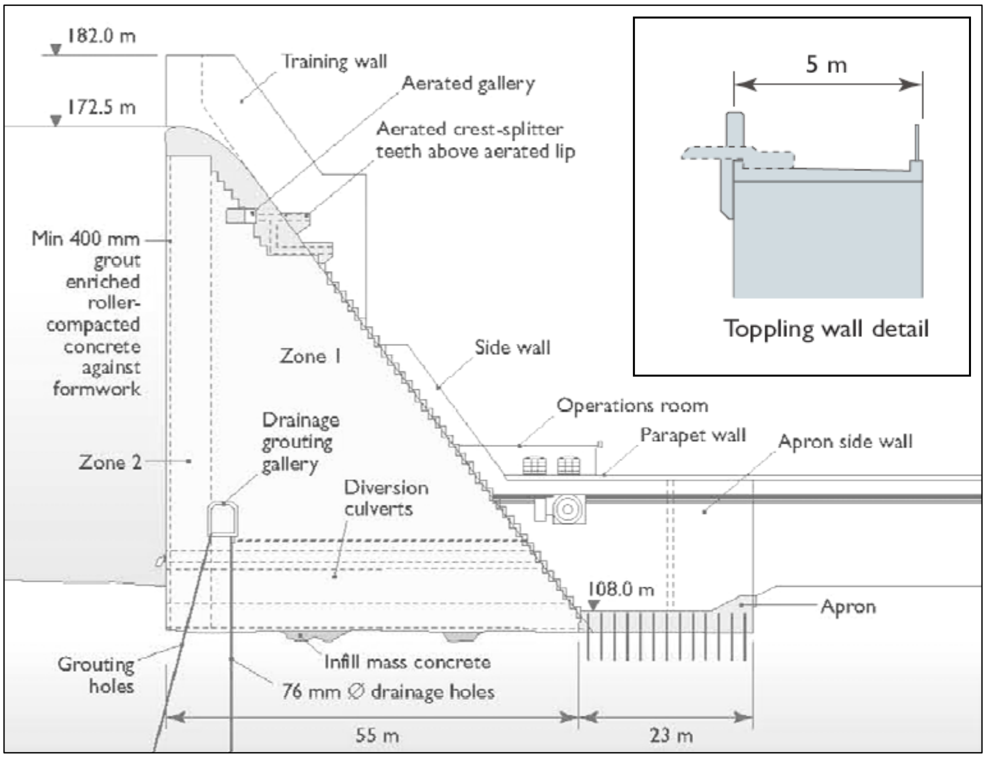

Figure 4. Main Dam cross-section

COUNTER BALANCED PARAPET WALL – DESIGN AND TESTING

The counter balanced parapet wall was introduced with the aim being to contain the 1:10,000 year flood, but to topple over in the event of significantly larger flood. Reducing the PMF maximum water level upstream of the dam by only 600mm was sufficient to meet the original design criteria for stability of the main dam cross section and to keep the PMF discharge rate over the main spillway within the validity of the previous model tests.

The wall was designed to tip when the upstream water level was overtopping the wall by 250mm to 300mm, although in practice it will be adequate for the wall to tip with the upstream water level between the top of the wall and one metre above. Experience from wave loadings on marine structures indicated that the transient pressures from waves would impact both the upper wall and lower counterbalance leg of the wall at similar times and balance each other out.

A 0.5m wide full scale unit was constructed of reinforced concrete and set up in a purpose built concrete flume to put the theory to the test. The prototype tests were sufficient to demonstrate that the wall units will function as required. Bedding the wall on mortar (as intended by the design) had a significant effect on the water level required to tip the unit.

Without a mortar bedding (or other such seal) the effect of the uplift below the wall made the wall tip prematurely.

CONSTRUCTION METHODS & PROGRAMME

The proposed modifications were selected so that they could be constructed by the Contractor using the same materials, methods, equipment and tower crane layouts as were being used to construct the original design.

Water in the wadi had been diverted into the culverts in November 2007 followed by construction of the dam without further floods; indeed in the 18 months following Cyclone Gonu less than 5 mm of rain was recorded at the dam site. At the end of June 2008 when the revised proposals were finalised the RCC in the Main Dam had been placed to approximately 20m above foundations and the Intake Tower to almost full height with the final pour "on hold" pending confirmation of Main Dam crest level. At the downstream toe of the Main Dam the apron was still under construction. The only area of conflict between the proposed design modifications and the works constructed at that date was at the toe of the right abutment of the Main Dam but this was readily overcome by relatively minor modifications to the 17m high wing walls.

Figure 5: Wadi Dayqah Main RCC Dam downstream face: Last concreting to spillway crest (June 2009)

The concreting of the body of the Main Dam was completed in May 2009, six weeks ahead of programme. By August 2009 the diversion culverts were closed and impoundment began. The completed Wadi Dayqah reservoir will capture flood waters that were previously lost to the sea and create an important strategic water reserve to help assure the water supply to Quriyat and Muscat.

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