The design and construction of Neckartal Dam

Edwin Lillie
Knight Piésold Consulting
Rivonia, South Africa

Gawie Steyn
Knight Piésold Consulting
Pretoria, South Africa

Introduction

Neckartal Dam is located on the Fish River, a tributary of the Orange River. The project will supply bulk water to a new irrigation scheme located 40km south-west of Keetmanshoop in Namibia. Keetmanshoop has a desert climate. The daytime temperature often rises well above 30°C during the summer and the mean annual precipitation is less than 150mm.

The construction of Neckartal Dam started in September 2014. The Employer is the Namibian Ministry of Agriculture, Water and Forestry. The Contractor is Salini Impregilo S.p.A and the engineering design and site supervision is being undertaken by Knight Piesold Consulting (Pty) Ltd. Neckartal Dam is the largest dam currently under construction in Southern Africa. Neckartal dam will be 78.5m high, with a crest length of 518m and a gross storage capacity of 857 million m³. The main dam wall contains over 900 000m^3 of RCC. The dam outlet releases water through two Francis turbines to an abstraction weir and pumping station located 13km downstream. Neckartal Dam will be the largest dam in Namibia and the eight largest dam in Southern Africa by storage volume. It is a very important development project for the Namibian government and is aimed at stimulating economic growth in the Southern Region of Namibia. This paper describes some of the challenges faced during the design and construction.

Necartal dam has to accommodate very large floods, both during construction and operation. The PMF is over 20 000 m^3/s. The diversion during construction has been undertaken in three phases, which included phasing for the dry season and wet season floods to provide an economic solution. The spillway was modelled tested and an optimum solution developed for the curved spillway.

The foundation material at the dam site has a low shear strength which is characteristic of horizontally bedded silt and sandstone found in the dam foundations. A number of large shear box tests were undertaken on the foundation material to determine the shear strength of the bedding planes. A 3D finite element model was developed to determine the optimum geometry and check the stability of the dam. The upstream face of the dam was given a 1 to 5 slope, a key was added to the dam foundation and the apron was provided with extra dowels to increase the sliding stability.

Neckartal dam is remotely located, approximately 1000km from the nearest cement factory located at Tsumeb in Northern Namibia and 1500km from the closest fly ash sources located in the highveld region of South Africa. This required an innovative approach to the RCC mix design. A key objective for the RCC mix design was to reduce the cementitious content and therefore a significant proportion of the overall project costs. This is being achieved by using the latest developments in RCC technology to adopt mixes suited to this remote site. Two quite different RCC mixes are used in the dam, a higher cementitious mix for the upstream face to provide an impermeable barrier and a lower cementitious mix in the core of the dam. With the aid of an RCC expert both the mix and aggregate specifications were carefully developed to ensure an economic solution. Through laboratory testing and trial sections the design mixes were furthered optimised. RCC needs to be placed in hot dry temperatures increasing the ratio of cold to hot joints and the potential of temperature induced cracking. This was mitigated by using a low cementitious mix for the dam core and by using retarders to reduce the set time. The Contractor was encouraged to place the bulk of the RCC during the winter period, which increases the set time and reduces the built in heat. A thermal model of the dam was developed to determine the optimum joint spacing.

A hydropower plant was included in the dam outlet to benefit from releases made to the downstream irrigation scheme. This resulted in a complex outlet arrangement. This was further complicated by the very steep left bank where the outlet is located. Using both the latest 3D CAD software and the latest experience in dam engineering in Southern Africa the outlet structure was designed to accommodate these requirements.

1. Neckartal Dam

1.1 Dam statistics

Neckartal Dam will be the largest dam in Namibia and the eight largest dam by storage volume in the Southern African region. The principal details of the Neckartal Dam are summarised in Table 1.1.

Table 1.1: Neckartal Dam statistics

General and Hydrological		Dam Statistics	
Location	26° 37' 30" S 17° 42' 51" E	Full Supply Level	787.5m
Catchment Area	45 620km^2	Non-Overspill Crest Level	796.5m
Mean Annual Precipitation	138mm	River Bed Level	725m
Mean Annual Evaporation	2510mm	Lowest Foundation Level	718m
Mean Annual Runoff	535 x 10^{6}m^3	Storage Capacity at FSL	857 Mm^3
Mean Annual Sediment Volume	74m^3/km^2	Reservoir Surface Area	3 980ha
Material Volumes		Dam Height above River Bed	71.5m
Excavation	368 000m^3	Dam Height above lowest foundation level	78.5m
RCC (Zone 1)	177 000m^3	Dam Crest Length	518m
RCC (Zone 2)	750 000m^3	Upstream slope	1.0V : 0.2H
GEVR	89 300m^2	Downstream slope	1.0V : 0.7H
Mass Concrete	31 560m^3	Recommended Design Flood	9 210m^3/s
Reinforced Concrete	75 460m^3	Safety Evaluation Flood	26 610m^3/s

1.2 Climate

The long-term average temperature at Keetmanshoop is 21°C. The long-term average winter temperature is 15°C while the long-term summer temperature is 26°C (October to December). The Neckartal dam site is 40km west of Keetmanshoop and approximately 200m to 300m lower in elevation. Therefore the temperature (See Table 1.2) at the site can be expected to be slightly higher than at Keetmanshoop.

Table 1.2 : Climate data for Keetmanshoop 26° 53' S 18° 11' E (1061masl)

Temperature (°C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average	26	27	26	22	18	15	13	16	20	23	24	26
Average Maximum	35	35	33	30	26	23	21	24	28	31	32	35
Average Minimum	18	19	17	15	11	7	6	7	10	13	15	17

At Keetmanshoop the average annual rainfall (MAP) is 138mm, according to the rainfall gauge 04191829 – Keetmanshoop Airport. The monthly average rainfall is summarised in Table 1.3 for the period 1949 to 2010.

Table 1.3: Monthly average rainfall at Keetmanshoop Airport

Average Monthly Rainfall (mm)												
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Precipitation	25	42	31	17	5	2	1	1	3	6	11	12

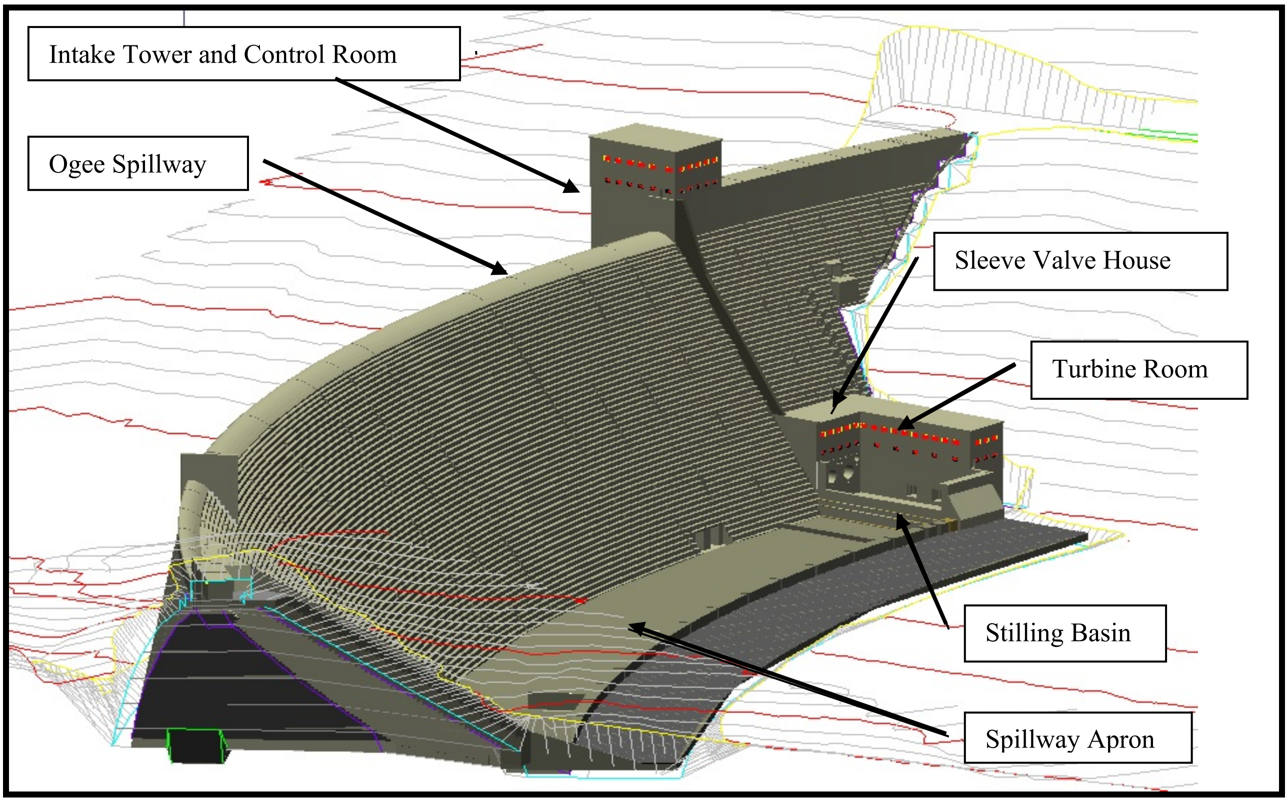

Figure 1.1: Neckartal Dam (Isometric view)

Figure 1.2: Neckartal Dam September 2016 (View from top of the right bank)

2. Large design floods

The Neckartal Dam has a catchment of 45 620km² of which an area of 13 787km² comprises the upstream Hardap Dam catchment. The analysis philosophy involved calculating the flood peak entering Hardap Dam, which in turn was then routed through the Hardap Dam, producing a routed outflow. The flood peak calculated for the incremental catchment lying between Hardap Dam and Neckartal Dam was then determined. Finally the two flood peaks, viz. the routed outflow from Hardap Dam and the incremental catchment flood peak, were superimposed on each other, producing the total inflow hydrograph for Neckartal Dam. This inflow hydrograph was then routed through Neckartal Dam. The recommended flood peaks for the Neckartal Dam catchment are summarised in Table 2.1.

Table 2.1: Recommended flood peaks for the Neckartal Dam catchment

Return Period (Year)	Recommended Values (m^3/s)
5	1006
10	3030
50	6060
100	8000
200	9210
RMF (k=4.6)	15720
PMF	21610

Figure 2.1: Neckartal Dam Spillway Model

2.1 Spillway design

The dam has been designed as a Category III dam in terms of the SANCOLD guidelines. The dam must be capable of passing the Recommended Design Flood (RDF) with sufficient freeboard, as well as the Safety Evaluation Flood (SEF) with zero freeboard. The RDF was selected as the 1:200-year event or 9 210 m^3/s and the SEF was selected as the PMF or 21 610m^3/s. Numerous options were investigated for the spillway configuration. The selected option was to increase the spillway to the maximum practical length to reduce the unit flow concentrations down the stepped spillway which suits RCC construction. This resulted in a 395m long ogee section, requiring a chute down the right flank to bring the flow back into the river section, which is approximately 240m wide at the dam site. This design was optimised using a physical model. The flow concentration for the RDF is 25m3/s/m. For spills greater than the RDF or 1:200year event, it was accepted that some erosion damage to the spillway could be tolerated.

2.2 River management during construction

In view of the fact that the main dam RCC works are substantially less sensitive to overtopping by low probability floods than is the case for most other dam types, a 5-year recurrence interval was adopted for river diversion design. The measured river flow peaks during the winter period are substantially lower than those measured during the summer months, therefore the river diversion strategy was divided into a wet season and a dry season. This resulted in a very economic river diversion. The river diversion was also divided into three phases which allowed the Contractor to work in specific areas during the construction of the permanent works. The river diversion also capitalised on the very wide river valley section.

Phase 1 of river diversion works diverted the flow to the right bank with the construction of a large coffer dam. This allowed work to continue on the left bank, the intake tower, the RCC conveyor and the diversion culvert during phase 1.

Phase 2 of the river diversion diverted the flow through the diversion culverts with the construction of new coffer dams on the left bank. This allowed the construction of the RCC dam and apron slab in the river section towards the right bank.

Phase 3 requires the river to be diverted through the culverts with the aid of the dam. The Contractor should maintain a 60m wide section of the dam at a level (3m below the working surface) during the wet season. As the dam height rises, the diversion capacity does increase. The intake tower must lead the RCC by a minimum of 5m during the wet season.

3. Design for a foundation with a low shear strength

The geotechnical conditions at the dam site were investigated by geophysical surveys, the drilling of 24 rotary cored boreholes and the testing of rock core samples in a laboratory to determine the rock quality and strength. Water pressure tests were performed in the boreholes to determine the in situ permeability of the foundation rock. The dam site is underlain by red **sandstone and shale** of the Gross Aub and Nababis Formations of the Fish River Subgroup, Nama Group. These sedimentary rocks can be subdivided into a number of regressive cycles of sedimentation, mainly of an alluvial fan origin. The geological contacts between rock types at Neckartal are often not well defined, but rather consist of a gradual transition with depth. The rock formation below the dam foundation comprises mostly sandstone with siltstone bands, becoming siltstone with sandstone bands below an average depth of 10m. Two fault lines occur in the vicinity of the dam site. The properties of the foundation rock as determined by laboratory tests are as follows:

- Unconfined Compression Strength (UCS)
    - unweathered sandstone : 130MPa
    - unweathered siltstone : 260MPa
- Elastic modulus of rock mass ($\mathbf{E_{mass}}$)
    - sound sandstone rock : 21GPa
    - sound siltstone rock : 13GPa
- **Shear strength parameters on bedding joints**
    - **friction angle (Φ) : 33°**
    - **cohesion (c) : 55kPa**
- Density
    - Sandstone : 2600kg/m³
    - siltstone : 2670kg/m³

3.1 Dam Type Selection

In the past, it had been suggested that a rockfill dam is constructed at the Neckartal dam site. Because there is no substantial clay source available in the vicinity of the dam location, it follows that a rockfill dam will require a reinforced concrete face, or an asphaltic or concrete core to provide a water tight structure. The alternative is a concrete gravity dam, more specifically a roller compacted concrete (RCC) dam. The dam spillway must be capable of passing the RDF of 9 210m³/s with sufficient freeboard and the SEF of 21 610m³/s with zero freeboard and without catastrophic damage. In terms of the RDD, the aim is normally to restrict the unit flow through a stepped spillway to less than 28m³/s/m width, which relates to a spillway length of at least 328m for Neckartal Dam. The river section at the dam site is 240m wide. The geotechnical investigation identified a suitable source of dolerite for concrete aggregate approximately 10km from the dam site, which supported the preference for an RCC gravity dam. The substantial spillway requirement can be accommodated into the RCC structure, which combined with a shorter construction time and lower cost, resulted in the RCC gravity dam option being selected.

3.2 Dam layout

The full supply level (FSL) of the dam was fixed at RL 787.5m, with the lowest foundation level in the spillway area at RL 718m. The maximum height of the spillway section is 69.5m and that of the non-overspill section is 78.5m, making Neckartal Dam the highest dam in Namibia. The dam is a 518m long mass gravity RCC dam. The dam wall curves along a 500m radius. The river section is very wide, and the left bank is much steeper than the right bank. The dam will have two galleries for grouting, drainage and instrumentation. There will be a chute down the right flank to maximise the length of the spillway.

3.3 Dam Stability Analysis

A Finite Element Method (FEM) stability analysis was undertaken to investigate the stability of the dam wall. A 3D model of the basic dam wall structure with the excavation profile on the flanks was used in the analysis. When using FEM analyses the acceptance criteria focus on acceptable stress and strain conditions in the structure, while the concept of a factor of safety has less significance, although equivalent safety factors were determined by changing the load factor by 10% increments until failure occurred. In terms of overturning stability the selected section has factors of safety well in excess of the required values, however sliding stability was problematic due to the low shear strength of the foundation material. The upstream face of the dam was sloped at 1V to 0.2H and a shear key added to ensure that the factors of safety remain within the design requirements.

4. RCC mix design for a remote site in the dessert

Neckartal dam is remotely located, approximately 1000km from the nearest cement factory located at Tsumeb in Northern Namibia and over 1500km from the closest fly ash sources located in the highveld region of South Africa. The daytime temperature often rises well above 30°C during the summer and the mean annual precipitation is less than 150mm. These constraints required an innovative approach to the RCC mix design. A key objective for the RCC mix design was to reduce the cementitious content and therefore a significant proportion of the overall project costs while having a mix which is still easy to work, compacts well and has a relatively long set time to minimise the number of cold joints. This was achieved by using the latest developments in RCC technology to specify and the develop mixes suited to this remote and very hot site. The approach adopted was to use two different RCC mixes in the dam, a higher cementitious mix for the upstream face to provide an impermeable barrier and a lower cementitious mix in the core of the dam to reduce cost as far as possible. The RCC mixes and both coarse and fine aggregate specifications were carefully developed with the aid of an RCC expert to ensure an economic solution for the site. Through on-site laboratory testing and trial sections, the specified design mixes were furthered optimised and improved. These mixes were also further tweaked during construction. Set retarders were used in both mixes to increase the set time. The set retarders are varied according to the prevailing weather conditions.

For Neckartal Dam, it was decided to use a 20/38 high cementitious mix for a 6m impermeable zone (Zone 1) in the upstream face of the dam and a 10/38 with a low cementitious but still with a relatively high paste content for the main body of the dam (Zone 2). This was achieved with a tight specification for the fine aggregate.

Table 4.1: RCC Mixture specified ranges and adopted RCC mix parameters

RCC	Fines Volume (ℓ/m³)	w/c ratio (by weight)		Vebe Grade (s)		Agg. Size (mm)	Sand / Agg. Ratio (by weight)		P / M Ratio (by volume)
	Min	Min	Max	Min	Max	Max	Min	Max	Min
Zone 1 (20 MPa)	20	0.60	0.65	8	15	38	0.39	0.42	0.40
RCC Mix 51	**76**	**0.64**		**13**		**38**	**0.42**		**0.46**
Zone 2 (10 MPa)	35	1.2	1.5	25	35	38	0.35	0.40	0.36
RCC Mix 52	**30**	**1.38**		**19**		**38**	**0.40**		**0.41**

Table 4.2: Specified Range of Mixture Proportions and adopted mixtures number 51 and 52

Material	Range of mixture proportions (kg/m³)			
	Zone 1 Specification (Grade 20/38)	**Zone 1 - Mix 51 (Grade 20/38)**	Zone 2 Specification (Grade 10/38)	**Zone 2 - Mix 52 (Grade 10/38)**
Type I Portland Cement	60 - 65	**65**	65 - 80	**65**
Pozzolanic material	110 - 140	**120**	0 – 20	**20**
Free water	110 - 130	**119**	100 - 120	**117**
Coarse aggregate	1300 - 1400	**1370**	1350 - 1550	**1500**
Fine aggregate	880 - 960	**990**	800 - 950	**1001**
Set retarding admixture	1 - 4	**1.1**	1 - 4	**1.2**

Table 4.3: RCC Quality Control testing results and average values and (the standard deviation)

RCC Zone	Temperature spread (°C)	Vebe time site (s)	Initial set on site (hr)	Final set on site (hr)	Compacted density (kg/m3)	Compacted density (%)	Comp. Strength 28 day (MPa)	Comp. Strength 180 day (MPa)	Tensile. Strength 180 day (MPa)
Zone 1	21.9 (+/-3.5)	11 (+/-2.0)	10	11	2663 (+/-16)	99.0 (+/-0.6)	16.1 (+/-2)	35 (+/-3.1)	1.5 (+/-0.21)
Zone 2	21.2 (+/-3.5)	28 (+/-2.5)	6	9	2684 (+/-25)	98.4 (+/-0.6)	15.6 (+/-2)	22.4 (+/-2.3)	1.2 (+/-0.16)

5. Dam outlet works including two turbines

Neckartal Dam is primarily for irrigation purposes. Water will be released into the river from the dam to be abstracted from the river some 13km downstream. The outlet works for Neckartal Dam serves the purposes of releasing the active storage in accordance with the irrigation and environmental release requirements.

The Neckartal Dam outlet works are located on the left bank. All isolation and control valves will be accessible from the downstream outlet control house, while the maintenance bulkhead gate will be stored on the dam non-overspill crest and operated using a permanent gantry crane. As a consequence of the infrequent movement and mixing of the live storage, stratification of the stored water is anticipated. In order to deal with the phenomenon and to enable water of an environmentally desirable temperature and quality to be released, provision has been made for selective withdrawal from the reservoir. A multilevel intake is has been constructed for the low capacity outlets at Neckartal Dam, while a single, bottom level intake is provided for the high capacity system.

The **high capacity outlet** takes the form of two 3000mm diameter pipes, with bellmouth intakes, in a trash rack box, which can be isolated using bulkhead gates lowered down slots from the crest and sealed against steel sealing frames cast into the concrete around the bellmouth intakes. The pipes run parallel, cast into the body of the dam and emerging in a sump at the toe of the dam structure, where flow will be released through 3000mm diameter butterfly valves. Discharges will be controlled using 1800mm diameter hooded sleeve valves immediately downstream of the butterfly valves. The sleeve valves will discharge into a stilling basin.

The **low flow release system** consists of two 1600mm pipe stacks. The intakes to the pipe stacks will be staggered at 6.0m intervals to allow for flexibility in selecting the most appropriate abstraction level. The pipe stacks can be isolated upstream with a bulkhead closure gate and butterfly valves, with discharges controlled downstream by means of 800mm and 400mm sleeve valves. The low flow release system also branches off to the turbines.

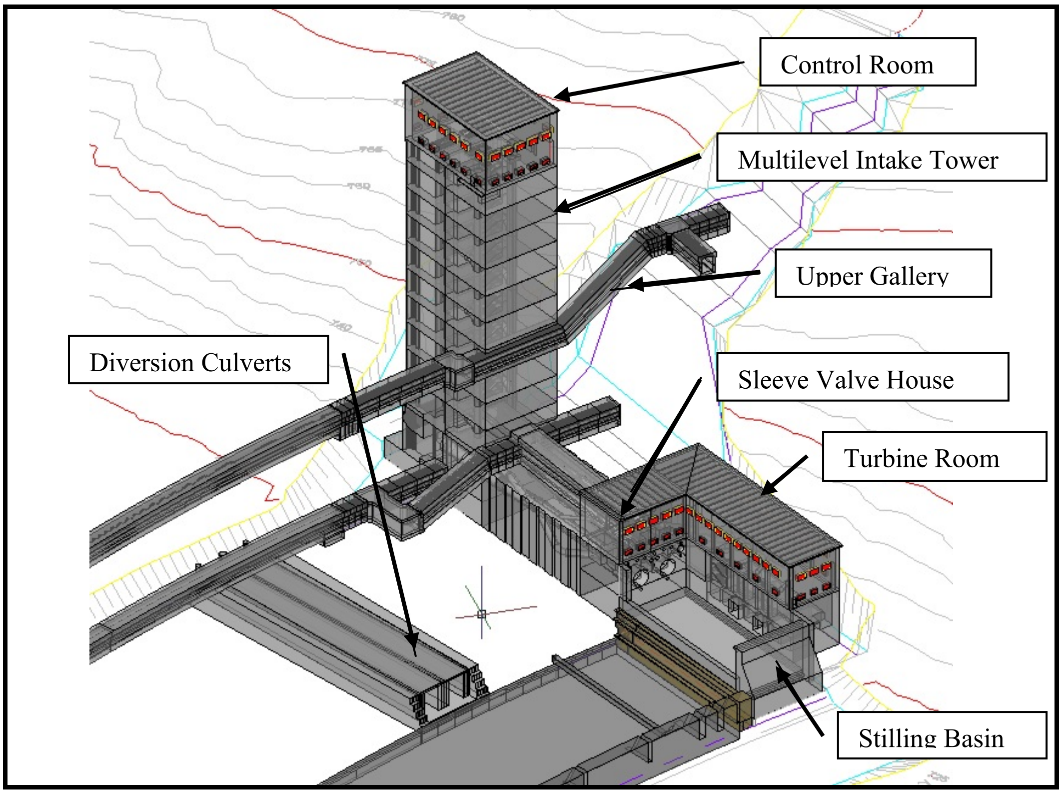

Figure 5.1: Neckartal Dam Outlet Works (isometric view)

The hydropower station will be operated to utilise the irrigation releases for power generation. The station is to comprise two units. The units will be housed in a turbine room adjacent to the sleeve valve house. The gross head is 60m and the rated flow is 6m^3/s. Francis turbines have been specified. The turbine-generator sets are to be a horizontal-axis configuration. The installed capacity of the plant is 2950kW and consists of two 1475kW units, each sized for a maximum flow of 3m^3/s of discharge. Energy production will depend on the dam water level and the irrigation scheme's water requirements.

6. REFERENCES

Knight Piésold (Pty) Ltd. (April 2010). Neckartal Dam Project Feasibility Study – Main Report. Ministry of Agriculture, Water and Forestry, Directorate Rural Water Supply. Report No. KHH1804/005.

Knight Piésold (Pty) Ltd. (August 2010). Neckartal Dam Project – Design Criteria Memorandum. Ministry of Agriculture, Water and Forestry, Directorate Rural Water Supply. Report No. KHH1804/006.

Prof SJ van Vuuren. Model Study of the Neckartal Dam – Namibia. Hydraulic Model Study. Ministry of Agriculture, Water and Forestry, Directorate Rural Water Supply. Sinotech CC. June 2010.

SANCOLD, August 1990. Interim Guidelines on Freeboard for Dams, South African National Committee on Large Dams, Report No 3.

SANCOLD. Guidelines on Safety in Relation to Floods. South African Committee on Large Dams, Report No 4. December 1991.

United States Bureau of Reclamation. Hydraulic Design of Stilling Basins and Energy Dissipators. Engineering Monograph No. 5. May 1984.

United States Army Corps of Engineers. Gravity Dam Design. Engineering Manual, EM 1110-2-2200. June 1995.

Hoek, E. Strength of Rock and Rock Masses. Extract from book entitled "Support of Underground Excavations in Hard Rock". by Hoek, Kaiser and Bawden. 1995.

Bieniawski, ZT. Determining rockmass deformability experiences from case histories. International Journal of Rock Mechanics. 1978.

Rooseboom, A. (1992). Sediment Transport in Rivers and Reservoirs – A Southern African Perspective. Report to the Water Research Commission by Sigma Beta Consulting Engineers. WRC Report No. 297/1/92.

Chanson, H. (1974). Comparison of Energy Dissipation between Nappe and Skimming Flow Regimes on Stepped Chutes. *Journal of Hydraulic Research, Vol. 32*.