Modelling, design and construction monitoring of Neckartal Dam

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Modelling, design and construction monitoring of Neckartal Dam

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Introduction

The Neckartal Dam is the largest dam in Namibia, with a full supply volume of 853 Mm^3, exceeding the volume of the existing largest dam–Hardap Dam, by a factor of three. Projects of this magnitude need innovative construction technology in order to be executed successfully, all the more Neckartal Dam, due to its desolate location in the arid climate of southern Namibia with irregular, high peak runoffs. During the design of Neckartal Dam, two physical models of the dam wall structure were performed. Physical models were constructed to scales of 1:60 and 1:120. The results from the physical models were used to improve the safety of the spillway and reduce potential scour erosion downstream. Throughout the construction of the dam, innovative techniques were implemented to ensure that high accuracy of the finished concrete works was achieved. These techniques included the construction of trial spillway crests and the three-dimensional surveying of the dam wall and spillway crest during construction with the use of unmanned aerial vehicles and photogrammetry.

1. Background

In the early twentieth century, German colonialists earmarked the site of the Neckartal Dam, in the arid southern Karas Region of Namibia. The Neckartal Dam and Phase 1 Bulk Water Supply Project is situated in the Fish River, approximately 41 km west from Keetmanshoop and some 22 km north of Seeheim. The Neckartal Dam has a catchment area of 45 365 km^2 and a mean annual runoff (MAR) of ≈ 397 Mm^3/a, categorising the storage volume of the dam as ≈ 2.14 the MAR. Upon the independence of Namibia in 1990, planning of the dam was initiated after a provisional design was undertaken in the 1960s (Knight Piésold Consulting, 2010). The Namibian Ministry of Agriculture, Water and Forestry (MAWF, also referred to as the Client) decided to implement the project with the aim of improving job scarcity and aiding the long term sustainable economic development of the Karas Region. The project envisages elevating the agricultural development of the region with 1960 hectares of irrigatable farmland to be developed during Phase 1 that may be further expanded to 5000 hectares.

The final design of the structure consisted of a 65.5 m high, curved, stepped, gravity, roller compacted concrete (RCC) wall with an uncontrolled Ogee spillway, consisting of a lower section as well as a higher section raised by 2.4 m. There is a multi-level intake structure with eight DN1600 and two DN3000 intakes. Other features of the dam include a spillway chute on the right bank to prevent flood erosion of the downstream foundation, two internal galleries, a control room and outlet works together with the turbine room and sleeve valve house. With a recommended design discharge (RDD) of 9 060 m^3/s and a safety evaluation flood (SEF) of 21 480 m^3/s the spillway length is significant and necessitates the widest possible spill area to reduce the unit discharge rate (q) to an acceptable criterion of less than 30 $m^3/s/m$.

This paper reflects the results obtained from the physical modelling, the design changes that were implemented as a consequence of the results obtained from the preformed physical modelling and the innovative construction monitoring implemented to ensure the accurate construction of the Ogee spillway section.

2. Physical modelling of the Neckartal Dam

Figure 1 provides a plan view and a section (top left insert) of the Neckartal Dam during the preliminary design stage of the project. The plan view shows the detail of the dam before improvements suggested by performing physical modelling were done. The figure shows a uniform Ogee spillway section with a total length of 395 m as well as 2.0 m high energy dissipating sills downstream of the spillway apron (Sinotech CC, 2011).

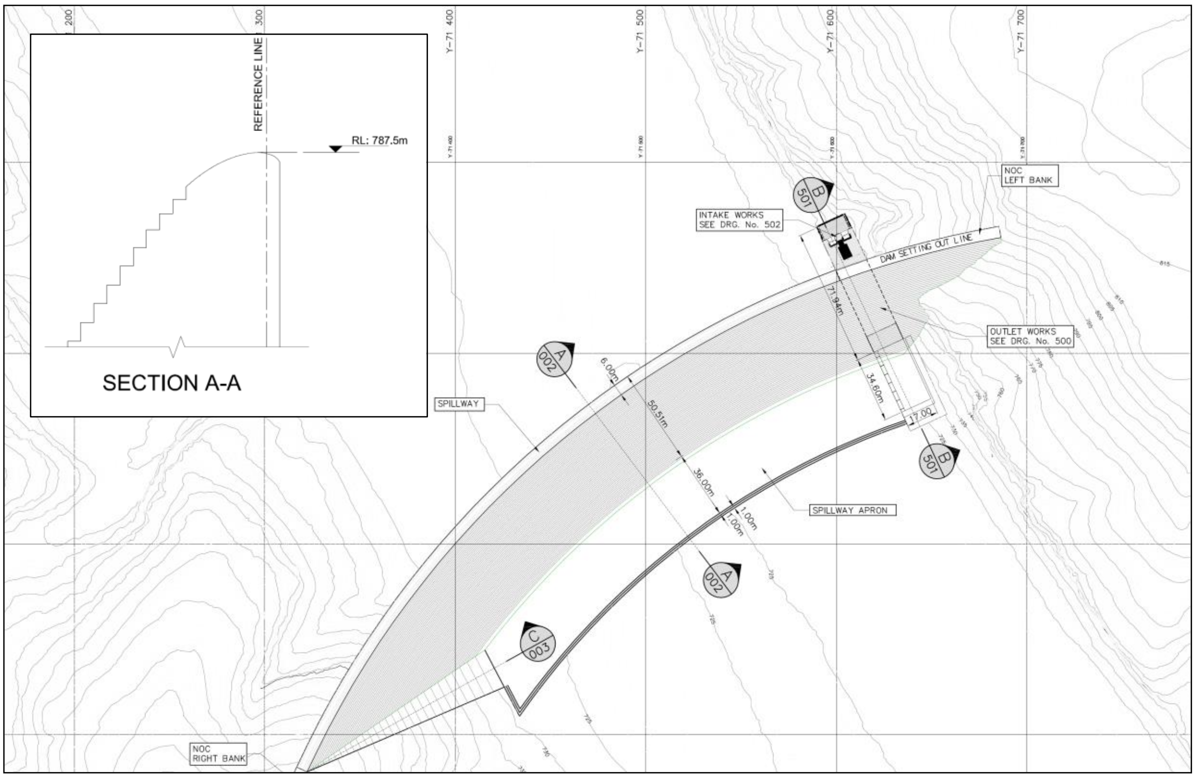


Fig. 1. Plan of the preliminary design of the Neckartal Dam (Top left insert: uniform Ogee spillway section)

Physical models were constructed to scales of 1:60 (*Model A*) and 1:120 (*Model B*) and included the upstream topography for the 1:120 physical model. The models are summarised below with dimensional proportions reflected in Table 1. Froude uniformity was used to size the undistorted models according to the available space and resources at the hydraulic laboratory.

- Model A represented a 60 m wide section of the prototype spillway and dam wall and was constructed to verify the hydraulic capacity of the spillway and to reflect the performance of the downstream energy dissipating structures; and
- Model B represented the entire dam wall and was constructed to review the effect of three-dimensional flow behaviour under conditions of the RDD and SEF. The model was also used to optimise the chute spillway design on the right bank of the dam and predict erosion patterns downstream of the spillway apron.

The initial aim of the study was to investigate the hydraulic behaviour of the stepped RCC and Ogee spillway and to determine the efficiency of the energy dissipation structures downstream from the spillway.

Table 1. Summary of model proportions for Model A and Model B

Variable	Prototype details		Model details		
	Units	Value	Units	Model A	Model B
Model Scale				1:60	1:120
Width modelled	m	60	mm	1 000	-
Height of wall	m	68	mm	1 133.3	566.7
Floods					
RDD	m^3/s	9 060	l/s	49.35	57.4
SEF		21 480		117.01	136.2

Table 1. Summary of model proportions for Model A and Model B (continue)

Spillway					
Spillway length	m	395	mm	-	3.29
Step height	mm	1 200	mm	20	10
Step width		870		14.5	7.25
Wall curvature	m	500	mm	833.3	416.7

2.1. Hydraulic capacity of the spillway

The flow depth variation along the spillway was recorded to assess its existing hydraulic capacity. The flow depth was observed to decrease progressively downstream and was associated with the flow velocity which increased from critical at the control, to supercritical downstream from the control. During the testing of *Model A*, the water surface profile was measured for the RDD and SEF, for a total prototype spillway length of 395 m, as depicted in Figure 2. Table 2 reflects the measured vertical flow depths at intermediate RCC steps along the spillway during the RDD and SEF.

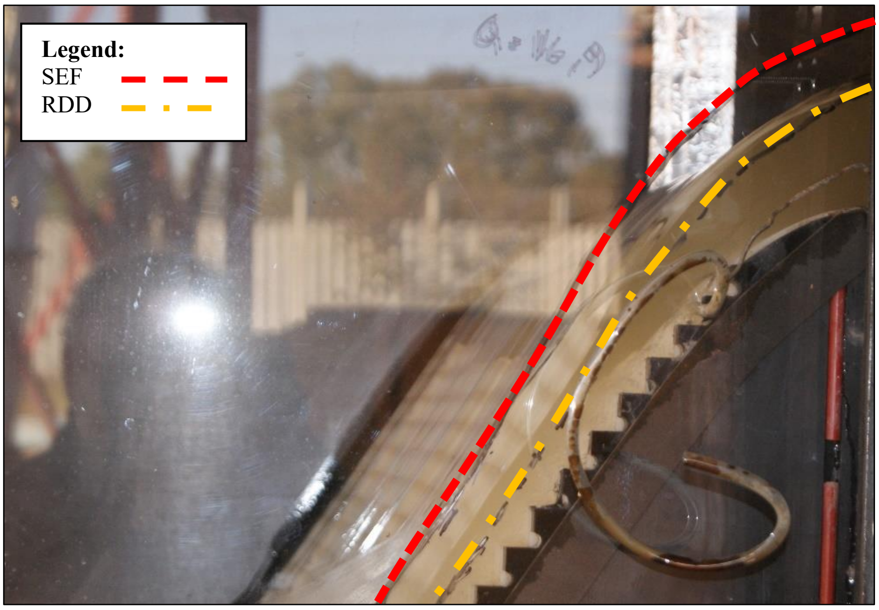


Fig. 2. Water surface profiles on the stepped spillway for the RDD and SEF

Table 2. Vertical measured flow depths on the spillway section (Model A)

Steps number downstream from Ogee crest	*Model A* flow rate (l/s)		Prototype flow rate (m^3/s)		Elevation of the step (masl)
	RDD 54.7	SEF 116.7	RDD 9060	SEF 21 480	
5	57 mm	112 mm	3.42 m	6.72 m	780.24
10	50 mm	109 mm	3.00 m	6.54 m	774.24
20	48 mm	92 mm	2.88 m	5.52 m	762.24

2.2. Separation of lower nappe from Ogee profile

In contrast to known literature, which suggests that skim flow conditions should exist during the RDD (Şentürk, 1994), *Model A* demonstrated that breakaway downstream of the Ogee crest was present during the design flood. Low-pressure was present along the Ogee crest, as well as the upper RCC steps, extending unto the fifth RCC step during the RDD, as depicted in Figure 3.

Fig. 3. Sub-atmospheric pressure zone downstream from the Ogee crest during the RDD (Insert: side view of spillway showing the region where the lower nappe of water tends to break away from the surface of the Ogee spillway profile)

The observation of the low-pressure zone created downstream from the Ogee crest from *Model A* conflicted what was expected from the application of the known relationships for the design of the Ogee profile spillway (Van Vuuren & Coetzee, 2015a & b; Coetzee & Van Vuuren, 2017). This raised a need to adapt the design Ogee profile such that positive hydrostatic pressure is present along the spillway without the breakaway of the lower nappe (Grzywienski, 1951).

2.3. Performance of the downstream energy dissipating structures

At the RDD, *Model A* demonstrated that the proposed design of the baffle sills, with a height of 2.0 m, resulted in the development of a weak hydraulic jump upstream from the sills and a large momentum transfer to the downstream side of the sills. The energy dissipation was deemed insufficient since the weak hydraulic jump caused excessive erosion of the loose bed material during the RDD. By incrementally increasing the baffle sill height, the reduction of downstream erosion during the same flood event was observed as shown in Table 3. A limited, uniform erosion pattern downstream from the spillway apron, observed for 4.5 m high baffle sills, was deemed the most acceptable. The higher baffle sills of 4.5 m developed a prominent hydraulic jumpe upstream of the sills transferring less momentum to the downstream loose bed material, resulting in less downstream scour erosion.

Table 3. Downstream erosion pattern of loose bed material for increased baffle sill height

Sill height	Downstream erosion pattern of loose bed material
2.0 m	

Table 3. Downstream erosion pattern of loose bed material for increased baffle sill height (continues)

Sill height	Downstream erosion pattern of loose bed material
2.5 m	
3.0 m	
4.5 m	

2.4. Spillway chute optimisation with full downstream erosion assessment

The results obtained from *Model B* reflected that the flow on the left side of the spillway had a tendency to breakaway. This was similar to the observations seen in *Model A*. The spillway chute on the right bank had a bottom width of 27 m and reduced to 0.0 m at the top of the chute. During floods, less than the RDD, it could be seen that:

- A standing wave was formed towards the middle of the spillway apron (Figure 4);
- The chute was insufficient in handling the volume of flow and showed overtopping of the downstream chute wall;
- The flow along the chute remained supercritical and pushed onto the downstream side wall of the chute, reflecting flow depths in the prototype of up to 18.8 m during the RDD; and
- The flow from the chute resulted in recirculation flow along the right bank in the downstream river.

Model B showed that excessive erosion of the river bed would occur if no modifications to the design are considered (Figure 4).

Fig. 4. Flow accentuated towards the downstream wall of the chute. Unacceptable high flow depths were experienced in the chute. Breakaway also observed towards the left bank of the spillway (Insert: Significant erosion and large recirculation flow present during the RDD).

The following modifications to the spillway chute were investigated with the intention of improving the hydraulic performance of the chute and mitigating downstream erosion:

- Option 1: Provide flip buckets on the steps of the chute and position the flip buckets one third from the bottom of the chute;
- Option 2: Include a deflector against the downstream wall, at the bottom of the chute, with the intention to deflect the flow back towards the dam wall to dissipate more energy; and
- Option 3: Widened the chute to prevent the flow accumulating onto the downstream wall of the chute.

Options 1 to *3* did not significantly improve the flow conditions on the spillway apron or within the downstream river section, nor did these alterations decrease the high flow depths experienced on the chute or negate the tendency of all the flow occurring next to the downstream wall of the chute. Thus *Option 4* was proposed: raise the Ogee on the right bank for the entire width of the chute, tapering the chute layout to direct the flow down the chute with a top chute width of 7.0 m and a bottom chute width of 27 m and erect staggered baffle sills on the spillway apron to dissipate the energy.

The alternations implemented for *Option 4* caused the flow depth on the spillway chute to reduce during the RDD significantly. Furthermore, the staggered baffle sills on the spillway apron assisted in the formation of a prominent hydraulic jump, which dissipated the energy well before being transferred downstream by the main spillway flow. The result was that sub-critical flow was directed downstream, significantly reducing the movement of loose bed material in the downstream river section.

Figure 5 indicates the flow depth on the spillway chute for the condition where 103 m of the Ogee crest, on the right bank, was raised by 2.4 m and the dimensions of the chute was 7.0 m wide at the top and 27 m wide at the bottom during the RDD.

Fig. 5. Option 4: Flow depth on the spillway chute where the last 103 m of the Ogee crest was raised by 2.4 m and the dimensions of the chute was 7.0 m on the top and 27 m at the bottom during the RDD

The flow depths as measured on different steps of the spillway chute with equivalent prototype flow depths are reflected in Table 5.

Table 5. Flow depths along the downstream wall of the spillway chute

Steps above the Stilling basin (722 masl)	*Model B* flow rate (l/s)		Prototype flow rate (m³/s)		Elevation of step (masl)
	RDD 56.7	SEF 128.4	RDD 9 060	SEF 21 480	
5	50 mm	130 mm	6.0 m	15.6 m	734
10	60 mm	110 mm	7.2 m	13.2 m	746
15	70 mm	80 mm	8.4 m	9.6 m	758

3. Design of the Neckartal Dam

Both physical models showed that the influence of three-dimensional flow may not be neglected during the design of hydraulic structures and that due consideration should be given during the design phase to quantify the presence of three-dimensional flow and validate two-dimensional simplification. In the case of the Neckartal Dam shown in Figure 6, the river cross-section is asymmetrical, the dam wall has a curvature and the wall is orientated at an angle with the centreline of the cross section/flow lines (Figure 6: insert). These factors contributed to the observed three-dimensional flow phenomena observed during the physical modelling phase of the design as discussed above (Van Vuuren, et al., 2011).

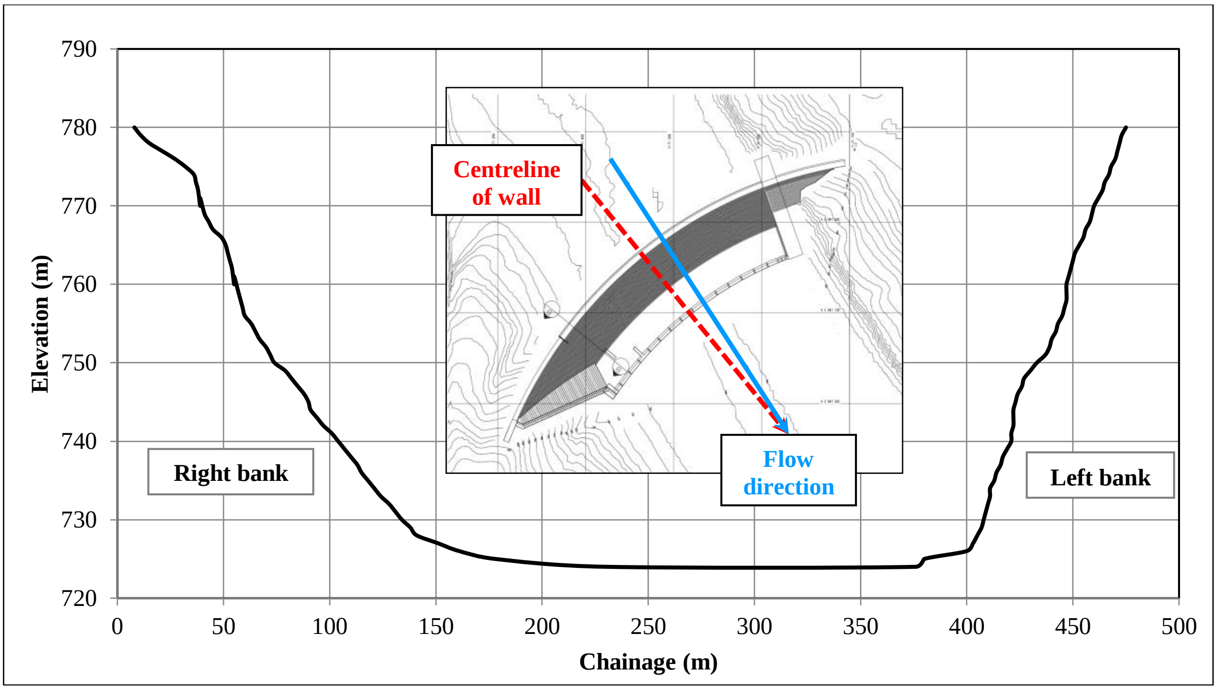


Fig. 6. The asymmetrical cross-section of Neckartal dam (Upstream view) (Insert: a plan view of final structural design reflecting the curvature of the dam wall and the flow orientation to the river)

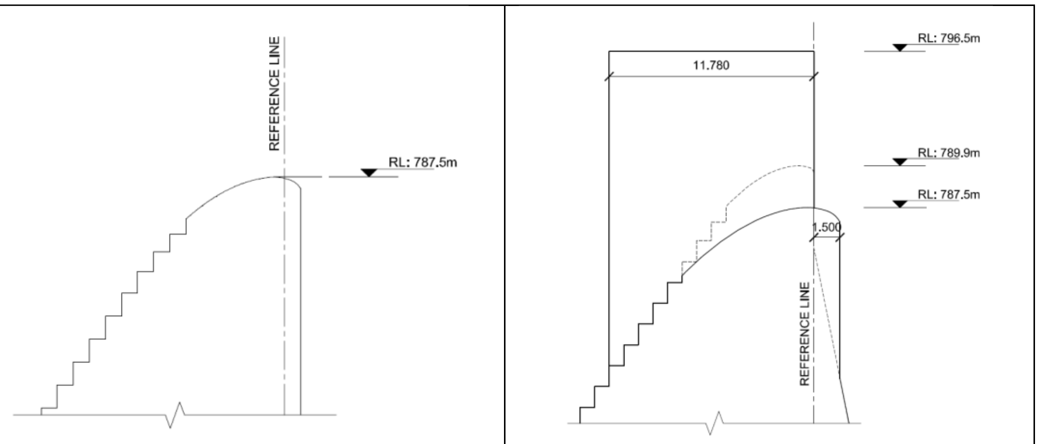
The following design improvements were made as a result of the observations noted during the physical modelling. As reflected by *Model A* (a section of the spillway):

- The proposed training wall height should maintain the SEF, and hence the wall height had to be 7.5 m;
- From the fifth step from the top, the wall height should increase to merge with the non-overspill crest for the revised Ogee spillway configuration;
- The profile of the Ogee spillway must be increased to ensure that the breakaway of the flow just downstream of the spillway is prevented. Figure 7 provides a comparison of the revised Ogee crest for the Neckartal Dam after assessing the results from the physical modelling. The profile of the lower section of the spillway was increased to a design head of 6.6 m; and
- The sill wall height of 2.0 m at the downstream end of the spillway apron was insufficient. The sill did not effectively dissipate energy and induced significant loose bed erosion downstream from the spillway apron. Modifications to the sill height showed that the height had to be increased to 4.5 m.

Model B (an undistorted scaled model with upstream and downstream topography included) demonstrated that:

- 103 m of the spillway crest length on the right bank had to be raised to limit the flow down the spillway chute. For this section of the spillway, the Ogee crest had to be raised by 2.4 m, and two staggered 4.5 m high deflector walls placed on the spillway apron; and
- The spillway chute had to be tapered in a triangular fashion to direct the flow down the chute, with a top width of 7 m and a bottom width of 27 m.

These modifications eliminated the high flow depths observed on the chute during the original design. Furthermore, a reduction in the erosion downstream from the spillway apron was observed. The modifications reduced cross flow on the spillway apron and mitigated the re-circulation of flow along the right, downstream bank of the river.



Original Ogee profile (USACE (a), 1987) | Revised Ogee profile and raised section on the right bank

Fig. 7. Comparison of the different Ogee Curves

4. Construction monitoring of the Neckartal Dam

Innovative construction techniques were implemented to ensure that high accuracy of the finished concrete works was achieved. These techniques included the construction of trial spillway crests and the three-dimensional surveying of the dam wall and spillway crest during the construction process by making use of unmanned aerial vehicles and photogrammetry surveys.

4.1. Construction of trial spillway crests

The construction of the Ogee crest is one of the most complex components to construct on a dam. Designers specify low tolerances for these components because of their high susceptibility to cavitation damage. Gradual tolerances in the order of 1.0 mm over 1.0 m are typically specified at high-velocity sections of the spillway and can only be achieved by precise control and skilled workers (Jansen, 1988). In addition, spillways are usually constructed towards the end of the project when Contractors are in haste to finish resulting in negligence to enforce the proper construction techniques required. Unfortunately the construction of Ogee crests is generally underestimated by Contractors who then neglect to provide enough resources when tendering for a project.

At the Neckartal Dam, a trial section of the Ogee crest was constructed to investigate the implementation of the most accurate and time-efficient construction method. The trial sections consisted of 6.0 m wide Ogee crests, that were a duplication of the raised spillway Ogee crest that was to be constructed on the right bank of the dam wall. The Contractor opted to construct the Ogee crest with conventional formwork lined with a perforated membrane known as a CPF liner (Continuous Perforated Formwork) (Coetzee, 2018). Different CPF liners and application techniques were investigated. Figure 8 shows the construction of one of the full-scale trial Ogee crests.

The trail Ogees showed that the upper crest zone area tended to be the most difficult to construct and that special attention to detail had to be given when finalising this area of the works. The CPF liner that showed the best result was the *Zemdrain Classic*, second to this was the *Zemdrain MD self-adhesive* CPF liner. The self-adhesive CPF liner was used for the final construction of the Ogee crest at the Neckartal Dam due to its ease of installation onto the inside of the conventional formwork.

More than 10 trials, with different sizes and formwork configurations, were made before the construction technique was successfully optimised and ready to be implemented at the main dam.

Figure 8. Full-scale Ogee crest trial construction (Insert: formwork erection before concrete placement with CPF liner installed)

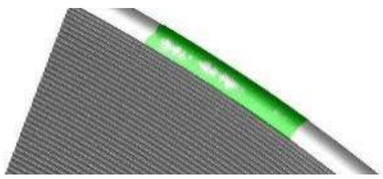
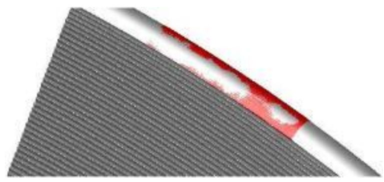
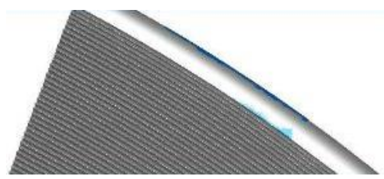
4.2. Three-dimensional photogrammetry surveying

Unmanned aerial vehicles (UAVs) are now, more than ever, used for the monitoring of construction dam sites. High-resolution built-in cameras and special photogrammetry software are utilised to generate accurate three-dimensional models of construction sites and the surrounding topography. These three-dimensional models assist both site and design engineers with construction monitoring, progress development and measuring of the volumetric quantity of periodic production rates. With a bird's eye view, offered by UAVs, large-scale projects can be monitored and managed more effectively and efficiently. The Neckartal Dam Project was the first construction project in Namibia to deploy UAVs for this purpose of construction monitoring. The accurate photogrammetry surveys assisted site engineers in sharing insights around the construction site with designers in head office.

The photogrammetry survey of a portion of the constructed Ogee crest is shown in Figure 9. Accuracies of less than a few millimetres can be achieved depending on the camera resolution and height of flight.

These three-dimensional models may be used, in combination with building information models (BIM) to determine the accuracy of final concrete surfaces during construction. In this case, it was used to assess the accuracy of the concrete finish of the Ogee crest, where offsets of less than 15 mm were achieved. The offset between the constructed model and the designed structure is shown by the coloured surfaces, reflecting areas where an offset is between 0 and 15 mm in Table 6 (Coetzee, 2018).

Table 6. The calculated deviation between constructed Ogee crest and theoretical design curve

0-5 mm deviation	5-10 mm deviation	10-15 mm deviation
		

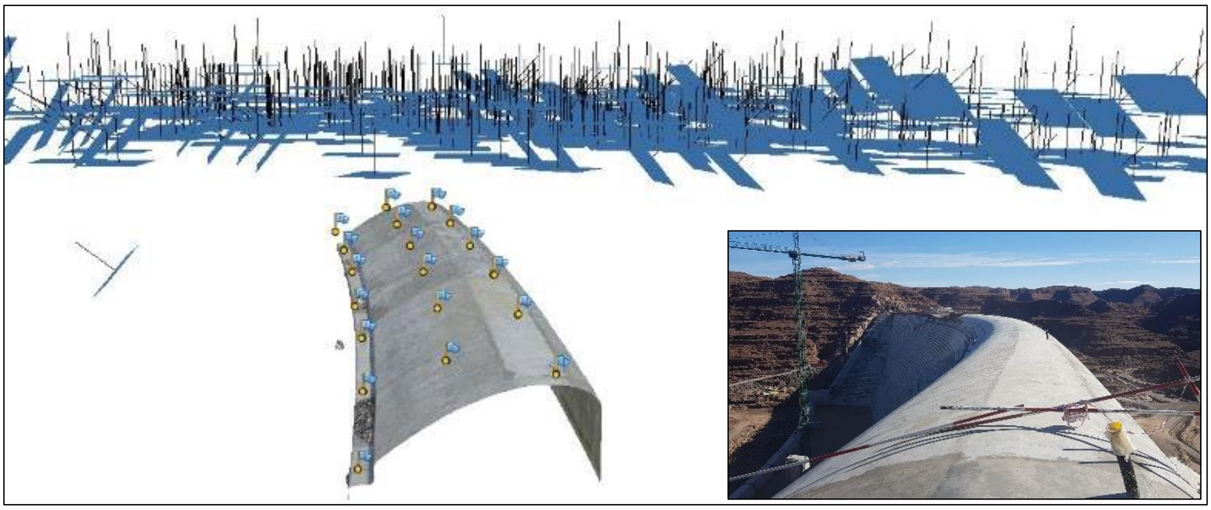


Figure 9. Position and orientation of all cameras along with the markers set-out on the Ogee crest used for the accurate geo-referencing of the 3-dimensional model (Insert: isometric view of the 3-dimensional model generated from UAV photogrammetry)

5. Conclusions

The initial aim of the study was to investigate the hydraulic behaviour of the stepped RCC and Ogee spillway and to determine the efficiency of the energy dissipation structures downstream from the spillway. However, the study revealed that a low- pressure region occurred downstream from the Ogee spillway crest during the assessment of the RDD flood event. This low-pressure region was further accentuated for larger discharges. The results of the physical model tests were in contradiction with known literature, which predicts hydrostatic pressure to be present during the RDD (USACE, 1992). The physical models showed that the effect of three-dimensional flow is accentuated by the topographical layout and dimensions of the structure. Factors that contribute to the effect of three-dimensional flow are (Van Vuuren & Coetzee, 2015a; 2015b & 2016):

- The symmetry of the approach channel upstream of the spillway;
- The orientation and position of the spillway; and
- The curvature of the spillway.

These results were consequently used to develop significant improvements to the spillway layout as well as the energy dissipation structures of the dam.

Both physical models showed that the influence of three-dimensional flow may not be neglected during the design of hydraulic structures and that due consideration should be given during the design phase to quantify the presence of three-dimensional flow and validity of two-dimensional simplification.

The photogrammetry survey revealed that the Ogee crest at Neckartal Dam was constructed with acceptable tolerances, which can be tributed to the attention that was given to the implementation of the most appropriate construction methodology.

6. Acknowledgements

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The Authors CVs

G.L. Coetzee joined the academic environment of the University of Pretoria directly after completing his undergraduate Civil Engineering studies. He has since obtained his BEng (Hons), MEng (Water Resources Management) and is pursuing his PhD studies. He has been involved in various consulting work, has a particular interest in numerical and physical modelling of hydraulic structures and has presented courses on flood determination, flood lines, drainage structures, stormwater modelling and drainage systems.

S.J. van Vuuren obtained his MBA and PhD in engineering degrees from the University of Pretoria. His professional experience included working for the government and municipal sectors, contractors and serving as a director of consulting engineering firms before he opted for an academic career. He has lectured locally and abroad, published several papers and research reports and has presented numerous courses on pipelines, pump stations and drainage systems. He is currently an Emeritus Professor for the Water Division of the Department of Civil Engineering at the University of Pretoria.