Modelling, design and construction monitoring of Neckartal dam, Namibia

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Neckartal is the largest dam in Namibia, with a full supply volume of 853 × $10^6 m^3$, exceeding the volume of what was previously the largest dam, Hardap, by a factor of three. Projects of this magnitude need innovative construction technology to be implemented successfully. In the case of Neckartal, a special challenge was its isolated location in the arid climate of southern Namibia, with irregular, high peak runoffs. During the design of the dam, two physical models were built. Results from the physical model testing were used to improve the safety of the spillway and reduce potential scour erosion downstream. Throughout the construction of the dam, innovative techniques were used, which are described in this paper.

In the early 20th century, German colonialists identified 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 on the Fish river, about 41 km west of Keetmanshoop and some 22 km north of Seeheim. The dam has a catchment area of 45 365 km^2 and a mean annual runoff (MAR) of ≈ 397 × $10^6 m^3$/year, categorizing the storage volume of the dam as ≈ 2.14 of the MAR. At the time of Namibia's independence in 1990, planning of the dam was initiated, although a provisional design has been undertaken in the 1960s. 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 employment and aiding the long-term sustainable economic development of the Karas region. The project envisages elevating the agricultural development of the region with 1960 ha of irrigable farmland to be developed during Phase 1, which may be further expanded to 5000 ha.

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 spillway section and a higher spillway 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 machine hall and sleeve valve house. With a recommended design discharge (RDD) of 9060 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 to an acceptable criterion of less than 30 $m^3/s/m$.

1. Physical modelling of the dam

Fig. 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 identified by the physical modelling were incorporated. The Figure shows a uniform ogee spillway section with a total length of 395 m, as well as 2 m-high energy dissipating sills downstream of the spillway apron [Sinotech CC, 2011[1]].

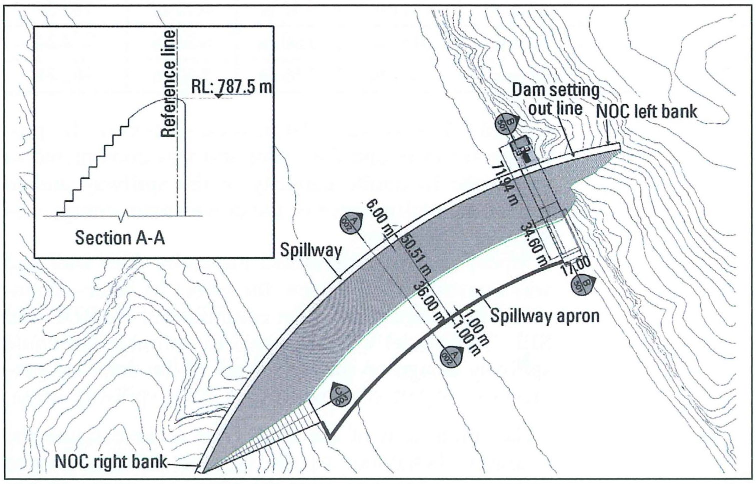

Fig. 1. Plan of the preliminary design of the Neckartal dam (inset top left: uniform ogee spillway section).

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 described briefly below, and dimensional proportions are given in Table 1. Froude uniformity was used to size the undistorted models according to the available space and resources at the hydraulic laboratory.

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
Spillway					
Spillway length	m	395	mm	-	3.29
Step height	mm	1200	mm	20	10
Step width		870*		14.5	7.25
Wall curvature	m	500	mm	833.3	416.7

** Step width was reduced to 840 mm during the final design*

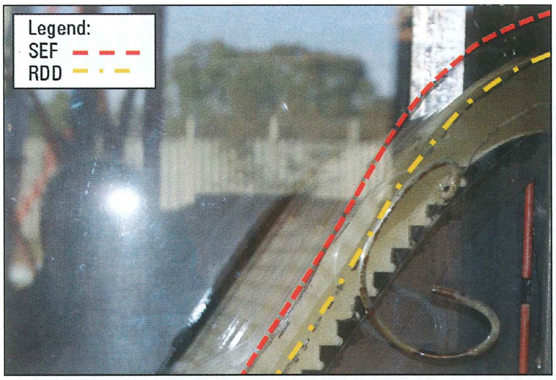

Fig. 2. Water surface profiles on the stepped spillway for the RDD and SEF.

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 (m³/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

- *Model A*. This was 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.
- *Model B*. This 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 optimize 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.

1.1 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 shown in Fig. 2. Table 2 gives the measured vertical flow depths at intermediate RCC steps along the spillway during the RDD and SEF.

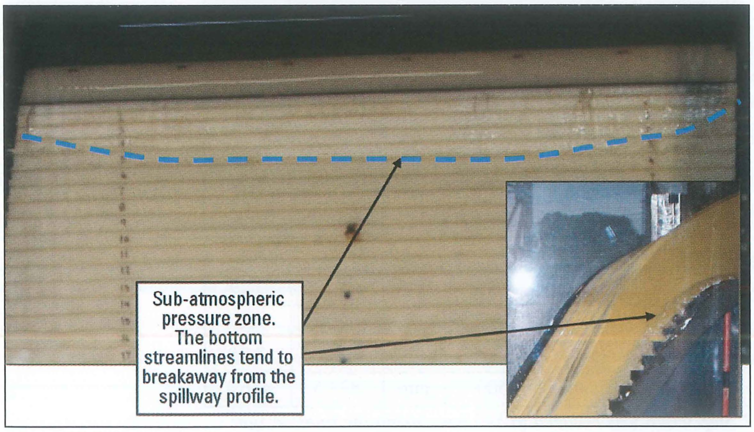

Fig. 3. Sub-atmospheric pressure zone downstream from the ogee crest during the RDD (inset: side view of spillway showing the region where the lower nappe of water tends to break away from the surface of the ogee spillway profile).

1.2 Separation of lower nappe from ogee profile

In contrast to known literature, which suggests that skim flow conditions should exist during the RDD, [Senturk, 1994[2]], 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 to the fifth RCC step during the RDD, as shown in Fig. 3.

The observation of the low-pressure zone created downstream from the ogee crest from Model A contradicted what was expected from the application of the known relationships for the design of the ogee profile spillway [Van Vuuren & Coetzee, 2015[3,4]; Coetzee and Van Vuuren, 2017[5]]. This made it necessary to adapt the design of the ogee profile such that positive hydrostatic pressure will be present along the spillway without the breakaway of the lower nappe [Gryzywienski, 1951[6]].

1.3 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 m, would result in the development of a weak hydraulic jump

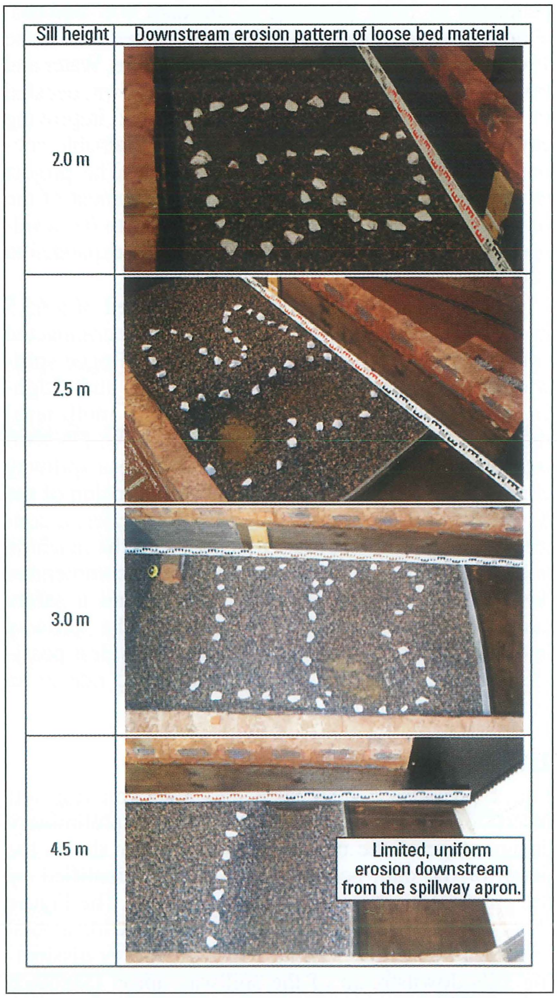

Fig. 4. Reducing downstream erosion by increasing baffle height.

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 in downstream erosion during the same flood event could be observed, as shown in Fig. 4. 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 jump upstream of the sills, transferring less momentum to the downstream loose bed material, and resulting in less downstream scour erosion.

1.4 Spillway chute optimization 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 break away. This was similar to the observations seen in Model A (see Fig. 5). The spillway chute on the right bank had a bottom width of 27 m, which reduced to zero 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;
- The chute was insufficient in handling the volume of flow and overtopping occurred at the downstream chute wall (see Fig. 5);
- 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 (see Fig. 5).

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 of the distance from the bottom of the chute;
- *Option 2*: Include a deflector against the downstream wall, at the bottom of the chute, with the aim of deflecting the flow back towards the dam wall to dissipate more energy; and,
- *Option 3*: Widen the chute to prevent the flow accumulating on 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 prevent the tendency for all the flow occurring to be 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 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 significantly during the RDD. 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.

Fig. 5. Flow accentuated towards the downstream wall of the chute. Unacceptable high flow depths were experienced in the chute. Breakaway was also observed towards the left bank of the spillway (Inset: Significant erosion and large recirculation flow present during the RDD).

Fig. 6 indicates the flow depth during the RDD 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 were 7 m wide at the top and 27 m wide at the bottom.

Fig. 6. Option 4: Flow depth on the spillway chute during the RDD. The last 103 m of the Ogee crest was raised by 2.4 m and the dimensions of the chute were 7 m on the top and 27 m at the bottom.

Table 3: 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 9060	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

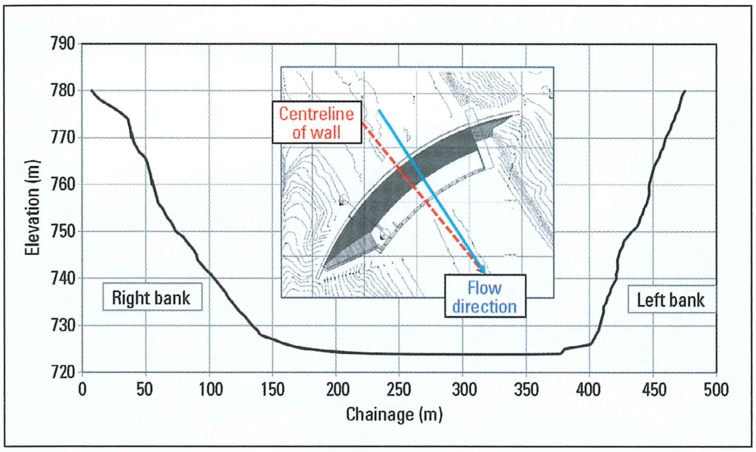

Fig. 7. The asymmetrical cross-section of Neckartal dam (upstream view). (Inset: a plan view of final structural design reflecting the curvature of the dam wall and the flow orientation to the river).

The flow depths as measured on different steps of the spillway chute with equivalent prototype flow depths are shown in Table 3.

2. Design of the Neckartal dam

Both physical models showed that the influence of three-dimensional flow should not be neglected during the design of hydraulic structures, and that due consideration should be given during the design phase to quantifying the presence of three-dimensional flow and to validate two-dimensional simplification. In the case of the Neckartal dam (shown in Fig. 7), 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 (see inset in Fig. 7). 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[7]].

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. Fig. 8 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.

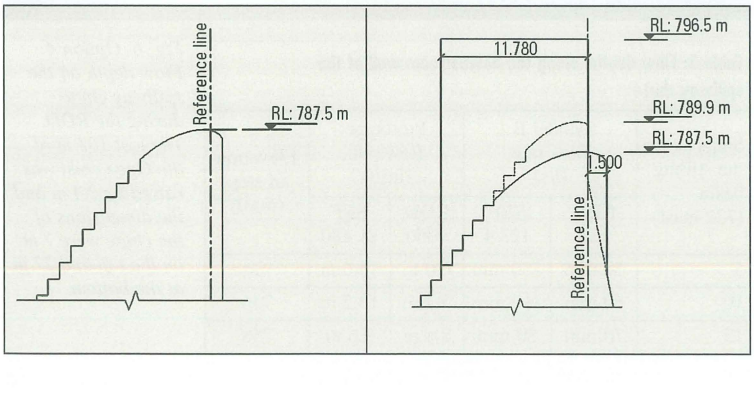

Fig. 8. Comparison of the ogee curves.

- The sill wall height of 2 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 increased 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.
- The spillway chute had to be tapered in a triangular way, 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.

3. Construction monitoring of the Neckartal dam

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

3.1 Construction of trial spillway crests

The construction of the ogee crest is one of the most complex components to build on a dam. Designers specify low tolerances for these components because of their high susceptibility to cavitation damage. Gradual tolerances, of the order of 1 mm over 1 m, are typically specified at high-velocity sections of the spillway, and can only be achieved by precise control and skilled workers [Jansen, 1988[8]]. In addition, spillways are usually constructed towards the end of the project, when contractors are in haste to finish, which can result 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 m-wide ogee crests, that were a duplication of the raised spillway ogee crest to be constructed on the right bank of the dam wall. The contractor opted to construct the ogee crest using conventional formwork, lined with a perforated membrane known as a CPF (continuous perforated formwork) liner [Coetzee, 2018[9]]. Various CPF liners and application techniques were investigated. Photo (a) shows the construction of one of the full-scale trial ogee crests.

The trial ogees showed that the upper crest zone area tended to be the most difficult to construct, and that special attention had to be paid to detail when finalizing 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 Neckartal because of its ease of installation onto the inside of the conventional formwork.

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

3.2 Three-dimensional photogrammetry surveying

Unmanned aerial vehicles (UAVs) are now, more than ever, being used for the monitoring of dam construction sites. High-resolution built-in cameras and special photogrammetry software are used to generate accurate three-dimensional models of construction sites and the surrounding topography. These models assist both site and design engineers with construction monitoring, progress in the work, and measuring of the volumetric quantity of periodic production rates. With the 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 Fig. 9(b). 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 the 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 Fig. 9(a) [Coetzee, 2018[9]].

4. 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[10]]. 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 discussed in previous papers [Van Vuuren and Coetzee, 2015[3,4]; 2016[11]] and are as follows:

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

(a). Full-scale ogee crest trial construction (inset: formwork erection before concrete placement with the CPF liner installed).

The results from the physical modelling 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 should not be neglected during the design of hydraulic structures, and that due consideration should be given during the design phase to quantifying the presence of three-dimensional flow and the validity of two-dimensional simplification.

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

Acknowledgement

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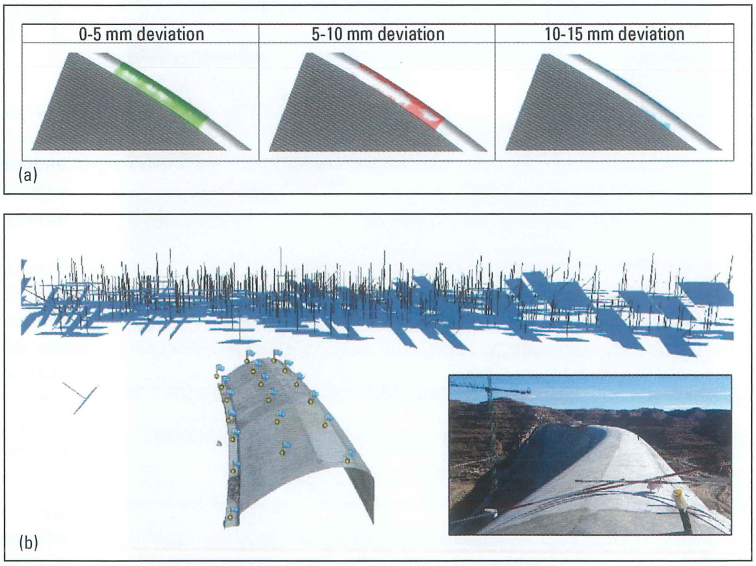

Fig. 9. Position and orientation of all cameras with the markers set out on the ogee crest used for the accurate geo-referencing of the 3-dimensional model (inset: isometric view of the 3-dimensional model generated from UAV photogrammetry).

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