SOUTH AFRICAN RCC ARCH TECHNOLOGY YIELDS BENEFITS AT CHANGUINOLA 1 DAM IN PANAMA

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ABSTRACT

The next step in the development of South African RCC technology was recently taken at Changuinola 1 Dam in Panama. Although the 105 m height and 595 m crest length may seem far from ideal for an arch dam, the design development and optimisation was able to demonstrate valuable savings in concrete volume for an arch/gravity dam type.

The structural design concepts for the arch/gravity dam were based on the negligible stress relaxation behaviour of high cementitious materials, fly ash-rich RCC and monitoring and processing of instrumentation data during construction and first filling demonstrated a very close correlation between predicted and measured behaviour. With a definitive validation of the design assumptions, it is not expected that it will ever become necessary to grout the induced joints at Changuinola 1 Dam.

While the benefits associated with the arch/gravity configuration at Changuinola 1 gave rise to concrete savings of approximately 20%, substantially greater savings have been demonstrated to be possible at more efficient arch sites, with lower crest length/height ratios.

1. BACKGROUND

During the early years of RCC dam development towards the close of the 1980s, the South African Department of Water Affairs pioneered arch dam technology in RCC through the design and construction of the Knellpoort and Wolwedans arch/gravity dams. The Chinese followed soon after and since the early 1990s, it was only China where this dam type continued to see widespread application. With the recent completion of Gomal Zam Dam in Pakistan and Changuinola 1 Dam in Panama and the ongoing construction of Portugues Dam in Puerto Rico, however, this situation has changed.

While Gomal Zam is described as an arched gravity-type dam and was designed and constructed by the Chinese company Sinohydro, Portugues Dam represents the first venture of the US Army Corps of Engineers into the RCC arch/gravity dam type. Changuinola 1 Dam in Panama, however, represents a design development of the South African technology, with many of the design principles based on intensive research into the performance and behaviour of the South African RCC arch/gravity dams.

2. INTRODUCTION

2.1 Objectives

In this article, the development and application of South African RCC arch dam design technology for the Changuinola 1 Dam in Panama is described. Focussing on the concepts and principles that make the technology work and will see the broader application of this dam type worldwide, the inherent economic benefits that can be associated with this dam type are also discussed.

2.2 Changuinola 1 Dam & HEPP

Plate 1: First Spilling at Changuinola 1 Dam

The 24th June 2011 saw the first spilling at Changuinola 1 Dam in Panama (see Plate 1). With the river diversion culvert closure achieved on 22nd May and an average inflow of 127 m^3/s, the 388 million m^3 reservoir filled over the subsequent 33 days. Immediately on reaching the full/maximum operating level, a minor flood arrived at the dam and the water level rose to a peak elevation of 166.25 mASL at 06h00 on 25th June, when spillage peaked at approximately 412 m^3/s. Routing a typical hydrograph through the reservoir suggests a peak inflow of the order of 760 m^3/s.

Changuinola 1 Dam is a 105 m high RCC arch/gravity dam with a total crest length of 595 m. The structure is configured on an upstream face radius of 525 m and the central section has a downstream face slope of 0.5H:1V and a vertical upstream face. The central arch/gravity configuration transitions to a gravity dam section on both flanks, remaining on a curve on the right flank and terminating in a straight wall on the left flank (see Figure 1). A high capacity, uncontrolled spillway was constructed over the dam structure as an aerated reinforced concrete chute and flip bucket.

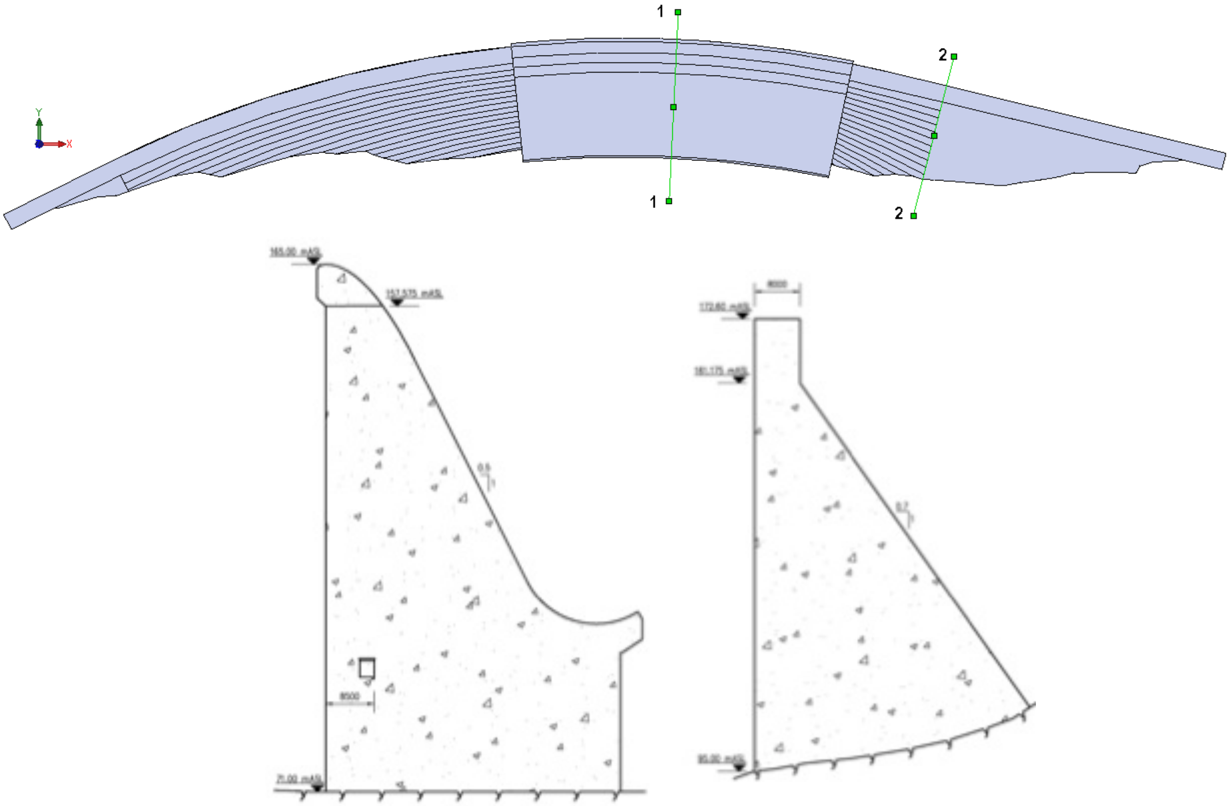

Figure 1: Basic Layout of Changuinola 1 Dam

3. THE CONSTRUCTION OF ARCH DAMS

The heat generated through cement hydration can take years, or even decades to be dissipated from a large concrete dam structure. While this is of no impact on structural performance in the case of a gravity dam, the subsequent contraction compromises the three-dimensional transfer of stress in the case of an arch dam. In this instance, contraction is caused not only by the reduction in temperature from placement to final equilibrium, but also by the stress relaxation creep that occurs as a result of restrained thermal expansion during the hydration temperature rise. Consequently, it is necessary to post-cool a conventional concrete arch dam to a pre-determined temperature before the contraction joints between the individually constructed cantilevers can be grouted to create a single, monolithic structure.

In the case of a RCC arch dam, the sections are usually heavier and so total cooling energy requirements are higher, while the installation of extensive cooling pipe networks is not practical and counter-intuitive to the concept of rapid, efficient construction, arguably the prime advantage of RCC. Consequently, it has generally been considered necessary to use shrinkage-compensating expansion agents in RCC for arch dams, to post-cool the concrete, or to allow the concrete to cool sufficiently naturally before grouting of the induced joints. However, all of these measures generally imply a lesser, or greater delay of the first impoundment after completion of the RCC placement, again compromising the primary benefit of RCC dam construction.

4. DEMONSTRATION OF PERFORMANCE & BEHAVIOUR ON FLY ASH-RICH RCC DAMS

4.1 Research Investigations

Recent research using modelling and the data from instrumentation and structural monitoring on various RCC arch and gravity dams(1) has demonstrated that the stress relaxation creep that occurs in high cementitious content, fly ash-rich RCC is in fact substantially less than is the case for other RCCs and CVC (conventional vibrated concrete). As a result of the relatively elastic thermal expansion of immature fly ash-rich RCC during the hydration temperature rise, a general upstream movement of the arch is experienced during construction, an effect that increases with placement height. In the case of an arch gravity dam and all heavy-section RCC arches, a progressive upstream leaning that develops as a result of gravity load during construction also results in an additional effective lengthening of the crest.

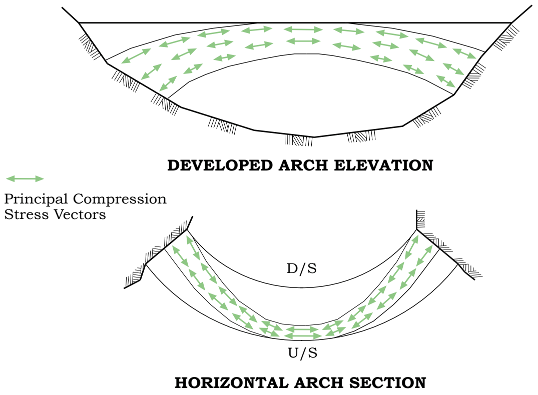

Figure 2: Primary Pattern of Stress Transfer in Arch

As a consequence of the above effects, the crest sections of a RCC arch are effectively constructed longer than the length measured on the drawings, typically by approximately 50 microstrain. Due to the fact that the majority of the arch stress transfer occurs through the crest in an arch/gravity structure, or a heavy-section arch structure, as indicated in Figure 2, the minor stress relaxation creep that might occur in fly ash-rich RCC is fully compensated by this extension in length and the structure effectively acts as though no stress relaxation creep has occurred.

Whilst it is not the intention of this article to present an explanation of the mechanisms that cause fly ash-rich RCC to behave so differently from CVC and low strength RCC in respect of creep during the hydration cycle, the key factors are negligible autogenous shrinkage and a particularly well developed aggregate skeletal structure.

5. THE DESIGN OF CHANGUINOLA 1 DAM

5.1 Design Analyses

With an effective RCC hydration heat temperature rise of 20 to 21°C, design modelling for Changuinola 1 Dam(2 & 3) using the COSMOS Finite Element (FE) analysis software demonstrated that the crest would lean upstream by a maximum of approximately 48 mm as a result of the combined effects of gravity load (self weight) and elastic thermal expansion, assuming no stress relaxation creep, as illustrated in Figures 3 & 4.

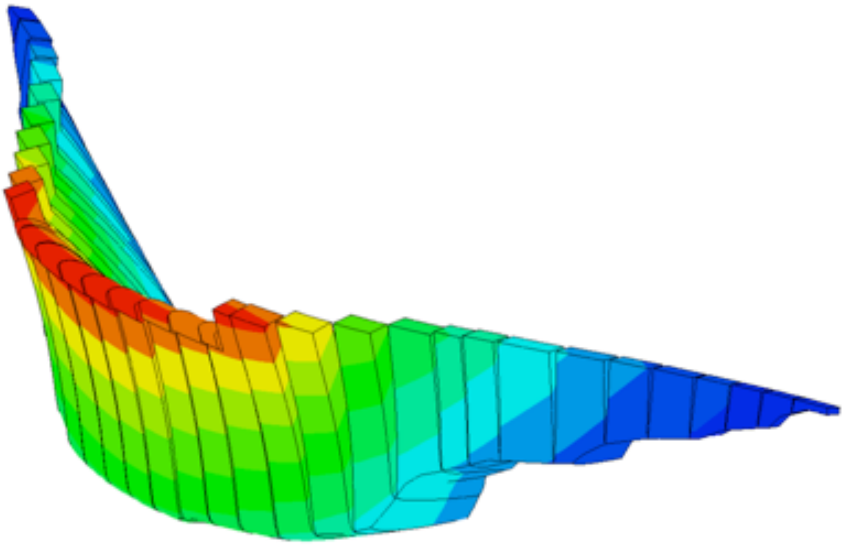

Figure 3: Exaggerated Upstream Displacement

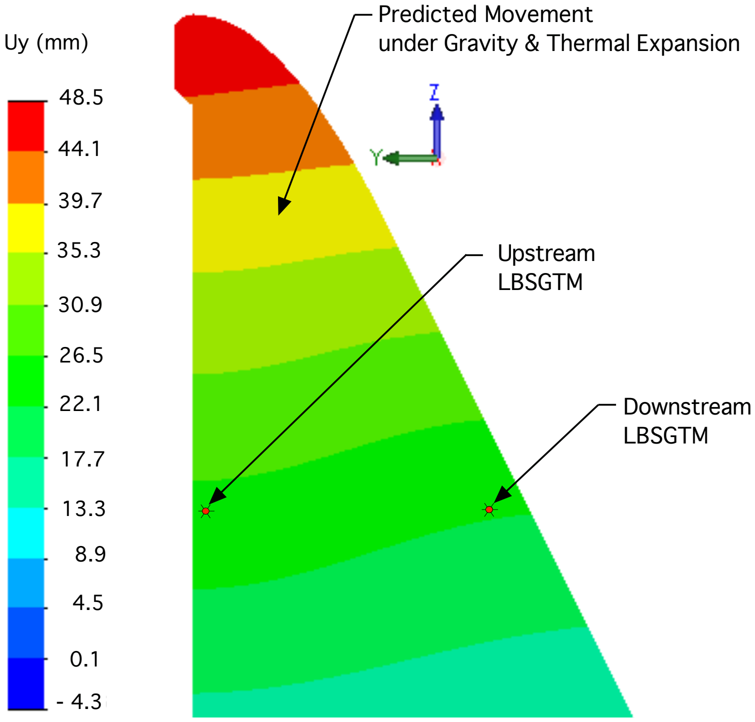

Figure 4: Predicted Upstream Arch Crest Displacement under Gravity & Thermal Expansion

The analyses demonstrated that the above behaviour would give rise to expansion at the spillway crest of approximately 50 microstrain (a microstrain equals the strain that produces a deformation of one part per million); i.e. that the behaviour described would effectively cause the upper section of the dam structure to be constructed too long by 50 microstrain, compared to the lower part of the structure. This implies that a stress relaxation creep of approximately 50 microstrain could occur in this area before any shrinkage associated with temperature drop would be incurred.

If the contraction joints on a CVC arch dam are not grouted, the contraction to be experienced can be defined as the shrinkage from placement temperature to final equilibrium temperature + the stress relaxation creep that occurs during the hydration cycle. Without pre-cooling and in a relatively temperate climate, the total applicable shrinkage might typically be 200 to 250 microstrain. For such a level of contraction, the dam structure cannot safely be allowed to carry load before final cooling and grouting of the joints has been achieved. With negligible stress relaxation creep and the effects described above, however, the total effective contraction applicable without grouting and in the very temperate climate of Panama would not exceed 40 microstrain, implying that it would be possible to design the dam to avoid the need for grouting of the contraction joints. This development allows the full concrete volume saving benefits associated with the RCC arch dam to be combined with the full benefit of rapid RCC construction, implying that storage can be allowed immediately on completion of the RCC placement.

5.2 Design Approach

In the case of Changuinola 1 Dam, the design analyses(2) demonstrated that the structure could easily accommodate a total contraction shrinkage of over 70 microstrain and consequently, as long as the RCC behaved in accordance with the indications of the research investigations into similar mixes, the structure could be safely designed without induced joint grouting. Furthermore, all indications from testing and early instrumentation installed in the dam indicated that the Changuinola 1 RCC was behaving in accordance with these expectations.

While a high level of confidence existed on the part of the designers in the predicted behaviour of the RCC of Changuinola 1 Dam, it is a very large dam and it was considered that an appropriate degree of conservatism should be maintained. To this end, a system was devised whereby a contingency arrangement could be made for contraction joint grouting, should higher than predicted stress relaxation creep finally materialise. By post-cooling and grouting the CVC spillway crest cap, it was possible to include a structural arch/strut in the crest of the dam, at the top of all of the tallest cantilevers, which would definitely not experience any subsequent contraction (see Figure 5). Due to the heavy section of the applicable arch/gravity structure, the analyses demonstrated that this arch was quite adequate to carry virtually all of the necessary arching stress in a worst-case scenario of greater than expected creep in the RCC beneath. Should such creep occur, the cooled CVC arch/strut would also prevent the downstream tilting of the cantilevers, allowing the induced joints to open and enabling grouting of the critical areas of the induced joints while the dam remains under load.

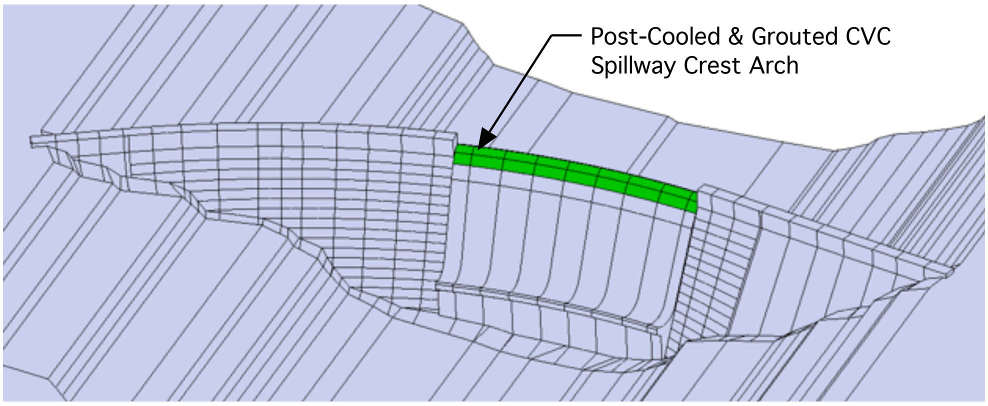

Figure 5: Dam Structure Mesh Indicating Post-Cooled Arch

Consequently, a “belts-and-braces” approach was devised for Changuinola 1 Dam to eliminate any risk in the full application of this new technology.

6. VALIDATION OF DAM BEHAVIOUR THROUGH INSTRUMENTATION DATA

6.1 General

Using instrumentation data and tested materials properties(4), a report and back-analysis was completed for Changuinola 1 Dam after first filling(5) to validate the structural behaviour of the dam on the basis of measured behaviour against the design predictions. The analysis further served the purpose of allowing an evaluation of the current and future need for grouting of the induced joints. A summary of the findings of this analysis is subsequently addressed herein.

6.2 Pre-Impoundment Arch Behaviour

During late construction and prior to impoundment, a clear pattern of behaviour was evident from the Long-Base-Strain-Gauge-Temperature-Meters (LBSGTMs) and the strain gauges installed at elevation 130 mASL, approximately 2/3 dam height.

At EL 130 mASL, two LBSGTMs were installed across each joint; one 2 m from the upstream face and the other a little over 4 m from the downstream face. Immediately prior to impoundment in May 2011, the temperature at the up- and downstream gauges was approximately 39°C and 32°C, respectively, which can be compared to an average placement temperature of approximately 27°C. At the upstream LBSGTMs, a cumulative induced joint opening of approximately 8.9 mm was evident over the arch section of the dam structure, which translates into a direct tensile strain of approximately 32 microstrain. At the downstream LBSGTMs, an average compressive strain of between 70 and 90 microstrain was evident. The apparent measurements can be seen to be reflecting an upstream movement of the arch caused by thermal expansion, which consequently compresses the downstream side of the arch and opens the upstream side.

Applying the above data into a simple geometrical model suggested that the arch had moved upstream by approximately 25 mm and that an associated expansion equivalent to approximately 35 microstrain had occurred.

Comparing residual horizontal strain values, contraction of 75 to 80 microstrain predicted by the FE model (as indicated in Figure 6) at the location of the downstream LBSGTM can be compared with values of 70 to 90 microstrain measured on the prototype dam, while a predicted expansion of approximately 15 microstrain can be compared with a measured value of 32 microstrain at the location of the upstream LBSGTM.

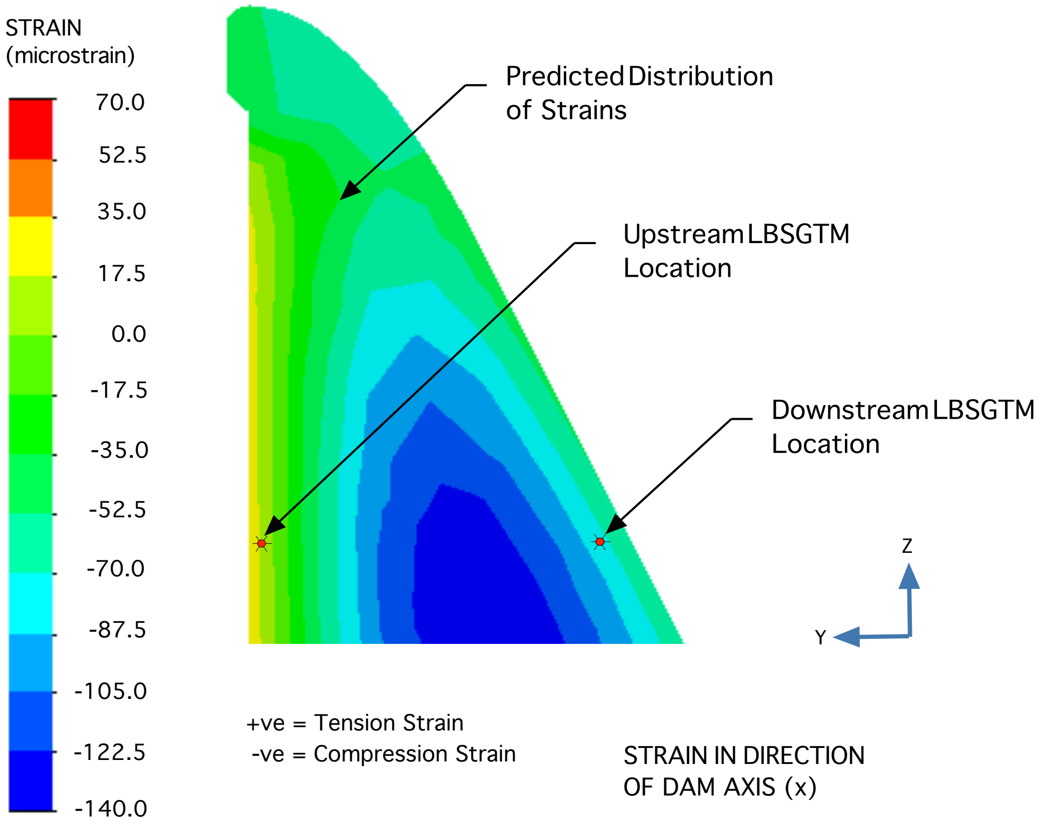

Figure 6: Predicted Distribution of Arch Strains (x direction)

The above comparison illustrates a close correlation between the predicted and measured behaviour, validating the applicable negligible stress relaxation creep behaviour of the constituent RCC at Changuinola 1 Dam.

6.3 Behaviour during First Filling

To compare the actual behaviour of the dam structure during first filling with the analysis predictions, reference was made specifically to the data from the LBSGTMs, the hanging and inverted pendulums and the survey crest targets. The locations of the pendulums and the important survey targets are illustrated in Figure 7.

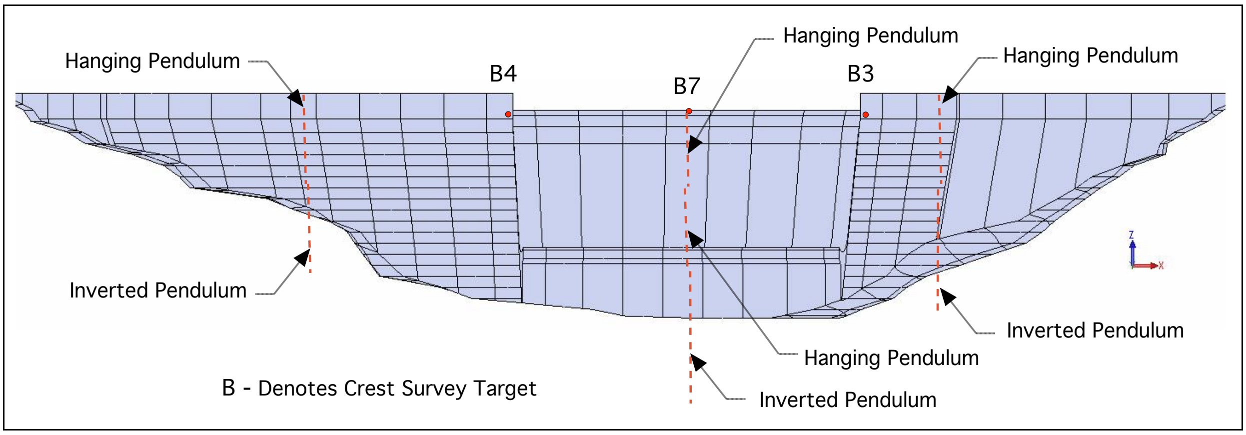

Figure 7: Illustration of Pendulum & Survey Target Locations

Due to the fact that measurement on the pendulums and on the crest displacement targets was only initiated immediately on first filling, when some upstream displacement of the dam structure would have been evident, it was necessary to make some assumptions and adaptations of the total predicted displacements. Table 1 below accordingly presents a comparison of the total downstream displacements measured during dam filling and a comparative conservative estimate of the equivalent predicted values evident from the FE analyses. Beacon B3 is located at the end of the non-overspill crest (NOC) on the left flank, B7 is located on the centre of the spillway crest and beacon B4 is located at the end of the NOC on the right flank.

Table 1: Comparison of Predicted and Measured Downstream Displacements

Data Origin	**Downstream Displacements** (mm)		
	Beacon		
	B3	B7	B4
Predicted (for negligible creep)	28.5	43.4	31.3
Measured (Water level 165.4 mASL)	25.1	39.8	27.2

As can be seen, the measured displacements are consistently approximately 10% less than the equivalent conservatively predicted figures.

At EL 130 mASL, the impact of the rising water level could be seen clearly on the LBSGTMs, with a general trend towards closure of the upstream face induced joints and an increase in the compressive strain towards the downstream. The total joint closure at the upstream face represents a reduction in the apparent tensile strain of a little more than 6 microstrain, while the increase in compressive strain at the downstream LBSGTM gauges equates to approximately 27 microstrain. For an RCC deformation modulus of approximately 20 GPa, the associated increase in compressive strain translates into a compressive stress of approximately 500 KPa.

It is particularly interesting to note here that a very distinct levelling out and stabilisation of the readings on virtually all of the gauges occurred immediately after the dam reached full capacity.

6.4 Comparisons with Typical CVC/Low Strength RCC Behaviour

6.4.1 General

While the above analyses and evaluations demonstrate an effective correlation between the model and reality, it is considered of value to evaluate this against the situation should stress relaxation creep of 150 microstrain, as might typically be expected for CVC and low strength RCC(1, 6, 7 & 8), have occurred.

6.4.2 Pre-Impoundment

Considering the pattern of concrete temperatures measured immediately before impoundment and the corresponding strains indicted in Figure 6, it is apparent that stress relaxation creep of approximately 150 microstrain would have caused all but the core of the dam to be experiencing tension before first filling. With small compressions remaining in the core, and conservatively assuming no related thermal expansion, tension strains of approximately 70 and 100 microstrain, respectively, would be evident at the downstream and upstream LBSGTMs. Should differential creep have occurred across the section, with least occurring at the surface, the measured tensions at the two LBSGTMs would simply decrease accordingly. However, in the case of such an eventuality, a situation could never develop when significant compression is evident close to the downstream face and tension at the upstream face, as measured in reality and discussed under paragraph 6.2. This latter effect is only possible when upstream thermal expansion is developed on the curvature of the arch (as illustrated in Figure 3).

6.4.3 First Filling

In late May 2011, the temperature at the core of the critical structural zone between 130 and 160 mASL was between 37 and 41°C, or approximately 12°C above placement temperature. Should 150 microstrain of stress relaxation creep have occurred in the Changuinola RCC, a net shrinkage from placement of approximately 45 microstrain, equivalent to a 5°C temperature drop, would have occurred. This would imply that a maximum downstream displacement of more than 53 mm would have been expected at beacon B7 under full water load. The fact that this figure exceeds the measured displacement by 33% is a clear indication that the RCC did not suffer the same level of creep as might be expected for CVC, or low strength RCC.

6.5 Summary

The measured behaviour of Changuinola 1 Dam has followed the design predictions very closely, validating the design assumptions of negligible stress relaxation creep during the hydration cycle. The different mode of structural behaviour that would have been evident should the typical 150 microstrain stress relaxation creep associated with CVC and low strength RCC have occurred further serves to confirm the validity of the design models.

7. THE COST BENEFITS OF THE ARCH/GRAVITY DAM AT CHANGUINOLA 1

7.1 Savings Associated with the Arch/Gravity Dam

The final dam structure and spillway constructed at Changuinola 1 contained approximately 900 000 m^3 of RCC and concrete. This can be compared with an equivalent volume for a gravity dam that would have exceeded 1,1 million m^3, indicating a concrete volume saving of approximately 200 000 m^3. For various reasons, this in fact represents a conservative estimation of the consequential savings associated with the arch/gravity structure. However, considering this figure at a net unit rate for RCC of US$ 73,40/m^3 indicates a direct cost saving of approximately US$ 15 million. To this figure, a reduction in P&G costs for the dam of approximately 3 months, equivalent to US$ 13,50 million, can be added and a saving in completion penalties, at US$ 90 000 per day, of approximately US$ 8 million, suggesting a gross cost saving of over US$ 35 million.

7.2 Additional Costs Associated with the Arch/Gravity Dam

While estimating the additional costs associated with the arch/gravity dam is a little less straightforward, additional work and cost can be associated with the following items and activities:

- An increase in the CVC volume of approximately 3 500 m^3.
- The procurement, manufacture and installation of approximately 19 500 m of groutable crack joint inducers.
- The selective grouting of the induced joints.
- The cooling of the CVC placed in the spillway crest cap and the installation of groutable joints.
- The grouting of the joints in the cooled CVC spillway crest cap.
- The installation of shear keys and a groutable joint system up to EL 111.375 mASL at Joint No 18.
- The increased complexity of the spillway construction (with overhangs and aeration, etc).
- Additional consulting services fees for the Arch/Gravity structure design.

The total estimated cost of the above additional items and work is approximately US$ 2,2 million.

7.3 Net Cost Benefit Associated with the Arch/Gravity Dam

Setting off the additional costs against the apparent savings associated with the arch/gravity dam, a net cost saving benefit of more than US$ 34 million can be seen to have been derived by implementing an arch/gravity dam at Changuinola 1, a figure that represents 21% of the cost of the dam.

8. DISCUSSION & CONCLUSIONS

8.1 The Advantages of RCC Arch Dams

The crest length/dam height ratio for Changuinola 1 Dam exceeds 5 and the site would not be considered as typically ideal to develop substantial benefit from an arch dam and accordingly, the 21% cost saving realised is all the more significant. For dams recently evaluated in southern Africa and Turkey, where crest length/height ratios have been lower, typical concrete volume savings of between 46 and 53% have been demonstrated to be possible for arch/gravity and heavy-section arch dams, compared to the postulated gravity dam.

In Turkey, even though the climates are generally more extreme and fly ash is not always economically available, a cost benefit has successfully been demonstrated and the case proven in several instances for the application of RCC arch dams. While testing and investigation is currently underway in Turkey for the first use of a natural pozzolan in a RCC arch dam, the application of this dam type can still offer significant cost advantages even when pre-cooling of the RCC at placement is necessary in order to limit the final applicable structural temperature drop.

In parts of the world where cost minimisation on capital projects is considered important, where commercial agencies are developing dams for hydropower and where clients recognise the importance of stretching their development dollars as far as possible, the time and cost saving advantages of RCC arch dams are being increasingly acknowledged. It can be stated with some confidence that Turkey will undoubtedly soon see the construction of the country's first RCC arch dam.

8.2 Dam Wall Structural Grouting

The correlation between the measured behaviour of the dam and the FE simulation analysis have definitively confirmed the predicted negligible creep behaviour of the Changuinola RCC. Consequently, it is not expected that structural grouting of the induced joints in Changuinola 1 Dam will never become necessary, as the effective temperature drop load will never be significant and certainly lower than that for which the dam was designed.

9. REFERENCES

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