Innovation in the Thermal Design and Application for the Köroğlu RCC Arch/Gravity Dam

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Introduction
RCC arch and arch/gravity dams have now been constructed in a number of countries around the world, with the significant majority in China. Most RCC arches and arch/gravity dams have to date been designed on the basis of similar principles to those traditionally applied for comparable CVC dam types, except with induced, as opposed to formed contraction joints. While the dams located in colder, or more extreme climates have generally been post-cooled to allow the grouting of the induced joints, some dams in milder climates have not required joint grouting and others, previously only in temperate climates, have taken advantage of the low stress-relaxation creep properties of fly ash-rich RCC to obviate the requirement for joint grouting.

Analyses for the Köroğlu RCC arch/gravity dam in the north-east of Turkey demonstrated that a strategic approach to post-cooling and grouting of the dam structure represented the optimal design solution. Adopting such an approach with a low stress-relaxation creep RCC reduces the requirement for post-cooling pipes to strategic areas within the dam structure, results in reduced energy and time for post-cooling and produces a dam structure in which higher arch compressions are developed, reducing final sensitivity to long-term temperature drop loads.

In this paper, the author discusses the related technological innovation, which can be applied to reduce dam construction implementation costs and time, thereby increasing project economy and sustainability for hydropower and water supply projects.

1 Background
1.1 The history and development of RCC arch dams
While the first two RCC arch dams were constructed in South Africa in the late 1980s, it was China where this dam type has been most keenly adopted, with more than 20% of all RCC dams in China now being arches, the highest of which is 167 m(1). Despite RCC arch dams now also having been constructed in Panama, Pakistan, Puerto Rico, Laos and Turkey, an associated history of over 25 years and exemplary performance on the part of all operating dams of this type, RCC arch technology remains slow to be universally accepted.

As a consequence of its 2-dimensional structural function and associated insensitivity to contraction on transverse induced joints, a conventional, straight gravity dam is easily adapted to horizontal construction. With a requirement to transfer load in 3-dimensions, on the other hand, an RCC arch dam must include measures and systems by means of which the structural continuity that is compromised by contraction on the induced joints can be restored. Over the history of the development of RCC arch dam technology, a number of different systems and approaches have been applied to achieve this objective, each of which is quite different to the systems typically used in CVC arches, which in turn are not well-suited to the continuous horizontal placement associated with RCC.

1.2 RCC arch dam joint systems
In the case of a conventional concrete arch dam, post-cooling through chilled water circulation is applied to draw out the hydration heat and to bring the concrete temperature down to the closure temperature, at which the joints between the vertical monoliths are grouted. In the case of RCC arches, this is not always the case and two different types of joints are used in China, depending on whether post-cooling is applied, or whether some, or all of the post-hydration cooling is allowed to occur naturally(1).
What is termed a “conventional transverse contraction joint” creates de-bonding over the entire contact area of the section and this joint type is used in conjunction with post-cooling, when full grouting of the joints is completed before impoundment, in the same manner as for a conventional mass concrete dam. When only partial post-cooling, or natural cooling is considered in the design, an “induced transverse joint” is created through only partial (typically between 1/6 and 1/3) de-bonding of the joint contact area. In such instances, all joints are grouted before impoundment, but facilities are included to re-grout the joints, or multiple grouting systems are included, which allow grouting again at a later stage once further cooling has occurred. Some RCC arch dams have also been constructed with a combination of “conventional” and “induced” joints and have applied partial post-cooling, together with natural cooling.

In conjunction with these joint systems, lightly burnt MgO powder has been used to compensate for cement paste autogenous shrinkage, while short-joints and hinge-joints have been provided to safely accommodate increased arch displacements caused by higher temperature-drop loadings. In arch/gravity RCC dams constructed outside China, a simple joint inducing and grouting system has successfully been used that is installed in the RCC after compaction, with the consequential advantage that it does not interfere with, nor impact, RCC placement.

1.3 Other research and development
The establishment of low stress-relaxation creep in certain RCC types, particularly in fly ash-rich RCC, has demonstrated behaviour during the construction of RCC arch dams that is quite different to that typically experienced in CVC arch dams\(^2\). With horizontal construction implying the presence of a continuous arch immediately from placement and low stress-relaxation creep of the RCC giving rise to reduced hydration-related shrinkage, some upstream movement of the arch during construction as a consequence of thermal expansion has been measured.

1.4 The elements that make an RCC arch the optimal solution
While the majority of RCC arches constructed in China are double-curvature structures, an average base length/dam height (B/H) ratio of 0.24 implies that the associated dams would not often be classified as thin arches (B/H < 0.2). By contrast, all of the RCC arches constructed outside China to date are arch/gravity, or thick arch structures. This situation can be explained by the fact that the most efficient arch dam structures can be designed for sites with a low crest length/dam height (L/H) ratio, which implies a valley with steep slopes for which construction access is difficult. Such dam sites are consequently significantly better suited to vertical construction, using cranes, and consequently, CVC arches become substantially more competitive with RCC arches on sites where a thin arch is suitable.

At the other end of the spectrum, in a valley with a high L/H ratio, an arch/gravity, or a thick arch configuration will demonstrate less benefit in terms of reduced concrete volume compared with a conventional, straight gravity dam. In view of the marginally increased complexity of constructing an arch, with groutable transverse joints, a reasonable reduction in concrete volume will be required before a designer will select an arch. As a good part of the benefit of reduced concrete quantities relates to a shorter construction period, delaying impoundment for post-cooling and contraction joint grouting is counterproductive. When the design of an arch gravity, or a thick arch structure requires that the contraction joints be grouted at the closure temperature prior to impoundment, the costs and delays associated with the necessary post-cooling could accordingly tip the balance in favour of a simple gravity dam.

2 RCC arch design options
2.1 Factors that influence arch configurations
Beyond the topography and geotechnical conditions of the proposed dam site, the local climatic conditions will also influence the most efficient arch solution. The critical issue can be defined as the arch closure temperature in relation to the placement temperature. In a temperate climate, these two temperatures need not be significantly different, while in an extreme climate, or a particularly cold climate, these temperatures will often be significantly different. In the former situation, the applicable stress-relaxation creep of the RCC plays an important role in determining whether pre-cooling of the RCC, or post-cooling and joint grouting is necessary.
2.2 The optimal RCC arch

As a consequence of the above, it is apparent that the RCC arch dam type is likely to be most competitive on sites where a heavier section arch dam is the optimal solution. Accordingly, the optimal RCC arch dam will generally take the form of a thicker arch, with simple double curvature, or a single curvature arch, or an arch/gravity structure.

Where some degree of double curvature is applied, the cantilevers are less stiff and/or the closure temperature is low compared to the placement temperature, post-cooling and contraction joint grouting is likely to be necessary. The applicable RCC stress-relaxation creep is less critical in such a situation. Where cantilevers are relatively stiff, the placement and closure temperatures are not significantly different and the RCC stress-relaxation creep is low, the arch will often be able to accommodate the long term temperature drop shrinkage without the need for transverse induced joint grouting.

2.3 Additional considerations

While an avoidance of the need to grout transverse induced joints in a milder climate can be seen an advantage of an arch with stiff cantilevers, the differential heat dissipation across a structure of variable thicknesses necessitates that the temperature-stress state be evaluated throughout the period until full heat dissipation has been achieved. Whereas, it is usually assumed that the critical thermal loading condition, associated with maximum thermal shrinkage, is developed once all the hydration heat has been dissipated, this may not be the case for low stress-relaxation heat RCC. With low stress-relaxation creep some expansion of an arch/gravity dam will occur during construction as a result of thermal expansion. As the heat of hydration is dissipated, the arch will tend to move, or tilt downstream. Due to the fact that the heat will be dissipated more rapidly from the thinner crest, as compared to the broader base, the transverse joints in the upper part of the dam structure will experience an exaggerated opening that will only start to close again once the base of the dam cools. With arching only realistically occurring through the upper part of the structure in the case of an arch/gravity dam, if the dam structure is under load during this period of differential cooling, the top of the cantilevers will need to displace farther downstream to close the joints in the upper arch. This situation can develop consequential vertical tensions in the upstream face of the dam and can represent the critical thermal design condition.

Conversely, this effect can be used to some advantage. Whereas most scenarios that consider impoundment before full hydration-heat dissipation require subsequent re-grouting of the transverse contraction joints, strategic post-cooling of the upper arch while the base remains hot and expanded will give rise to a situation in which compressions in the upper arch subsequently increase once the joints are grouted and the base of the structure continues to cool. This implies that only a single grouting of a limited part of the joints will be necessary, together with limited and strategic post-cooling of the thinner part of the dam section, which can be achieved very rapidly.

3 The Köroğlu RCC arch/gravity dam

3.1 Background

The Köroğlu dam & HEPP is situated on the Kura River in north-eastern Turkey, a short distance upstream of the country’s border with Georgia. The project is being developed in conjunction with the Kotanli HEPP, located immediately downstream, by EBD Enerji A.S. to generate a total of 130 MW of electricity. Construction is being undertaken by EBD’s sister company Ünal Construction. The Kotanli HEPP was commissioned in 2015 and first run at its full 50 MW capacity during the snow melt period in April/May 2016.

Köroğlu dam will be 94 m in height, will contain approximately 560 000 m$^3$ of RCC and will impound a gross storage of 71 million m$^3$. A centrally located spillway of 33 m in length will be controlled with three radial gates. Energy dissipation of flood discharges will be achieved with Roberts crest splitters discharging onto a reinforced concrete slab. The general layout is illustrated in Figure 1.
With a L/H value of marginally below 4, the Köroğlu dam site could be considered topographically suitable for a thick arch, or an arch/gravity structure. Considering the low elastic modulus characteristics of the abutment rock masses on both flanks (3.3 GPa), however, an arch/gravity configuration was identified as the optimal solution.

The final design layout comprises a simple, single curvature arch with an upstream face radius of 183 m. The central arch section indicates a vertical upstream face and a constant downstream face slope of 0.6H:1V. At the extremes of both flanks, a straight gravity section is included, for which the same downstream face slope is applied, but the upstream face is sloped at 0.2H:1V.

3.2 Climatic conditions

As indicated in Table 1 below, the Köroğlu dam is located in a cold climate, with mean monthly temperatures never exceeding 20°C, but reducing below 0°C for four months of the year.

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Ave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Temp (°C)</td>
<td>-9.9</td>
<td>-8.3</td>
<td>-2.4</td>
<td>5.8</td>
<td>10.2</td>
<td>14.0</td>
<td>17.8</td>
<td>17.8</td>
<td>13.8</td>
<td>7.3</td>
<td>0.3</td>
<td>-6.4</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Mean annual precipitation in the general area of the Köroğlu dam site is approximately 470 mm, which occurs throughout the year, with elevated figures between April and August, peaking in June.
3.3 Construction schedule

As a consequence of the extreme cold between December and March, it was only possible to place RCC at the Köroğlu site between late March and November, implying that the RCC placement was split into two periods in 2015 and 2016. With placement only started in late April 2015 and delays experienced due to restrictions in aggregate supply, approximately 220 000 m³ of RCC was placed before the cold weather caused construction to be interrupted, by which time the dam had reached a height of approximately 31 m.

3.4 Concrete materials and behaviour

The cementitious materials of the RCC for Köroğlu dam comprise ordinary Portland cement and a Trass natural pozzolan, in the proportions 85 kg/m³ + 130 kg/m³, respectively. The same mix was used for the construction of the smaller Kotanlı RCC arch/gravity dam during 2014 and 2015 and consequently, instrumentation data was available to provide an indication of the stress-relaxation character of the RCC. Kotanlı dam indicated a broader section and only required arching at the crest, allowing the dam to be impounded and to cool naturally before being grouted in the upper zone alone. Comparing the strain response with temperature in the RCC at Kotanlı reflected a comparable behaviour to fly ash-rich RCC, suggesting minimal stress-relaxation creep during the hydration process.

4 Design analysis

4.1 Design methodology

The process of the structural design of Köroğlu RCC arch/gravity dam was initiated with a thermal analysis to establish the anticipated structural behaviour during the process of post-hydration heat dissipation. The initial analysis assumed natural cooling due to external air and water temperatures and this indicated a required period of 20 years after construction completion to reach thermal equilibrium, with full hydration heat dissipation. Subsequently, scenarios that involved post-cooling over the upper portion of the dam structure, as illustrated in Figure 2, were analysed.

The installation of post-cooling pipes in every 6th layer was considered a practical and feasible option, while the use of river water, which rarely exceeds 8˚C, would avoid the requirement for a water chilling plant. Furthermore, no cooling pipes were included in the upstream 6 m, as it was considered that their inclusion might compromise the full achievement of impermeability in this zone. Analyses were subsequently undertaken to identify cooling options and the consequential behaviour of the dam structure under various scenarios.

4.2 Thermal studies

The first stage of the thermal analysis involved a 3-dimensional block between induced joints containing cooling pipes at 1.5 m vertical intervals (see Figure 3). This model was developed for the purpose of evaluating the cooling effect of circulating 8˚C water in pipe loops at approximately 1.5 m centres, both vertically and horizontally. To reduce modelling analysis time, the block height was limited to 13.5 m and for modelling purposes, it was assumed that the cooling water circulation was initiated simultaneously with the evolution of hydration heat when a full 1.5 m lift was placed. Subsequently, the profile of cooling with time indicated from this initial model was applied to a 2-dimensional, sectional model of the dam crown cantilever, constructed in accordance with a programme that envisaged lifting of the dam structure to full height by the beginning of December 2016. Cooling at each elevation was applied for 14 days after placement and the model was run for a simulation period of 20 years after dam construction completion.

Comparing the temperature profile at construction completion with that at placement (T1), a 2-dimensional stress analysis was completed to determine the stresses that will be developed as a consequence of the steep thermal gradients created through forced cooling of only restricted areas of the dam section. For this purpose, a zero stress relaxation creep was assumed, implying that the consequential stress intensities were the maximum possible and consequently probably slightly exaggerated. The temperature profile at this time increment was subsequently applied to a 3-dimensional finite element model to establish whether, and how much, the induced joints had been opened.
through the process of post-cooling. The temperatures were also compared with the final equilibrium temperatures (T4) to establish the extent of temperature drop still to occur across the structure.

Figure 2: Area where post-cooling applied  Figure 3: “Block” used to establish cooling effect of pipe loops

4.3 Parametric study to identify design solutions

In addition to the basic study of 14 days of post-cooling, additional scenarios of 28, 42 and 56 days cooling were evaluated. In each case, the temperature distributions were reviewed over the full cycle from construction completion to full dissipation of hydration heat, while the stresses in 2-dimensions at construction completion were evaluated to establish whether the post-cooling might cause tension cracking that might lead to secondary structural problems. Example 2-dimensional sectional temperature profiles are illustrated in Figure 4.

Figure 4a: No post-cooling  Figure 4b: 14 days post-cooling  Figure 4c: 42 days post-cooling

Figure 4: Temperature profile at construction completion

The comparative post-cooling study revealed little benefit in cooling beyond 28 days and certainly no further benefit after 42 days, with a maximum consequential tension stress of 1.2 MPa at 28 days post-cooling, which did not increase with further cooling (see Figure 5).
4.4 Joint Studies

4.4.1 Initial thermal studies

The primary objective of the initial phase of the thermal studies was to establish the post-cooling necessary to create adequate openings on the induced joints to allow grouting at construction completion, without inducing deleterious tensile stresses within the structure that might result in cracking. Consequently, the temperature profiles at construction completion for 14, 28 and 42 days post-cooling were applied to a 3-dimensional FE model of the dam, with interface elements on the cross sections where the induced joints are constructed (see Figure 6). The interface elements were ascribed a tensile strength of 250 kPa, allowing the joints to fail in tension and open for any higher levels of stress.

Figure 6: 3-Dimensional FE mesh for dam

Two stress-relaxation creep scenarios were subsequently considered. In the first scenario, zero stress relaxation creep was assumed. In the second, where compression strains exceeding 100 microstrain were indicated, 50 microstrain of stress-relaxation creep was assumed. Applying the placement temperature (T1) as 2°C above the applicable average monthly temperature at the time of placement, the “zero stress” temperature (T3) was taken as T1 + 0 in the case of a zero stress relaxation creep scenario, and T1 + 5°C (equivalent to 50 microstrain of shrinkage creep for a coefficient of thermal expansion of 10 x 10^-6) for the 50 microstrain stress-relaxation creep (SRC) scenario.
4.4.2 Joint opening

Assuming that a significant area of the induced joint surfaces would need to have opened beyond 0.5 mm to provide confidence that joint grouting would be effective, the initial thermal study demonstrated that the 14 day post-cooling scenario would not realistically produce sufficient joint opening to ensure fully effective induced joint grouting, unless the full 50 microstrain stress-relaxation creep can be assured. The analyses confirmed, however, that sufficient joint opening was created when post-cooling was maintained for at least 28 days, even when zero stress-relaxation creep was assumed (see Figure 8).

The T4 (final equilibrium) temperatures over the area for which post-cooling was applied were demonstrated to range between 2°C and 6°C (see Figure 7), implying that a temperature drop from T3 to T4 of 5°C to 9°C would still remain for a zero stress-relaxation creep 14 day post-cooling scenario, compared to 2°C to 6°C in the case of a 28 day post-cooling. The former situation implies that re-grouting of the structure after perhaps 5 years would probably consequently be necessary should post-cooling only be maintained for 14 days after RCC placement. Consequently, 14 day post-cooling was eliminated from further consideration.

![Figure 8: Joint opening at end of construction for 28 day post-cooling & zero stress-relaxation creep](image)

4.4.3 Post grouting analyses

For the 28 and 42 day post-cooling alternatives and the two stress-relaxation creep scenarios, the arch structure was evaluated over the 20 year cycle from construction completion, assuming that all areas of the induced joints where openings exceeding 0.5 mm were grouted at construction completion. Grouting of the induced joints was modelled by re-setting the applicable areas at zero stress before dam impoundment.

In terms of temperature load, the worst-case condition after joint grouting will occur when the structure has finally cooled to its winter equilibrium temperature profile (T4) and this was modelled by the application of a temperature drop from “zero stress” temperature, T3 to T4. To simulate the effect of joint grouting and an associated re-set at zero stress, for the areas of the induced joints opened beyond 0.5 mm, the T3 temperature was equated to that to which the area was cooled at grouting, while for the remainder of the section, T3 was equated to T1 for the zero SRC scenario and T1 + 5°C in the case of a 50 microstrain stress relaxation creep scenario.

Under full temperature drop, hydrostatic, uplift and gravity loads, the structural function of the dam was consequently reviewed.

5 Analysis Results

5.1 Comparative behaviour

The usual procedure by which the overall structural behaviour of an arch dam is demonstrated is through an evaluation of the pattern of the principal stresses on the upstream and downstream faces. Such an approach, however, is not applicable when the selective post-cooling and joint grouting processes have effectively created a structural strut inside the dam structure. The effectiveness of the proposed post-cooling approach is consequently best
illustrated through a comparison of total displacements and the magnitude and distribution of horizontal stresses on the crown cantilever section for the various cooling and stress-relaxation creep scenarios. The analysis results indicated a negligible difference between 28 and 42 days post-cooling and consequently, only the shorter period was considered further.

In respect of the apparent dam behaviour, the most extreme situations can be considered to be 28 days cooling with zero stress relaxation creep and joint grouting at construction completion and no cooling and no grouting, in combination with 50 microstrain stress-relaxation creep (SRC). While the former indicated a maximum downstream crest displacement of 27.1 mm and the latter of 42.8 mm, the respective crown cantilever horizontal (arch) stress distributions are illustrated in Figure 9.

![Figure 9a: Grouted + 0 stress-relaxation creep](image)

![Figure 9b: Un-grouted + 50 microstrain SRC](image)

**Figure 9: Horizontal (arch) stresses at T4 equilibrium temperature**

As can be seen from Figures 9a and 9b, compression is present in the upper half of the dam structure in the case of the post-cooled and grouted scenario, while compression in the naturally cooled and un-grouted scenario is limited to the upstream side of the upper-most crest. Furthermore, vertical upstream heel tensions exceeding 2 MPa were apparent in the latter scenario, penetrating to significant depth.

**5.1.1 Zero & 50 microstrain stress-relaxation creep**

Comparing Figures 9a and 10, it can be seen that the role of the “structural strut” is even more pronounced in the scenario of 50 microstrain stress-relaxation creep. While the overall levels of displacement are also higher in this case, the maximum crest displacement is actually reduced from 27.1 to 25.7 mm. Figure 11 is presented with every other block omitted in order to illustrate the transfer of arch thrust through the dam structure, for a scenario of 28 days post-cooling, grouted joints and no stress-relaxation creep.

**5.2 Discussion**

The results of the analyses discussed in this paper clearly demonstrate that strategic, rather than general post-cooling of the Köroğlu dam is an appropriate solution to ensure a safe dam with effective, 3-dimensional arch action, whether zero stress-relaxation creep, or as much as 50 microstrain stress-relaxation creep develops during hydration.
The analyses also successfully confirm that a single joint grouting operation immediately on dam completion is fully effective in maintaining compression within the post-cooled zone of the arch through the full period until the final equilibrium temperature state is reached, consequently eliminating the need for a second phase of joint grouting during dam operation.

![Figure 11: Illustration of compression movement through the arch (post-cooled and grouted arch)](image)

Applying a cooling water temperature of 8°C for analysis represents a conservative assumption due to the fact that the river water temperature will in fact be lower during the placement of the crest of the dam in the late part of 2016. Furthermore, the analysis approach applied does not take full cognisance of the 1.8 mm upstream movement of the dam structure that will occur as a result of the base of the dam structure retaining almost full hydration temperature rise when the induced joints are grouted over the upper, post-cooled zone of the dam structure, implying a further degree of conservatism.

6 Conclusions

The analyses presented in this paper confirm the appropriateness of an innovative technology that enabled the construction of the Köroğlu dam as an RCC arch/gravity structure in a relatively extreme climate. A technology that was first developed in temperate climates has consequently been demonstrated to have a wider application and can now undoubtedly be applied more generally to reduce dam construction implementation costs and time, thereby increasing project economy and sustainability.

7 References


The Author

Dr Quentin Shaw is a director with ARQ Consulting Engineers. He has worked exclusively in dams during his 32 year career, specialising in RCC, with over 6 million m³ placed to date, concrete and arch dams. He has worked on more than 100 dams of all types from 5 to 280 m in height on projects in 26 countries and has been involved in RCC arch dams since the technology was first introduced in South Africa in the late 1980s. Quentin has acted as an expert/specialist in the fields of RCC, concrete and arch dams on major international projects and has been a member of the client’s expert/technical review panel for 8 large projects to date. He has published more than 50 technical papers on dam engineering and he is currently leading the team for the update of the ICOLD RCC bulletin (No 126).