Construction innovations for RCC Cofferdams to speed up construction and reduce costs

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This paper deals generally with the planning, design and construction of RCC cofferdams and draws on recent experience in simultaneously building of the upstream and downstream RCC cofferdams for the Nam Theun I Hydroelectric project in Laos (NT1). On this project, the Engineer and Designer (Pöyry) faced the challenge to enable building the cofferdams, which are subject to significant overtopping resulting in a short seasonal construction window, by appropriate design modifications and an innovative approach to construction. The modifications and innovations introduced on this project led to faster construction under seasonal storm conditions with attendant benefits of reduced costs. The innovations included elimination of formwork to the greatest extent possible and eliminating conventional advance foundation treatment by treating foundations as part of the RCC production process through the use of GERCC Pre-Mix in lieu of conventional CVC for dental and levelling concrete at the dam foundation interface and treating the abutment foundations with GERCC as the construction proceeded. Once the geometry of the structure permitted, Sloped Layer Construction was introduced to reduce the impact of storm events and to take formwork and lift joint preparation from the critical path, again saving time and reducing costs. The RCC Mix Design was influenced by the approaching increasing risk of the structure being overtopped. The paper in intended to provide guidance to engineers planning the construction of cofferdams for RCC dam projects and commends the use of RCC in preference to embankment cofferdams which may not survive overtopping.

1. RCC Cofferdams designed for speed of construction and durability

Cofferdams are "temporary structures" in that their service life is short. However, it must be borne in mind that many major dam projects have suffered from extended delays due to technical, financial and other issues. Often there is a narrow time window in which the cofferdams are to be constructed and unforeseen circumstances can narrow that window even further. Therefore, rapid construction is a prime requirement. On several projects to date, cofferdams constructed of earth and rockfill materials while being quick to construct, have proven to be only too temporary and have failed, usually because of overtopping, resulting in delays to the main project e.g. Ralco Dam in Chile [1].

Therefore, provided the foundations are suitable, RCC construction can offer the best solution with least risk. The Designer should take the following issues into consideration:

- The design flood can be well below the design flood generally required for embankment dams.
- In case planned overtopping is considered, the energy dissipation and erosion protection measures have a short life and may be minimal.
- Leakage through and around the structure must be reduced to a level that can be handled by pumps.
- Elimination of foundation grouting and drainage from the design if possible for speed of construction.
- Elimination of galleries from the design.
- Simplification of contraction joint design.

- Contraction joints may not be required as any leakage though transverse cracks in the dam may be minimal during the life of the structure.
- Simplicity of geometry for rapid construction.
- Appearance is not a consideration.
- RCC strength requirements, taking into account possible overtopping at early age.

After the above issues are taken into account, the RCC cofferdam so designed may require a greater volume of RCC than for an optimal RCC design but should be faster and more economical to construct.

Construction of cofferdams in RCC will require the mobilisation of basic aggregate and RCC manufacturing and placing equipment ahead of time required for the main dam, but provides an opportunity for early field trials of RCC mixes and methodologies and the Specification should reflect this.

2. Design of the Nam Theun 1 Cofferdams

The typical upstream and downstream facing option for most RCC dams is to place the RCC directly against purpose-designed formwork with a suitable anchoring system for retarded RCC mixes which allows continuous placement of RCC without interruptions. Generally, grout enriched RCC (GERCC, GEVR or IVRCC), or CVC that can be consolidated by immersion vibrators is used as facing concrete to meet the requirements in terms of strength, durability and appearance. Typical RCC dams have stepped downstream faces all constructed using vertical formwork with the advantage that the stepped downstream faces provide a degree of energy dissipation in case of overtopping. However, placing and raising formwork is a major constraint on speed of RCC construction.

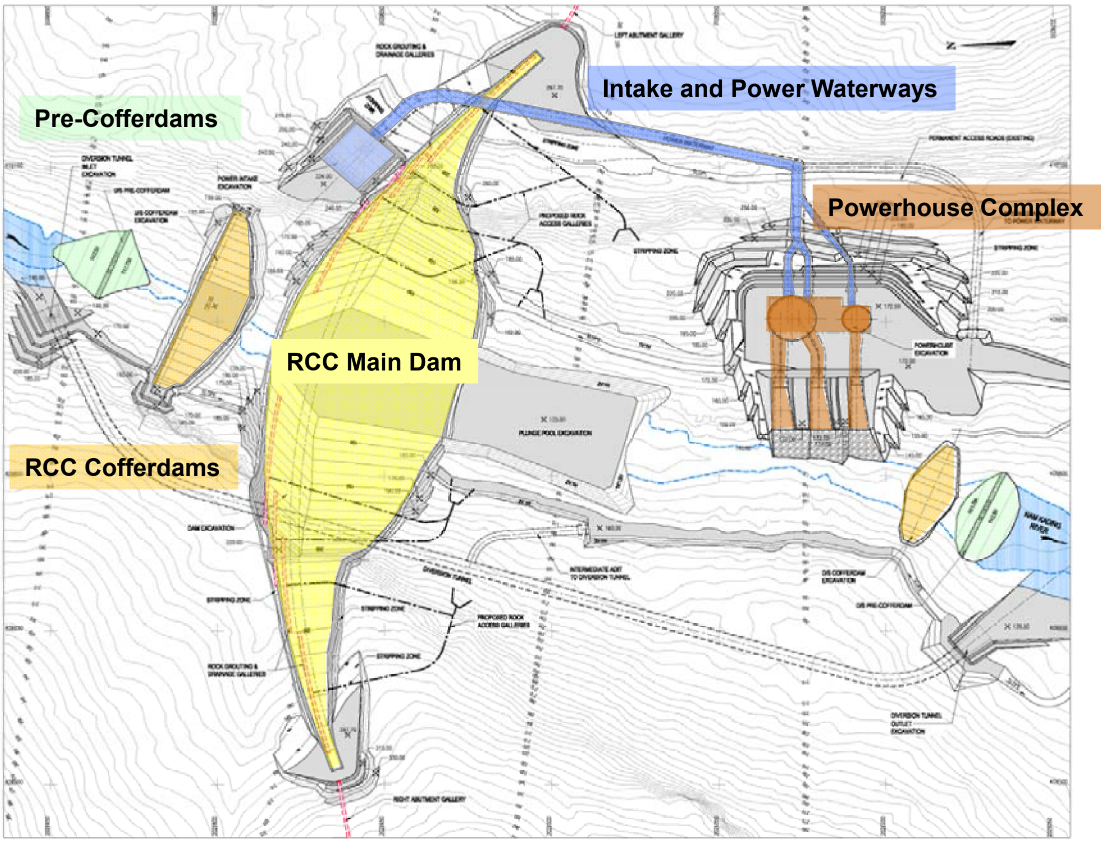

Fig. 1. Overview of NT1 Hydroelectric project showing Dam, Powerhouse, Diversion Tunnel, and Upstream and Downstream Pre-cofferdams and Cofferdams

At the Nam Theun 1 (NT1) hydropower project in Laos, the crest of the downstream cofferdam is some 17m lower than the crest of the 42m high upstream cofferdam (42m high) and the afflux at the downstream cofferdam is high, being dependant on the backwater from the Mekong river. This configuration resulted in high tail waters for both structures during overtopping assisting in energy dissipation of the passing flood. The layout of the cofferdams at the NT1 site is shown in Fig. 1. In the interests of speed of construction, the steps on the downstream faces of these structures were eliminated in favour of unformed sloping faces of compacted RCC with the acceptance of lower energy dissipation downstream of each structure. The formed vertical upstream face was retained on the upstream cofferdam to save time in view of the height of the structure and the difficulty of excavating the foundation some 5m below the river bed. Whereas for the downstream cofferdam, an unformed upstream sloping face at 0.4:1:H to 1.0 V was ultimately adopted.

The upstream cofferdam which is 42m high, has a maximum crest width of approximately 10m (at el. 167.00 masl), a vertical upstream face and a downstream slope of 0.8H:1.0V. The volume of RCC placed was approximately 120,000m3. The crest was profiled to give a 6m deep and 160 wide notch with side slopes of 10H:1V to:

- Divert flood flows away from the abutments downstream and as an erosion minimisation measure, and to,
- provide access across the river for heavy equipment to the Diversion Tunnel Inlet structure for diversion closure operations and commencement of reservoir impoundment.

The cofferdam was designed to be stable without a grout curtain and drainage. The Q10 flood over the cofferdams is some 8,300 m3/s. The final cross-section is shown in Fig. 2. It can be seen that the unformed downstream slope was steepened from 0.8H:1.0V to 0.4H:1.0V near the crest as greater confidence was gained in the compaction of RCC on slopes by vibrating plate compaction.

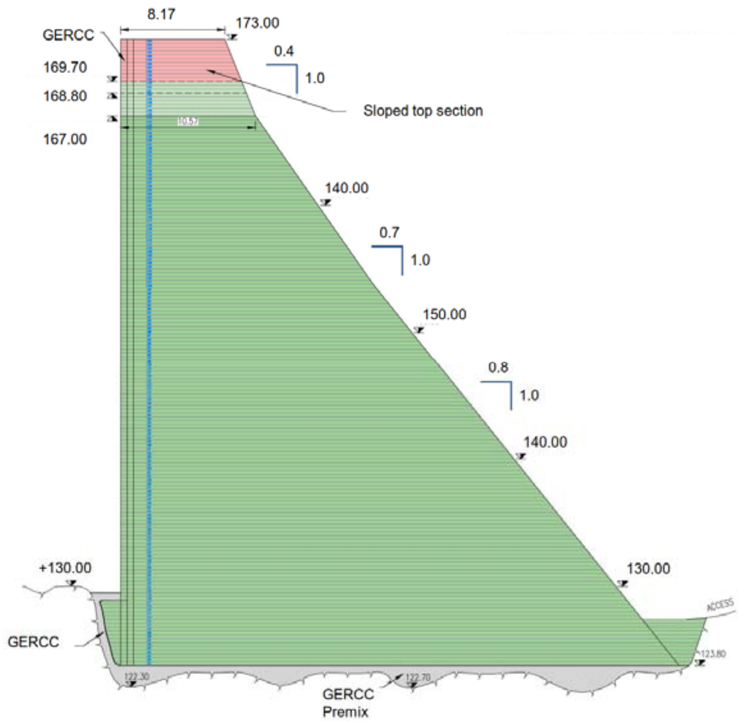

Fig. 2. Cross-section of Upstream Cofferdam

The downstream cofferdam is 25m high and ultimately has an upstream unformed slope of 0.4H:1.0V and a downstream slope of 0.7H:1.0V and a crest width of around 6m. The crest was profiled to 1.5m depth in similar way to the upstream cofferdam. The volume of RCC placed was approximately 45,000m3. Fig. 3 below shows the final profile. The structure was designed for a lower strength foundation with a generally symmetrical cross section and the design width at the base widened to suit the anticipated foundation conditions.

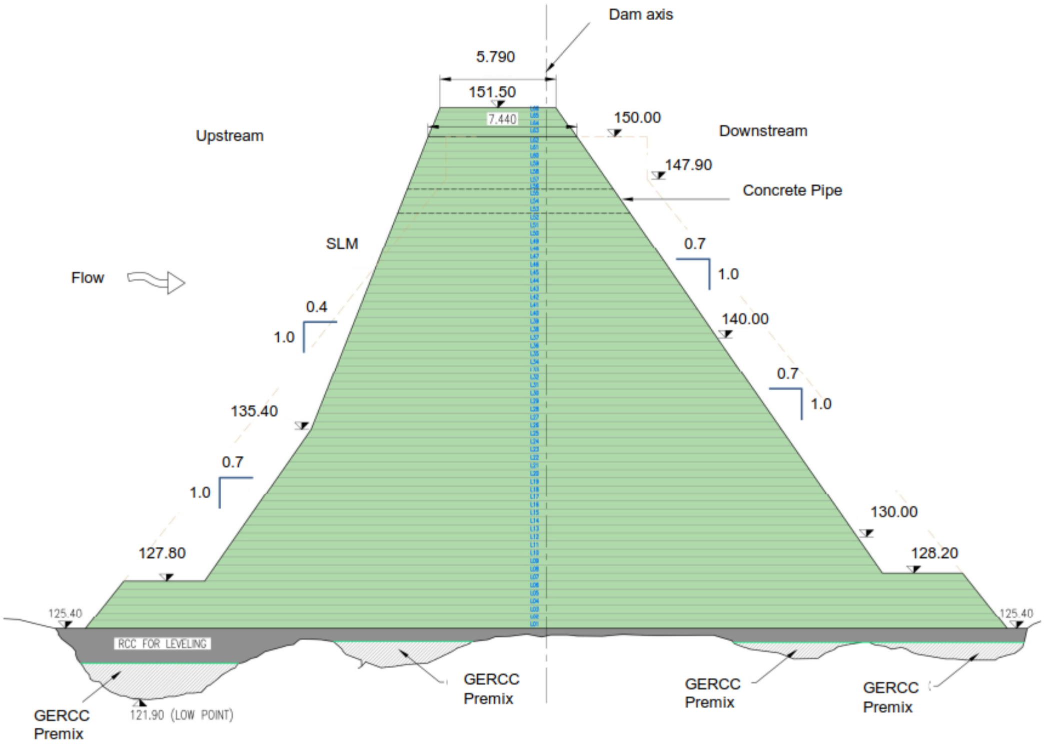

Fig. 3. Cross-section of Downstream Cofferdam

The RCC Mix adopted was a high cementitious mix using sandstone aggregates. The aim was to produce RCC with a compressive strength of 20MPa @ 28 days or before the structure might be overtopped whichever was the longer. This was achieved by increasing the cement content of the mix as the construction neared the crest of the cofferdams and the projected time to overtopping became shorter. Due to the less critical design of the downstream cofferdam, placing of the RCC in 400mm horizontal and sloped layers was permitted for this structure (not allowed for the upstream cofferdam or the main dam which use 300mm horizontal and sloped layers). GERCC was used against foundation rock.

3. Control of water for Cofferdam construction

Unlike CVC, RCC cannot be placed in water so the placement area must be fully dewatered. For the main dam this dewatering is best achieved by means of borehole pumps followed by grouting. At NT1 there was significant water ingress from the foundation rock as springs. Due to the robust design, as illustrated in Fig. 4 it was feasible to place gravel drains over the springs and to pump the water down from sumps in the RCC. The sumps were extended upwards through the RCC until the inflow was controlled and the sumps could be backfilled with CVC. Grout pipes were installed in the gravel drains for later grouting up the gravel drains. As it happened the grout pipes were lost when the cofferdams were overtopped. However, after completion of the structures, leakage through the foundation is marginal. In this context it needs to be stressed, that the described approach is not appropriate for the main dam, where full dewatering by borehole pumps is essential.

Fig. 4. Control of seepage water in the cofferdam foundation using gravel drains

4. Faster foundation treatment speeds up RCC Cofferdam construction

Conventional foundation treatment for RCC dams comprises rock cleaning and dental works. Rock cleaning includes removal of all loose and weathered material by excavator, handwork, barring, picking, brooming, water jetting and air jetting. Before RCC can be placed, holes, grooves and areas of deeper excavation are filled, typically with conventional vibrated concrete (CVC). Then levelling CVC concrete is placed to create horizontal areas suitable for the placement of RCC with its attendant large equipment

This standard approach requires a “green clean” of the CVC surfaces and additional re-cleaning of the foundation area to ensure adequate bonding. There is a time delay of up to 7 days while the CVC hardens and gains strength.

At NT1, no CVC was placed in advance for foundation treatment. Foundation treatment was done using a combination of GERCC Pre-Mix and GERCC placed as the construction proceeded.

GERCC Pre-Mix is a GERCC mix batched in the RCC Batch Plant. Typically the mix can be designed assuming 0.6:1.0 Water:cement grout added to the mix assuming 50 to 75 litres/m3. The water content is adjusted to give a slump between 3 and 4 cm. Set retarder is added as required to meet the conditions.

From a pure design viewpoint, the use of GERCC Pre-Mix in lieu of CVC, reduces the dissimilarity of the materials.

The process followed was to progressively fill the hollows in the foundation with GERCC Pre-Mix which was brought in in trucks and vibrated into place using 90mm immersion vibrators (see Fig. 5). Once a sufficient level area was created and before the GERCC Premix has reached initial set, and RCC layer was placed on top (see Fig. 6). This process started from the downstream toe of the upstream cofferdam and advanced across the foundation until the upstream face was reached (reverse direction for the downstream cofferdam). In this way truck access was established from the outset. The technical concern would be difficulty of compaction of the RCC over the semi fluid GERCC Pre-Mix underneath but no problem was detected in this case.

Once RCC placement had commenced final excavation and foundation treatment were carried out as the RCC surface was raised. Seams and defects as well as the contact between the RCC and the foundation were treated with GERCC (see Fig. 7).

It is fair to say that not one cubic metre of CVC was used in the treatment of the foundations for the cofferdams in the interests of saving time (and cost). RCC placement started in conjunction with foundation treatment with GERCC Pre-Mix.

Fig. 5. Placing and vibrating GERCC Pre-Mix

Fig. 6. Placing RCC over fresh GERCC Pre-Mix and Truck travelling over advancing layer of RCC for upstream RCC cofferdam

Fig. 7. Foundation treatment of Abutments with GERCC simultaneously with the RCC construction

5. Formed and unformed faces for RCC Cofferdams

The system of placing the RCC slopes of the NT1 cofferdams was a refinement of previous work of constructing RCC faces by using vibrating plate compactors. The RCC was end dumped by trucks and worked out to the face by dozer. The larger (12 tonne single drum) rollers could work close to the face. The edge was then confined and simultaneously compacted by a vibrating plate compactor mounted on a rubber-tyred excavator. Safety concerns were addressed by eliminating manual operations.

Poor compaction adjacent the face was not of concern as any unravelling would generally be limited to the depth to the more densely compacted RCC. This zone of lower density should be considered as “sacrificial concrete” and should not be included in the concrete mass for stability analysis. However, the faces proved to be well compacted as evidenced by the performance over the time the cofferdams were subjected to high flood flows.

Without special equipment or forms, the steepest face that can reasonably be constructed using crushed aggregate in the RCC mixture and without containing the face is 0.8H:1.0V. When using a plate compactor mounted on a wheel excavator steepness of the face can be increased maximum to 0.4H:1.0V as it was demonstrated at NT1 (see Fig. 8).

Fig. 8. Placing RCC to face by dozer; Compaction first with 12 tonne roller and then by vibrating plate compactor; Custom plate compactor

The steepness can be further increased up to vertical, if RCC is placed against reinforced wire mesh. In contact with the wire mesh, grout enriched RCC is used following the same principles as for “normal” facing concrete. This method is particularly cost effective and time efficient for RCC access ramps in case RCC is conveyed onto the dam by trucks (see Fig. 9). It has also been successfully employed for the upstream RCC/CVC interface of a spillway ogee section.

Fig. 9. Vertical Steel Mesh 'Formwork' for placing RCC/GERCC

6. Sloped layer placement speeds RCC Cofferdam construction

Sloped layer construction is gaining increasing acceptance as an improved method of placing RCC and, in particular, a "high paste" RCC [2].

The system was introduced to the NT1 cofferdams to minimise delays due to heavy rainfalls which came in the form of daily storms during the onset of the wet season. The system assisted in allowing the rain to run off quickly and greatly reduced the lift area affected. The approach also had benefits of removing formwork raising and most of the lift joint preparation from the critical path. A further benefit was that the formwork for the upstream face of the upstream cofferdam could be erected just ahead of the advancing toe of the sloped layer thus minimising the area of formwork exposed to damage in an unexpected overtopping event. Of particular significance was that the compaction of the unformed slopes by plate compactor was unaffected. The height of the sloped layer was 3m for the upstream cofferdam to match the formwork height and up to 4.2 m for the downstream cofferdam where no formwork limitations applied.

Fig. 9. Slope layer construction of downstream cofferdam in 400mm layers without formwork (left) and the upstream cofferdam with upstream vertical formwork in 300mm layers(right) for Nam Theun 1 hydropower project

7. Effects of flooding

Minor overtopping of the cofferdams occurred during construction as shown in Fig. 10. However, recovery of placing operations was rapid. The only damage was slumping of a localised section of the upstream (0.4H:1.0V) face of the downstream cofferdam which was quickly repaired using steel mesh formwork and CVC.

Fig. 11. Minor overtopping of the RCC Upstream Cofferdam during construction

Immediately following substantial completion of the RCC works, both cofferdams were subjected to overtopping for more than 2 months with sustained floods as deep as 6.8m over the central crest section of the upstream cofferdam, as shown in Fig. 11 below.

Fig. 11. Floods overtopping the RCC upstream cofferdam (left) and the largely unaffected and intact downstream face of the RCC upstream cofferdam (right)

8. Speed of construction

The two cofferdams were constructed within the same time frame with priority being given to the larger upstream structure until superseded the upstream pre-cofferdam.

The work entailed the placement of 165,000m3 of RCC and was completed in a total of 15 weeks following exposure of the foundations. This period included approximately 5 weeks of delays due such circumstances as materials shortages, wet weather flooding and plant breakdowns.

9. Conclusions

The paper summarizes the different approach to design which is possible with RCC cofferdams in the interests of saving time and cost. It goes on to present a case study of RCC cofferdam construction on a particular project where tight time constraints applied. It describes innovations that were adopted to speed up and reduce costs during construction, including expedited foundation treatment, unformed RCC faces and sloped layer construction.

On this project, time delays due to foundation treatment were eliminated through the use of GERCC Pre-Mix as an alternative to backfilling, dental and levelling concrete. RCC was directly placed on the GERCC Pre-Mix before initial set of the mix providing access for RCC placement from the outset without surface treatment of the lift joint.

It was demonstrated that RCC slopes up to 0.4H:1.0V can be successfully compacted by custom-built plate compactors. It was also demonstrated the conventional downstream formed steps may not be required for hydraulic energy dissipation purposes for cofferdams.

It must be stated that introduction of these fast track approaches is only feasible where there is close cooperation between the designer, the supervising Engineer and the Contractor. Provided an enlightened approach is followed, such as described herein, RCC construction remains the Authors preferred solution for cofferdam construction where circumstances allow.

10. Acknowledgement

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