UPDATE OF ICOLD BULLETIN 126 ON RCC DAMS

Shaw QHW

1, Director: ARQ (PTY) Ltd, +27 12 348 6669, Fax ,quentin@arq.co.za

Abstract: The original 2003 ICOLD Bulletin 126 on Roller Compacted Concrete dams proved to be the most successful ICOLD bulletin to date, with the highest number of copies published and being translated into more languages than any previous ICOLD bulletin. Over the past decade or so, the number of RCC dams in the world has essentially doubled, with approximately 700 now completed, or under construction. More importantly, some significant developments have occurred in various aspects of RCC technology for dams and to ensure that the current ICOLD bulletin reflects the state of the art, an update of Bulletin 126 was considered necessary. A decision to update the bulletin was consequently taken at the ICOLD annual meeting in Seattle in 2013.

While many of the developments in RCC dam engineering since the publication of Bulletin 126 have been complementary and have come about through experience on RCC structures of ever increasing size and height, several significant developments in our knowledge influence how we should design and build our RCC dams.

The update of ICOLD Bulletin 126 is being prepared by a task team of the ICOLD Committee on Concrete Dams lead by Quentin Shaw and comprising Rafael Ibanez de Aldecoa, John Berthelsen, Marco Conrad, Tim Dolen, Marco Conrad, Malcolm Dunstan, Francisco Ortega, Mike Rogers, Ernie Schrader, Del Shannon and Tsuneo Uesaka.

In this paper, the author describes the developments that will form part of the Bulletin 126 update and discusses the novel manner in which the bulletin update will be published.

Key words: ICOLD, RCC Bulletin 126.

1 Background and introduction

Roller compacted concrete dam construction has a history of more than 30 years, with approximately 700 RCC dams completed, or under construction worldwide as of 2015. Despite having evolved to reach a state of some maturity over this period, the technology continues to develop and while certain aspects can be considered to be undergoing a process of ongoing refinement with increasing experience, in other areas necessary changes to current practice remain in the process of being adopted.
The technology for roller compacted concrete dams was first addressed by ICOLD in Bulletin No. 75 “Roller-Compacted Concrete Gravity Dams”[1], which was published in 1989, and subsequently in Bulletin No. 126 “Roller-Compacted Concrete Dams: State of the art and case histories”[2] published in 2003. While the latter document saw wide and successful application over the intervening period, a number of important recent developments now need to be addressed to ensure that the current ICOLD publication realistically reflects the contemporary state of the art. With much of the contents of Bulletin No. 126 remaining valid, it was considered that the important developments should be addressed through a bulletin update, rather than a new bulletin.

Particularly important developments in RCC dam technology that necessitated the present update of Bulletin No. 126 include the following:

1. New developments in the understanding of the early behaviour of different types of RCC that influence design and construction;
2. The important design differences that relate to the horizontal construction of RCC dams, compared to the vertical construction of conventional vibrated concrete (CVC) dams;
3. Developments in mix designs and construction techniques, most particularly related to super-retarded, high workability RCC (see Figure 1);
4. Developments in the design and construction of RCC arch dams; and
5. Developments arising from the use of RCC in more extreme environments.

In this paper, the author outlines in broad detail the developments in RCC technology since the original publication of Bulletin 126 that will be addressed and included in the update.

2 Bulletin purpose

The purpose of the ICOLD RCC Bulletin is to make available to all engineers a synopsis of current best practice in the use of roller-compacted concrete for dams. The Bulletin update will accordingly present a comprehensive review of the state of the art of the design and construction of RCC dams as at 2015. In principle, the update is a revision of the original document, which will include improvements to aspects through which some increased knowledge and developments in technique have been gained through experience, while adding substantial new sections where significant developments in understanding have changed the basic approaches and methodologies, particularly in respect of dam design.

The Bulletin will address all aspects of roller-compacted concrete for dams, from planning, to design and construction and performance in operation. Materials selection, concrete mixture proportioning and quality control will also be addressed, although the first mentioned will be covered in less detail than previously, as reference can now be made to the recently published ICOLD Bulletin 165 “Selection of Materials for Concrete Dams”[3] for a more exhaustive review of materials selection requirements.
In the process of updating Bulletin 126, the section on Hard-fill will be removed, as the related technology is currently being addressed through a new ICOLD committee on cemented materials dams (CMD), who intend to publish a bulletin on these dam types.

![Figure 1. RCC dam construction](image)

(illustrating modern, cohesive, non-segregating, high-workability RCC)

### 3 Bulletin importance

Various different approaches can be applied for RCC dam design and construction and success is not always easily achieved. Consequently, the ICOLD RCC Bulletin is a very useful and important document in providing information and guidance on best practice and the most successfully applied variations thereof. The particular significance of the RCC Bulletin 126 can be seen in the fact that it is reported to have the highest print numbers and to have been translated into more languages than any other ICOLD bulletin to date.

### 4 Developments in RCC technology for dams since 2003

#### 4.1 Developments in the understanding of the early behaviour of RCC

Many RCC dams have been comprehensively instrumented and this has allowed significant developments in knowledge and the understanding of the performance and behaviour of the material, in the fresh state, during the hydration process and in its mature form. With this knowledge, it is apparent that RCC can essentially be assumed to behave in a similar manner to CVC only in a mature state. It has been demonstrated that it is not appropriate to assume that the generic rules that were developed to define the stress relaxation creep in CVC during the hydration process can be applied for RCC, with certain low cementitious materials RCCs indicating substantially higher stress relaxation creep and certain higher cementitious materials RCCs
The 7th International Symposium on Roller Compacted Concrete (RCC) Dams

(particularly containing fly ash) indicating very substantially lower stress relaxation creep. Furthermore, horizontal construction, with induced, as opposed to formed joints, increases the sensitivity of the structural performance to the level of stress relaxation creep applicable, with structural bridging in narrow valleys far more likely to develop in low stress relaxation creep RCC than in CVC constructed in independent vertical monoliths.

![Changuinola 1 arch/gravity dam - designed on the basis of improved understanding of early RCC behaviour](image)

Research has demonstrated such low levels of stress relaxation creep during the hydration process in high workability, fly ash-rich RCC that an upstream movement on a curved dam has been observed during construction (see Figure 2), while high levels of stress relaxation creep have been indicated in lean RCC dams through the measurement of progressively increasing compressive stresses in the surface zones[4]. The evident broad variation in this parameter in different types of RCC implies that the traditional assumptions that are valid for CVC are only appropriate for RCC when no design sensitivity to the level of stress relaxation creep exists.

The above implies that an additional characteristic, or design parameter, should be considered when designing and developing an RCC mix for a specific dam. In this regard, low, or high stress relaxation creep will be a positive characteristic in certain circumstances and a negative in others and careful consideration, investigation and laboratory testing is necessary during the RCC mix development process for dam structures where a design sensitivity to the actual level of hydration-cycle stress relaxation creep exists.

4.2 Design differences related to horizontal construction

Over its development history to date, in many respects RCC has been treated in a similar manner to CVC and it has been assumed that many “rules of thumb” that apply for CVC dams are equally
applicable to RCC dams. The above developments in the understanding of the early behaviour of different RCC mix types, however, have emphasised important structural behaviour differences in RCC compared to CVC. RCC can consequently be designed for a range of behaviours when a single characteristic is often applied in the case of CVC. The reduced early stress relaxation creep in fly ash-rich RCC has also proved very advantageous for the design and construction of more efficient RCC arch dams[4]. The same effects, however, can cause deleterious 3-dimensional bridging in high RCC gravity dams in narrow valleys[5].

Furthermore, in combination with continuous horizontal construction, the manner in which we currently design induced joints in RCC implies that we are in fact often constructing 3-dimensional structures. With a practice of 2-dimensional design for RCC gravity dams that exists due to its heritage in CVC dam technology, the design differences associated with continuous horizontal construction, compared to the separate, vertical monolith construction of CVC dams will be addressed for the first time in the Bulletin update.

Figure 3. “Older” technology RCC (less cohesive, with more segregation, no set retarder and less paste mobility)

4.3 Developments in RCC mix design

Since the first generation of RCC dams (see Figure 3), a general trend towards high-cementitious RCC types has been apparent, most likely as a consequence of the following:

- While RCC was initially considered as a low strength mass concrete for which design changes might be applicable compared to a traditional gravity dam, developments in the technology have since demonstrated that roller-compaction can be used to produce high quality concrete in large dams;
- High-cementitious RCC is perceived as allowing the construction of gravity dams that are fully equivalent to conventional mass concrete dams;
Lean RCC is perceived to require modifications in dam design, compared to a conventional mass concrete dam;

A large dam is a structure with a long design life and designers tend to be conservative, adopting what might be perceived to be a least risk solution and tending not to favour a solution dependent on a geomembrane, or the “separate” approach; and

Developments in high-cementitious, super-retarded, all-RCC dam construction have produced a methodology that ensures a very efficient, rapid and very cost-effective high quality concrete dam. While this RCC dam type requires cost-effective access to cementitious materials and pozzolans, good aggregates and suitable founding conditions, it undoubtedly currently represents the most efficient approach for the construction of a large, high-strength gravity dam.

The last listed of the above implies that High-cementitious RCC will tend often to be applied unless site-specific conditions, such as cementitious materials availability problems, compromise its efficiency. Notwithstanding this fact, all of the listed RCC types represent workable solutions that should be considered within the constraints and opportunities inherent to each specific dam site.

A polarisation of Lean RCC and High-paste RCC occurred as a consequence of distinctly different approaches preferred by various protagonists during the early development of RCC design and construction technology. While a distinct difference is apparent when adopting the “separate” (permeable RCC with an upstream impermeable barrier), or the “overall” approach (impermeable RCC) and while each RCC approach has a number of unique features, the increased use of non-plastic fines in paste has caused more commonality to develop across the various RCC types.

As a consequence of the above, revised terminology will be introduced in the Bulletin 126 update, whereby the previously applied term “High-paste” RCC will be replaced by the term “High-cementitious” RCC. Furthermore, the term “cementitious paste” will be used to define the combination of cementitious materials and water, while “total paste” will refer to all materials in the mix that would pass through a 75 micron sieve. Although the general terminology for RCC indicates a requirement for a cementitious materials content exceeding 150 kg/m³, modern super-retarded, High-cementitious RCC in fact generally requires a cementitious content exceeding 190 kg/m³ in order to produce sufficient paste for high-workability modified Vebe times of around 8 seconds. While all such mixes contain high percentages of pozzolan, cementitious materials contents of this level usually produce RCC compressive strengths at a one year age exceeding 35 MPa. Concrete strengths of this level are generally unnecessary in gravity dams, unless subject to high seismic loading, and a trend is evident in combining non-plastic fines in slightly lower cementitious materials RCCs (> 160 kg/m³) to gain the benefits of high-workability, super-retarded RCC while reducing the cost of cementitious materials (see Figure 4).

---

1 RCC dams are designed in accordance either with the “Overall” approach, whereby the RCC creates the impermeable barrier, or the “Separate” approach, whereby a separate impermeable barrier is created on the upstream face, usually in the form of a geomembrane (PVC).
Depending on the shaping and grading of the aggregates, more than 200 litres of paste will typically be required to produce a cubic metre of high workability RCC. Considering cementitious materials alone, such a paste volume will generally only be possible with contents exceeding 200 kg/m³. Where non-plastic fines are used to enhance the paste volume, however, the benefits of high-workability, super-retarded RCC construction have been successfully extended to lower strength mixes.

Whether high-cementitious, or Lean, modern RCC is generally more cohesive, less easily segregated and more easily compacted. Modern RCC generally has a softer, or less bony appearance than the original RCC variants, an aspect most noticeable in the high paste RCCs, for which the paste rises to the top surface under compaction (see Figure 4 & 5).

The “all RCC” dam approach continues to see increasing application, with facings and interfaces being formed in GERCC (Grout-enriched RCC – grout from top), GEVR (Grout Enriched Vibrated RCC – grout on bottom) and IVRCC (Immersion Vibrated RCC). With GERCC and GEVR being variations of grout enrichment to allow the compaction of RCC with an immersion vibrator, IVRCC is RCC that contains sufficient mobility (and paste) to be compacted by immersion vibrator without the need to add grout. Depending on the nature of the aggregates and the RCC, GERCC and GEVR might require the addition of between 50 and 80 litres of paste to enable compaction by immersion vibrator, while, in principle, IVRCC will generally require a paste content of between 230 and 250 litres to allow vibrator compaction, unless particularly well-shaped and well-graded aggregates are used.
An additional trend in RCC dam design is a more restrictive aggregate specification, in terms of shaping and void content. With impermeability and density of RCC being possible only when all voids are filled and high workability RCC requiring mobility and excess paste that will rise to the surface under compaction, a tighter specification for the constituent aggregates than is applied for CVC is specifically beneficial in reducing the total paste requirement and accordingly the cementitious materials content. Consequently, additional attention and expenditure on the aggregate processing plant can often be demonstrated to give rise to a net total RCC unit cost reduction through a lower cement and pozzolan content.

Success has also been achieved in the application of the “overall” approach with the less favoured “medium-cementitious” RCC type. In the cementitious materials content range of 100 to 149 kg/m³, insufficient paste is generally present to develop impermeability. Consequently, it will often be more economical to increase the cementitious materials, particularly the pozzolan content, or to adopt the “separate” approach, apply an upstream face geomembrane and reduce the cementitious materials content. In certain circumstances, however, particularly when pozzolans are not economically available, adequate impermeability in “medium-cementitious” RCC can be created using non-plastic fines, or milled rock powder.

A range of solutions are now possible with RCC and similar principles and approaches can now be applied for the mix design and construction application of RCC with a significant range of cementitious materials contents.
4.4 Developments in RCC arch dams

In the Bulletin 126 of 2003, only RCC arch dam technology in China was presented. Since 2003, RCC arch dams have been completed in Panama (see Figure 6), Pakistan, Puerto Rico and Turkey. The Bulletin update will cover a more inclusive summary of the full development of RCC arches to date.

It is significant to note that all of the RCC arches outside China to date have been arch/gravity structures, while the majority of examples in China are thin arches. The reason for this situation is probably a combination of the fact that significantly more sites suitable for thin arches exist in China, while RCC loses competitiveness to CVC on sites with difficult access and low volumes of concrete, where the speed advantages of RCC construction cannot effectively be exploited.

An interesting benefit that forms a common aspect of the design of several recent arch/gravity RCC dams is the concept of designing for hydrostatic loading as a gravity structure and relying particularly on arch action for stability under seismic loading.

Figure 6. Changuinola 1 RCC arch/gravity, Panama

4.5 Secondary benefits of RCC construction speed

Another particular advantage of RCC dam construction has been demonstrated on hydropower schemes, when it is often possible to bring forward the date of scheme commissioning with RCC construction. If the application of an RCC dam might be able to reduce the implementation period for a 500 MW hydropower scheme by six months, the net project benefit is likely to exceed US$ 50 million. Such a benefit of RCC dam construction can substantially influence the selection of dam type and represents a significant factor in the ongoing growth in the application of RCC dams.

5 General discussion on RCC technology

The maximum benefit of RCC construction is realised when full advantage can be taken of the associated high capacity production, delivery and placement equipment and plant. Such an eventuality requires that simplicity be considered as the key element in design and in construction methodology and logistics planning, configuring all works and activities to ensure that all plant can continuously maintain maximum production.

The design and design development for an RCC dam and the optimisation of the RCC mix can be more involved and time consuming than is the case for a traditional, mass concrete dam. Design for an RCC dam is a process of iteration, more similar to that of a fill dam than to that of a traditional...
mass concrete dam, whereby materials design (cementitious and aggregates) and structural design are developed in parallel to identify an optimal solution. In certain circumstances, RCC mix development can be time-consuming and sometimes it may be advantageous to initiate this process prior to tender, implying a requirement for additional forward planning.

RCC dams can typically be raised at rates exceeding 10 m per month, or more than one 300 mm layer per day. Bond between RCC placement layers can impact the structural and permeability performance of the concrete mass of the dam and different construction methodologies and RCC mix types are applied dependent on the respective performance levels required in terms of a particular dam design.

Although early concern focussed on the apparent low shear strength properties between RCC placement layers, construction techniques have since been developed that can assure high levels of cohesion between placement layers. However, a good RCC mix and stringently controlled construction are required to confidently and consistently realise vertical, inter-layer tensile strengths exceeding 1.5 MPa and it is consequently the vertical tensile strength capacity between placement layers that remains the critical limitation on RCC dam height.

Over its development history to date, RCC has grown from a low strength, mass fill to a material capable of producing low strength, low deformation modulus, high creep concrete to very high strength, high deformation modulus, high density, low creep and impermeable concrete. It is now realistically possible to produce RCCs with strengths ranging from 2 to more than 40 MPa. With appropriate construction techniques and high-workability high strength RCC, it is also possible to achieve good bond, and accordingly vertical tensile strength, between placement layers. Consequently, RCC is now used for the construction of a range of concrete dam types from low stress, prismatic gravity structures to relatively high arch dams.

6 Publication of bulletin update

The original Bulletin 126 was finally published in 2003 after more than 10 years in preparation. With RCC technology continuing to develop, it was considered essential to take every possible measure to avoid such an extended period of preparation for the current Bulletin update. Indeed, this objective was the prime motivation for deciding to proceed with an update of the existing Bulletin, as opposed to compiling a completely new Bulletin.

The ICOLD Committee on Concrete Dams consequently proposed a more modern approach to making the updates available more rapidly. With approval from ICOLD, the update of Bulletin 126 is accordingly being tackled by chapter, with each completed chapter being made available electronically through the ICOLD website on completion. Only once all chapters are completed will the full update be printed in hardcopy. The first drafts of all chapters of the bulletin update are scheduled for completion by the end of 2015.

7 References


