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ADVANCED CONCRETE ENGINEERING

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Paradise Dam
Shear Strength Evaluation Comments

Scope

Provide an independent review of the Design Consultant's assessment of RCC lift joint shear strength and associated implications for failure potential through the RCC lift joints at Paradise Dam as documented in References 1 and 2 below.

Provide comment on the general stability and RCC shear strength assessment approach that has been applied by the Design Consultant. The report should include particular reference to:

- Any risks or uncertainties that may be inherent with the assessment approach adopted by the Design Consultant
- Recommendations on alternate approaches or tests that should be considered
- Whether the core drilling process has the potential to negatively impact the core, particularly considering that the Paradise Dam RCC is a relatively low strength mix
- Whether the diameter of the core when compared to the aggregate size is an adequate size to provide reliable results. For example, do tests on a 100mm core with 75mm aggregate bias towards aggregate properties as opposed to the broader RCC mass?
- The suitability of the testing methods that have been employed

The review of these documents was performed by [redacted] and [redacted] of Tatro Hinds Advanced Concrete Engineering, Inc. In addition, [redacted] made a site visit to the Paradise Dam, inspected the RCC core, visited TriLab Testing Laboratory, and met with individuals from SunWater, GHD, Dam Safety, SMEC, and the project Technical Review Board.

Reviewed Documents

1. GHD memorandum "Review of RCC shear strengths" dated 5 September 2019 (Reference 1)
2. GHD Memorandum "Dam stability analyses" dated 5 September 2019 (Reference 2)
3. SMEC draft report "Draft Geotechnical Investigation Factual Report" dated 16 August 2019 (Reference 3)
4. Comprehensive Risk Assessment – Appendix K – Peer review comments (Reference 4)
5. Existing Dam drawings - Burnett Dam Alliance Design Report (Reference 5)

6. Select Construction records. Photos, Memo's and monthly Quality Report (Reference 6)

Summary of Relevant Events

2005	Completion of dam construction
Jan 2006	Drilling of 6 inch angled core for limited testing (no shear testing performed)
Jan 2011	Significant flood event
Jan 2013	Significant flood event (flood of record - peak discharge of 16,500 m^3/s)
Dec 2014	Drilling of horizontal core for testing
May 2015	Drilling of vertical and horizontal core for testing
Aug 2015	TRP review of core conditions
2018	Drilling of horizontal core for testing
2019	Evaluation Reports by GHD

Summary of Findings

After review of the GHD reports and the supplied reference information we have concluded the observed and anticipated extent of unbonded lifts in the structure is sufficient to invoke the ANCOLD requirement to assume no bonded lift joints in the structure and limit stability analyses to only residual shear strength. This determination is based on review of several core drilling programs, mixture properties, and construction records. The laboratory testing of residual shear strength provides reliable values of shear strength and the noted testing issues are not expected to have a significant impact on the test results determined to date. However, additional testing as recommended may narrow the range of variability and improve assurance in the test results.

General Comments

This report primarily addresses specific issues related to materials, sampling, testing, and subsequent evaluations and analyses of the shear strength of RCC lift joints at the Paradise Dam project. However, several general initial observations are provided as follows:

The construction of the RCC structure was completed in 2005. Extreme river flows on the Burnett River were experienced in 2011 and 2013. Erosion damage to the stilling basin and discharge channel occurred from the resulting flood flows. Evaluation is ongoing for the remediation of that damage. Independent of the erosion damage is the evaluation of shear strength of RCC lift joints in the dam and its effect on the stability of the structure for the various design load cases. The importance of the effort to evaluate the RCC joint quality to assure or re-establish that the structure meets criteria established during initial design and subsequent revisions is considered to be essential.

The ANCOLD *Guidelines on Design Criteria for Concrete Gravity Dams*, September 2013 (ANCOLD), states in Section 5.1 "unless there is strong evidence to support bonded lift joints or investigations based on cored samples are undertaken, all concrete lift joints should be considered to be unbonded." Consequently the only appropriate factors of safety against sliding (ANCOLD, Table 6.1) must be for residual strength.

Reference 1 provides the analytical basis for determining peak shear strength and residual shear strength and concludes that insufficient bonded joints exist to proceed with peak shear strength analyses. The report details testing and the analyses performed to provide the basis for the assumed residual shear strength parameters. The subsequent stability analyses (Reference 2) uses only residual shear strength and the associated safety factors as the basis for the stability analysis.

The sampling, testing, and evaluation of shear strength properties of lift surfaces constructed with low cement content RCC mixtures is very difficult. Inherent in the design of low cement content RCC, the cement matrix may not have sufficient strength to resist the loads imposed by sampling and testing and the final results can be biased.

Drilling Methodology

In general, successful core recovery is defined as core that is not mechanically fractured during the drilling, handling, and storage process. There are many steps in the drilling process that can adversely impact RCC lift joint recovery. The type of drill, the type of core barrel, use of split sleeves, core handling and core storage all contribute to core recovery. Furthermore the techniques used in drilling, the drill rate, the water pressure, and the drilling fluids also contribute to core recovery.

The drilling equipment used in the 2006 coring program utilized a very heavy, very thick-walled bit, with split inner sleeves. The wide kerf on the bit creates potentially large stresses on the RCC core samples during the drilling operation. Although the use of drilling fluids was done (at least stated) and the core hole was angled, the recovery of intact lift joints may have been negatively affected because of the wide kerf bit. The use of thin-walled core drilling bits with inner sleeves that protect the core during drilling generally improves the recovery of intact joints.   We have no information on the manner in which the core was handled.

Truck mounted drills with split inner barrels were used for the subsequent vertical drilling conducted in 2014 and later. It is presumed that narrow kerf drill bits and inner core barrels were used for this drilling.

Horizontal drilling completed in 2019 was performed using concrete surface coring equipment with a bolted jack stand and a portable electric motor. A narrow kerf, 1.5 meter core barrel having an approximate hole diameter of 150mm was used. The equipment is lightweight and readily adjustable. It is not capable of applying the same high torque as truck mounted drills to the lift joint. More importantly though, the drilling orientation is parallel to the lift joint and results in the greatest potential for intact core recovery since the lift joint is not subjected to high torque as is the case for joints in vertical cores. However, the difficulty with drilling horizontally is the elevation of the lift joint varies and it is difficult to keep the core barrel alignment centered on the joint. This may result in cores that do not capture the lift joint in the core. It is presumed the same coring equipment was used in 2014 when that horizontal core was drilled.

RCC Core Observations

The core from many of the drill holes exhibits segregation. Where present, the segregation is primarily located at the bottom of the lift adjacent to the previous underlying lift surface. These zones are identified in many of the core logs and observable on the photographs. Our concern prior to the site visit was that the presence of segregated aggregate at a lift joint was also categorized as an unbonded joint. Very careful examination of unbonded lift joint surfaces is required to definitively classify a joint with segregated RCC as unbonded. A well-conducted visual examination of unbonded lift joint surfaces should include close inspection with a magnifying glass. It should result in an estimate of the percentage of the lift joint surface that appears to have been bonded prior to separation.

It was not possible to conduct a detailed lift surface evaluation at this point in time as the core has been moved and handled several times and has been in dry storage for many months or years. Typically, detailed inspection and estimates of potentially bonded surfaces of separated lift joints in core samples should be performed as soon as possible after drilling. However, there was no evidence that unbonded lift joints were incorrectly categorized.

Televiewer inspection of the holes appears to be very useful in clarifying the breakage of the core. Observations in Reference 1 were that lift joint breakage in the core was more widespread than the same joints observed in the drill hole wall. This is not unexpected. It confirms expressed concerns regarding adverse impacts of drilling and segregated materials affecting the quality of the recovered core while the sidewall appears more intact.

Reference 1 and the supporting documents report the percentage of unbonded lift joints in the various coring programs to be as follows:

<u>2006 Angled Coring Program</u>

One angled core hole was drilled in monolith L and progressed with depth into monolith K. Detailed core logs and PowerPoint photographs of all the core were provided. Coring was done from elevation 77.7 to elevation 50 crossing in excess of 80 lift joints. In conjunction with drilling the core the condition of the lift joints was assessed and logged. Approximately 10-20% of the lift joints were noted as intact after drilling.

<u>2015 Vertical Coring Program</u>

Two vertical cores were drilled and identified as DD600 in Monolith C and DD601 in Monolith N. Although drill holes were deeper, the limit of the drill hole imaging equipment appeared to be approximately 15 meters and 9 meters respectively. Photographs in Reference 1 show only a portion of these cores (approximately 3 meters each). On the photographs, 4 locations where intact joint samples for shear strength testing were removed are identified; however, photos and logs of the entire length of core were not provided. SunWater, at the time of drilling, reported that intact joints were 10-20%. Judging from the limited photographs that were available and presuming some amount of separated joints as a result of drilling and handing, it is estimated that possibly as much as 30% of the lift joints were recovered as intact.

<u>2014 Horizontal Coring Program</u>

Four horizontal core holes were drilled into Monoliths F and G. No logs exist of the coring and joint recovery. TRP reports indicate that where the RCC joint was encountered there was no bedding mortar and the majority of the lift joints were intact in 3 of the 4 core holes.

<u>2019 Horizontal Coring Program</u>

Detailed core logs and photographs are contained in Ref 3. Cores were drilled horizontally in Monoliths B, C, N, P, Q, R, S, and U. Difficulties in aligning the core barrel with the elevation of the lift joint resulted in an appreciable length of core in which there is no lift joint present. Of the lift joints observable in these core, approximately 50% were removed in an intact condition. None appeared to be damaged by the coring process.

<u>2019 Vertical Coring Program</u>

Detailed core logs, photographs and borehole imaging are contained in Reference 3. A series of PQ (85mm diameter) core were drilled for geotechnical purposes. Four of these core where designated to explore the extent of lift joint debonding in one monolith. The holes are designated PD-04, PD-10, PD-11, PD-12. Reference 1 identifies that approximately 60% of the lift joints are unbonded or exhibit segregated aggregate. It is agreed that after review of core photographs in the reference documents, that lift joint debonding is at least as extensive as stated. It should be noted that recovery of intact core becomes increasingly more problematic as core diameter becomes smaller. The 85mm diameter is quite small and higher numbers of unbonded lift joints should be expected.

Sampling of RCC by horizontal coring greatly improved the recovery of intact joints compared to vertical or angled coring, however, the results indicate the preponderance of the core lifts are unbonded indicating that overall lift surfaces exhibit the same predominately unbonded condition. The drilling of angled core hole should have improved core lift joint recovery. For this project, that does not seem to be the case. The specific drilling equipment may have been a factor.

We agree with the GHD assessment that sufficient intact lift joint recovery did not occur to meet the ANCOLD standard for analysis using peak shear strength and therefore any stability analyses must assume that all joints are unbonded.

Shear Testing Samples

Cores provide a better sample to test than do cast cylinders as the cylinders have edges that are molded and reconfigured differently than the in-situ condition. Core, by the nature of drilling are more consistent to the very edge. However cores, compared to large blocks, offer a small area to test where edge effects and aggregate size can dominate the observed performance. Hence larger core are better than smaller core. Our shear testing is done nearly exclusively on sawn blocks (nominal shear surface ranging in size from 250mm x 250mm to 300mm x 300mm) in order to achieve a more consistent and representative sample. Although this is not convenient for post construction evaluations, it should be noted that larger samples are more representative and can be more effective in defining shear parameters for lower strength and less well-bonded samples.

The effect of aggregate size is very significant. The general 3:1 ratio of sample diameter:aggregate diameter is very appropriate It is our experience that shear performance will test lower when tests are performed on samples with too large of aggregate. This is especially true for mixtures with relatively strong rock and a weak paste matrix as is the case here. Additionally, the recovery of intact core will be less for samples with strong aggregate embedded in a weak paste matrix where the aggregate is too large in comparison with the overall specimen size. Since the maximum aggregate size is 50mm, it appears that the nominal 150mm diameter core samples for these testing programs met the 3:1 ratio criterion.

Shear Test Method

The "shear box" testing of the RCC lift joints was done in accordance with ASTM D 5607. Multiple loadings or stages of test were done on a single sample to maximize the number of test results for the limited number of available lift joint samples tested at each testing phase. The testing procedure adopted for most of these core samples is explained in detail in Reference 1.

ASTM D 5607 does not stipulate submerged testing as a condition of the test and therefore should not have been done. The test method, however, does allow for samples to be saturated prior to the test and tested while in a saturated condition and this process should have been followed in lieu of submerged testing. Our testing process has never allowed us to test in a submerged condition; however, we always test in a condition that is as close as possible to saturated surface dry (SSD). Typically, specimens are stored underwater for a period of many days. They are removed from the curing tank and immediately loaded into the shear test machine. This process of removing samples from the curing tank and setting up to begin the shear test typically takes approximately 15 minutes so samples are not subjected to appreciable drying. We agree that a saturated condition is the proper moisture condition for shear testing of RCC. The difference in testing dry vs saturated specimens has been shown; however, it is not clear if testing in a submerged condiion further affects the test values. Although the difference in results between tests performed submerged verses tests performed in a saturated condition is likely minor; however, good practice suggests that the relative effects of submersion on test results should be evaluated.

The 2019 shear testing program tested 9 samples; 3 samples each at normal loads of 200, 500, and 1000 kpa. One time load application was done for intact strength and multiple applications of normal and shearing load were done for unbonded peak (sliding shear) and residual shear strength. The results of these tests are compiled in Ref 1 in Figures 4.1, 4.2, and 4.3.

Within the limitations of the test, we consider the results to be valid tests for the bonded joints as all were determined on individual samples. Although the hard rock and weak paste matrix of the samples are major limitations of the test this is more likely a greater concern for unbonded samples where repetitive applications of normal load and tests for residual shear tests were performed.

It is our opinion the method of repetitive testing for unbonded peak and residual strengths is problematic. This method appears to degrade the sample surface and may negatively affects the sliding friction strength and residual shear strength test results. It is possible this method is more appropriate for hard rock of uniform consistency and not for a concrete composite of high strength rock within a low strength matrix. Testing of residual strength of individual samples will provide a reasonable comparison to evaluate the effect of repeated shearing

It would be interesting to observe the sample faces after the intact test and before the multiple surface shearing/grinding that was subsequently performed. If large material displacements or edge failures within the sample were observed after the intact test, this would bring into question the method of sample encasement or the appropriateness of the testing method for these materials.

In this program of shear testing it appears that an insufficient number of tests have been conducted given the high consequences associated with poor performance. This testing is presumed to have been designed to be a quick spot check of strength conditions to assure in-situ strength is as intended. The number of tests may be satisfactory to perform this spot check However, the results were not satisfactory, hence this independent review. We recommend that many more shear tests be conducted in order to more accurately determine the strength condition of the RCC. The current number is too few for such an assessment.

Shear Failure Surfaces

The shear testing results in Reference 1 include photographs of the upper and lower failure surface of the tested RCC lift joint surface. In general, these surfaces are very fractured and disturbed. They also show significant displacement of material at the perimeter of the test specimen. Higher strength samples would have more intact surfaces showing less distress except for occasional aggregate breakage. However, even lower strength concrete should have a more well-defined shear surface with only minor aggregate breakage and gouging. The photographs of test samples after test show shear surfaces that are obviously highly degraded due to repetitive shearing and appear to be more representative of a crushing and grinding failure as opposed to a shear failure.

The extreme shear surface distress seems to have occurred on all test samples thus strongly suggesting that repetitive loading as specified in the test method is not appropriate. Our conclusion is that the test method is overly aggressive in the application of load and repeated re-application and is not suitable for this low strength matrix and RCC in general.

Statistical Evaluation

The removal of core from a dam structure is not a random sampling event. Samples are extracted at locations convenient for access and in a manner to minimize core lengths, core diameter, and the overall cost of sampling. The question after testing is always whether the sampling was representative of the situation. The likely answer is no. Cohesion can only be determined from intact lift joints

The method employed here is better in quantifying the uncertainty and variability of test results. However, it may be premature given the lack of sufficient test data. Too few data and wide variability are apparently driving confidence limits to very low values. More data should improve this situation along with some careful evaluation of some of the outlying data points. It may be the effect of changing phi angle is not a linear process. The statistical analysis was performed on a linear distribution of test results. It may be the shear parameters do not behave linearly and the analysis excessively penalizes the shear strength.

Required Material Properties

In general, stability analyses check the acceptability of a selected strength property against various configurations of the structure and the various load cases at the controlling location, generally the base of the structure. Although the analyses are not normally done to determine the minimum required shear strength parameters for various vertical locations in the structure and load cases, it may be very useful to calculate the required shear strength parameters for every few vertical meters of the structure. This exercise may point out the locations where shear performance is below the minimum required and better targets where remediation should be done.

RCC Unit Weight (Ref.2)

Records from the dam construction compute the average density of the RCC to be as low as 2464 kg/m^3 whereas the unit weight of RCC used in the calculation of self-weight for the stability analysis was 2400 kg/m^3. It is our opinion that it would be appropriate to base the self weight on the average density of the RCC. This would add a minimum of 64 kg/m3 to the self-weight of the RCC and would positively impact (albeit minor) the stability analysis for the RCC structure.

Uplift Determination (Ref. 2)

The Carpi membrane system is advertised to provide uplift reduction of approximately 50%. However, Reference 2 (top of Page 5) provides a good clarification that a 50% reduction is of the head differential between reservoir and tailwater. The report further points out that this criterion has been demonstrated for the reservoir levels experienced to date. There appears to be no uplift data collected during the periods of high flow, hence the data qualification. Is there any reason to believe that a similar uplift reduction would not occur at higher water surface elevations and that drains would continue to function as designed? More critical may be that more current foundation pressure information may indicate a changing condition.

Conclusions

1. The vertical and angled coring shows 10-20% intact joints. The horizontal coring results in recovery of up to 50% intact joints. Drilling orientation is a factor in joint recovery. The composition of the RCC (segregation) is also a factor in core recovery.

2. The stated degree of unbonded joints resulting from the various coring programs is indicative of a high degree of unbonded lift joint areas throughout the structure.

3. The ANCOLD guidelines are clear that the degree of unbonded joints requires stability analyses to be performed using residual strength and reduced safety factors.

4. Segregated materials visible along a core lift line should not always be assumed to be unbonded.

5. The aggregate size in the samples appears to generally be proper for the size of the sample.

6. The testing process to determine intact shear strength is appropriate as one-time loadings are used on individual samples. Additional testing would establish a more reliable trend since the 9 tests performed in the 2019 testing program comprise only one family of test results. It is noted however, that shear parameters of intact lift joint surfaces is of a lessor concern than shear parameters of unbonded lift joints.

7. The sliding and residual shear determination method used on unbonded RCC lift joints for this evaluation was very aggressive and, in our opinion, adversely affected the test results, creating lower values than if testing were done by a different method. We consider this repetitive shearing method to be questionable.

8. Shear testing of submerged samples is not specified in the test method and should not have been done. The method limits the extreme moisture condition to saturated

samples and testing in a dry location. The relative effects of submersion on test results should be evaluated.

9. The condition of the samples after testing shows significant damage to the point where repetitive testing seems very problematic. The method seems very inappropriate for samples of this composition.

10. The number of samples tested for this evaluation is very small and as a result may not accurately quantify the actual joint conditions. Since the testing relied on repetitive shearing on a single sample, the number of samples that were tested to fully characterize shear strength appears to be insufficient.

11. The statistical method used is a reasonable approach. Significantly more analysis is required to integrate the effects of missing data.

12. Consider using the average RCC unit weight determined from construction records.

13. Shortcomings in RCC shear strength may only impact specific locations in the structure. Establish where shear parameters are deficient and, if possible, limit remediation accordingly.

14. Given the opportunity for more testing, the safety factor presentation may need to be revised.

Suggested Future Actions

1. If a need exists for more reliable in-situ shear testing to be done, additional horizontal coring should be considered.

2. There may be an opportunity to secure RCC lift joint samples during the upcoming spillway modification.

3. Consider a few larger specimens for parallel evaluation.

4. Perform single pass testing of shear samples. Do not repetitively shear samples.

5. Develop baseline residual shear tests. Simulated lift joints can be induced in parent RCC by scribing and cracking. Other samples can be prepared by sawcutting the core to simulate a lift joint. Residual strength should be determined on these specimens to establish a baseline strength from which future residual strength test results can be compared.

6. Revise the statistical analyses

Respectfully Submitted,

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