

In-Situ Stress Measurements and Instrumentation Installation Duke Energy Walters Dam, Waynesville, North Carolina

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Abstract--

This paper serves as a case study for the application of current overcoring stress measurement methods for the structural investigation at an operating United States Federal Energy Regulatory Commission (FERC) dam. Drilling and testing were performed at Walters Dam to characterize the structural effects of concrete growth due to Alkali Aggregate Reaction. The project owner, Duke Energy Carolinas, LLC, engaged HDR, Inc. and Agapito Associates, Inc. to perform drilling and testing on-site for later development of a nonlinear, finite-element model by HDR. In 2016–17, AAI performed concrete and bedrock core drilling, in-situ stress measurements, installed permanent monitoring instruments, and collected baseline instrument readings and concrete samples for lab analysis.

Three specialized overcoring stress measurement techniques were utilized: USBM borehole deformation gauge, the CSIRO HI stress cells, and the Sibra, Pty. Ltd. in-situ stress measurement tool. A total of 41 USBM, 6 HI cells, and 28 Sibra measurements were completed. In addition, inclinometer casings, a multi-point extensometer, and downhole temperature sensors were installed.

I. INTRODUCTION

Core drilling and specialized testing was conducted at the Walters Dam to characterize the large-scale structural effects of concrete growth due to Alkali Aggregate Reaction (AAR) since the dam's construction in 1929. Walters Dam is a 192-ft (58.5-m) tall, variable-radius, concrete arch dam located on the Pigeon River in western North Carolina (Figure 1). The dam is owned by Duke Energy Progress, LLC (Owner) and is operated as part of the Walters Hydroelectric Project, which also includes an intake, a 6.2-mile-long (9.98 km) power tunnel, and a three-unit powerhouse with a total nameplate capacity of 108 MW.

Walters Dam is the subject of an ongoing concrete growth investigation being conducted by HDR Inc. (HDR). Agapito Associates, Inc. (AAI) was commissioned by HDR to perform difficult-access core drilling and in-situ stress measurements throughout the dam, and install geotechnical instruments. The purpose of the drilling and testing was to collect fundamental input data for the concrete growth evaluation and for calibration of HDR's three-dimensional (3D), nonlinear finite-element model of the dam.

The field program was unique in that three specialized overcoring techniques were utilized to measure stress in the dam: (1) the United States Bureau of Mines (USBM) borehole deformation gauge (BDG) method,¹ (2) the Commonwealth Scientific and Industrial Research Organization (CSIRO) hollow inclusion stress cells (HI Cells) method, and (3) the Sibra, Pty. Ltd. (Sibra) in-situ stress measurement tool (IST) method. All three methods require a measurement tool, or gauge, to be

¹ ASTM International (2008), "Standard Test Method for Determination of In Situ Stress in Rock Mass by Overcoring Method—USBM Borehole Deformation Gauge," D4623-08, 14 pp.



Figure 1. Location map of the Walters Dam, North Carolina.

set inside a small-diameter pilot hole protruding from the end of a larger diameter borehole drilled into the dam. The pilot hole and tool are subsequently “overcored” using a larger diameter core bit, thereby allowing the tool to measure strain relief in the remaining concrete or rock annulus. Strains are converted to stress via the elastic properties of the concrete or rock. The measurement yields either a two- (2D) or three-dimensional (3D) in-situ stress tensor depending upon the method.

Multiple methods were required at Walters Dam to satisfy the technical objectives of the project. The USBM BDG tool was selected as the baseline method because it is the oldest and most widely applied method in the industry. The BDG measures 2D stress in the plane normal to the borehole. The BDG can be used in holes of any orientation, including up-angled holes, but is practically limited by the gauge’s downhole cable length and setting tools to a downhole depth of approximately 65 ft (20 m).

The Sigra method is similar to the USBM BDG method in that it measures 2D stress in the plane normal to the borehole. However, the Sigra tool is wireless, relies on an onboard data logger to collect readings during the overcoring process, and operates in conjunction with a wireline coring system. Because there are no cables, the Sigra tool can be set to downhole depths of more than 3,000 ft (914.4 m). The Sigra tool can only be use in vertical downholes. Because the project required measuring stress to a depth of more than 140 ft (42.8 m), which is beyond the reach of the USBM BDG, the Sigra tool was chosen.

Walters Dam was the first ever application of the Sigra tool in a North American dam. The Sigra tool could have been used to acquire the same measurements as the USBM BDG at shallower depths; however, the project team elected to use the

USBM BDG for all shallow depth stress measurements based on the satisfactory performance of the USBM BDG on prior investigations subject to FERC review, core specimen diameter requirements, and to minimize risk considering that this was the inaugural use of the Sigra tool. The project team's interest in the Sigra tool was derived from successful applications in Australian dams and the need to measure stresses beyond the depth limitations of the USBM BDG.

The CSIRO HI Cell gauge was utilized at Walters Dam so that the full 3D stress tensor could be measured and compared with the 2D results derived from the other methods. Like the USBM BDG, the HI Cell can be set at any angle of hole, but is limited by cable length and setting tools to a downhole depth of about 65 ft (20 m). Unlike the BDG and Sigra gauges which are reusable, the HI Cell is a single-use gauge that is consumed by the overcoring process.

AAI completed the field work at the dam between November 3, 2016 and April 20, 2017. AAI's diesel/hydraulic Ingetrol 75E drill rig was used for coring/overcoring work on-site (Figure 2). The work was performed by five AAI personnel. A two- or three-man AAI crew worked one shift per day at the dam during the project. The project took 103 shifts, averaging approximately 12 hours per day.



Figure 2. AAI diesel/hydraulic Ingetrol 75E drill rig at the toe of Walters Dam.

Stress measurements were conducted in three vertical holes drilled from the crest of the dam and one horizontal hole drilled from the toe of the dam (Figure 3). A total of 41 USBM BDG, 6 HI Cell, and 28 Sigra stress measurements were completed. In addition, two Geokon Model 6500 inclinometer casings, one Geokon Model A6 multi-point extensometer, and four Geokon Model 4700 downhole temperature sensors, manufactured by Geokon Inc., were installed at strategic locations to monitor long term deformations and temperature changes within the dam. Table 1 summarizes the work completed in each borehole.

II. SITE DESCRIPTION

The Walters Dam is a variable-radius concrete arch structure with a maximum height of 192 ft (58.5 m), a crest length of 900 ft (274.3 m), and a thickness at the base of 41 ft (12.5 m). Photographs of the dam and equipment accesses are shown in Figure 4. The minimum arch thickness is 16 ft (4.9 m) under the spillway ogee and 22 ft (6.7 m) at the spillway. The spillway is controlled by 14 radial gates, each 24 ft (7.3 m) wide and 10 ft (3.0 m) high. The dam was constructed using mass concrete with the diameter of site-sourced aggregate typically ranging from 2 to 4 inches (50 to 100 mm). The dam foundation consists of fresh rock with a base elevation in the central portion of the dam at 2,070 ft (630.9 m). The fresh rock foundation material is metamorphosed feldspatic quartzite and arkose with sparsely occurring thin lenses of dark-colored metasiltstone.

The dam is located on the Pigeon River in Haywood County, North Carolina. The drilling location on the right non-overflow section (right and left dam directions refer to perspective looking downstream) of Walters Dam is accessible for equipment and personnel from the dam access road. Drilling locations on the left non-overflow section are accessible by personnel only via stairs and narrow corridors around gate hoist equipment (2-ft [0.6-m] maximum width). Drilling locations at the downstream toe of the dam are accessible by personnel only via stairs. Drilling locations are shown in Figure 3. Equipment, tooling, and materials were lifted into position on the left non-overflow section and downstream toe using a crane and barge.

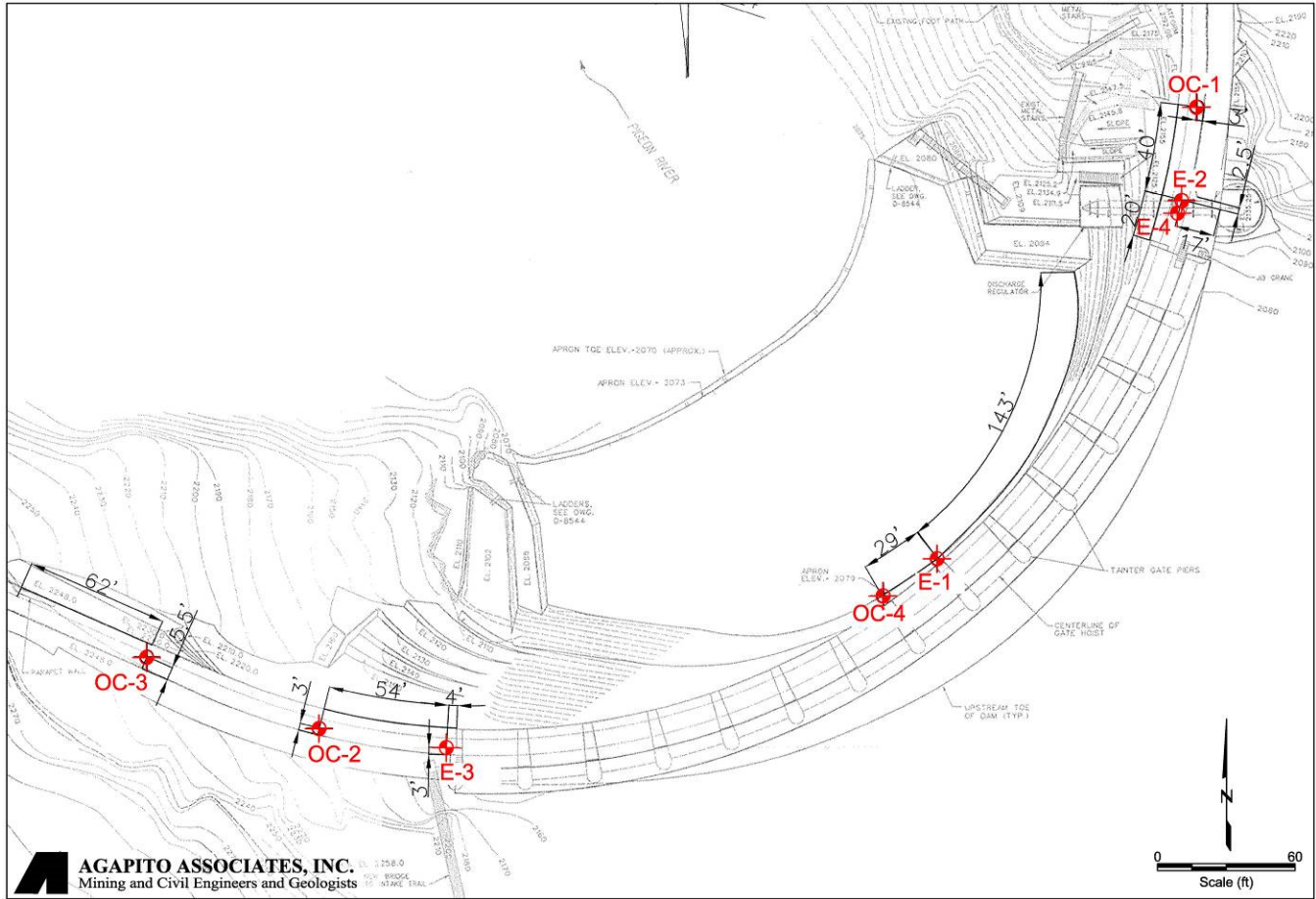


Figure 3. Walters Dam stress measurement and instrumentation locations.

TABLE 1
Borehole Summary

| Hole | Location | Spud Date | Completion Date | Total Depth (ft) | Inclination (°) | USBM BDG Tests | HI Cell Runs | Sigma Runs | 6-inch Core (ft) | HQ Core (ft) | Completion Method |
|------|----------------|------------|-----------------|------------------|-----------------|----------------|--------------|------------|------------------|--------------|-------------------------|
| E-1 | Downstream/toe | 11/6/2016 | 11/9/2016 | 37.0 | 45 | 0 | 0 | 0 | 0 | 37 | Extensometer |
| E-2 | RNOS | 11/20/2016 | 12/1/2016 | 122.8 | 90 | 0 | 0 | 0 | 0 | 123 | Tremie Grout Backfill |
| E-3 | LNOS | 2/15/2017 | 2/27/2017 | 162.7 | 90 | 0 | 0 | 0 | 0 | 163 | Tremie Grout Backfill |
| E-4 | RNOS | 4/21/2017 | 5/5/2017 | 145.3 | 90 | 0 | 0 | 0 | 0 | 145 | Flush-mount Steel Cover |
| OC-1 | RNOS | 12/3/2016 | 2/10/2017 | 157.3 | 90 | 10 | 3 | 13 | 63 | 94 | Temperature Probes (3) |
| OC-2 | LNOS | 3/1/2017 | 3/17/2017 | 155.7 | 90 | 11 | 2 | 13 | 61 | 95 | Inclinometer Casing |
| OC-3 | LNOS | 3/19/2017 | 3/29/2017 | 105.7 | 90 | 11 | 1 | 2 | 60 | 46 | Inclinometer Casing |
| OC-4 | Downstream/toe | 11/11/2016 | 11/17/2016 | 25.3 | -5 | 9 | 0 | 0 | 25 | 0 | Temperature Probe |

RNOS = right non-overflow section; LNOS = left non-overflow section; inclination is in degrees below horizontal.



Figure 4. Aerial photographs of Walters Dam.

III. MOBILIZATION AND OPERATIONAL CONSTRAINTS

The drilling equipment was mobilized to the dam via cranes (Figure 5) and floating barges (Figure 6) from the upstream side of the dam. Drillholes on the right side of the dam were accessed with skids and rubber-tired equipment. Access to the left side of the dam was from a barge and crane. Access to the toe of the dam was via a crane from the dam crest (Figure 7). When working at the toe, personnel access was via a metal stairway located on the downstream right abutment.

The drillhole sites were predetermined by HDR. The holes were strategically located to obtain stress measurements at optimum locations within the structure for input into the numerical stress analysis to follow. Accessibility was a secondary priority, but did play into location of some of the drillholes. The Occupational Safety & Health Administration (OSHA) as well as the owner's, HDR's, and AAI's safety plans were formulated into an extensive and concise safety program designed to protect employees, the environment, and equipment throughout the project.



Figure 5. Accessing the drillholes using cranes.



Figure 6. Access the drillholes using barges.

IV. STRESS MEASUREMENTS

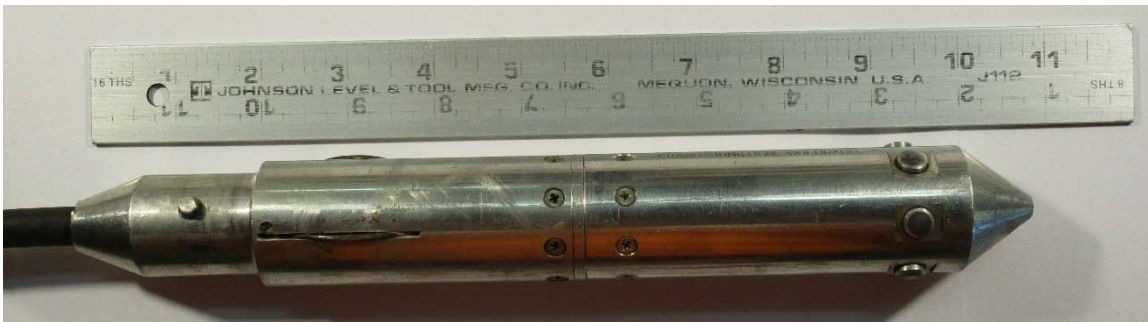
Stress measurements were conducted in four of the drillholes at three locations in the Walters Dam. Hole OC-1 was drilled on the right, non-overflow section and OC-2 and OC-3 were drilled on the left, non-overflow section. Hole OC-4 was drilled in the toe/spillway apron of the dam. Hole locations were selected based upon HDR's recommendations and overcoring tests within each hole were conducted as close as possible to designated test intervals. A total of 41 USBM tests, 6 HI Cell, and 28 Sigra runs were conducted; 39 USBM, 6 HI Cell, and 23 Sigra tests were successful.

The USBM and Sigra gauges measure the 2D strains in a plane orthogonal to the axis of the gauge. The HI Cell is glued in-place and measures the 3D strains at the location of the gauge. Using the strains and physical properties of the core, the 2D (USBM and Sigra) and 3D (HI Cell) stress tensors can be calculated. Figure 8 shows photos of the USBM and Sigra gauges. Figure 9a shows a HI Cell prior to installation and Figure 9b depicts a cutaway of a HI Cell glued into the core in which it was overcored with the 6-inch (15.2-cm) thin-walled core bit.

Biaxial tests were conducted on the overcores to determine the Young's modulus of the concrete at each measurement location. Biaxial tests were performed in a specifically designed biaxial chamber (Figure 10) for the 6-inch (15.2-cm) USBM and HI Cell overcores, and in a standard Hoek Cell for the HQ Sigra overcores. Biaxial testing was conducted on-site as soon as the overcores were retrieved from the hole. A total of 70 biaxial tests were performed on-site. Some overcores could not be tested due to defects in the concrete core.



Figure 7. Accessing the toe of the dam using rubber-tired vehicles and cranes from the top.



a) USBM BDG gauge



b) Sigra IST gauge

Figure 8. USBM and Sigra gauges used to measure strains in the core during overcoring.



a) HI Cell



b) Cutaway view of HI Cell (glued in place)

Figure 9. Views of HI Cells used to measure 3D strains.



Figure 10. Biaxial test chamber used to determine elastic modulus.

Data from the overcoring runs and biaxial tests were collected and transmitted to AAI's Grand Junction, Colorado, office for immediate analysis and verification that the run was acceptable. Communication between HDR, AAI's Grand Junction office, and the on-site overcoring technicians made for efficient decision-making regarding results, hole completion, and hole sequencing. Select stress profiles for OC-1 are shown in Figure 11. The USBM BDG and Sigra results shown in Figure 11 represent the estimated vector magnitude of major principal stress (P) and minor principal stress (Q) on a 2D plane that is orthogonal to instrument axis. The HI Cell results shown in Figure 11.a include the estimated vector magnitude of major principal stress (P) and minor principal stress (Q) in 3D at the instrument depth.

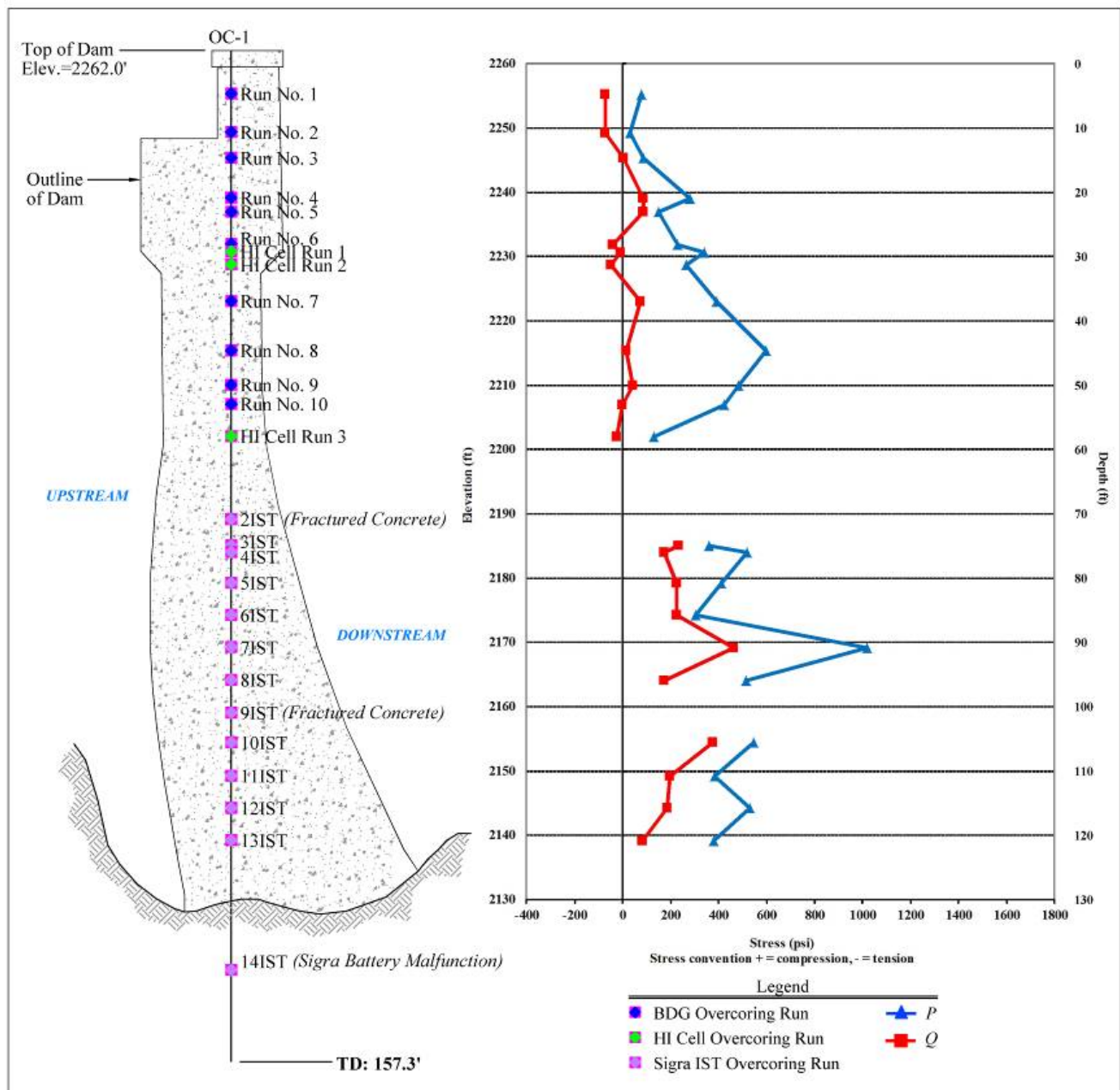


Figure 11. Overcore stress measurement results profiles in Holes OC-1.

A. Validity of the Methods

Benchmark testing was conducted in AAI's laboratory for each of the three overcore gauge types used on this project. Results on standardized samples of aluminum machined into core-sized specimens showed the three methods produced the same elastic modulus on samples of aluminum 6061 T6511. The elastic modulus of this alloy is specified to be 10 million psi (69.0 GPa).

B. Judgment of Success

AAI performed an evaluation of each overcore run and biaxial test to judge the success of field measurements. Successful field measurements were generally characterized by the following:

- Strain gauges were initially positioned correctly.

- The strain response prior to and during the overcoring run was stable.
- No mechanical fracturing or diskings from the overcoring process, as observed in the recovered overcore sample.
- The strain response during biaxial testing was linear and isotropic.
- Stress calculation could be completed in accordance with manufacturer recommended procedures and/or software.
- If a modulus value from biaxial testing of the recovered overcore sample was not available, stress calculation could be assumed from nearby tests.

Field measurements not meeting one or a combination of the general characteristics of a successful field measurement were excluded as an unsuccessful test. Using the criteria above, 7 overcoring runs (out of 75 attempted measurements) were deemed unsuccessful.

IV. INSTRUMENTATION AND GROUTING

Grouting was performed with AAI’s ChemGrout grout plant using Type I/II Portland cement supplied by Giant Cement Company (Giant) from their Harleyville, South Carolina plant. Backfill grouting to the surface was completed in Holes E-2 and E-3. A flush-mount steel cover was installed over Hole E-4.. Three temperature probes were installed in OC-1, inclinometer casing in OC-2 and OC-3, one temperature probe in OC-4, and a multi-point extensometer in E-1.

All grout was mixed to project specifications with a maximum water-to-cement (w:c) ratio of 0.45 by weight (5 gallons [18.9 liters] of water to one 94-pound [42.6-kg] sack of cement). Flush-mount steel manhole covers were installed in all instrumentation-completed holes.

A. Temperature Probes

Geokon Model 4700 temperature probes were installed in OC-1 and OC-4. OC-1 was completed with three separate probes grouted in at 20 (6.1 m), 40 (12.2 m), and 60 ft (18.3 m) below the surface. OC-4 was completed with one temperature probe grouted in at 20 ft (6.1 m) into the face of the dam from its collar position. Initial temperature readings were recorded for all sensors and are reported in Table 2.

TABLE 2
Initial Temperature Probe Readings

| Date | Location | Depth (ft) | Depth (m) | Reading (°C) | Recorded By |
|------------|----------|------------|-----------|--------------|-------------|
| 12/3/2016 | OC-4 | 20 | 6.1 | 27.5 | AAI |
| 12/3/2016 | OC-4 | 20 | 6.1 | 20.1 | AAI |
| 12/5/2016 | OC-4 | 20 | 6.1 | 15.9 | AAI |
| 12/19/2016 | OC-4 | 20 | 6.1 | 13.3 | AAI/Owner |
| 1/12/2017 | OC-4 | 20 | 6.1 | 12.6 | Owner |
| 3/7/2017 | OC-4 | 20 | 6.1 | 11.5 | Owner |
| 3/31/2017 | OC-1 | 20 | 6.1 | 15.0 | AAI |
| 3/31/2017 | OC-1 | 40 | 12.2 | 14.6 | AAI |
| 3/31/2017 | OC-1 | 60 | 18.3 | 14.7 | AAI |
| 4/12/2017 | OC-4 | 20 | 6.1 | 11.1 | Owner |

Completion photos for OC-1 and OC-4 with and without the flush-mount covers are shown in Figures 12 and 13, respectively. The flush-mount covers were grouted into place and then sealed with caulk. The temperature probe connector pins were sealed within a polyethylene wrap to prevent moisture deterioration.

B. Extensometer

A Geokon Model 1280 A6 Borehole Extensometer was installed and grouted into place in Hole E-1 on the downstream toe, with 0.9-ft (0.27-m) anchors set at 8.3, 20.3, and 34.3 ft (2.5, 6.18, and 10.5 m) (top of anchor) into the 45°-inclined borehole. The interface between the concrete dam and bedrock occurs between 18 (5.5 m) and 19 ft (5.8 m). Table 3 summarizes the initial anchor readings and Table 4 lists the anchor depths.

Completion photos for E-1 with and without the flush-mount covers are included in Figure 14. The flush-mount covers were grouted into place and sealed with caulk.



Figure 12. Hole OC-1 temperature probe and flush-mount cover photos.



Figure 13. Hole OC-4 temperature probe and flush-mount cover photos.

TABLE 3
Initial Extensometer Readings

| Date | Reading (inches / mm) | | | Recorded By |
|------------|-----------------------|---------------|---------------|-------------|
| | Anchor 1 | Anchor 2 | Anchor 3 | |
| 12/3/2016 | 0.746 / 18.95 | 0.893 / 22.68 | 0.770 / 19.56 | AAI |
| 12/5/2016 | 0.748 / 18.99 | 0.905 / 22.99 | 0.786 / 19.96 | AAI |
| 12/19/2016 | 0.743 / 18.87 | 0.909 / 23.09 | 0.869 / 22.07 | AAI/Owner |
| 1/12/2017 | 0.745 / 18.92 | 0.910 / 23.11 | 0.870 / 22.10 | Owner |
| 3/7/2017 | 0.747 / 18.97 | 0.910 / 23.11 | 0.870 / 22.10 | Owner |
| 4/12/2017 | 0.747 / 18.97 | 0.910 / 23.11 | 0.870 / 22.10 | Owner |

TABLE 4
Extensometer Installation Depths

| Anchor | Depth from Faceplate (inches / mm) | |
|--------|------------------------------------|---------------------|
| | To Top of Anchor | To Bottom of Anchor |
| 1 | 8.3 / 210.8 | 9.2 / 233.7 |
| 2 | 20.3 / 515.6 | 21.2 / 538.5 |
| 3 | 34.3 / 871.2 | 35.2 / 894.1 |



Figure 14. Hole E-1 cover and extensometer photos.

C. *Inclinometers*

Geokon Model 6500 Inclinometer Casing was installed and grouted into OC-2 and OC-3 to depths of 155 ft (47.2 m) and 106 ft (32.3 m), respectively. Both casing installations were inspected with a borehole camera for defects in the casing and casing grooves after installation.

Inspection of OC-3 revealed the casing was compromised between 90 (27.4 m) and 106 ft (32.3 m) deep as a result of grout entering the casing and filling the grooves. AAI successfully cleaned the casing grooves to a depth of 94 ft (28.6 m), and subsequently filled in the bottom portion of the compromised casing to a depth of 87.6 ft (26.7 m) with 78 mesh pea gravel per HDR's recommendation.

A Geokon Model 6000-10E “dummy” inclinometer probe was run in both the A (perpendicular to dam) and B (parallel to dam) axes of each inclinometer casing prior to conducting baseline measurements with the Geokon 604D Digital Inclinometer. The baseline measurements for both the A and B axes were recorded and then processed along with the spiral data in SiteMaster, V4.0.7.3:000, a software product of Deep Excavation (2011).

Completion photos for OC-3 are presented in Figure 15. Figure 16 depicts recording a baseline measurement with the Geokon 604D.



Figure 15. Hole OC-3 inclinometer photos.



Figure 16. Hole OC-2 inclinometer baseline measurement recording.

V. SUMMARY AND CONCLUSIONS

The field work conducted at Walters Dam represents the state-of-the-art in in-situ stress measurements in North American dams, both because of the high density of stress measurements undertaken for detailed finite-element modeling and the application of three different overcoring stress measurement methods. A total of 68 successful stress measurements were completed out of 75 measurement attempts, representing a 90% success rate. The overall success rate achieved at the dam exceeded AAI's global success rate of 65% based on more than 1,800 overcoring runs in a variety of environments over a 40-year history (Figure 17). The quality and reliability of the overcoring results were demonstrated to be high based on strong spatial repeatability and the mutual corroboration of results produced by three independent overcoring tools. The project offers evidence that overcoring is well suited for application in concrete dams and that the individual overcoring methods can be used interchangeably as best suited for site conditions.

Overcoring is the most direct method for measuring stresses inside concrete dams. When overcoring stress measurements are combined with other geotechnical structural response instrumentation, the impacts of concrete growth and other structural phenomena can be more completely assessed. HI Cells can be installed and used as long-term stress monitoring devices, with or without automatic and/or telemetric data acquisition systems. When used in this capacity, HI Cells can record relative stress changes over time, which can include the seasonal effects of temperature and pool elevation changes and the progressive trends of concrete creep and other structural stress redistribution phenomena.

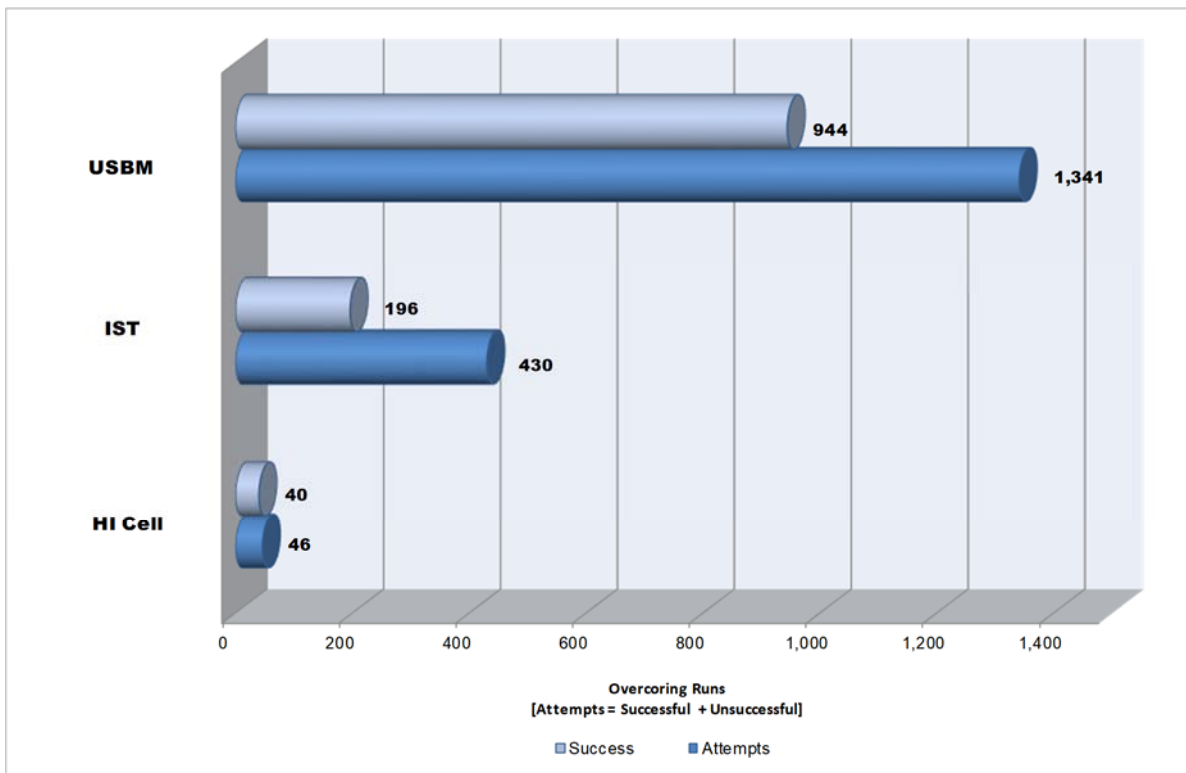


Figure 17. AAI successful versus total attempted runs for the three overcoring methods from 1978 to May 2018.

VI. ACKNOWLEDGEMENTS

An abundance of geotechnical and structural information was collected at Walters Dam during the concrete growth investigation and collection of this data has aided the owner and the engineers of record, HDR, to gain a better understanding of the structural behavior of the Walters Dam. Access to each location, whether on the toe or upstream side of the dam, presented unique logistical challenges, particularly during inclement weather. AAI wishes to thank the owner and HDR for their outstanding support during the concrete growth investigation which proved to be both safe and technically successful.

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