Comprehensive Foundation Rehabilitation at Bear Creek Dam

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ABSTRACT

The Tennessee Valley Authority (TVA) Bear Creek Dam is a high-hazard potential embankment dam in northwest Alabama that provides water supply, flood control, and recreation benefits. Since its initial filling in 1969, the dam has experienced significant seepage through its karst limestone foundation. After experiencing limited or temporary success at controlling seepage using supplemental grouting programs and downstream seepage collection systems, TVA elected to embark on an extensive rehabilitation effort for the existing dam's deficiencies, as follows: (1) foundation seepage leading to a potential loss of embankment material at the foundation contact and (2) the potential loss of the embankment dam as a result of overtopping during the potential maximum flood (PMF). Paul C. Rizzo Associates, Inc., was hired to design a permanent solution for the dam's deficiencies. Performance of this rehabilitation consists of construction of a downstream roller-compacted concrete reinforcement structure to prevent loss of the dam during PMF overtopping and installation of a composite seepage barrier consisting of a two-line grout curtain with cutoff wall panels at select locations to reduce potentially hazardous foundation seepage. The existing emergency spillway as well as the existing sluiceway tunnel and associated intake structure were preserved as a part of this new construction. This article presents the means and methods employed to effectively treat the karst limestone geology present at the Bear Creek Dam, with emphasis on the evolving nature of the design and construction of the final seepage barrier, whereby continuous, 'real-time' evaluation of the geologic conditions encountered during each phase of the foundation treatment process was used to tailor the scope and design of the next step of the rehabilitation.

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INTRODUCTION

Bear Creek Dam is a 1,385-ft–long, homogeneous fill embankment dam constructed in the late 1960s and first filled in 1969. The Dam's crest elevation is 618 ft and has a maximum height of 85 ft. The Dam is equipped with a reinforced concrete ogee crest overflow chute spillway (crest elevation, 602 ft) and a gated intake tower to a 9 ft–diameter sluiceway tunnel and stilling basin that are used to control lake levels under normal conditions.

The Dam was constructed with a single-line grout curtain and key trench for approximately two thirds of the embankment foundation. During the initial construction, numerous solution features ("solution features" refer to the solubility of calcium and magnesium ions from the rock mass when it comes into contact with slightly acidic groundwater, resulting in dissolution of the rock mass) were encountered and backfilled, large volumes of extremely weathered rock were removed, and large grout takes were common. The aforementioned treatment procedures were not performed on a section of the foundation from the left abutment at the spillway that extended 300 ft across the foundation. Upon first filling in 1969, seepage was discovered along the toe of the embankment and has been the subject of various studies and treatment programs since that time. Sustained foundation seepage flows captured and measured near the surface—on the order of 800 gpm at normal summer pool levels—indicate the existence of higher flows through the untreated cavernous subsurface near the left abutment. Subsequent grouting programs have been successful at temporarily reducing flows to approximately half of the historical maximum. However, the grouting efforts were never brought to closure, and over time, flow reductions returned to previous seepage rates.

In December of 2004, a high-headwater event resulted in the appearance of numerous boils, small sinkholes, and new seepage flows from the toe. A study comprising piezometer installation, coring of the foundation rock, and cone penetration testing in the embankment confirmed the left abutment foundation to be the pathway of the majority of the seepage.

The Dam provides flood control, water supply, and recreational benefits to the area. In order to preserve these benefits, the Tennessee Valley Authority (TVA) elected to embark on an extensive rehabilitation effort. Paul C. Rizzo Associates, Inc. (RIZZO) was hired to design a permanent solution for the dam's deficiencies Following an exploratory drilling program and preliminary design phase, and based on input from the TVA and its independent review board (IRB), the following rehabilitation scheme was selected as the best solution for remediation of Bear Creek Dam:

- To prevent loss of the dam as a result of overtopping of the embankment during the potential maximum flood (PMF), a downstream roller-compacted concrete (RCC) reinforcement structure or berm would be constructed.
- To eliminate the potentially destructive seepage flows through the foundation, a composite seepage barrier consisting of a two-line grout curtain and localized "positive" cutoff panels was selected within the RCC berm foundation. Cutoff panel locations and depths were selected based on the results of the foundation preparation and drilling and grouting activities. In addition, during the foundation treatment phase, a large solution feature that intersected the sluiceway tunnel was encountered that required an additional grout treatment program to be conducted approximately perpendicular to the two-line grout curtain to ensure the integrity of the seepage barrier.

Site Geology

Bear Creek Dam is located in southwest Franklin County, Alabama, and lies at the contact of the Cumberland Plateau and the Fall Line Hills of the Coastal Plain Physiographic Provinces of Alabama. The vicinity is characterized by stream valleys incised into Mississippian rocks of the Parkwood and Bangor Formations and ridges and plateaus capped by Cretaceous sedimentary sequences of the Tuscaloosa Group.

The site is underlain by Mississippian Age (320–355 Ma) rocks of the Bangor Formation. In summary, from rock surface to depth, the geologic cross section of the foundation consists of the upper Bangor Limestone (cherty crystalline limestone and fossiliferous packstone), the Bangor Shale (a 12- to 18-ft–thick mudstone unit, referred to as shale in previous TVA reports), and the lower Bangor Limestone (fine-grained oolitic packstone). The various rock characteristics within the Bangor Formation have proven significant to rehabilitation of the foundation. Specifically, the packstone portion of the Bangor (which occurs, approximately, between elevations of 538 and 560 ft [a.m.s.l.] at the site) has proven, through field observations and in laboratory results, to be much more susceptible to solution activity. The packstone has proven the most challenging zone of the subsurface with respect to grouting and foundation preparation as a result of the large solution features and weathered zones that are not present to the same extent in overlying and underlying crystalline and cherty limestone layers.

Initial Exploratory Program

The initial subsurface exploration program for the Bear Creek Dam reinforcement structure included core drilling, borehole pressure testing, limited soil sampling, geophysical borehole logging, surface geophysics, field and laboratory testing, and groundwater flow analysis. Site investigation began in June of 2007 and was completed in September 2007.

The main objectives of the site investigation were as follows:

- To determine characteristics, such as rock quality designation, uniaxial compressive strength (ASTM D 7012), bedding thickness and composition, degree of solution feature development, and weathering of the upper and lower units of the Bangor Limestone and the Bangor Shale unit C. This information was used to identify the excavation surface of the RCC berm foundation.
- To determine the hydraulic properties of the rock mass, including extent and nature of karst development.
- To determine the "groutability" of the karst features: features containing significant amounts of detrital and residual material that provide potential erosive zones that could compromise the completion of the grout curtain.
- To determine the thickness and characteristics of residual soil, fill material, and alluvium in and upstream of the proposed foundation to assist in

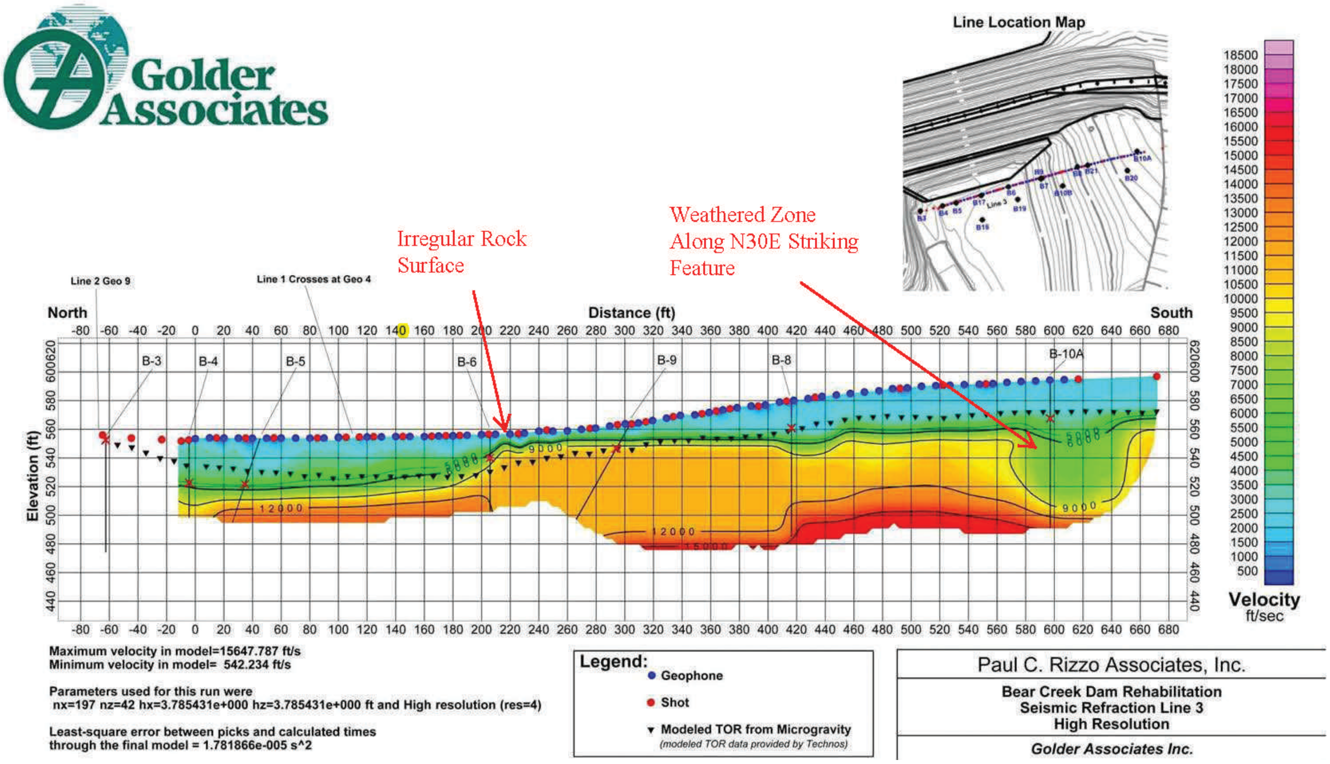

Figure 1. Seismic refraction line along RCC berm foundation centerline (work performed by Golder Associates, Inc.).

de-watering system design and to estimate excavation quantities.

Twenty-four core borings were advanced through overburden, the upper Bangor Limestone, Shale Unit C, and into the lower Bangor Limestone, and water pressure was tested to determine the hydraulic properties of the rock mass. Surface geophysical investigations, including spectral analysis of surface waves (SASW), seismic refraction, and microgravity in multiple lines in strike with the proposed foundation of the RCC berm, were completed. Electrical resistivity and ground-penetrating radar (GPR) were used in limited locations in combination with additional core borings to better define weathered zones near the rock surface. In addition to site investigation field activities, TVA construction records and previous remedial grouting program records were reviewed and incorporated into the development of the overall site geologic model.

The use of the aforementioned geophysical methods during this project can now be assessed relative to drilling and foundation excavation data. The microgravity, SASW, and seismic refraction geophysical surveys completed in 2007 occurred when a cover of residual soil and alluvium measuring 20–40 ft thick existed across the site. These surveys were useful in providing an approximate top of non-rippable rock. These surveys were not as successful in establishing discrete zones of deeper weathering not completely related to limestone dissolution along N30E solution features. The refraction survey method did, however, pick up the location of a large zone of weathered rock that exists near RCC station 9+20 along the RCC crest centerline and that extends to the southwest under the spillway. In addition, the very irregular top-of-rock surface between RCC station 5+00 and 6+50 appears to be accurately captured and portrayed, to some extent, in the Golder seismic refraction lines presented in Figure 1 (and shown after excavation in Figure 2).

GPR, microgravity, and electrical resistivity surveys conducted in Phase III (within the historic Bear Creek channel) during June of 2008 were performed from the rock surface after excavation of up to 30 ft of alluvium, so comparing their performance with those identified during the 2007 surveys is not valid. The electrical resistivity survey proved fairly successful for the purpose of identifying weathered zones within the upper Bangor Limestone and Bangor Shale Unit C. The microgravity and GPR surveys did not prove as effective for this task. Resistivity successfully identified weathered zones within the Bangor Shale Unit C that were verified with two borings as well as mapping of cutoff panel walls during cutoff panel excavation. Figure 3 presents the

Figure 2. Irregular packstone surface detected in seismic refraction survey.

locations of the weathered zones identified by the resistivity surveys and the locations of the two borings, B22 and B23, and Figure 4 shows the actual zones of weathered shale encountered during excavation of Panel 3.

Rock Excavation and Cleaning of Features

The foundation design criteria for the RCC reinforcement structure (berm) foundation at Bear Creek is defined as "competent" rock, as initially determined by the 2007 subsurface investigation and verified during foundation preparation. The design criteria for foundation acceptance were "slightly weathered rock," a rock mass rating of "good" (score of 60 or higher), and treatment of discontinuities according to the industry criterion of a minimum excavation to depths of three times the width of the feature, or (0.3)(width) + 5 ft for features that are greater than 2 ft in width. In practice, excavation, cleaning, and dental concrete structural backfill of solution features or discontinuities extended much farther than this industry criterion, generally to the maximum dig reach depth of the available construction equipment.

Foundation rock was shaped to remove overhangs and steep surfaces. High rock surfaces were shaped to provide a relatively continuous profile and to reduce differential settlement and stress concentrations within the RCC berm. The methods employed for treatment of the exposed rock surface after removal of overlying soils depended on the type of rock and the irregularities present. The presence of weathered zones and solution features along geologic discontinuities has the potential to negatively affect both the stability and the deformation modulus of the foundation. In cases in which weathered rock and detritus in open cavities and along discontinuities had to be removed and cleaned to depths as great as 20 ft below the foundation grade, dental concrete was used to fill excavated deep weathered zones.

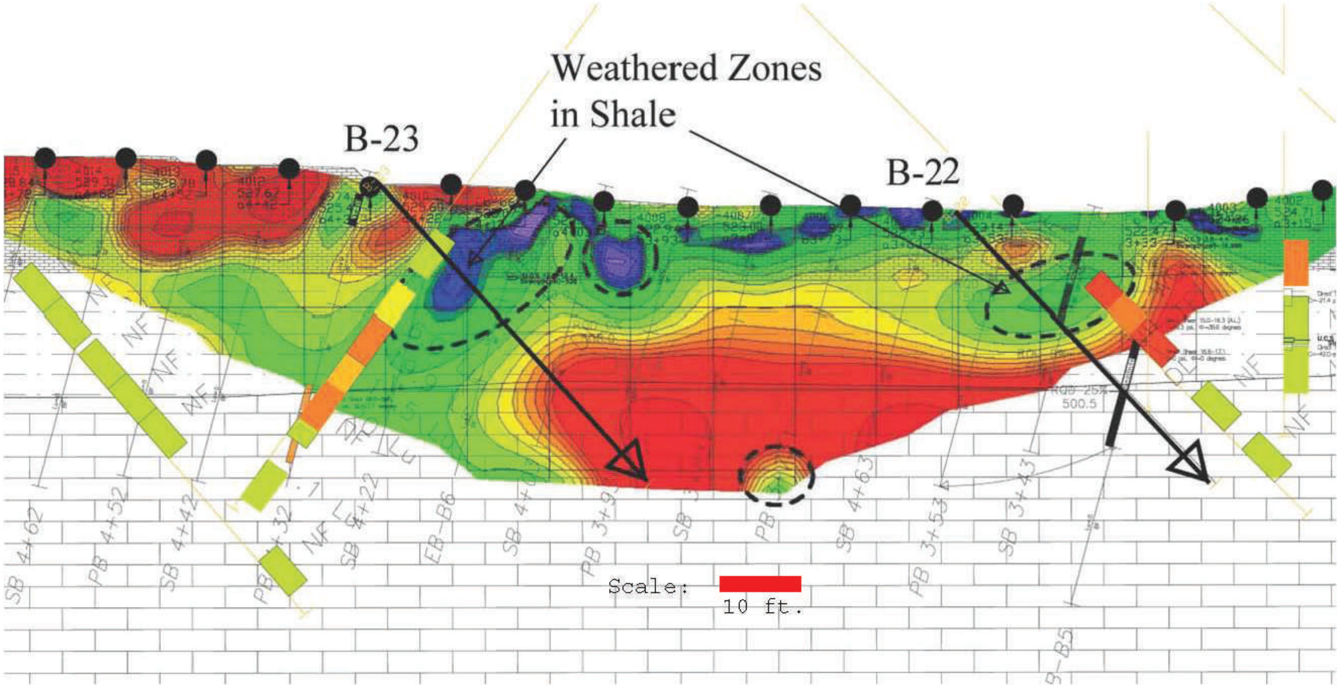

Figure 3. Resistivity profile showing weathered zones in Bangor Shale Unit C beneath historic Bear Creek channel.

The configuration of the final rock surface was significantly controlled by stratigraphic and structural characteristics. Specifically, in laboratory analyses, a packstone layer containing up to 21 percent (by wt.) SiO_2 and up to 53 percent (by wt.) CaO, bounded above and below by a cherty limestone containing 56 percent (by wt.) SiO_2, exhibited significant karst features. Figures 5 and 6 show magnified views of the packstone and overlying cherty limestone, respectively. Figure 7 shows the exposed contact of the packstone and overlying cherty limestone. The blue arrows in Figure 5 point out the oolitic grains in the packstone.

In addition, joints associated with bedding planes and two steeply dipping regional fracture sets striking roughly N30E and N55W acted as zones of accelerated weathering. Figures 8 and 9 show exposed N30E weathered zones and the intersection of N30E and N55W features, respectively (note the 3 in.–diameter yellow hose for scale in Figure 9). Depending on discontinuity orientations, these features sometimes resulted in horizontal surfaces, vertical surfaces, benches, deep depressions, or overhangs. Generally, the foundation surface was shaped adequately by conventional excavation using a track hoe and hoe ram. Over-excavation was appropriate in zones of weathered rock along the aforementioned discontinuities.

Final Cleaning and Foundation Approval

The bedrock foundation for the RCC berm was cleaned under the guidance of the resident geologist to provide acceptable conditions of contact between the body of the dam and its foundation and to provide for observation and documentation of details of foundation conditions at the foundation interface. Exposure of potentially adverse conditions during cleanup provided the opportunity to undertake remedial activity. The rock surface was cleaned so that partially weathered to fresh rock was exposed for dental concrete placement.

After excavation, all loose or otherwise objectionable (weathered) material, detritus, and spoil was removed by handwork, water jetting, and/or air jetting. Accumulated water and debris from washing operations were typically removed by a hydro-excavator or vacuum truck. Loose or unsuitable material in cavities, fractures, or seams was also removed using the aforementioned techniques. The rock surface and all pockets or depressions were carefully cleaned of soil and rock fragments before dental concrete could be placed. Final foundation cleaning was achieved with the use of picks, shovels, pressure washers, and a vacuum truck.

Once cleaned, a RIZZO geologist mapped the foundation at a scale of 1:120 or 1 in. to 10 ft in order to describe the degree of weathering, hardness, lithology, and locating and describing discontinuities, in accordance with the USBR Engineering Geology Field Manual (U.S. Department of the Interior, 1998). Once the area was mapped, photographed, and verified as a suitable foundation surface, the geologist completed a foundation acceptance form for

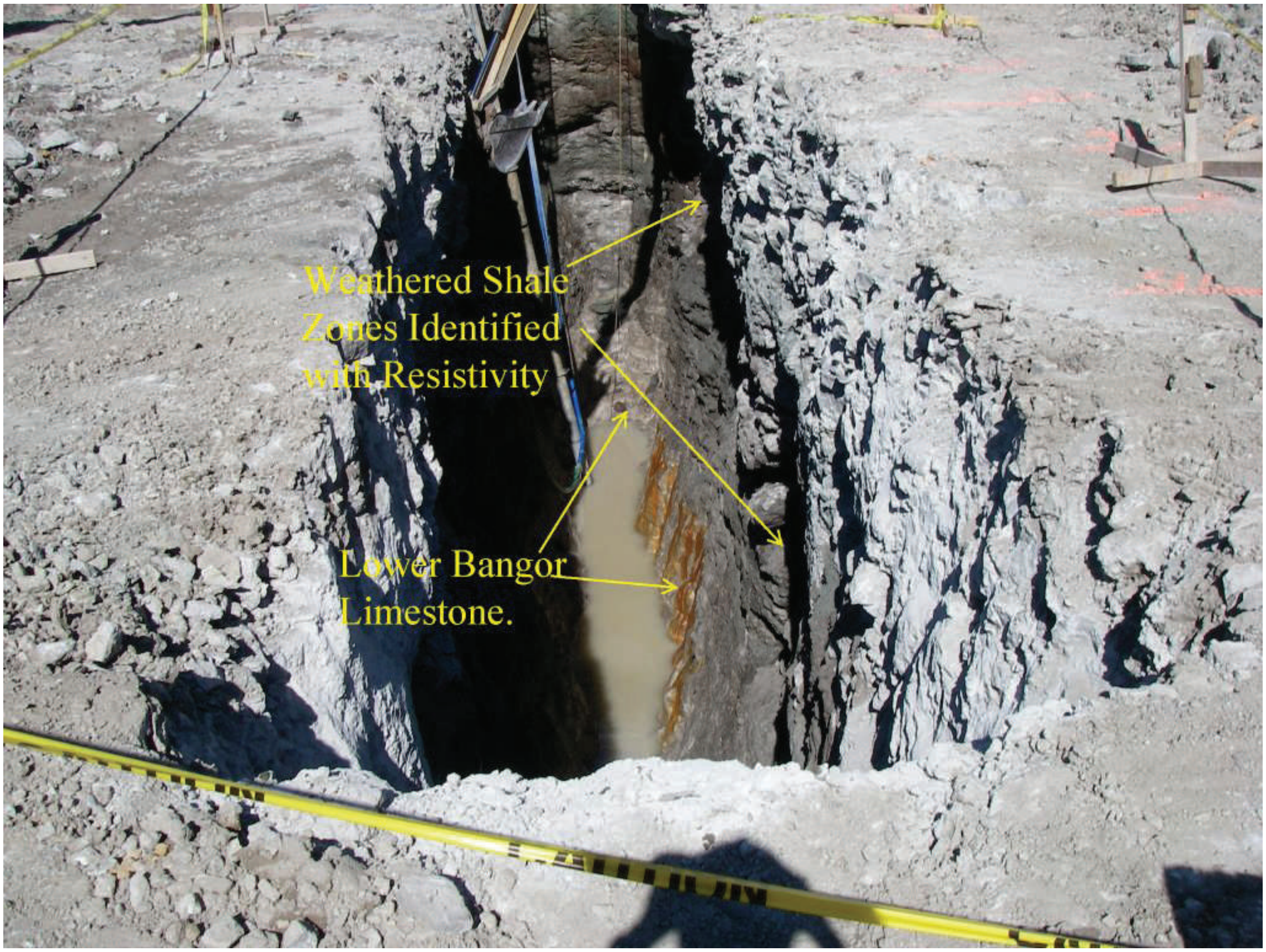

Figure 4. Weathered zones mapped in Bangor Shale Unit C beneath historic Bear Creek channel.

the prepared area in order to track the approval procedure. Field data acquired in the geologic mapping process were then converted to AutoCad maps to provide a final record of foundation conditions. Figure 10 provides an example plan view foundation geologic map showing the prominent N30E excavated zones.

The rock surface was thoroughly cleaned, as described above, and moistened prior to concrete placement to promote bonding between the concrete and the rock surface. Dental concrete was also used to fill or shape holes, grooves, and extensive areas of vertical surfaces created by fractures, buried karst features, and other irregularities. Thin areas of dental concrete over rock projections on a jagged rock surface are likely places for crack propagation and were avoided by providing short forms or trimming feather edges after curing. When overhangs were filled with dental concrete, the concrete was well vibrated and forced into the opening by keeping the head of the concrete higher than the upper surface of the overhang. Dental concrete was typically wet cured, and heavy equipment operations were not permitted over the dental concrete until 48 hours of curing had been achieved.

Dental concrete was placed in approximately 1-ft lifts using a pump truck in order to prevent segregation during deep placements and over large areas. Once dental concrete was placed in cleaned solution features and crevasses, an as-built micro-topographic survey of the top of the concrete was completed in order to track the foundation treatment progress. Additional assessment of the foundation cleaning and the dental concrete placement was completed using confirmatory depth and position data from the grouting program, which followed the foundation excavation and dental treatment process. Water pressure tests of core holes through the segments of dental concrete that reached thicknesses as great as 18 ft and visual inspection of the core through the concrete rock interface yielded evidence of no water takes and clean concrete-rock contacts.

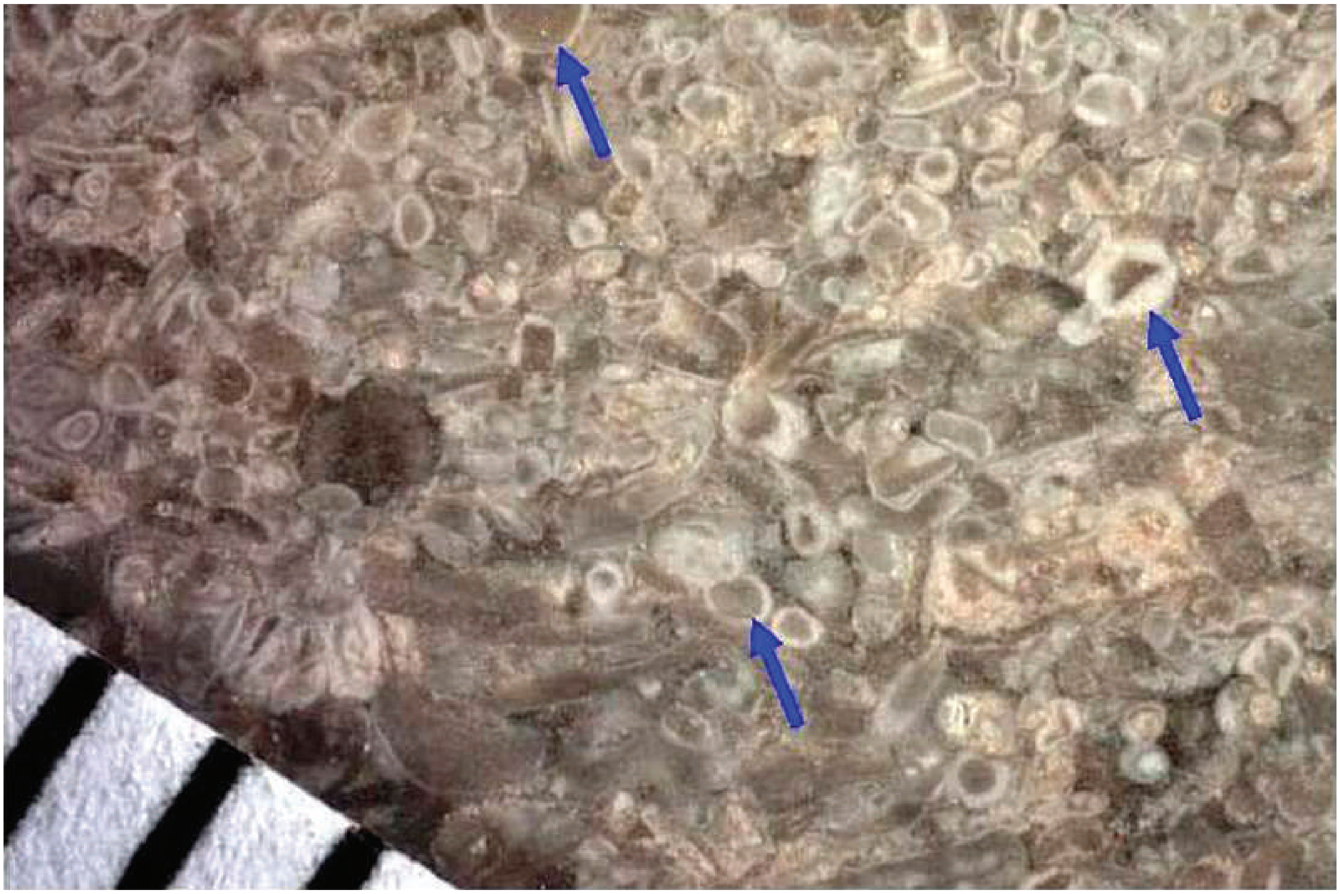

Figure 5. Packstone (scale is marked in millimeters).

Water pressure tests were not performed in situations in which there were fewer than 10 ft of dental concrete above the top of the test interval.

Preparation of the foundation required excavation of approximately 40,000 cubic yards of residual soil, 25,000 cubic yards of alluvium, 6,000 cubic yards of fill, and 10,000 cubic yards of moderately to intensely weathered rock. Approximately 100 cubic yards of existing detritus was removed from solution cavities. Five thousand five hundred cubic yards of minimum 3,000-psi dental concrete was placed in irregularities in the foundation, and an additional 1,200 cubic yards was placed in order to prepare a more level working surface for drill rigs and to provide a surface conducive to RCC placement.

DRILLING AND GROUTING PROGRAM

Design and Implementation of Drilling and Grouting Program

The Bear Creek drilling and grouting program was designed with the following three objectives:

- to effectively seal ‘‘groutable’’ (i.e., relatively clean and open) fractures and voids in the dissolved and weathered rock mass under the foundation of the RCC reinforcement structure;
- as an exploration and design tool to determine the necessary extents of the cutoff wall panels at locations where ground conditions, such as clay infill and intense weathering, would limit the effectiveness of a grout-only barrier; and
- to act as a preliminary treatment to facilitate the possible construction of cutoff panels.

In order to meet these objectives, the program was designed using information from the initial subsurface exploration and foundation excavation and cleaning work. The program was developed and operated to provide the maximum amount of subsurface information possible in real time in order to increase understanding of the foundation conditions, to create a treatment spacing with enough resolution to limit the possibility of leaving untreated windows in the seepage barrier, and to provide grout mix properties that would facilitate treatment of the foundation.

Figure 6. Cherty limestone (scale is marked in millimeters).

Subsurface Exploration

In order to further develop understanding of the foundation conditions, a comprehensive system of logging both exploratory (HQ size core) and production (rotary percussive drilling) borings, including downhole geophysical methods, was enacted for the drilling and grouting program.

A total of 34 exploratory HQ-size core holes were placed on 80-ft centers on both lines of the grout curtain. These borings were logged conventionally by a geologist in the field as the core was recovered and were then subjected to geophysical logging after being washed thoroughly when the coring was completed. Geophysical logging included photographic logging of the walls of the core hole with a downhole optical televiewer camera capable of identifying bedding features and fractures and producing a 360° view of boring sidewalls, gamma logging to assist in delineating bedding features (primarily shale lenses), and caliper logging to measure spatial deviations in the sidewalls of the core hole. The addition of the geophysical logs to conventional logging practice enhanced understanding of the subsurface fracture patterns and solution mechanisms and proved very valuable to the generation of an accurate portrait of the site stratigraphy. Figure 11 is a portion of a log produced by the optical televiewer showing the camera shot of a vertical fracture encountered in the core hole within the cherty zone of the Bangor Limestone and the corresponding mapping data recorded by the televiewer.

Upon completion of coring and logging of the exploratory borings, the borings were water pressure tested using five-step Houlsby tests (Houlsby, 1990) and grouted as production grout borings, when necessary.

Upon completion of the exploratory borings in a given area, production drilling (starting with primary holes) was performed using a rotary percussive drill rig, with water used as the flushing medium. In order to gain information from these destructive drilling techniques, a Drilling Parameter Recorder (DPR) was installed on the drill rig; this DPR recorded drilling rate, thrust pressure, drilling torque, and water flow through the drill string for every boring performed (Weaver and Bruce, 2007). Through the course of the project, the DPR logs proved to be a valuable resource for identifying areas of fractured rock, clay

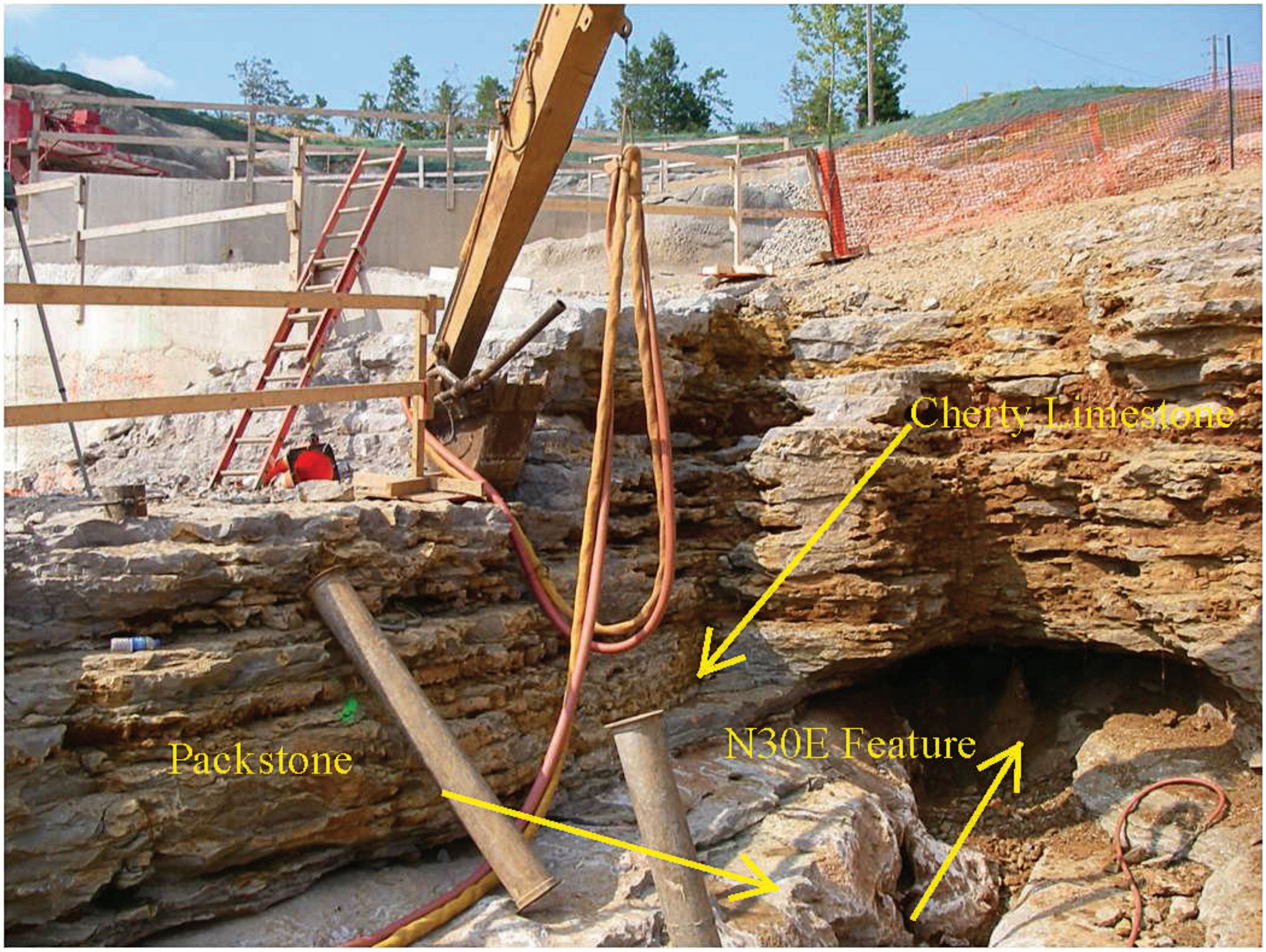

Figure 7. Cherty limestone and packstone contact.

infill, and changes in stratigraphy, particularly as the driller's understanding of site-specific ground conditions improved. Figure 12 shows a typical DPR log output.

Real-Time Monitoring, Data Collection, and Reporting

Computer-controlled, real-time data monitoring of water pressure test and grouting parameters was required for all stages of water pressure testing and grouting. Real-time data logging proved invaluable to effective treatment of the foundation, either by indicating the type of flow condition in a water pressure test or as a tool to guide grout mix changes to effectively react to the ground conditions being encountered in a particular stage during grouting. To ensure that all available information was accessible as a resource to guide the grouting program, foundation preparation activities, and selection of cutoff panel sections, daily updates regarding the drilling, water pressure test results, and grout results were required. Results of daily activities were plotted on a color-coded subsurface profile showing the existing geology, borings, stages, and takes during pressure tests and grouting. The use of a color-coded scale for water pressure test results made identification of areas of high conductivity in the foundation simple and intuitive, guiding the selection of higher order treatments and helping to further develop details in the site geologic model. An example portion of the water pressure testing and grouting subsurface profile is shown in Figure 13.

Grout Mix Properties

To a large extent, grout mix properties such as viscosity, pressure filtration, and bleed dictate the effectiveness and durability of grout injection treatments. For example, very low-viscosity (highly flow-

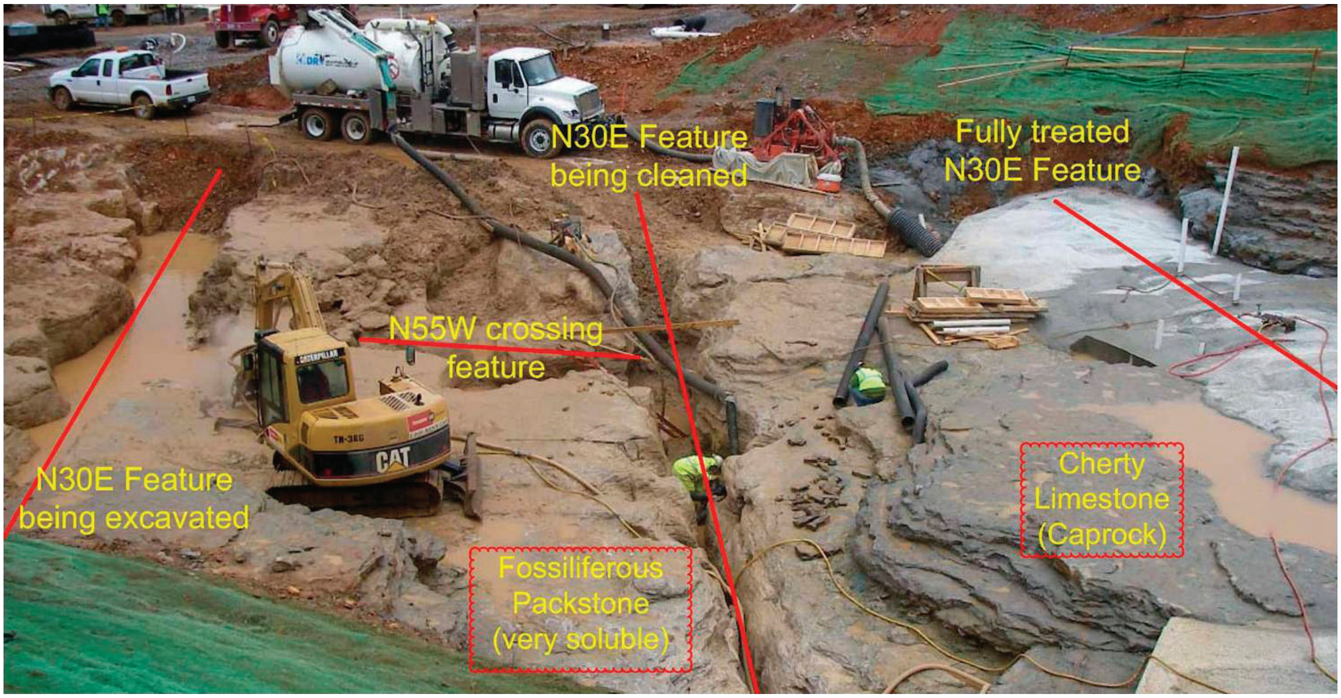

Figure 8. Cleaning of N30E features.

able) grouts are suitable for treatment of relatively fine fractures, while higher viscosity grouts are typically necessary to effectively seal more open fractures. In cases of large voids and/or flowing groundwater, low-mobility grout (LMG) may be required to arrest flow and fill the void.

As a result of the extreme variability of the subsurface conditions at Bear Creek Dam, we employed both high-mobility grout (HMG) for relatively small, open features and fractures and LMG for large voids and subsurface flows that cause washout of HMG. A suite of three balanced, stable HMG mixes with the properties shown in Table 1 was required in the design phase.

In addition to the required suite of mixes, the contractor performing the drilling and grouting program elected to add a "medium-mobility grout" mix to the suite, consisting of Mix C batched with fly ash. This mix proved very useful in bringing large take holes to closure through the course of the project.

Because of the particular nature of LMG injection, a mix and method were not directly specified; rather, it was left to the discretion of the contractor to propose a method according to his proprietary equipment and experience.

Grout Curtain Resolution and Closure

In order to provide a continuous seepage barrier and to clearly characterize the subsurface under the foundation of the RCC berm, the two-line grout curtain extends from the area downstream of the left abutment of the existing embankment across the existing spillway structure, and it terminates at the right abutment of the RCC berm to the north. Figure 14 shows the layout of the drilling and grouting program.

To provide a tight-enough treatment spacing to limit the possibility of leaving untested or untreated windows in the foundation, two grout lines (located 10 ft apart) of opposing holes inclined 15° from vertical were planned. The "A" line parallels the RCC centerline to the upstream, while the "B" line parallels the RCC centerline to the downstream. Primary and secondary borings on each line were set at 20-ft center-to-center spacing, with tertiaries and higher order borings split spaced, as indicated by the results of lower order holes. To provide a clear means of identifying the order of performance and location of borings, a system employing the boring order, grout line, and RCC stationing at the location was developed, as shown below: For a primary boring on the "A" line at RCC Station 4+50, the boring label is PB 4+50. Figure 15 shows the typical grout hole layout.

Primary borings were extended into the Bangor Shale layer, while the depths of higher order borings were generally selected based on available information, such as stratigraphy and previous water pressure test results. In light of the highly variable nature of

Figure 9. Intersection of N30E and N55W features.

the karst at the site and because of the need to provide fine resolution of the curtain, completion of drilling and grouting activities through second-order borings was required as a minimum, regardless of the results of primary borings.

The criterion for achieving closure of a given portion of the curtain lines was a water intake pressure test result of less than 5 Lugeons in the next higher order borings after having had takes in lower order holes. For example, after takes in adjacent primary and secondary borings, a tertiary boring would be drilled and the water pressure tested. A test result of less than 5 Lugeons in the tertiary boring would stop the progression to higher order borings. As both lines in a given section of curtain were brought to closure, verification borings (HQ-size core) were performed between the A and B lines at areas of interest, as indicated by previous grouting and foundation treatment results. A multi-stage water pressure test result of 5 Lugeons or less in the verification borings was the criterion used for acceptance of closure of the grout curtain.

Results of Drilling and Grouting Program

Two-Line Grout Curtain

Pressure grouting using balanced, stable mix designs and closely monitored injection methods was an effective seepage treatment method for the majority of the footprint of the RCC reinforcement structure. The combination of carefully controlled grout mixes with predictable rheological characteristics combined with real-time data collection allowed the contractor and engineer to respond directly to grouting conditions, ensuring quantifiable results and guiding the progress of further treatments. Proof of the effectiveness of grouting the karst foundation at Bear Creek Dam includes the results of the verification testing performed between the grout lines at

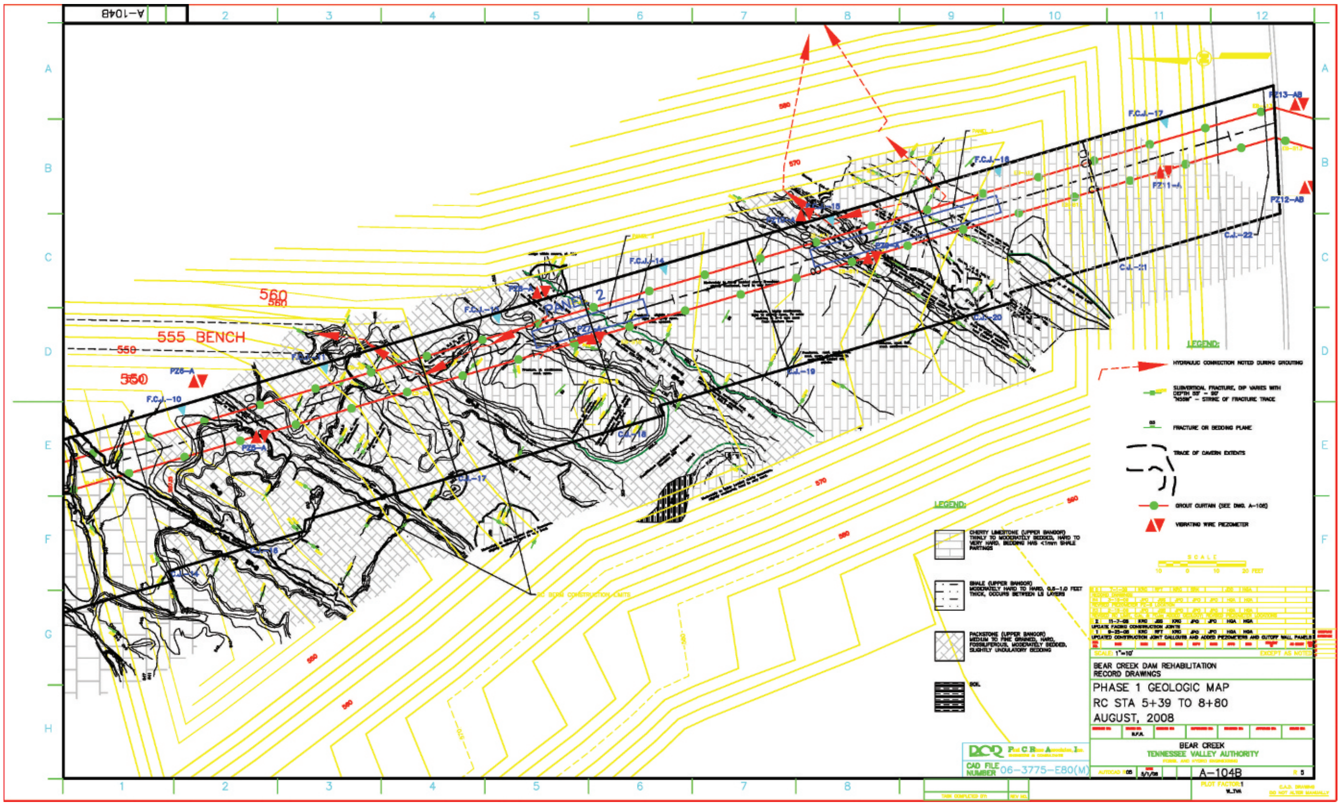

Figure 10. Geologic map of foundation.

locations of high pre-treatment permeability, visual observations of reduced downstream flows into the spillway tailrace, and post-treatment excavations performed in–the–dry within the foundation. One example of a visual expression of the grout curtain's effectiveness is discussed below.

Indications for Cutoff Wall Panels

At several locations, ground conditions prevented the grouting program from providing a robust seepage barrier that would be effective in the long term. These ''ungroutable'' conditions correspond to significant subsurface clay infill encountered at two locations near the left abutment and to the existence of very weathered zones in the Bangor Shale geologic unit in the old river channel.

Clay infill conditions were encountered in the drilling and grouting program between RCC stations 7+00 to 7+40 and 8+00 to 8+67 from depths as shallow as 5 ft up to depths of 25 ft. Clay infill conditions at these locations were determined to be caused by intersecting solution features or caves concealed by very hard cherty caprock, as opposed to the larger solution features, which had surface expression. These connecting caves were full of clay and detritus to varying degrees, with some large voids with significant underflows encountered. Those locations in which voids with significant seepage were encountered required the injection of approximately 50 cubic yards of LMG to arrest the seepage flows.

In the area of the old river channel, much less limestone cover exists over the underlying Bangor Shale. As a result of being less protected from weathering, the shale layer, which at other locations on the site acts as a near-continuous water barrier, was found to have several intensely weathered zones through it. Where slightly weathered, the shale typically would demonstrate hydraulic conductivity in water pressure testing that ranged from 0 to 10 Lugeons, and this shale would exhibit very low grout takes. Where intensely weathered, grout takes were high, and grouting operations often resulted in grout connections to other borings and the rock surface in the surrounding area.

Geologic conditions encountered in the foundation preparation and drilling and grouting program indicated the need for a total of four cutoff panels at depths ranging from 23 to 35 ft. Careful collection and review of field data by the Team (TVA, IRB, and RIZZO) made possible the very directed treatment of non-groutable zones and minimization of cutoff panel costs. The following section summarizes the final design and installation of the cutoff panels.

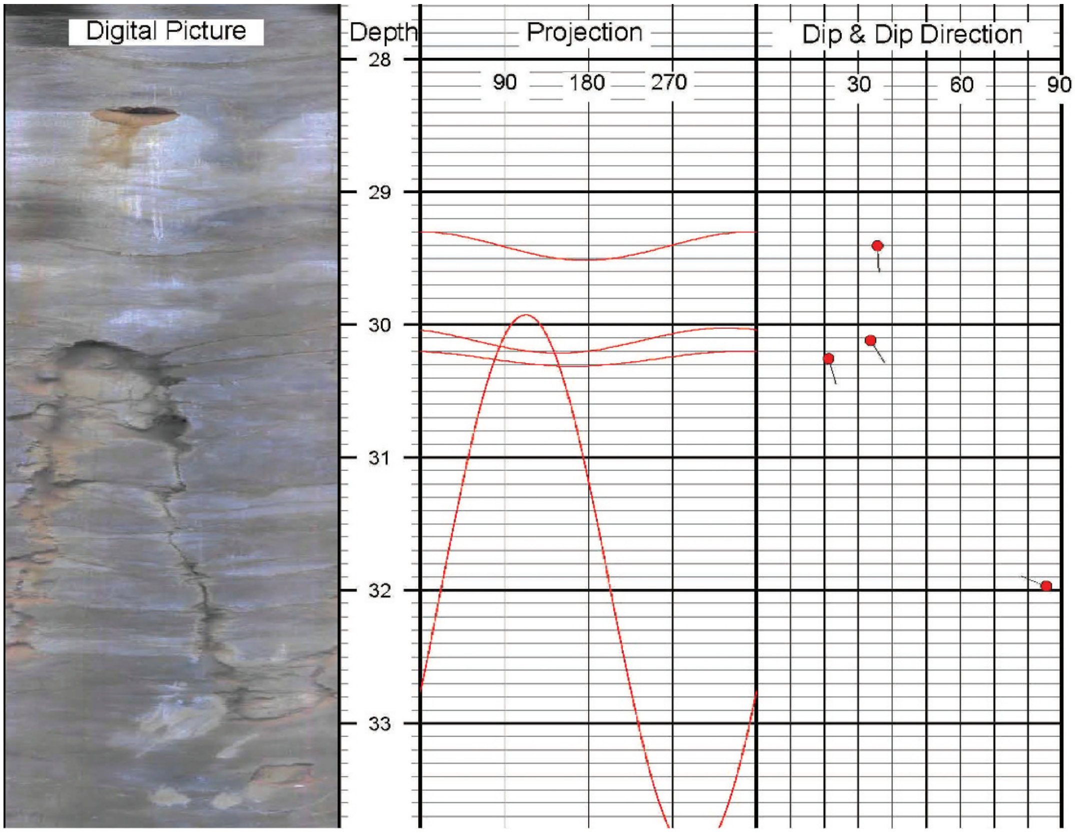

Figure 11. Section of optical televiewer log showing mapped fracture. Depth in feet.

CUTOFF PANEL INSTALLATION PROGRAM

Cutoff Panel Design and Construction Method Selection

In all, four cutoff wall panels were prescribed in light of the results of the drilling and grouting program and a supplemental exploratory drilling program consisting of rotary percussive borings on 2- or 3-ft centers. DPR drilling logs from the supplemental drilling were used to clearly identify the vertical and lateral extents of clay infill for Panels 1 and 2. The panels, their limits, and the reasons for which the panels were necessary are outlined in Table 2.

Cutoff panels were centered between the A and B lines of the drilling and grouting program in order to make best use of the pre-treatment afforded by the previously performed grouting. Several construction methods were evaluated for the construction of these cutoff panels, including drilling and blasting prior to excavation, use of a secant pile wall system, and the use of an excavator-mounted hoe-ram and long-reach excavator to remove the material from the cutoff wall sections. Drilling and blasting was eventually discounted as a viable construction method as a result of concerns over damage to the thinly bedded overlying limestone and because of concerns about the effectiveness of blasting in the shale unit. Secant pile installation was the technically preferred method of installation of the cutoff panels, as it was method that was least likely to cause damage to the foundation and previous grout treatments and because it offered relative ease of installation at depth and relatively low volume of excavation to be backfilled. However, the high cost of mobilization of a secant pile contractor, in relation to the small area treatment, in addition to schedule availability issues prevented the use of a secant pile contractor. In the end, the construction method utilizing excavation with a hoe-ram and long-reach excavator was selected because of the availability of the necessary equipment within TVA's Heavy Equipment Division.

Cutoff Panel Construction Details

Construction of the cutoff panels began with Panel 4, which served as a proof-of-method test. Panel 4 was chosen to test the hoe-ram and excavation construction method because of its smaller size and shallower depth. Based on successful performance in the installation of Panel 4, the method was approved for the remaining sections of cutoff wall. Prior to

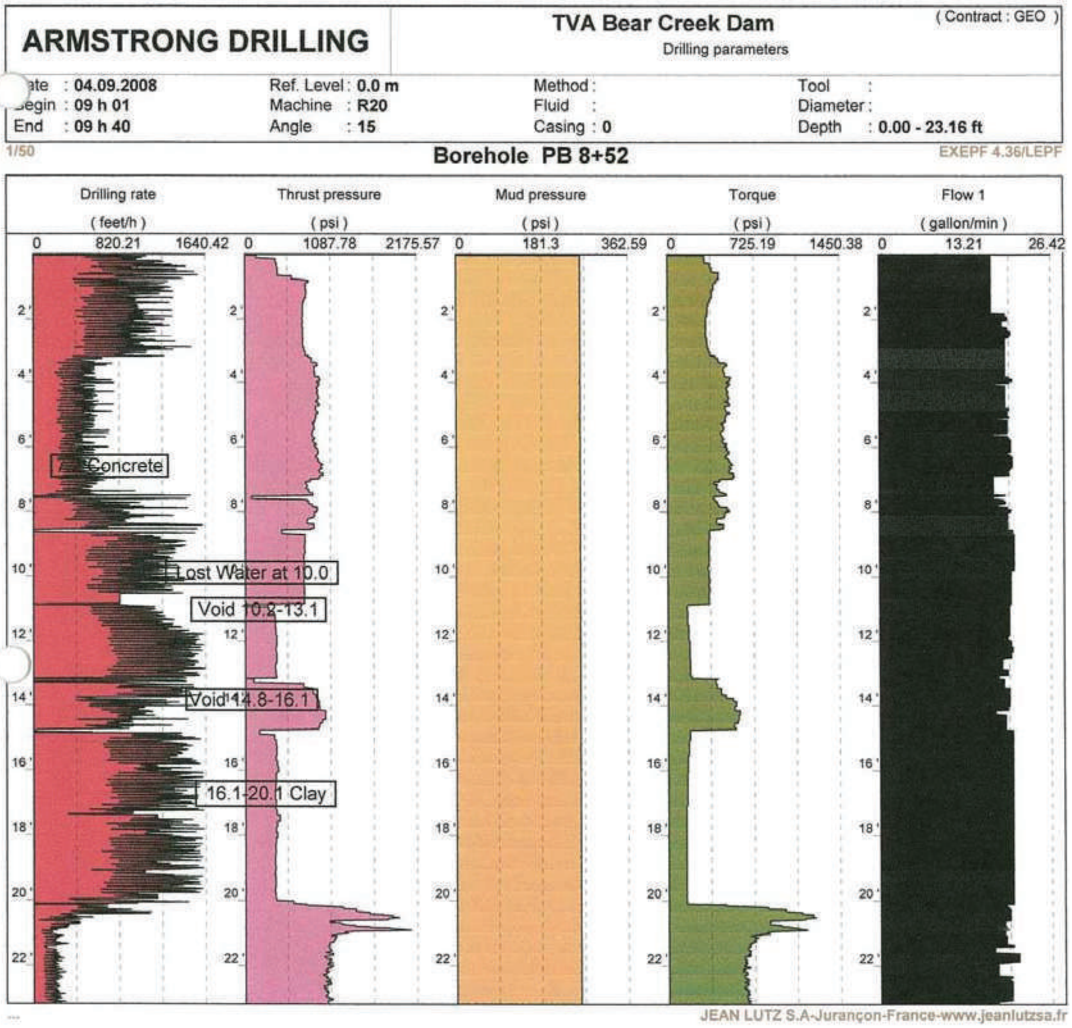

Figure 12. Typical DPR log output.

construction of Panels 1 and 2, an exploratory program consisting of rotary percussive borings on 2- to 3-ft centers around the upstream and downstream faces of the planned panel locations was performed to clearly delineate the extent of the clay infill to be treated by these panels. The DPR logs recorded during this additional exploration provided a basis for depth reduction along the panels at several locations.

Cutoff panel construction generally consisted of an excavation phase, followed by thorough washing of the sidewalls and floor of the panel (similar to the specifications of the previously performed dental concrete treatments), survey of the surface extent of the panel, mapping of the excavation sidewalls by a geologist, and then backfill of the cleaned, mapped excavation with concrete. While a minimum 2-ft panel width was specified, the construction method resulted in widths at the bottom of each panel ranging from 6 to 8 ft and widths at the top of each panel ranging from 8 to 10 ft. De-watering issues during panel excavation were minimal, as the two-line curtain was complete at the time of panel excavation. The only notable seepage occurred in Panel 3B at the interface of the lower Bangor Limestone and Bangor Shale Unit C. At this interface, an estimated 5 to 7 gallons/min seeped into Panel 3B between RCC centerline Stations 3+20 to 3+40. This area coincided with a weathered zone in Banger Shale Unit C. Panels 1, 2, and 4 exhibited no stability issues, while Panel 3 had two significant areas in which Bangor Shale Unit C periodically sloughed off into the excavation. As a result, a geologist had to map the upstream and downstream surface panel walls from the foundation surface at the edge of the panel while tied off to a loop anchored in the rock.

Construction of these cutoff panels was completed in December 2008. Table 3 summarizes the final extents, depths, and total concrete volumes placed to backfill the panel excavations.

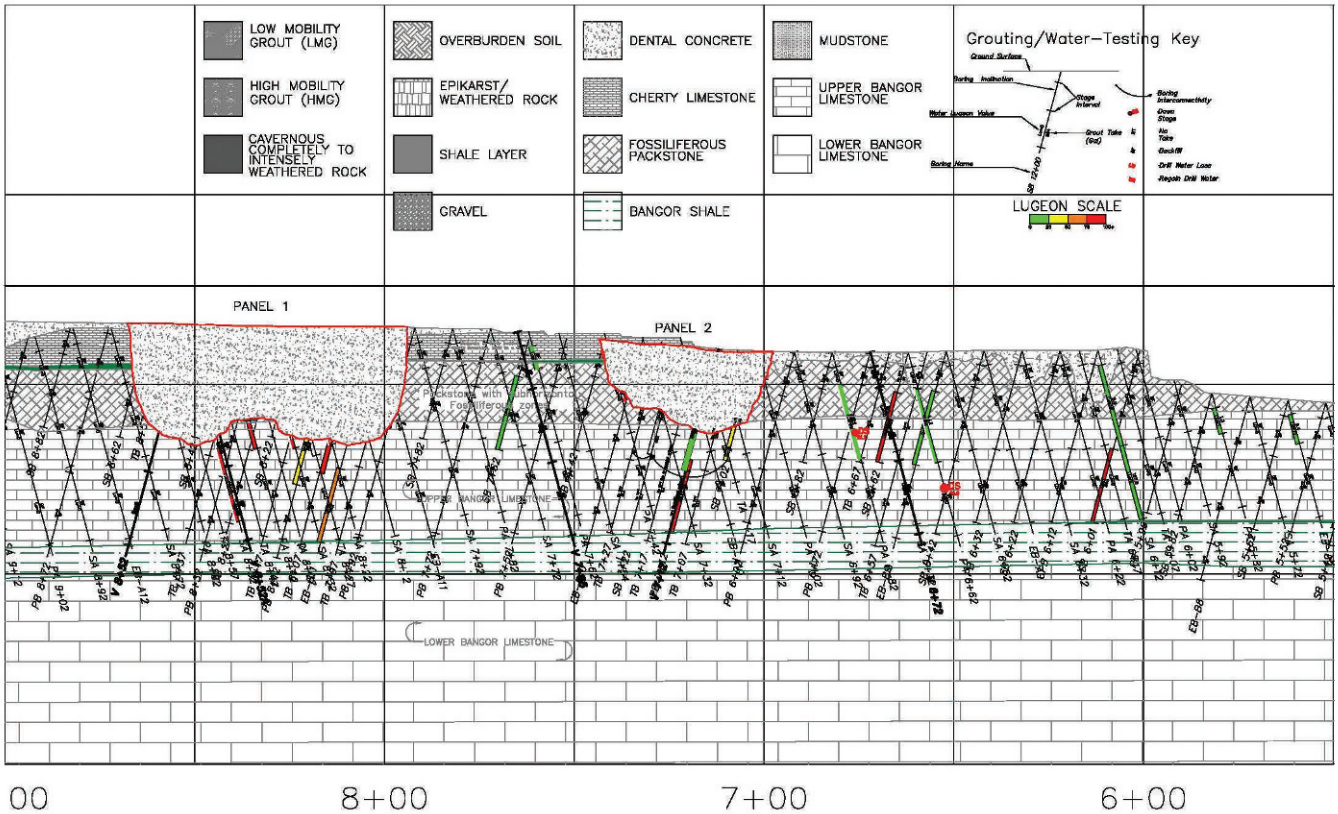

Figure 13. Example subsurface profile. Width of profile is 35 feet.

Results of Cutoff Panel Construction Program

After several days of set time, verification core borings were drilled along the centerline of each panel at 20–30-ft spacing, and five-step, Houlsby-type water pressure was tested to verify the integrity of the panel. Boring locations were chosen to intercept the abutments of the panels, the bottom contact of the panel with the foundation, or in some cases areas of interest or concern based on foundation conditions noted during the mapping process. The acceptance criterion for the cutoff panels was 5 Lugeons, the same as for the two-line grout curtain. In fact, all verification tests performed through the cutoff panels yielded ‘‘no take’’ (0 Lugeon) results. After completion of the water pressure testing and acceptance of the panel, verification boreholes were backfilled with a high-strength cement.

CONCLUSION

TVA’s Bear Creek Dam is a high-hazard potential embankment dam with a history of potentially hazardous seepage flows developed or exacerbated during its service history through the karst limestone foundation of the dam. In addition, the dam had a potential danger of failure as a result of PMF overtopping. Historically, limited success at reducing seepage flows was achieved with additional remedial

Table 1. *High-mobility grout properties.*

Parameter (unit)	Mix A	Mix B	Mix C	Purpose of Requirement
Bleed (percent)	≤3.0	≤3.0	≤3.0	Low bleed prevents voids caused by grout settlement (stability)
Pressure filtration, K_{pf} (minutes$^{-1/2}$)	≤.040	≤.040	≤.040	Low pressure filtration corresponds to less mix water being pressed out of the grout, promotes long-distance penetration into fractures
Marsh viscosity (seconds)	35	50–55	80+	Provide range of viscosities to adjust, as appropriate to subsurface conditions
Initial stiffening time (hours)	≥3	≥3	≥3	Provide enough time for mix, injection, and travel prior to initial set

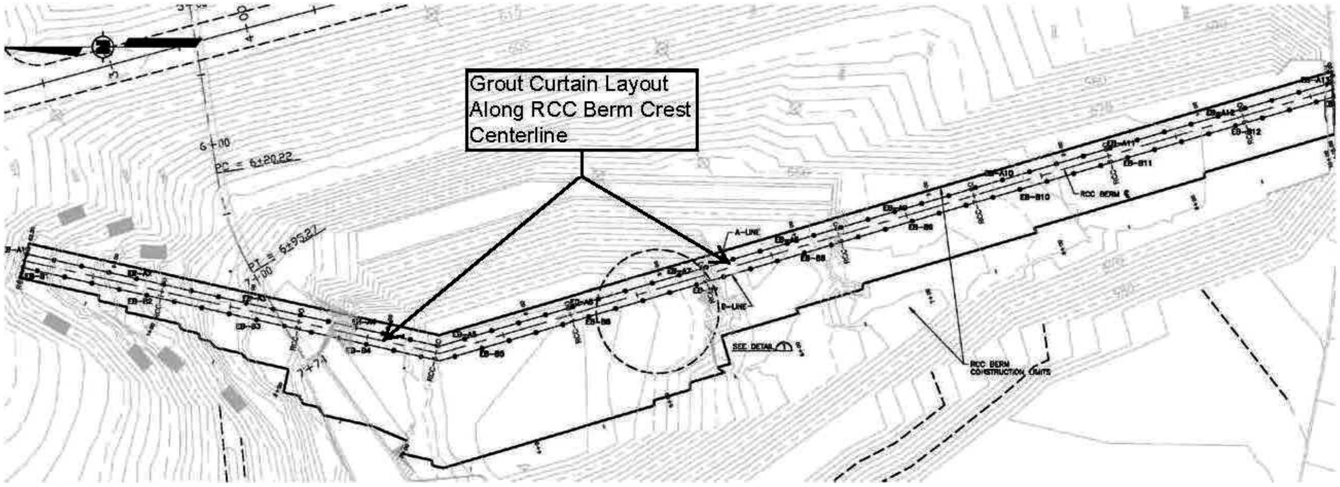

Figure 14. Drilling and grouting program layout.

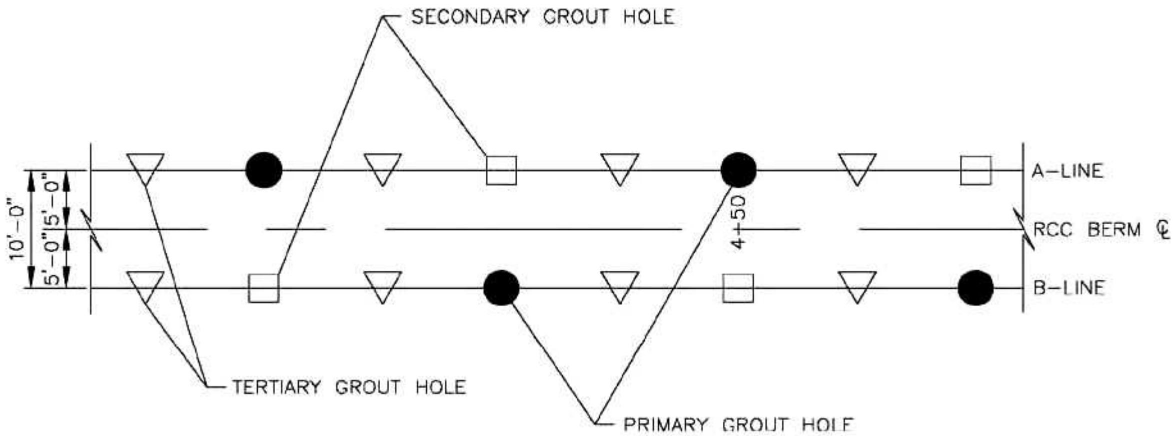

Figure 15. Typical grout hole layout.

Table 2. *Cutoff panel information.*

Cutoff Panel No.	Station Extents	Expected Maximum Depth (ft)	Geologic Rationale for Panel
Panel 1	8+00 to 8+67	35	Clay infill/void activity at depths of 25–30 ft
Panel 2	7+00 to 7+40	35	Clay infill at depths of up to 30 ft
Panel 3	3+10 to 4+77	35	Cutoff very weathered zones in the Bangor Shale at the maximum section of the new structure
Panel 4	2+40 to 2+50	23	Cutoff the continuation of N32E sluiceway solution feature, act as test panel for construction method

Table 3. *Cutoff panel construction details.*

Cutoff Panel No.	Station Extents	As-Built Maximum Depth (ft)	Cutoff Panel Area (SF)	Concrete Volume Placed (CY)
Panel 1	8+00 to 8+67	32	2,013	594
Panel 2	7+00 to 7+40	22	754	276
Panel 3	3+10 to 4+77	32	5,490	1,416
Panel 4	2+40 to 2+50	23	250	100

grout treatments; however, these reductions have been lost over time. In order to provide a robust, long-term seepage barrier, a comprehensive treatment program was designed to provide effective control of subsurface flows in the difficult karst terrain; this program consisted of an extensive foundation cleaning and dental treatment program; use of a two-line grout curtain using balanced, stable mix designs and real-time computer monitoring; and a cutoff panel installation program at locations indicated by the previous treatments. Additionally, an RCC reinforcement structure downstream of the existing embankment has been completed.

Successful rehabilitation of the karst foundation at Bear Creek Dam was achieved by implementing a progressive series of construction measures to fully treat the complicated geology. To effectively tailor the individual aspects of the foundation rehabilitation, it was critical to continuously update the understanding of the site geologic setting as more data were procured in successive treatments. To that end, real-time data collection and processing in conjunction with daily reporting of relevant conditions and maintenance of an evolving concept of the site-specific karst system in CAD models enabled the team to effectively and successfully manage the treatment program.

DISCLAIMER

It should be noted that in allowing publication of this article, the TVA does not endorse any entity or firm associated with this work.

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