SUCCESSFUL FOUNDATION PREPARATIONS IN KARST BEDROCK OF THE MASONRY SECTION OF WOLF CREEK DAM

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Abstract

Extensive foundation preparations during construction of the Wolf Creek Dam concrete masonry section precluded the need for additional rehabilitation to mitigate seepage through karstic limestone bedrock. Wolf Creek Dam on the Cumberland River in southern Kentucky has become well known for karst related seepage issues underneath the embankment section, and yet has had little to no seepage issues associated with the concrete masonry portion of the dam. Post-construction efforts to control seepage underneath the embankment began in 1967 and 1968. Emergency grouting commenced and continued through 1970. Between 1975 and 1979 a more permanent solution of a concrete diaphragm cut-off wall was constructed through the centerline of the left portion of the embankment section down to competent bedrock. The wall interrupted the progression of foundation erosion, but post construction monitoring, instrumentation readings, and persistent wet areas downstream showed that seepage paths under or around the wall continued. A second cut-off wall upstream of the first was constructed between 2007 and 2013, extending nearly the entire length of the embankment and up to 75 ft (22.9 m) deeper than the original wall. Cost of the second wall and other concurrent rehabilitation efforts reached nearly \$600 million. Exploratory grouting beneath the concrete masonry section of the dam in 2012 resulted in low grout volume takes, so no further remediation efforts below the masonry dam were conducted. The original construction photographs and foundation reports for the concrete masonry section of Wolf Creek Dam instill confidence that the designers and builders of the monoliths took adequate, if not excessive measures to ensure that all the monoliths were founded on competent bedrock. These measures included extensive borehole investigations both prior to and during excavation, efforts to locate, delineate, remove, and clean all karst solution channels, the removal of all loose rock, grouting in the foundation and side vertical faces, large stair-step faces on the left abutment, extended excavations to remove soft beds, final manual cleaning of rock surfaces, and the careful documentation of foundation preparations. These measures do not guarantee that seepage issues will not develop under the concrete dam

over time, but they do show with reasonable certainty that the monoliths were originally founded on competent bedrock, and that future seepage issues are either unlikely or will be significantly inhibited by the preparation made to the foundation prior to the construction of the concrete monoliths.

Introduction

Wolf Creek Dam, built and operated by the U.S. Army Corps of Engineers on the Cumberland River in southern Kentucky, is a flood control and hydropower dam that impounds Lake Cumberland, the largest Corps reservoir east of the Mississippi River storing about four million acre-feet (4.9 billion cubic meters), with up to six million acre-feet (7.4 billion cubic meters) maximum storage. The dam has a maximum height of 258 ft (78.6 m) and consists of a 3940 ft (1200.9 m) long compacted clay embankment dam extended from the right, or east abutment, which ties into a 1796 ft (547.4 m) long concrete masonry dam and gated spillway extended from the left, or west abutment (Figure 1). Flow is passed through six turbines rated at 45,000 kW each, and through an additional six sluice gates 4 ft by 6 ft (1.2 m by 1.8 m) each. Floods are passed over the spillway through ten tainter gates 37 ft by 50 ft (11.3 m by 15.2 m) each. The safety of the dam has come into question in recent years and it is estimated that a breach of the dam would result in

Figure 1. Aerial view looking upstream at Wolf Creek Dam.

between 100 and 1,000 fatalities, mostly within the city of Nashville, TN, located 246 miles (395.9 km) downstream of the dam (USACE, 2014).

Designed and constructed from 1938 to 1952 over karstic limestone bedrock efforts were undertaken before, during, and after construction to prevent the seepage of reservoir water through the foundation from compromising the integrity and safety of the dam. These efforts included but are not limited to the construction of an embankment cut-off trench near the upstream toe, grouting before and during construction, emergency grouting of the downstream embankment in the late 1960s and early 1970s, construction of a concrete diaphragm barrier wall in the embankment from 1975 to 1979, and the construction of an additional concrete barrier wall from 2007 to 2013. The latest remediations to the embankment alone cost nearly \$600 million. Since construction the masonry section of the dam has had few costs beyond normal operation and maintenance with no issues of seepage, settlement, stability, or other potentially karst related problems. This is due to the extensive foundation preparations undergone during construction which included the removal of all soft and solutioned bedrock.

Geologic Setting

The dam was built across the Cumberland River valley within the Highland Rim; a low plateau of nearly horizontal beds of limestone, shale, and chert ranging from Ordovician to Mississippian in age. The dam is located approximately 20 miles east of the crest of the Cincin-

nati Arch, a broad up-fold extending northeast-southwest across central Kentucky, which gives the bedrock a slight dip of 30 ft per mile (5.7 m/km) to the southeast or upstream direction.

The foundation of the dam is composed of mostly limestone bedrock with some river alluvial deposits left below the embankment portion of the dam (Figure 2). The Catheys Limestone Formation underlies the entire area and is described as hard, thin-to-massive bedded, dark gray, and argillaceous limestone interbedded with thin, well-cemented, calcareous shale. The Leipers Limestone Formation sits unconformably above and is very similar to the Catheys. In general it is thinner bedded, more argillaceous, and more fossiliferous. It forms the valley floor and the lower portion of the abutments. Within the abutments the Leipers is overlain by the Cumberland Limestone Formation, which is a dense, greenish-gray, massive, non-fossiliferous, arenaceous to argillaceous, dolomitic limestone. The Chattanooga Shale sits above that, which is primarily a fairly hard, well cemented, fissile, black, carbonaceous, and silty shale, with a 4 to 5 ft (1.2 to 1.5 m) base of gray shale that is more susceptible to weathering and erosion. The upper abutments are topped off with the Fort Payne Formation, a series of argillaceous limestone, calcareous shale, and thin beds of cherty limestone (USACE, 1940).

Karst

Although no faulting is present at the site, relatively close centered jointing is prevalent and follows two well

Figure 2. Wolf Creek Dam axis in profile with foundation geologic stratigraphy.

defined joint sets. Solutioning by water infiltration along these near vertical joints and bedding planes of the limestone has occurred over millions of years, particularly across the valley. The exploration programs and foundation preparation for the masonry dam and cut-off trench revealed a rock foundation riddled with solutioned features ranging in size from a few inches (centimeters) to 40 vertical ft (12.2 m) along the joints (Figure 3). These karstic solution features were found primarily within the Leipers Limestone Formation, which was susceptible to higher groundwater flow being the uppermost bedrock across the valley floor and the formation through which the river channel flows. The interconnected nature of the karst system has been well documented by the foundation preparation during construction, through the various exploration programs, pool responsive piezometers, and wet areas downstream of the dam. These open features within the rock mass have been variably filled or partially filled with residual and alluvial deposits of sands, silts, and clays.

Performance History

The reservoir was first impounded in 1950. Seepage issues beneath the dam were first indicated in 1962 by wet areas near the downstream toe toward the right abutment. By 1967 the area had become too wet to mow, and in August of that year a small sinkhole formed near those wet areas. That fall muddy flow began to exit 150 ft (46 m) downstream of the powerhouse into the tailrace of the dam, and the following spring two sinkholes formed near the switchyard. Piezometers were soon installed in the area and dye tests were conducted, which indicated that seepage was occurring under the dam and by-passing the upstream cut-off trench through a system of so-

Figure 3. Karst channels and caves uncovered and cleaned out during excavation of upstream cut-off trench.

lution features in the foundation rock that ran generally perpendicular and parallel to the dam axis. This seepage was piping materials from these solution features and transporting embankment material that collapsed into the features.

Emergency grouting of the subsurface solution features began in April 1968 and continued through 1970, installing a series of grout lines within and beneath the downstream embankment where it wraps around the masonry dam. This quick action likely prevented a breach of the dam, but was not considered a permanent fix due to the karst foundation. Between 1975 and 1979 a concrete diaphragm wall was installed across the left portion of the embankment from the crest of the dam down to competent bedrock, to cut-off seepage paths through the karst solution features of the Leipers Formation. A smaller additional wall was also installed between the switchyard and the tailrace to prevent the exit of material from beneath the dam.

The barrier wall was expected to significantly drop the water levels in the downstream piezometers, but only a slight reduction occurred. It was then predicted that over time the water levels would drop, but instead the measurements in the downstream piezometers began to rise over the years. A surface elevation monument installed in 1981 near the embankment and masonry dam interface showed continued settlement of the embankment, with an increase in settlement rate after 1997. Downstream wet areas near the right abutment persisted through the remediation efforts, but those near the left end of the embankment largely disappeared after the grouting and barrier wall construction of the 1970s. Over time the wet areas returned, and those near the right abutment steadily grew in extent from 1990 until they reached a maximum extent in the spring of 2004. In 2002 and 2003 borings drilled into the embankment downstream of the barrier wall encountered zones of soft saturated clay several feet thick at the base of the dam material.

It was decided that additional remediation was necessary to reduce seepage below the embankment dam to maintain safe dam operation. Between 2007 and 2013 an additional concrete barrier wall was constructed in the embankment upstream of the first wall. The new wall was extended up to 75 ft (22.9 m) deeper into bedrock, below the Leipers-Catheys contact, and extended nearly across the entire embankment to the right abutment. New grouting reached depths at least 50 ft (15.2 m) below the new wall and into the right abutment. A deeper extension was also added to the subsurface wall between the switchyard and the tailrace. Exploratory grouting below the masonry dam resulted in small grout volume takes,

so no additional remediation was conducted within the masonry dam foundation (USACE, 2014).

Masonry Dam Construction

The seemingly superior performance of the masonry dam foundation over the embankment dam foundation to prevent seepage and safety issues is largely due to the extensive foundation preparations that were conducted prior to the construction of the dam.

The concrete masonry portion of Wolf Creek Dam is divided into 37 primary monoliths, all of which are founded on competent bedrock. The monoliths are grouped into four sections which include 1) the Left Non-Overflow Section (Monoliths 1-7) along the steeply sloped left abutment, 2) the Spillway Overflow Section (Monoliths 8-18) within the Cumberland River channel, 3) the Power Intake Section (Monoliths 19-26) on the shallow right bank of the channel (the Powerhouse is located immediately downstream of this section), and 4) the Right Non-Overflow Section (Monoliths 27-37) at the embankment wrap-around area (Figure 1). To reach competent bedrock it was necessary to excavate down to the Lower Leipers Formation or Upper Catheys Formation, which both consist of limestone and interbedded shale. Weathering, karst, and solution features were largely concentrated within the Leipers Formation across the valley floor within the primary groundwater flow regime, but were less prevalent within the abutments.

Site Investigation and Preparation

Care was taken during construction of the masonry section to remove all overburden and weathered or deteriorated bedrock. Estimates of depths to competent rock were made based on early 1930s site investigation borings made on 100 ft (30.5 m) centers. Then after the removal of the overburden, additional boreholes at least 16 ft (4.9 m) deep were drilled into the bedrock both parallel and normal to the dam axis on 20 ft (6.1 m) centers covering the entire exposed concrete dam area. Based on the data collected from these holes final excavation depths were determined so that all soft beds and solution channels would be removed from underneath the dam. During bedrock excavation, which was accomplished primarily by blasting and power shovels, the crews continued to look for issues, and some additional borings were ordered for problem areas. These further investigations led to decisions to deepen excavation for Monoliths 24-19, dig out the caves in Monoliths 37 and 36, add more grout than had been originally planned, and other special fixes to ensure the integrity of the bedrock foundation. When large solution features were encountered within the limestone they were dugout, widened, cleaned, and filled with concrete. Final rock preparation

consisted of barring and picking, cleaning with air and water pressure hoses, and brooming in a ½-inch layer of grout just prior to the placement of the concrete. After the construction of the grout gallery near the upstream axis of the dam, angled pressure grouting was placed and drains were installed into the foundation bedrock (USACE, 1952).

Overburden Removal

Overburden at the dam site consisted largely of sandy and silty alluvial river deposits across the valley, or thin colluvium layers on the abutment slopes. To prepare the monolith foundations all overburden and alluvium were removed by either hydraulic dredging, a dragline, a clamshell, or diesel power shovels (Figure 4). Depths of overburden averaged about 25 ft (7.6 m) for Monoliths 37-27, but increased to an average of 40 ft (12.2 m) for Monoliths 26-14 since the top of bedrock was deeper and closer to the river channel. Overburden depths only averaged 6 ft for Monoliths 13-1 since channel flow limited sediment deposits on bedrock within the river and the steep slopes on the left abutment prevented the deposit of thick layers of sediment, leaving the bedrock exposed or narrowly covered.

The dredge operated from the spring to fall of 1946, between the areas of Monolith 29 to 18. It was then used in the summer and fall of 1948 to remove a sand bar known as Cooper's Island from the river, and then used in 1949 to fill cells for Cofferdam No. 2. The power shovels, clamshell, and dragline removed all the rest of the overburden, commencing on the right side near the embankment, and then working in various stages near the river channel; as cofferdams were moved, monoliths were constructed, and areas became available for work to proceed (USACE, 1952).

Bedrock Excavation

Bedrock excavation was conducted primarily by blasting. As faces were established, new shot holes would be drilled on 3 ft (0.9 m) centers behind the face. Shot hole depths were generally 6 to 8 inches (15.2 to 20.3 cm) above an established bedding plane, but did not extend over 8 ft (2.4 m) deep. Forty percent dynamite was the blasting substance, used in the proportion of 0.75 pounds per cubic yard (0.44 kg/m³) of rock to be removed. Blasting in delayed series was initially tried but quickly abandoned since primary blasts sometimes severed the connections to the secondary blasts, resulting in unexploded dynamite and a hazardous situation. Power shovels and a clamshell were used to load the rock onto dump trucks. During the final foundation clean-up operations, rock removal was being conducted by hand labor using picks, shovels, pry bars, and high pressure hoses. All

Mon. No. 20 Removal of Overburden by Dredge
Photo No. 114

Mon. No. 20 Removal of Overburden by Dredge
Photo No. 137

Mon. No. 20 Final Removal of Overburden by Shovel
Photo No. 159 after Dredging Operation

QR-61/27 Masonry Monolith 37-32 1+00 B

Figure 4. Photographs of overburden removal, showing dredge operations and final removal by shovel.

rock that was not “firmly bedded” had to be removed from the horizontal and vertical surfaces of the foundation. During this operation waste material was loaded into skip pans and hauled away by the cableway that had been constructed above the site (USACE, 1952).

Non-Overflow Right Bank Section (Monoliths 37-30)

On 30 April 1946 work began on the foundation of the right end of the concrete dam. Excavation within this section was started at each end, with one group working between Monoliths 37-35 and another working between Monoliths 31-30. Rock removal was more difficult than anticipated due to the irregular patterns of soluble limestone channels and mud filling, especially at Monoliths 37-35. At that end two major mud-filled cavernous solutions were uncovered which were a continuation of the solutions beneath the embankment section that the

upstream cut-off trench followed. Stability of the bedrock and the hazards it posed to the workers became a major concern, so both groups proceeded cautiously by conducting only shallow blasts; hoping to shoot out the smaller solution channels and reveal the larger and deeper solution caverns. The patterns eventually revealed themselves as two large channels extending across Monoliths 37, 36, and part of 35. At Monolith 35 the two channels converged into one more narrow channel that eventually was revealed to extend across Monoliths 35, 34, 33, 32, 31, 30, 29, 28, 27, and a portion of Monolith 26. As large channels and caverns were revealed, the side walls were cut back until only satisfactory bedrock remained (the channels were wide enough for a clam-shell bucket to reach the bottom), and the mud and loose rock was removed from the bottom until the channel was completely cleaned out (Figure 5). About 40% of the material removed was mud and 60% rock. Eventually

these channels were filled with concrete. Rock excavation in this area was completed February 1947.

Power Intake Section (Monoliths 29-19)

Dredging began in the area between Monoliths 29-19 on 15 April 1946, removing up to 51 ft (15.5 m) of overburden. On 12 July 1946 the dredge was moved downstream and excavation of the final 5 ft (1.5 m) of overburden along with the bedrock commenced with a power shovel and trucks. At Monolith 22 another solution channel was uncovered, and a clamshell was brought in to help define it. It was discovered to extend from Monolith 24 – 18, be mud filled, of irregular pattern, and approximately 8 ft (2.4 m) deep. This prompted additional test drilling along the solution channel to determine the soundness of

the surrounding rock. Much of the rock was determined to be inferior, so the test holes became blast holes and the inferior rock was removed taking along with it the solution channel. Investigations in the area continued with drilling several more 6 inch diameter holes and two 30 inch (76.2 cm) Calyx holes, one in Monolith 20 and the other in Monolith 22. These investigations determined that a continuous inferior bed existed at elevation 523.0 ft (159.4 m) above sea level (NGVD29) under the entire area from Monoliths 24 to 19. It was decided to remove all bedrock in that area to elevation 523.0, which was 12 ft (3.7 m) lower than the previously determined elevation of 535.0 (Figure 6). Removal of the additional rock began on 1 December 1946, and was completed on 10 April 1947. In Monolith 20 a flood on 3 January 1947 displaced foundation rock near the Calyx hole, so addi-

Figure 5. Photograph of cleaned solution channel across the foundations of Monoliths 35-37.

tional grout was placed without pressure in a radial pattern across Monolith 20 prior to the placement of concrete (Figure 7). Initial concrete cover of the bedrock was completed on 20 April 1947.

Bedrock excavation in the area of Monoliths 29-25 encountered few if any solution channels, so the exca-

vation was not required to extend deeper. It was even determined to leave in place an upstream rock ledge from Monoliths 29 to 25 (Figure 8). Though the rock in the ledge was determined to be competent, there was some concern for seepage pathways eventually working through the bedding planes to the base of the dam. Contact grouting was pumped into bedding planes of con-

Figure 6. Photograph of the cleaned foundation of Monolith 21. Remnants of the solution feature that was removed are visible on the floor and on the downstream wall.

Figure 7. Photograph of the cleaned foundation of Monolith 20. Remnants of a solution feature is visible on the floor, as are the grout holes placed in a radial pattern from the Calyx hole.

cern along the vertical faces of the ledge (Figure 9) after it had been cleaned and all loose rock removed. Excavation and initial concrete placement was completed by 10 April 1947.

Spillway Section (Monoliths 18-9)

Foundation excavation in the area of Monoliths 18-14 began on 3 November 1947. The proximity to the river channel required the partial removal and reconstruction of the cofferdams in order for work in the area to continue. Excavation resulted in few incidents, since weathered rock in the Liepers Formation had likely already been removed by river channel erosion. Up to 48 ft (14.6 m) of overburden had to be removed to reach bedrock. After the removal of the overburden rock excavation was conducted in a single shallow lift, except in the downstream bucket sections where the design required excavation down 6 ft (1.8 m) lower than the abutting monoliths. It was also within the bucket sections that the solution feature from Monolith 24 cut across these monoliths, but it was completely removed by the lower excavation depth in the bucket sections. A shallow sump was excavated below the grout gallery in Monolith 18.

Spillway Section within River Channel (Monoliths 13-9)

To begin foundation work within the Cumberland River channel required additional removal and reconstruction of the cofferdams to redirect flow away from the area.

Figure 8. Photograph from above showing the initial placement of concrete monoliths on the foundation, and rock benches that were not excavated.

Figure 9. Photograph of the contact grout pipes placed on the vertical face of the rock ledge left in place at Monolith 25. The pipes eventually were connected to the grout gallery so that additional grout could be placed as necessary after construction.

Once dewatered, about 3 ft (0.9 m) of overburden was removed containing boulders, gravel, and sand. A cableway was employed to place excavation equipment within the cofferdam, and work commenced in June 1949, but was stopped on 1 July 1949 due to a general strike. The equipment was removed and the area was re-flooded during the duration of the strike. Work recommenced on 23 September 1949, and all overburden was removed by 1 October 1949. The exposed rock showed a mud-filled solution channel present in the downstream bucket section across Monoliths 13-11. It was determined to be about 8 ft deep and varied in width between 10 and 25 ft (3.0 and 7.6 m). It was determined to remove the entire solution channel. Rock excavation began on 28 September 1949 and was completed on 15 November 1949.

Non-Overflow Left Bank Section (Monoliths 8-1)

Since the bedrock was shallow and/or exposed along the left abutment foundation work began early there on 5 April 1946 commencing high on the slope at Monolith 2; removing overburden down the slope towards the river channel. With the overburden and some weathered rock removed, foundation preparation then began at the bottom of the slope at Monolith 8 to better constrain the work limits of the area. Initial concrete placement at Monolith 8 began on 6 December 1947. Work then commenced again from the top of the slope, working downward, by removing rock and cutting in stair step benches on which the laborers could work and concrete could be placed. The left abutment foundations were primarily limestone except for the Chattanooga Shale at the base of Monolith 2. Monoliths were excavated sufficiently deep to maintain a minimum distance of 10 ft (3.0 m) below the top of original rock so that rock exposed to surficial weathering was removed. Between Monoliths 7 and 5 the shallow step-ups were replaced with deeper, larger step-ups (Figure 10) to avoid the Monoliths being founded on structurally weak beds that exhibited conchoidal structure during excavation. Large solution features were not present in the left abutment limestone. Contact grout systems were installed on the vertical rock faces prior to the placement of concrete, to close off bedding planes and joints along the abutment (Figure 10). The systems were left in place and connected into the grout gallery so that future grouting in the abutment could occur.

Grouting and Drains

After the foundations were excavated, cleaned, and fully prepared it was decided to drill supplementary grout holes along the dam axis to fill any extensive subsurface openings and crevices, and confine the high pressure grouting that would occur later. The 2 inch (5.1 cm)

diameter holes were drilled to a depth of 25 ft (7.6 m) and angled 22.5° from vertical towards the left abutment. The drill holes were washed and cleaned with water, and then compressed air was used to remove all the water. Grout was then poured into the holes without pressure until refusal occurred.

To prepare for the high pressure grouting, 3 inch (7.6 cm) diameter steel casing pipes were installed at 5 ft (1.5 m) centers along the axis of the dam during the foundation preparations (Figure 10). These pipes were angled 7° towards the left abutment, and were positioned such that as they would emerge in the floor of the grout gallery near the dam axis at the base of the masonry dam (Figure 11). Once the grout gallery floor was constructed, grout holes were drilled through the casing and into

Figure 10. Photograph showing the cut "stair steps" into the left abutment at Monolith 5 and 6, with the pipes in place for the contact grout system on the vertical faces and the casing pipes in place for the grout gallery drains and grout holes.

the foundation bedrock. High pressure grout was then pumped into the foundation.

During the foundation preparation, 5 inch (12.7 cm) diameter casing pipes were placed downstream of the grout pipes, angled 12.5° from vertical in the downstream direction. After the high pressure grouting was completed within 100 ft (30.5 m) of these downstream pipes they were drilled to install drains from the foundation into the grout gallery, providing relief points for future pressurized water seeping under the dam foundation to escape without cracking or damaging the structure (USACE, 1952).

Conclusion

The original construction photographs and foundation reports for the concrete section of Wolf Creek Dam instill confidence that the designers and builders of the monoliths took adequate measures to ensure that all the monoliths were founded on competent bedrock. These measures include: extensive borehole investigations

both prior to and during excavation; efforts to locate, delineate, remove, and clean all karst solution channels; the removal of all loose rock; grouting in the foundation and vertical faces; the large stair-step faces on the left abutment; the extended excavations to remove soft beds; the final manual cleaning of rock surfaces; and the careful documentation of foundation preparations. These measures do not guarantee that seepage issues will not develop under the concrete dam over time, but they do show that the monoliths were originally founded on competent bedrock and that future seepage issues are either unlikely or will be significantly inhibited by the preparation made to the foundation prior to the construction of the concrete monoliths.

References

- USACE. 1940. Wolf Creek Dam and Reservoir basis of design for definite project report. U.S. Army Corps of Engineers, Nashville, Tennessee District, p. 32-36.
- USACE. 1952. Wolf Creek Dam and Reservoir project completion report, Volume 1, Appendix B: Foundations. U.S. Army Corps of Engineers, Nashville, Tennessee District.
- USACE. 2014. Post implementation evaluation Wolf Creek Dam. U.S. Army Corps of Engineers, Nashville District.

Figure 11. Typical cross-section of non-overflow monolith, highlighting the location of the grout gallery.