HYDROCUTTER-EXCAVATED SLURRY WALL FOR CENTER HILL DAM FOUNDATION REMEDIATION

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ABSTRACT

Center Hill Dam is a critical part of the infrastructure controlling floods at the Caney Fork River and reducing flood levels at the Cumberland, lower Ohio and Mississippi Rivers. The Center Hill Dam Foundation Remediation Project was necessary to address Karst features in the foundation rocks and observed signs of distress of the dam. From 2011 to 2014 BAUER Foundation Corp. (BFC) performed deep foundation works for this project. The executed features of work include the installation of two walls. The first wall extends throughout the clay embankment into the underlying rock to provide encasement during the construction of the second wall. Its width of 7.4 feet makes it the widest diaphragm wall ever installed. The second wall is the actual seepage barrier and provides a continuous 2-feet wide wall. It extends through the first wall into the underlying rock and is up to 300 feet deep. The paper introduces the project, the requirements specified by United States Army Corps of Engineers (USACE) for encasement and barrier wall and the approaches taken by BFC. It discusses the ground conditions and describes the excavation equipment as well as the excavation methods used. A special focus is put on the steering capabilities of the hydrocutter equipment and the verticality performance.

Keywords: slurry wall, hydrocutter, dam rehabilitation,

PROJECT

Beginning in 2011, BFC was tasked by the USACE with the installation of a seepage barrier/cutoff wall at the Center Hill Dam Foundation Remediation project under a partially performance based specification. The remediation was necessary due to karst features in the foundation rocks and observed signs of distress, which led USACE to rate the dam with the most critical dam safety action classification (DSAC I). The executed features of work include the installation of two walls. The first wall, an encasement wall, extends vertically through the clay embankment and is embedded minimally into the underlying bedrock to provide embankment stability during the construction of the second wall, the barrier wall. The encasement wall is constructed of overlapping panels 7.4 feet (2.25 m) wide, which is the widest diaphragm wall ever installed, and up to 210 feet (64 m) deep. The second wall is the seepage barrier and provides a continuous 2 feet (0.6 m) wide wall consisting of overlapping panels. It extends through the encasement wall into the underlying bedrock and is up to 307 feet (93 m) deep. BAUER BC40 and BC50 hydrocutters mounted on MC96 and MC128 foundation cranes were used to perform the majority of the works (Figure 1). Excavations were performed under bentonite slurry (encasement wall) and water (barrier wall) and concrete was poured with the tremie method. Adding to the challenges, the project had to be executed in an environmentally sensitive area. Based on the high risk, a special focus was put on monitoring, quality control and geometric accuracy. The WallTracker information management system was used to share all relevant data between BFC and USACE (Roff et al. 2014).

Figure 1. BAUER MC 128 (left) and MC 96 (right), both equipped with hydrocutters, working during barrier wall installation

GROUND CONDITION GROUND CONDITIONS AND PRIOR REMEDIATIONS

The following description is based on the Geotechnical Baseline Report (USACE 2011). The right rim of the Caney Fork River is characterized by a steep rock slope, while the left rim rises more gently about 240 feet (70 m) from the riverbed to the crest of the earthen embankment. The earthen embankment section of the dam wraps around the left end of the concrete monolith and extents about 850 feet (260 m) at the crest to its end at the intersection with the left rim. The earthen embankment consists of compacted fill made of impervious silty clay and clayey silts.

The embankment was constructed directly on the existing overburden after topsoil was stripped. A cutoff trench was excavated in the centerline of the embankment removing the alluvium and the weathered surface rock. The alluvium is underlain by the flat lying Catheys, Cannon and Hermitage formations, with the Hermitage being underlain by the non-daylighting Carters and Lebanon formations (Figure 2). The Catheys, Cannon, Carters and Lebanon formations consist of limestone with bands of shale, while the Hermitage is composed of two limestone and two shale members. The Carters formation is divided into an upper and lower layer by 1.5 to 2 feet (0.45 to 0.6 m) thick bentonite layer. The Cannon formation is massive bedded, all other formations are thin bedded or medium to thin bedded. The limestone contains two well-defined vertical joint sets. The unconfined compressive strength of the rock was up to 32,000 psi (220 MPa) in the Cannons with formation averages ranging from 7,000 to 27,000 psi (50 to 190 MPa).

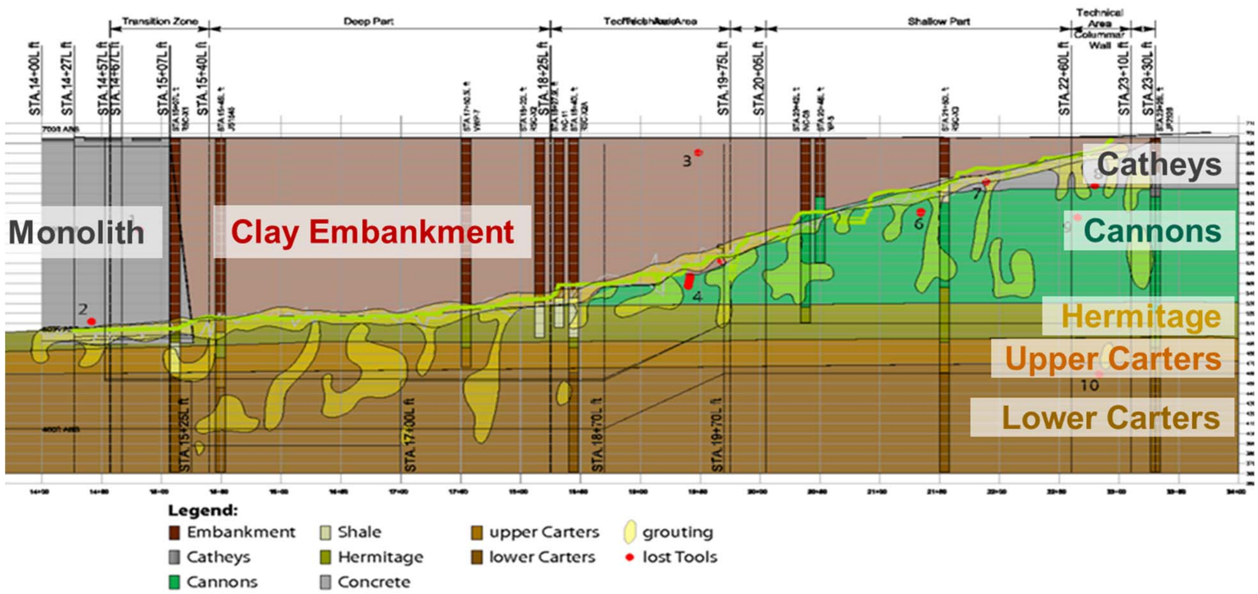

Figure 2. Geological profile in the wall alignment including areas of high grout takes (looking upstream)

Physical evidence of karst is visible throughout the site including disappearing streams, sinkholes, caves and extensive solution features. Limestone bedding planes and the contact zones between Catheys, Cannon and Hermitage show localized karst development. The vertical joints also promote solution processes and have created vertical soil-filled or open fractures. Bedding planes and vertical fractures have the potential to form interconnected systems of open features. These systems are especially threatening if they reach the embankment, creating piping features in the soil rock interface and potentially causing an erosion failure of the embankment.

A grout curtain was installed from and below the cutoff trench during original construction of the dam. Later, after several potential conditions were detected in the late 1970's, a grout curtain was installed about 10 feet (3 m) downstream of the embankment center line through the embankment into the bedrock from 1982-1984. Finally, in order to reduce seepage through the bedrock and in order to allow for a safe Barrier Wall construction, grout curtains were installed 12 feet (3.6 m) upstream and downstream of the wall alignment from 2009 to 2010.

HYDROCUTTER AND SUPPORT TECHNOLOGY

The encasement wall and barrier wall were excavated using BAUER trench cutters mounted on BAUER foundation cranes. The encasement wall, which included panel elements 7.4 by 10.5 feet (2.25 by 3.2 m), was executed with a BC50 trench cutter mounted on a MC128 foundation crane. The barrier wall, which included panel elements 2.7 by 10.5 feet (0.83 by 3.2 m), was executed utilizing the BC50/MC128 setup with different cutter wheels and a BC40 trench cutter mounted on a MC96 duty cycle crane. All cutters were equipped with inclinometers as well as with a gyroscope providing the operator with real-time information on inclination, deviation and rotation on the B-Tronic screen (Figure 3). Based on this information the operator controls the steering plates (flaps) via the B-Tronic touchscreen (Figure 4) to steer the cutter into the desired direction.

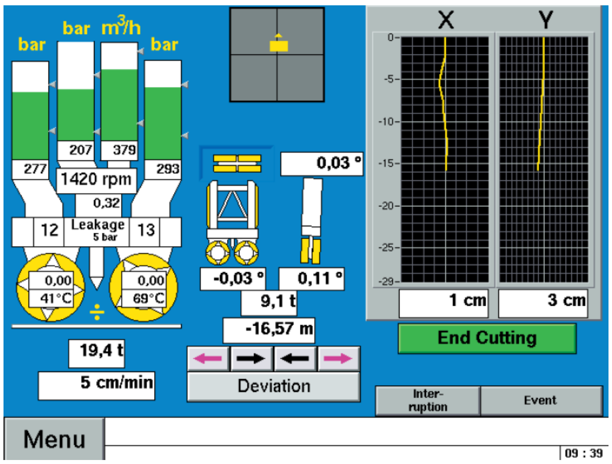

Figure 3. B-Tronics screen with deviations profile (BAUER 2016)

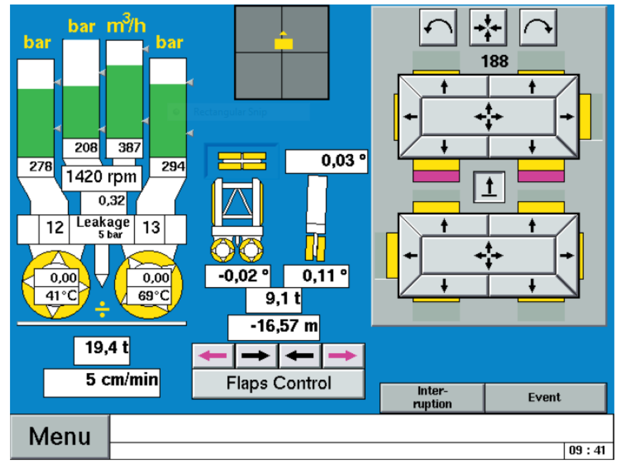

Figure 4. B-Tronics screen with control window. (BAUER 2016)

During encasement wall construction, which included excavation through embankment clay and in-situ rock, bentonite slurry was used to stabilize the excavation and transport cuttings from the excavation. Bentonite slurry was chosen over polymer slurry due to environmental concerns in case of a slurry loss into the tailwater, namely overloading the Caney Fork river with nutrients and endangering the trout population in it. During barrier wall construction, which included excavation through the encasement wall concrete and in-situ rock, water was used to transport cuttings from the excavation as no stabilization was required in the Encasement Wall and underlying rock. Under both scenarios, a substantial de-sanding plant was used to clean and recycle the fluid to the trench.

The de-sanding plant was capable of supporting two trench cutters operating simultaneously around the clock. The plant was assembled utilizing a series of machines to progressively remove cuttings of increasingly smaller sizes until the fluid was clean enough to return to the trench. These machines included scalpers, shakers, de-sanders, de-silters and a centrifuge. During encasement wall construction, the bentonite slurry was recycled approximately three times before its properties exceeded specification requirements and needed to be replaced with fresh slurry. During barrier wall construction, where the excavation was through concrete and rock, the water had to be replaced more often, typically after each panel excavation.

One of the most significant achievements of the project was the level of precision in which the verticality and orientation of the panels were excavated. This accuracy was achieved through a system that allows the trench cutter's verticality and orientation to be monitored and controlled in real time during the excavation process. The BC40 and BC50 trench cutters are equipped with an inclinometer that measures the inclination of the cutter frame continuously in both the x-axis and y-axis. A gyroscope was also fitted to the frame to measure the rotation of the trench cutter on the vertical (z) axis. All of this information is transmitted to the BAUER B-Tronic control system in the cab of the machine. Using this information (and considerable knowledge and skill) the operator is able to steer the cutter using steering flaps and by independently controlling the rotational speed of the cutter wheels. For controlling verticality and orientation, the cutter frame is fitted with 12 individually controlled hydraulic plates that can adjust the position of the cutter frame in the trench in both the longitudinal and transverse direction. The rotational speed of the wheels can also be adjusted individually to correct measured deviations in the longitudinal direction.

ENCASEMENT WALL

Trenches excavated during barrier wall construction had the potential to intersect open solution features and connect the slurry-filled trench with the tailwater and in this way cause a sudden and substantial loss of fluid. This fluid loss could destabilize the excavation (trench) and therefore put the dam embankment at risk. To address this risk an encasement wall was built that extends from the crest of the dam down to a minimum of 2 feet (0.6 m) into the foundation bedrock. In this configuration, the encasement wall would support the embankment by bearing earth and water pressure in the event of trench fluid loss, protecting both the embankment and the excavation equipment. Based on the design strength of the encasement wall concrete of 3,000 psi, the required barrier wall cover was 12 to 17 inches (305 to 430 mm), depending on depth. The encasement wall was installed using three different approaches (see Figure 5).

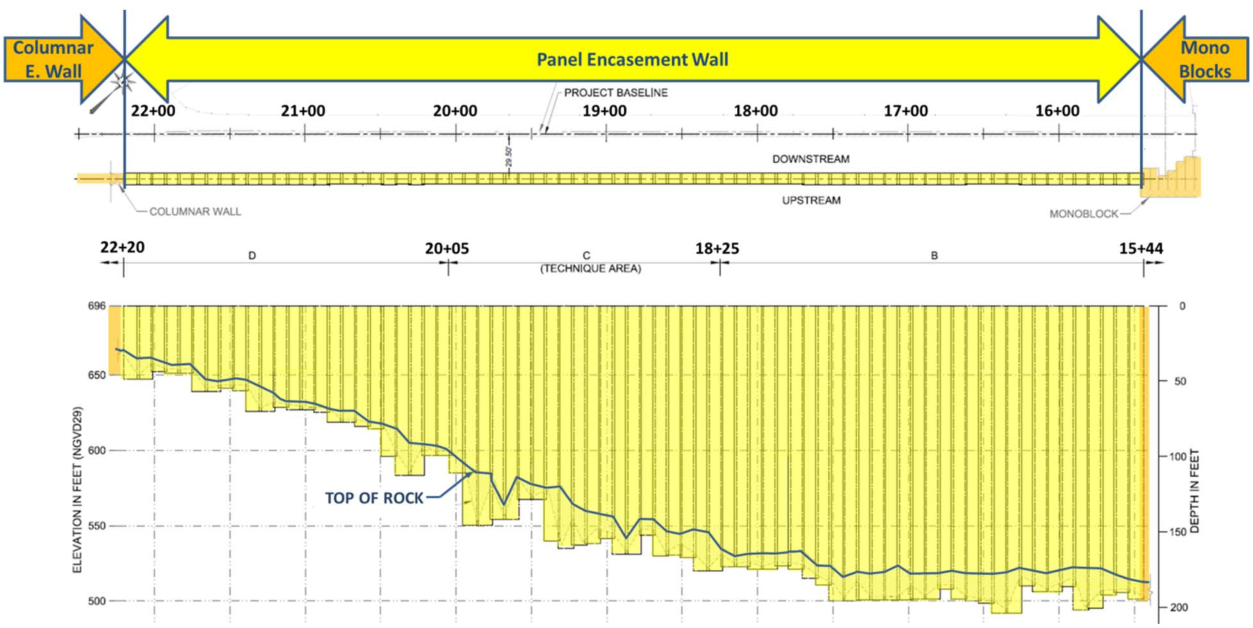

Figure 5. Panel encasement wall plan and profile (looking downstream, USACE 2011)

Columnar Encasement Wall and Mono Blocks

In the shallow section at the left rim, about 120 feet (36 m) long, the encasement wall was designed as a secant wall consisting of up to 35 feet (11 m) deep unreinforced concrete columns. The columns were excavated under dry conditions using fully cased Kelly drilling by a BAUER BG 50, the most powerful drilling rig currently made by BAUER.

In the area at the right end of the encasement wall where the barrier wall ties into the upstream face of the existing dam monolith, BFC decided to fully replace all soil with unreinforced concrete. This was achieved by a series of grab-excavated multi-bite panels (mono blocks) approximately 200 feet (60 m) deep, which touch each other along the long side. To seal the joints between the mono blocks and to allow for arching across the joints, concrete columns (mono block closing piles) were installed close to the ends of the joints by uncased Kelly drilling methods with the BG 50. The mono blocks were excavated under bentonite slurry, while the closing piles were excavated with minimal water.

Panel Encasement Wall

The 700 feet (210 m) long main section of the encasement wall was excavated in 10.5 feet (3.2 m) long panels reaching depths of over 200 feet (60 m) (Figure 5). Each primary panel was pre-excavated using a hydraulic grab mounted on the MC 96 (Figure 6). Due to the overlap of the panels, the length of the secondary panel pre-excavation was considerably shorter and therefore was performed by the BG 50 using uncased Kelly drilling. After pre-excavation, the panel was fully excavated using a BC 50 hydrocutter mounted on a BAUER MC 128 foundation crane (Figure 7). All excavations were performed in bentonite slurry-supported trenches and boreholes. Concrete was placed via two tremie pipes per panel.

Figure 6. MC96 with hydraulic grab

Figure 7. MC128 with BC50 cutter

The technical specifications (USACE 2011) called for tolerances of 0.25% maximum panel verticality deviation, maximum six degrees panel rotation (twist) and a minimum 6-inch (150 mm) overlap between primary and secondary panels throughout the full width and depth of the wall. To achieve these goals the cutter needs to be steered, which requires both precise in-formation about the actual position of the tool with respect to design and steering capabilities.

BFC used BAUER's proprietary Cutter Inclination System (CIS) in conjunction with advanced instrumentation to determine the position of the cutter in the trench. This information, in combination with the steering capabilities as discussed above, allowed the operators to excavate all elements well below the contractual tolerances despite locally adverse conditions of a steeply angled soil-rock interface at the slopes of the cutoff trench. As-built surveys were initially performed using the CIS, Koden and SoniCaliper methods as well as by performing free-fall passes with the tool. Analyses comparing the results of the different methods indicated the Koden method produced the most accurate as-built information. The Koden data were ultimately used to determine the as-built data set, which showed a maximum recorded deviation out of plumb of 0.43 feet (130 mm) and a maximum panel rotation of 4.3 degrees with averages being only a fraction thereof. The minimum overlap achieved was 0.58 feet (180 mm), providing more than the required overlap of 0.5 feet (150 mm).

BARRIER WALL

For barrier wall construction two wall types were specified: a 50 feet (15 m) long columnar section with depths up to 186 feet (56 m) and two sections totaling about 850 feet (260 m) of hybrid panel/column wall with depths up to 306 feet (93 m) deep (Figure 8). A 150 feet (45 m) long extension of the hybrid wall was later added to the contract scope. The objective was to create a continuous, minimum 2 feet (0.6 m) wide wall with elements overlapping by a minimum of 0.5 feet (152 mm) and a permeability of less than 1x10^{-6} cm/sec. Additional element verticality and panel rotation tolerances of 0.25% and 6 degrees, respectively, were imposed. The specifications (USACE 2011) also called for steerable exploratory pilot holes for all columns.

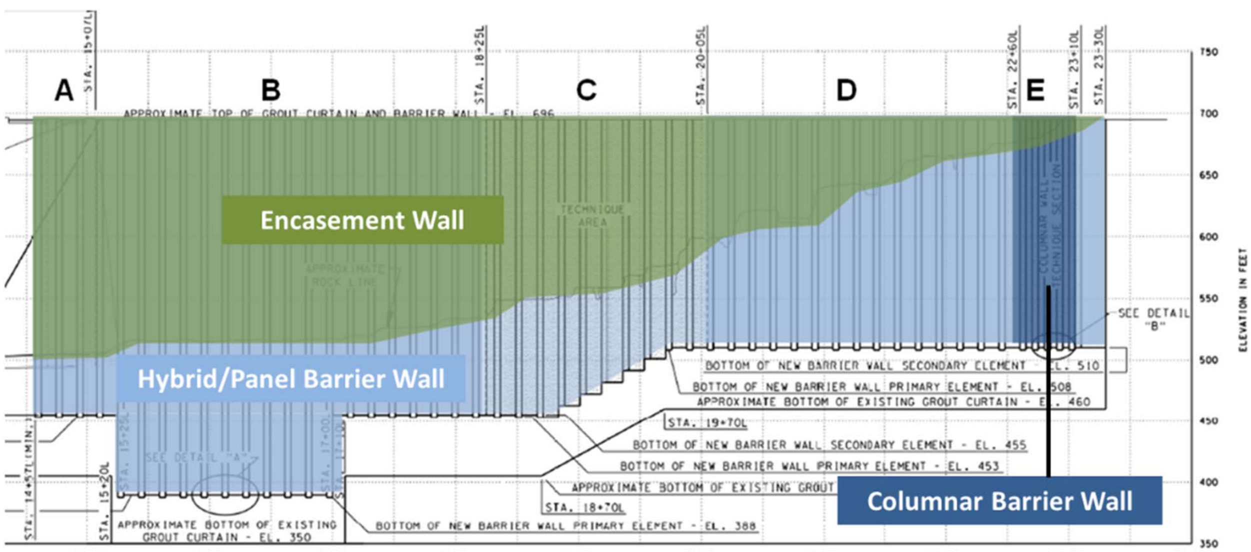

Figure 8. Barrier wall profile (looking upstream)

Columnar Barrier Wall

BFC's design consisted of twelve 4-foot (1.2 m) diameter primary columns up to 188 feet (45 and 57 m) deep, and eleven 4.5-foot (1.4 m) diameter secondary columns up to 186 feet deep. Pilot holes were used to guide the excavations. Downhole water hammers, Wassara W150 and W200, in conjunction with a Klemm KR 806-4 drilling rig were used to drill the pilot holes. Rock augers and drilling buckets, both equipped with stingers (extended pilot bits) to follow the pilot hole, were used to excavate the columns. Drilling was per-formed dry at the top and under water at depth with the BG 50.

Panel Barrier Wall

In their proposal, BFC followed specifications and proposed a hybrid wall configuration (Figure 9). The columns in the USACE plan were designed to provide additional wall thickness at the panel overlaps because of USACE concerns that the required vertical and rotational accuracies would be difficult to achieve at 300+ feet (90+ m) deep. However, based on the ability of the BAUER hydrocutter to excavate the hard rock and maintain excellent verticality as demonstrated at the panel encasement wall, BFC made a value engineering cost proposal (VECP) to eliminate the columns (red circles in Figure 9) including the required pilot holes without increasing the nominal overlap between the barrier wall panels. The government accepted the VECP, which saved approximately 100 columns, at a cost savings of over $13 million.

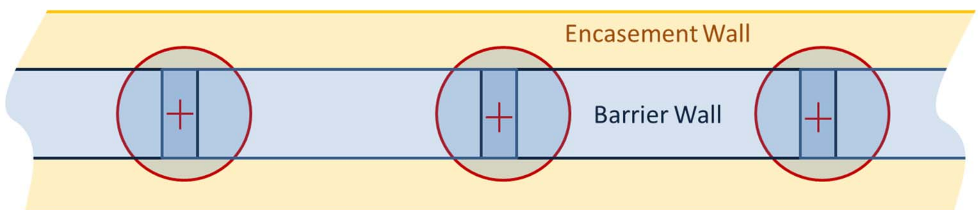

Figure 9. Schematic plan view hybrid barrier wall

The barrier wall was excavated through the encasement wall concrete into the foundation rock to depths between 146 feet (44 m) and 306 feet (93 m). A MC 128 and a MC 96 foundation crane (Figure 1) were used simultaneously; both equipped with BC 40 cutter units cutting panels with 10.5 x 2.7 feet (3.2 x 0.83 m) footprint. Water was used as trench support and transport fluid. No excessive water loss, defined in the specifications as a loss of three feet of water or more, occurred during the barrier wall works, demonstrating the effectiveness of the 2009/2010 grouting program. Concrete was again placed using two tremie pipes. The concrete of the secondary panels was dyed red to differentiate between different panels during the verification coring program. Cores and borehole images showed that the use of water as fluid in conjunction with a rigorous joint cleaning procedure with panel brushes (Figure 10) allowed for an excellent bond without any film between the primary and secondary panels.

To achieve the stringent geometric requirements resulting from the VECP, the operators focused on panel verticality and panel rotation and made use of the CIS to obtain the most accurate position of the cutter. Panel rotations of less than 2 degrees were targeted. As-built surveys were performed using the CIS, Koden and free-fall pass methods. The as-built Koden data set indicated a maximum recorded deviation out of plumb of 0.56 feet and a maximum panel rotation of 3.3 degrees. This means that both the verticality specification of maximum 0.25% as well as the rotational specification limit of maximum 6 degrees were met by all elements. The rotational target of 2 degrees was only exceeded in isolated cases.

Due to these excellent results the wall continuity was also achieved at all overlaps. Based on 6 inches (0.15 m) of minimum overlap along the wall axis the wall thickness at the overlap was at almost all overlaps 2.5 feet (0.75 m) or more with a recorded minimum of 2.33 feet (0.71 m). This represents a benefit of almost 25% in wall thickness over the specified wall thickness of 2.0 feet (0.6 m). The largest deviations and rotations were recorded at random depths typically above the bottom of the wall. This is a direct effect of the active steering of the hydrocutter during excavation.

Figure 10. Panel brush

CONCLUSION

The hydrocutter technology was used by BFC with great technical success at the Center Hill Dam Foundation Remediation project. The geometric accuracy of both the barrier and the encasement wall well exceeded the stringent specification requirements. This is even more remarkable as almost half of the originally planned number of elements were eliminated with a value engineering approach that also resulted in significant cost savings to the government. BFC was able to achieve this through the use of innovative techniques and hydrocutter equipment that allows for extremely accurate excavations in complex geotechnical conditions such as steeply inclined soil-rock interfaces and hard, massive bedded rocks.

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