CUTTER SOIL MIXING AND JET GROUTING FOR HERBERT HOOVER DIKE REHABILITATION

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ABSTRACT

In the framework of the Herbert Hoover Dike Rehabilitation project, BAUER Foundation Corp. has been tasked with the installation of 17.6 miles (28.3 km) of seepage cutoff wall distributed over three task orders. The cement deep soil mixing method of Cutter Soil Mixing (CSM) is being used to install the wall. Challenging ground conditions such as organic soils and limestone and sandstone layers found in large portions of the project require a pretreatment of the foundation soils. This is performed via replacement borings applying cased Kelly drilling techniques or via pre-drilling using continuous flight augers (CFA). The project also includes tie-ins of the new wall into existing cutoff wall segments and connecting the new wall to existing structures via jet grouting.

Keywords: cutoff wall, levee rehabilitation, cutter soil mixing (CSM), jet grouting

PROJECT

One major component of the Herbert Hoover Dike Rehabilitation project is the installation of a seepage cutoff wall. It includes the installation of a seepage cutoff wall at the southeast, southwest, and partially on the northwest side of Lake Okeechobee, located in south central Florida. As previously reported by Bruce and Sills (2009), Arnold et al. (2011) and Arnold (2015), BAUER Foundation Corp. (BFC) has installed 10 miles (16 km) of cutoff wall at the southeastern shores of the Lake from 2008 to 2013. In 2018, the U.S. Army Corps of Engineers (USACE) issued the Herbert Hoover Dike Rehabilitation Dam Modification Cutoff Wall MATOC contract, a multiple award task order contract (MATOC), in order to finish the remaining 29 miles (47 km) of planned cutoff wall at the west side of the Lake. Over the years of 2018 to 2020, BFC was awarded Task Orders 1, 3, and 5 (TO1, TO3 and TO5) totaling 17.6 miles (28.3 km) of cutoff wall. These three contracts include ten connections to existing concrete structures via jet grouting and six tie-ins to existing cutoff walls at previously installed culverts.

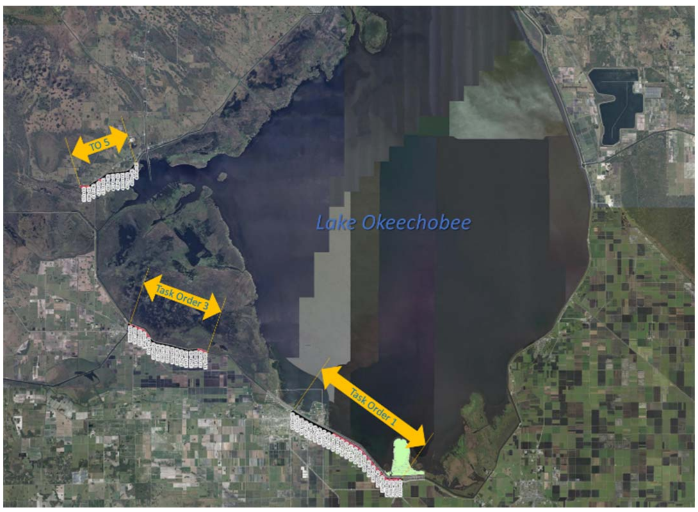

Figure 1: b-project Information Management System plan view showing locations of Task Orders 1, 3, and 5 at the southwestern and northwestern shores of Lake Okeechobee, Florida.

The crest of the existing levee is about 14 ft (4 m) wide. The crest elevation varies within the task orders between approximately +34 ft and +41 ft (all elevations in feet referencing the vertical datum NAVD88). The contractual cutoff wall extends from elevation +25 ft down to predefined tip elevations between -10 ft and -25 ft. As the specifications did not allow to degrade the crest, the total wall depth varies between 46 and 65 ft. Any wall constructed above elevation +25 ft is considered a spoils cutoff wall (Figure 7). The contract documents allowed the contractor to choose the cutoff wall alignment anywhere between the middle of the levee crest and a 20 ft (6 m) lakeside offset (i.e. in the lakeside slope), as long as a minimum cover of 3 ft (0.9 m) above elevation +25 ft was maintained.

The 'conventional cutoff wall' specifications (USACE 2018) are performance-based and do not require a specific installation method. The specifications require the cutoff wall to (i) be continuous and homogeneous, (ii) be at least 24 in (610 mm) thick throughout the entire depth, (iii) have a unconfined compressive strength (UCS) at 28 days of 100 to 500 psi (0.7 to 3.5 MPa) and (iv) have a permeability of no more than $1 \cdot 10^{-6}$ cm/sec. UCS is determined as a 10-point moving average (10-PMA) on core samples, with each sample not to fall below 75 psi (0.5 MPa). Furthermore, there are temperature limits for the placed grout and a minimum of 12 in (305 mm) longitudinal overlap between panels if panel methods are being used to install the cutoff wall.

GROUND CONDITIONS

The embankment is characterized by a relatively shallow slope at the lakeside and a steeper slope of about 3H:1V at the landside. The embankment fill consists of loose to dense, fine to medium, clean to silty or clayey sands with minor amounts of limestone gravel, cobbles, and shells. Locally, there are pockets of cobbles and boulders and traces of organic soils. Fill materials were dredged at the lakeside and/or the landside.

The embankment is partially underlain by a layer of organic materials with the majority being fibrous peat and the remainder being organic silts and clays. The organic soils are consistently present at the eastern portions of both TO1 and TO3 extending vertically up to 12 ft (3.6 m) with average thicknesses of about 3 ft (0.9 m) at TO1 and 1.5 ft at TO3. Limited stretches of organic soils are also encountered at the western portion of TO1, while the western portion of TO3 and the entire TO5 have no or only a few inches of organics. Underneath embankment and/or organic layer, there are interbedded layers of limestone, sandstone/cemented sands, sands, silts and clays and mixtures thereof. The thickness of the rock layers as encountered within the cutoff wall profile ranged from only 5 ft (1.5 m) at TO5 to 35 ft (11 m) at TO1. Rock strength was provided in the contract documents only for TO1, where UCS results between 650 and 5,900 psi (4.5 to 41 MPa) were reported. SPT testing showed N values for the rock layers from mid-teens to refusal. Generally, the thickness and strength of encountered rock layers decreased from TO1 over TO3 to TO5. The sand varies from poorly graded to silty and clayey, and medium dense to dense. Most of the fine-grained soils were of low plasticity and ranged from soft to stiff.

CONVENTIONAL CUTOFF WALL

BFC is pursuing an approach very similar to the one used previously at the Herbert Hoover Dike Rehabilitation project. The wall is installed using CSM Cutter Soil Mixing (Bauer 2020) at a width of 25 to 28 in (640 to 710 mm). The subsoil conditions pose two challenges to this method:

1. Organic soils: Organic materials impact the hydration process of binder materials, delaying the evolution of strength and reducing the final strength. Wherever the thickness of organics exceeded a few inches, BFC addressed this challenge by replacing those soils prior to cutoff wall installation.
2. Rock layers: CSM is a soil mixing technique. The CSM wheels are equipped with soil teeth and do not allow the installation of rock chisels like hydrocutters. Consequently, the cutting of rocks is slow for weak rocks or impossible for hard rocks. This challenge was addressed by predrilling.

As rock is present throughout all task orders, BFC predrilled 100% of the cutoff wall alignment. Replacement is needed only where substantial organic layers were present, at the eastern portions of both TO1 and TO3. Therefore, two pretreatment approaches are applied: (i) Replacement and predrilling using Kelly drilling methods and (ii) Continuous flight auger (CFA) predrilling.

Replacement and predrilling using Kelly drilling

A secant pile-like wall of non-organic backfill is created by a series of overlapping replacement columns with a diameter of 3.28 feet (1,000 mm). Fully cased boreholes extending through the embankment fill and the organics down to the top of the rock at 35to 40 ft (10.5 to 12 m) depth are excavated by Kelly drilling. As the black to dark brown organic materials can be well distinguished from the much lighter non-organic soils, the operator – based on visual inspection – shakes out augers containing any organic materials on piles separate from piles where only non-organics materials are placed. A geologist or geotechnical engineer acting as cutoff wall logger supervises this operation. After all organic materials have been removed from within the casing, the auger is screwed through the rocks and soils below the casing to wall tip and reversed out. This predrilling breaks up any present rock layer and allows for easier penetration with the CSM. The organic materials are disposed of and the excavated non-organic materials are blended with imported sand, which makes up for the removed volume. Subsequently, the blended soil material is placed back into the casing using a funnel. The replacement columns are installed in a primary-secondary sequence.

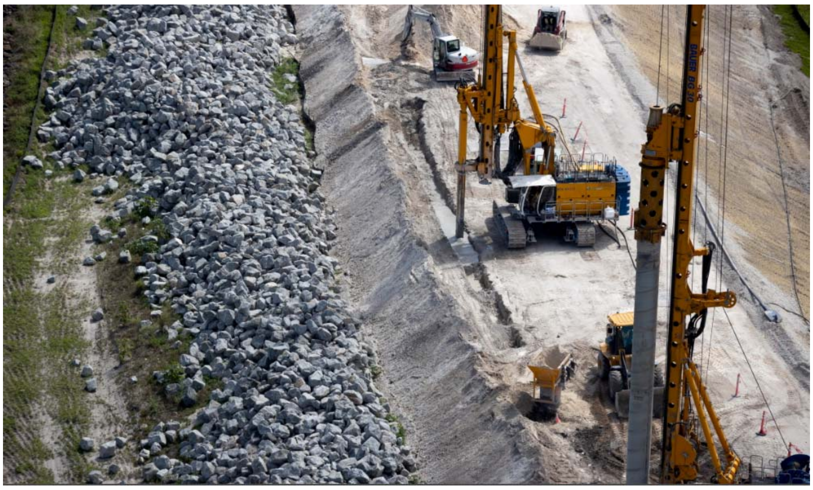

Figure 2: Kelly predrilling operation including backfilling (front) and CSM cutoff wall installation (back) at TO3 east.

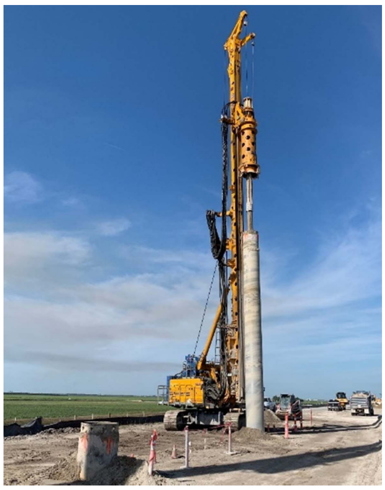

Figure 3: Kelly predrilling and replacement operation.

CFA predrilling

A series of overlapping 3-foot (915 mm) diameter predrills is created by simply screwing the CFA auger to planned wall depth and reversing back out. As the purpose of CFA predrilling is simply to break the rock, penetration and withdrawal rates in combination with the rotation rates of the tool are tailored to only slightly loosen the existing soils without removing material – any material brought to the surface during auger penetration is replaced during auger withdrawal. The predrills are installed in four passes: every other primary predrill is installed in passes 1 and 2, and every other secondary predrill is installed in passes 3 and 4.

Figure 4: Bauer BG 30 drill rig performing CFA predrilling (right) and RTG RG 27S installing CSM cutoff wall (left) at TO3 west.

Figure 5: CFA starter during positioning.

Cutter Soil Mixing (CSM)

BFC uses BCM 5 and BCM 10 cutter heads in conjunction with rigid Kelly bars and fixed-mast rigs for CSM. Throughout all three task orders, cement/bentonite slurry is pumped during both the downstroke and the upstroke, applying the single-phase system. Panels are installed 'fresh-in-fresh', meaning secondary panels are installed while the adjacent primary panels are still in a fresh state, forming a virtually jointless, continuous wall. The applied method has been described in detail in Arnold et al. (2011) and Arnold (2015).

Figure 6: Two RTG RG 27S (front) installing CSM cutoff wall in perpendicular mode at TO1 east.

Figure 7: Excavated spoils cutoff wall at TO3.

Operational concerns

The eastern, Kelly-predrilled portion of TO1 is installed with one heading consisting of two RTG RG 27S performing CSM and three Bauer BG 30 drill rigs performing replacement/predrilling. The number of predrill rigs will be reduced to two in the western portion of TO1 where most of the predrilling is performed using CFA techniques. The majority of TO3 is performed with one heading using one RG 27S for CSM and one BG 30 for CFA predrilling or one BG 28 and one BG 30 for Kelly predrilling. For portions of TO3, a second heading with one CSM and one CFA predrill rig is intended. TO5 operates one BG 30 for CFA predrilling and one BG 28 for CSM, forming one heading. The number of headings/CSM rigs per task order is based on the contract schedule.

As the levee cannot be degraded, the work platform is installed at crest elevation, incorporating the existing 10 to 12 ft (3 to 3.6 m) wide asphalt road and typically extending only over the shallow lakeside slope. Beyond the work area, the platform always allows for a 15 ft (4.6 m) wide haul road. At TO1, where there is more construction traffic due to the bigger operation and where at the same time the levee geometry has room for it, an additional haul road is created at the lakeside bottom of the embankment. This allows to separate the traffic hauling work platform material from the cutoff wall-related traffic, which helps to improve the safety in the cutoff wall work zone. As both CFA predrilling and CSM cutoff wall installation are possible to be performed in straddling mode, areas with CFA predrilling require a slightly narrower work platform than areas with Kelly drilling.

Quality control (QC)

The cement/bentonite slurry was mixed with different models of fully automated batch mixers. The mixers record the batched quantities of all mix ingredients. In addition, those quantities are recorded manually. Density, Marsh viscosity, and temperature of the slurry are tested directly after mixing with the slurry sample taken from the agitator tanks. The same testing suite is applied on samples taken from the slurry line at the rig, that means after the slurry has been pumped for up to 4,000 ft (1,200 m). Bulk samples of the pre-placement slurry are taken once per shift per heading and tested for UCS at 7, 14 and 28 days.

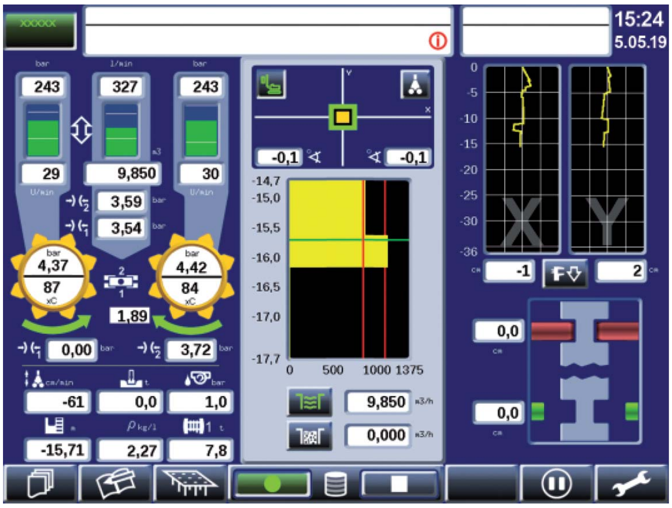

Figure 8: B-Tronic screen display.

Figure 9: Emptying the wet grab sampler.

The next element of the QC program is the monitoring of all method-related parameters by the B-Tronic onboard monitoring system. Beyond engine parameters of the base carrier, the system records parameters such as depth, slurry flow and cumulative volume, verticality in two dimensions, rotational speeds of the cutter wheels, wheel pressures and temperatures as well as crowd force and pulling force. These records are stored in data files and automatically transmitted to the cloud, where they are immediately available for further processing. All parameters are displayed at onboard screens (Figure 8) and allow the operator to make immediate corrections, e.g. to verticality and pumped volume. In this way, quality is not just monitored, but actively controlled.

'Post-placement' wet grab samples (Figure 9) are taken every 250 lineal ft (75 m) of cutoff wall from freshly mixed panels at three depths. The sample material is tested for temperature and slump. Cylinders samples are cast and tested for UCS after 14, and 28 days.

Verification

At about every 250 lineal ft (75 m) of cutoff wall, vertical 4.8 in (122 mm) diameter (PQ) verification borings (VB) are drilled into the wall using wire-line core drilling techniques. The locations for verification borings are determined by the owner. The locations vary between panel center, middle of overlap between primary and secondary panels, and the theoretical joint between primary and secondary panels. Three QC samples taken from the core are tested at day 28 for UCS. Additional three quality assurance (QA) samples are taken and tested for UCS by the owner. After drilling, logging and photo documentation of the cores, the borehole is flushed and an Optical Televiewer (OPTV) downhole camera survey is performed. Subsequently, the borehole is pumped empty and a CCTV camera survey is performed. The borehole is then filled with water and saturated for a minimum of 24 hours. The verification drilling and testing concludes with a 24-hour in-situ falling head permeability test.

Selected quality control and verification results

28-day UCS test results for both post-placement wet grab samples and core samples for TO3 are plotted in Figure 10 as green and purple points. Additionally, the 10-PMA of the core samples (purple line) along with the with the acceptance criteria (yellow and red lines) are shown. At the time of writing, about 7,000 LF have been installed and fully tested on the west side and 6,000 LF have been installed and fully tested on the east side.

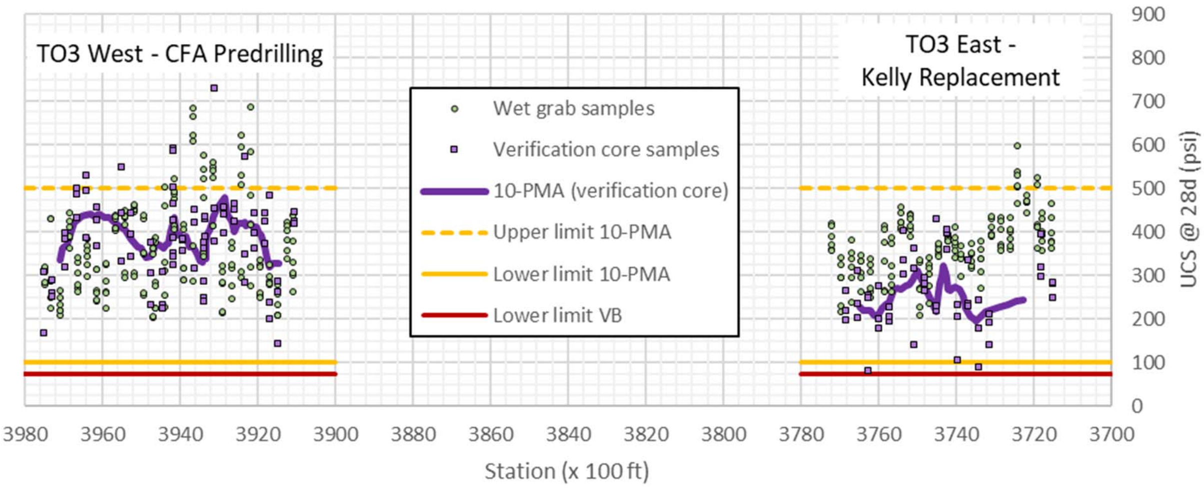

Figure 10: UCS test results of wet grab and core samples at TO3.

As previously mentioned, the west side had no organics, and was characterized by predominantly sandy materials, partially encountered as cemented sand/sandstone. Consequently, this area was predrilled using the CFA method. UCS for wet grab samples at the west side ranged from 202 to 686 psi (1.39 to 4.73 MPa) and averaged 356 psi (2.45 MPa). Core samples tested from 142 to 728 psi (0.98 to 5.02 MPa) with an average of 367 psi (2.64 MPa).

At the east side, Kelly replacement was used due to the presence of organics. While most of the soils were sands, those sands were siltier and more clayey with silt and clay layers. UCS of wet grab samples varied between 209 and 597 psi (1.44 to 4.12 MPa) with an average of 368 psi (2.54 MPa), thus very similar to the west side. The UCS of core samples however came in much lower – both in comparison to the wet grab samples at the east side and also in comparison to all results at the west side – with a range of 82 to 428 psi (0.57 to 2.95 MPa) and an average of 255 psi (1.76 MPa). While there is a multitude of reasons for results from wet grabs and core samples to differ, the author sees one factor contributing most. In order to remove larger, gravel and cobble-sized particles from wet grab samples, the material was run through a ½ inch (12.5 mm) screen, introducing more mixing energy, breaking down lumps of cohesive material, and thus creating a fairly homogenous material. In the retrieved cores, however, lumps of cohesive materials are still present as left behind by the mixing tool. Core samples – especially those with low breaks – were observed failing along small inclusions of cohesive materials, resulting in lower strengths than those recorded for the more homogeneous wet grab samples.

Though there were a few core samples testing below 100 psi (0.68 MPa), all were above the 75 psi (0.52 MPa) acceptance limit for single tests on core samples. The 10-PMA of core test results ranged from 321 to 479 psi (2.21 to 3.30 MPa) at the west side and from 196 to 322 psi (1.35 to 2.22 MPa) on the east side. Thus, all 10-PMA results fell well within the acceptance range from 100 to 500 psi (0.69 to 3.45 MPa). Thus, all UCS results met the acceptance criteria.

TIE-INS INTO EXISTING CUTOFF WALLS

TO3 included two previously replaced culvert structures and TO1 included one such structure (S-277). The conventional cutoff wall was supposed to tie-in into the cutoff walls at those structures. As an example, the tie-in at S-277 is presented in this section. Figure 11 shows the profile view as contained in the contract documents. The colored markups provide a slightly more accurate depiction of the situation.

A low strength cutoff wall had been previously installed in the framework of the S-277 replacement from approximately Sta. 3101+50 to Sta. 3102+70 as marked up in red. The three-barrel structure (blue) was enclosed in a soil-bentonite core (green), which extended along the wall alignment about 12 ft (3.6 m) left and right beyond the concrete structure (about Sta. 3101+83 to Sta. 3102+39). The soil-bentonite core is about 8 ft (2.4 m) wide and consists of a mixture of sand and 12% bentonite by dry mass, which had been mixed and placed at about optimum water content. The purpose of the soil-bentonite core is to create a connection between concrete structure and the cutoff wall segments below and to the side of the structure, acting as seepage cutoff. The contract required a minimum embedment of the new conventional cutoff wall of 2 ft (0.6 m) into the soil-bentonite.

As a first step, BFC used six probe borings to confirm the as-built location of both soil-bentonite and existing cutoff wall (c.f. TO1-EB labels in Figure 12). The probe borings were performed using the direct push method. All borings that were located within the known as-built footprint of the soil-bentonite confirmed its presence. Borings TO1-EB48, TO1-EB51A and TO1-EB52 refused on the existing wall and brought up between one and a few inches of cutoff wall material. TO1-EB51 was expected to confirm the cutoff wall at the down-station side of S-277, but did not refuse on cutoff material. Thus an additional boring (TO1-EB51A) was drilled at a 1-foot (0.3 m) up-station offset. It was subsequently concluded, that TO1-EB51 had deviated out of plumb. Borings TO1-EB48 and TO1-EB51A were conservatively assumed to mark the centerline of the existing cutoff wall and the minimum lateral extent of the soil-bentonite. The alignment of the new cutoff wall was centered on these borings and the lateral extent was corrected to 2 ft (0.6 m) beyond those borings into the soil-bentonite.

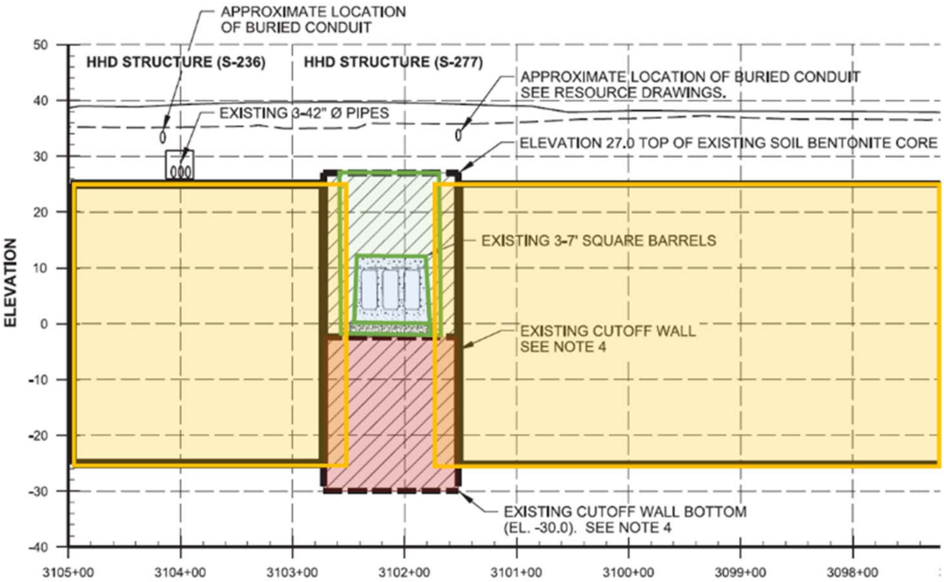

Figure 11: Profile view of structure connection with existing culvert barrels (blue), existing soil-bentonite core (green), existing cutoff wall (red) and new cutoff wall (yellow) (USACE 2018).

BFC did not rely on the existing wall outside of the soil-bentonite footprint and opted to install new wall through this material. This portion of the existing wall was considered 'man-made rock' and was predrilled the same way as the natural rock layers. S-277 is located within the eastern portion of TO1, where the Kelly replacement technique was applied. While CFA predrilling would have sufficed as there was no organics within the footprint of the existing wall, converting one rig to CFA drilling and back to Kelly drilling would not have been economical.

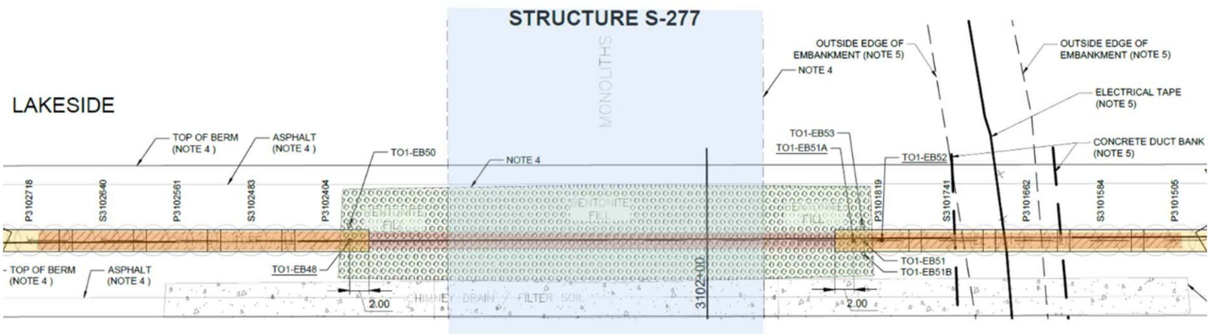

Figure 12: Plan view of structure connection with culvert barrels (blue), soil-bentonite core (green), existing cutoff wall (red) and new cutoff wall (yellow), from BFC shop drawings.

The last step of the cutoff wall installation was CSM through the fill material and the broken-up existing wall. The biggest challenge was overcutting the soil-bentonite core at panels P3102404 and P3101819 as shown in Figure 12. Upon contact with the water in the binder slurry, the bentonite begins to swell, which binds the water and substantially decreases the workability, causing the material to behave like an overconsolidated clay. Based on BFC's experience with similar tie-ins, this behavior was anticipated ahead of time and the volume ratio (pumped slurry volume per treated soil volume) was increased to create a workable mix. Overcutting the existing wall with a presumed strength of about 500 psi (3.5 MPa) by 3 to 4 ft (0.9 to 1.2 m) at greater depth posed no challenge to the CSM. With good preparation, as discussed above, the tie-ins were created without problems.

JET-GROUT CONNECTIONS TO EXISTING STRUCTURES

The task orders include ten connections to existing concrete structures such as locks and pump stations via jet grouting. The specifications require jet grout cutoff wall to (i) be continuous and homogeneous, (ii) be at least 18 in (460 mm) thick throughout the entire depth and 36 in (915 mm) thick when in contact with existing structures, (iii) have a minimum unconfined compressive strength (UCS) at 28 days of 100 psi (0.7 MPa) as determined by a 10-point moving average on core samples and (iv) have a permeability of no more than $1 \cdot 10^{-6}$ cm/sec. Additionally, the verticality of the jet grout columns shall not exceed 2%. The jet grout cutoff wall is subject to verification drilling and testing, similar to the conventional cutoff wall.

Due to the presence of rock that cannot be eroded by jetting, full-depth replacement will be performed at all locations where jet grouting columns extend into rock. The replacement is performed similarly to the replacement and predrilling for the conventional cutoff wall. For jet grouting however, the 3.28-feet (1,000 mm) diameter temporary casing is installed to 2 ft (0.6 m) below the planned wall tip. The casing is fully excavated and subsequently backfilled with sand and withdrawn from the ground.

Figure 12: Klemm KR 720 during pre-production trial column installation.

Figure 13: Verticality survey using a Measurand SAA.

Due to levee safety and quality concerns, BFC opted to use the single fluid method. The columns will have a nominal diameter of 4.26 ft (1.3 m) and will be installed in a linear sequence fresh-in-fresh. This alleviates the risk of drilling inside already hardened, previously executed jet grout material and produces no cold joints. Bauer BG 30 or Klemm KR 720 drill rigs will be utilized for the jet grouting.

At the time of writing, none of the structure connections have been performed. A pre-production trial program has been completed at TO3 (Figure 12). Three clusters of two jet grout columns each were installed. The jetting time, and consequently the specific energy, was varied to determine optimum parameters. All three clusters were installed in replaced soils applying the Kelly drilling approach discussed above. The verticality of the columns was surveyed after drilling using a Measurand Shape Accelerometer Array (SAA) inside the drill string. The diameters of primary columns were measured using an 'umbrella' tool and were confirmed with additional core drilling. The nominal diameter of 4.26 ft (1.3 m) was achieved or exceeded at all three clusters.

CONCLUSIONS

Cutter Soil Mixing (CSM), which had been utilized at Herbert Hoover Dike before, is currently being used to install another 17.6 miles (28.3 km) of cutoff wall distributed over three task orders. Pre-treatment of the ground via predrilling and partial soil replacement makes it possible to apply the CSM method in challenging ground conditions like interbedded rock layers and under demanding wall performance criteria. The CSM also allowed tying in into existing seepage cutoffs such as low-strength cutoff walls and soil-bentonite cores without additional measures.

Jet Grouting will be used to connect to existing concrete structures. Pre-production trial tests confirmed the selected parameters.

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