SEEPAGE CUT-OFF WALL INSTALLATION USING CUTTER SOIL MIXING FOR HERBERT HOOVER DIKE REHABILITATION

Michael Arnold, BAUER Foundation Corp., Odessa, Florida, USA, (727) 531-2577,
marnold@bauerfoundations.com

ABSTRACT

BAUER Foundation Corp. was one of three contractors awarded with the installation of a cut-off wall at the Herbert Hoover Dike Rehabilitation project. The cut-off wall was constructed up to 84 feet deep and 25 inches thick. It extended from the crest through the middle of the existing dike into the underlying peat, sand, and rock layers. BAUER used the cement deep soil mixing method of Cutter Soil Mixing (CSM) to install the wall. Soil mixing was facilitated by first removing the peat layer in the wall alignment using Kelly drilling and replacing it with suitable backfill, resulting in a secant pile wall arrangement of replacement columns. BAUER successfully finished four task orders with a total length of just over 10 miles. Up to six rigs of the types BAUER BG 28, BAUER BG 40 and RTG RG 25 were concurrently used to perform the replacement columns and the cut-off wall installation.

The paper introduces the project, the geotechnical site conditions, and the requirements specified by USACE. It focuses on the specific adaptation of the CSM method to the site conditions and on the equipment used. Strength and permeability results obtained from an extensive testing program are presented. The impact of the curing conditions on lab and *in-situ* test results is studied, and test results are related to soil conditions.

Keywords: cut-off wall, dike rehabilitation, cutter soil mixing (CSM)

PROJECT

The Herbert Hoover Dike is a 143-mile-long dike encircling Lake Okeechobee in south central Florida. When it was constructed in the 1930s and 1960s, the purpose of Herbert Hoover Dike was flood protection from hurricanes. However, during the 1970s a higher lake level was maintained permanently to provide local agriculture with water. Later, damage became apparent during two nearly back-to-back high water events in the 1990s, when numerous sink holes, seeps, pipes, and boils were observed (Fig. 1). In 2000, the Congress approved USACE to propose rehabilitation measures. The installation of a cut-off wall into the existing dike was chosen during the initial design process as the preferred measure to improve the safety of the dike (Davis et al. 2009).

The first section of the dike to be rehabilitated was Reach 1 located along the southeast side of the lake between the towns of Port Mayaca and Belle Glade. An indefinite delivery indefinite quantity (IDIQ) multiple award task order contract (MATOC) was issued for this 22.4-mile-long stretch by USACE in 2007. BAUER Foundation Corp. (BAUER) was one of the three contractors that succeeded in the qualification process. Each of the three successful contractors had their own novel construction techniques. In the years 2008 to 2012 BAUER executed four task orders totaling over 10.0 lineal miles of cut-off wall with 3.3 million square feet of design surface area.

Figure 1: Types of observed dike damage: (A) Sinkhole formation in crest, (B) heave of downstream toe, (C) piping at downstream toe of dike, and (D) saturated soils at the ground surface of landward toe (Toe Ditch in Fig. 2) and embankment slope (from Davis et al. 2009).

GROUND CONDITIONS

Figure 2 shows a simplified embankment cross section and soil profile. The embankment is typically about 14 feet wide at the crest and 140 feet wide at the base. The lakeside slope is about 1:6 (V:H), and the landside slope is about 1:3. The crest is about 25 feet above landward ground (Davis et al. 2009). The following description of the soil profile is based on the geotechnical reports provided by USACE (2008a-d). The embankment consists of grey loose to dense, fine to medium, clean to silty or clayey sands with minor amounts of limestone gravel, cobbles, and shells. The primary minerals of these materials are quartz and carbonate. There are pockets of cobbles and boulders. Locally, traces of organic soils are found. Fill materials were taken from the lake side of the dike, resulting in a navigable channel.

A layer of organic materials up to 12 feet thick was encountered at the top of the natural ground. These materials are mainly dark brown to black peat and soft organic silts, which are in part sandy and in part clayey. Below the organics there is a heterogeneous layer of decomposed limestone. This layer mostly consists of clay, silt and sandy clay and silt, but can also consist of sand and shell. In some parts of reach 1, a hard cap rock is encountered within this layer.

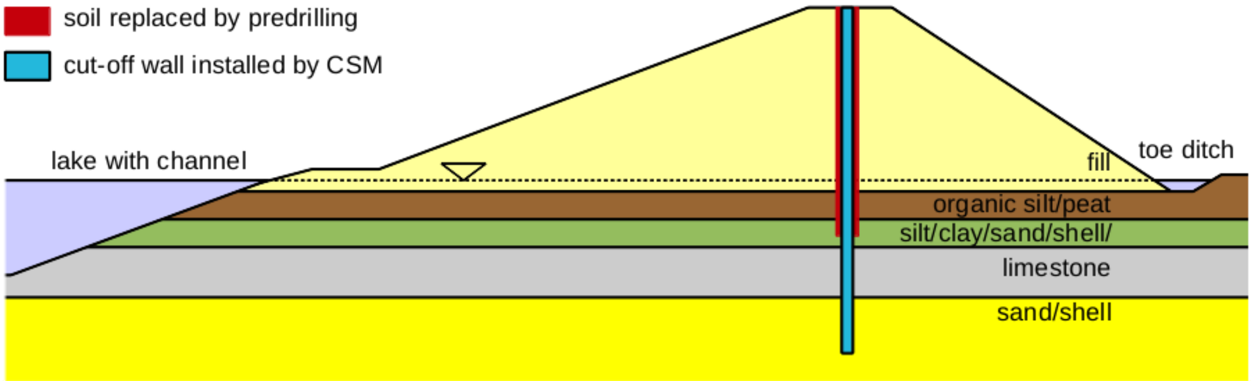

Figure 2: Idealized soil profile (from Arnold et al. 2011).

Below the heterogeneous layer of decomposed limestone is limestone with a thickness of up to 20 feet. This hard limestone layer is typically highly permeable, with an unconfined compressive strength (UCS) from 1,400 to 2,400 psi. Below the hard limestone, layers of quartz sand, shell, or mixtures of both are found. These layers are densely packed and highly permeable. A second rock layer, up to 5 feet thick is locally embedded in these layers. Its properties are similar to the upper hard limestone layer.

CUT-OFF WALL CONSTRUCTION

The cut-off wall was designed to extend from elevation 30.7 (all elevations in feet referencing the vertical datum NAVD88) down to elevations of -20 to -40. The performance-based contract required the cut-off wall to (i) be continuous and homogeneous, (ii) be at least 1.5 feet thick, (iii) have a UCS at 28 days of 100 to 500 psi, and (iv) have a permeability of no more than $1 \cdot 10^{-6}$ cm/sec.

BAUER used the cement deep soil mixing method of Cutter Soil Mixing (BAUER 2014, Fiorotto et al. 2005, Stoetzer et al. 2006) to install the wall. The work was performed from a platform that was constructed at crest elevation ranging from about 34 to 41, which resulted in a maximum panel depth of about 84 feet. Bauer concluded that due to the vertical accuracy of the CSM machinery that a minimum 18 inches wall thickness could readily be installed at these depths using panels that were 25 inches thick.

The organic layer posed a major challenge to cutter soil mixing. The CSM tool forces materials through shear plates, breaking up the soil matrix into very small particles thus producing highly homogeneous mixing of the materials within layers. However, the CSM's capabilities to vertically homogenize the soil layers over the entire wall depth and in this way to vertically distribute the organic materials are limited. As mixing the organic materials would result in a mix with delayed setting and low strength, BAUER chose to replace the majority of the organic materials in the cut-off wall alignment by replacement columns executed before soil mixing was performed.

Replacement columns

The overlapping replacement columns formed a secant-pile-like wall made of non-organic backfill. Kelly drilling was used to excavate the boreholes, which were fully cased down to the top of the hard limestone layer. The average depth of the replacement columns was about 40 feet. Professional geologists logged all replacement columns. The excavated soils were classified as organic or non-organic based on visual inspection by the operator and placed on separate piles next to the rig. The geologist supervised the operator in his decision-making. The non-organic material was blended with locally imported fine sand by running both materials over a portable vibrating screen. This blended material was dumped into the open casing using a funnel for backfill. Excavated materials classified as organic could not be used as backfill, and were stockpiled and later recycled for dike restoration. This beneficial use of the excavated organic materials reduced transport and disposal costs. Replacement columns were typically carried out by two teams per CSM operation. Each team used a BAUER BG 28 or BAUER BG 40 drill rig with two sets of casing (Fig. 3).

Figure 3: Two BAUER BG28 rigs (in front) drilling replacement columns (Arnold et al. 2011).

Since the soil-cement mortar is sensitive to the presence of organics, the final wall quality heavily depended on the proper and clean execution of the replacement columns. Therefore, a rigorous quality control (QC) procedure was established to address the numerous sources of potential error encountered during the replacement column process covering production planning, surveying, executing, and reporting.

Cutter Soil Mixing (CSM)

The BCM 5 cutter head (Fig. 4) mounted on a RTG RG 25 S or BAUER BG 28 base rig via a rigid rectangular Kelly bar (Mono Kelly) was used to install the cut-off wall panels. All rigs used were equipped with an on-board computerized monitoring and controlling *B-Tronic* system. This system allows the operator to control verticality during panel installation, and to control the slurry volume pumped by depth. It is also used for quality control purposes as it documents the entire panel installation process.

The panels were installed using the single phase system, which means that cement/bentonite slurry was pumped in during both penetration and withdrawal. The majority of the slurry was mixed into the soil during penetration to generate a sufficiently workable soil/cement/bentonite mix. The remaining volume of slurry was pumped during withdrawal. The volume added during penetration varies with depth, since 1) slurry is sometimes used to make the cutting process easier in the hard layer, and 2) the operator's focus during penetration needs to be more on verticality and tool temperature. As the volume pumped by depth is recorded and visualized by the B-Tronic system, the operator can balance the pumped slurry volume during withdrawal. This procedure ensures a uniform distribution of the slurry with depth.

The penetration and withdrawal rates control the mixing time. Slower rates mean longer times the soil is subjected to mixing, improving mix quality as represented by number and size of soil lumps in the mix, and by slurry distribution. Relatively high rates could be chosen because the backfill soils in the replacement columns and the existing subsoils are mostly coarse grained. However, the penetration process was locally slowed down by the hard limestone.

The wall was constructed using overlapping panels installed 'fresh-in-fresh', which means the secondary panels are installed while the adjacent primary panels are still 'fresh', resulting in a jointless, continuous cut-off wall. The two rotating cutter wheels rotate in opposite directions with the right wheel rotating clockwise and the left wheel rotating counterclockwise. The unmixed material being cut at the bottom of the tool is therefore moved towards the center of the tool where the cement/bentonite slurry enters and gets mixed with the cut material. In this manner no unmixed material of a secondary panel is being pushed into the already mixed primary panel.

Even under the conditions of quite permeable coarse grained soils of embankment fill and subsoil layers, the addition of slurry leads to an increase of mix volume in the panel. Also the Kelly bar adds volume to the panel during penetration. Thus, a small pre-excavation trench was established by a mini excavator before panel installation to provide space for the displaced mix (overflow). Parts flowed back into the panel during withdrawal because of the extraction of the Kelly bar's volume.

The mix design of the slurry included water taken from Lake Okeechobee, slag cement, type II Portland cement, bentonite, and retarding agent. Slag cement was used for two reasons: it causes delayed set, and shows a slower strength evolution. First, applying the single phase system as described above, the mix must not reach initial set until the tool is safely out of the ground. Second, the delay is also beneficial for the few cold joints created after weekend breaks. The slow hardening process during the first days allows the panels installed before and after the break to "grow" together. The quality of the cold joint is additionally improved by the rough interface created by the cutter wheels overcutting the old panel (Fig. 5).

BAUER used a stationary mixing plant throughout the project. The central components of the plant were the two batch mixers MAT SCC-20 and MAT SCC-40, and a continuous mixer MAT SKC-30. The bentonite was mixed with the water and was allowed to hydrate for 24 hours. The cement/bentonite slurry was mixed in batches and stored in an agitator tank. From there, the slurry was trucked to a mobile agitator tank next to the CSM unit. An eccentric screw pump, which was remotely controlled by the CSM operator, fed the CSM tool.

Figure 4: CSM tool BCM 5 being positioned over the pre-excavation trench.

Figure 5: Rough interface created by the CSM tool overcutting a hardened panel.

Operations

The cut-off wall was installed using one or two independent CSM operations. With each operation consisting of two drill rigs performing replacement columns and one CSM rig, up to six rigs of the types BAUER BG 28, BAUER BG 40, and RTG RG 25 were concurrently used. Typically the site worked double shifts Monday through Friday with scheduled maintenance on the weekends.

QUALITY CONTROL AND VERIFICATION TESTING

An extensive QC and verification testing program, in part required by the project specifications, was established targeting all phases of the production process as well as to verify the quality of the final product.

Materials and slurry quality control testing

The entire process of materials delivery, slurry production, storage, and transport was monitored. Samples of every delivery of cements and bentonite were retained. Density, Marsh time, and temperature of the slurry were tested directly after mixing, and again after the transport while being stored in the mobile agitator tanks. Additionally, one slurry sample was retained per shift to qualitatively check the curing of the slurry. The slurry volume was measured with a flow meter on the CSM rig, and recorded by the B-Tronic system. The total slurry volume pumped per panel was double-checked using a second flow meter for two panels per shift.

Contract-based quality control and testing

Two major groups of tests were specified by the client: (i) tests performed on bulk samples being cured under lab conditions, and (ii) tests performed in boreholes drilled into the actual wall (tested *in situ*) and on core samples taken from these borings (tested in the lab). Only the latter group of tests was used to assess the acceptability of the wall.

Daily bulk samples were taken from freshly mixed panels at four alternating depths. Additionally, so-called post-placement (bulk) samples were taken at three depths from a panel near the proposed location of verification borings. Cylindrical samples with a height of 6 inches and a diameter of 3 inches were prepared from these bulk samples. These cylinders were stored for three days at the site in an air-conditioned trailer at 73°F and then transported to the lab. The samples continued to cure at 73°F and 100% humidity in the lab. The daily bulk samples were tested for UCS and permeability after 7, 14, and 28 days. The post-placement samples were tested for UCS and permeability after 28 days of curing.

At about every 200 lineal feet of cut-off wall, vertical 4.8” diameter (PQ) verification borings (VB) were drilled into the wall after about 25 days of curing using wire-line core drilling techniques. The position of the verification borings alternated between the center of a primary panel, the center of a secondary one, and the over-cut between primary and secondary panel. Verification borings were logged by professional geologists. Additionally, video logs of the inside of the VB’s were created by scanning the boreholes using a Borehole Optical Televiewer downhole camera. Both logs were used to assess panel homogeneity and continuity. Four core samples were selected from different depths of the boring, cut with a hand saw, sealed watertight, and shipped to the lab. In the lab, the 3.3” diameter samples were trimmed to a 1D:2H ratio and tested at day 28 for UCS.

Falling head tests were carried out in the boreholes at day 28 with a test time of 30 minutes. The equation given by Hvorslev (1951), case 8, was used to determine permeability. Although the Hvorslev approach can be considered an industry standard, it is worth noting that the falling head tests carried out in the wall violate several of the assumptions made by Hvorslev with the infinite lateral extent of the tested media being the most prominent one. Hence, the permeability calculated in this way is questionable from a scientific point of view. It is therefore not directly comparable to results obtained by lab tests. For these reasons, the borehole permeability tests serve more as an integrity check with the computed permeability value representing a normalized water loss.

Selected test results

Figure 6 shows UCS and permeability test results plotted over station number for a one-mile-long stretch just south of the town of Port Mayaca. The strength evolution of the mix can be clearly seen in Fig. 6(a). The mix gains about 25% of the 28 day strength after 7 days of curing, and about 50% after 14 days. Daily and post-placement samples show about the same strength at day 28, as depicted by Figure 6(b), because they share the same sampling and curing conditions. The results of both samples vary between about 120 and 450 psi (average of 300 psi). This variation in strength is attributed mainly to the variation in subsoil conditions since the entire stretch was executed with the same mix design.

The UCS results obtained from the verification borings are plotted in Fig. 6(c). They show a slightly higher variation, and they average about 260 psi, which is lower than the bulk samples. The difference between the bulk samples and VB samples is attributed to different curing conditions. While the water is contained in the plastic molds, the mix can filter out *in-situ*. The mix curing in the ground is furthermore exposed to the humic acid of the organic layer. The 10-point moving average, which is used to evaluate wall acceptance, remains well in the middle of the 100 to 500 psi range. Although not necessary by contract, even all single values fall within the range.

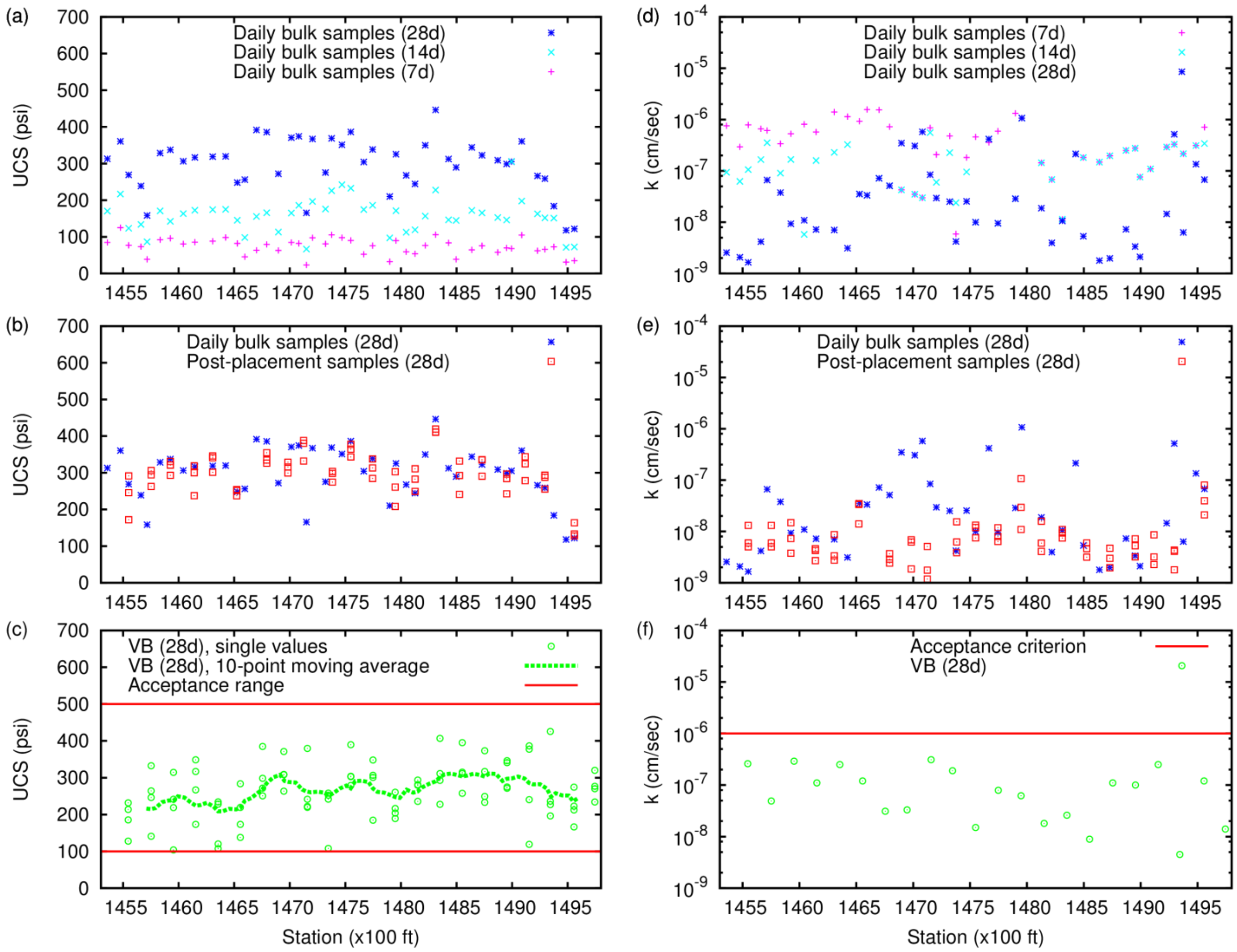

Figure 6: Unconfined compressive strength of (a) daily bulk samples after 7, 14 and 28 days of curing, (b) daily bulk and post-placement samples at 28 days, and (c) core samples at 28 days. Permeability of (d) daily bulk samples at 7, 14 and 28 days, (e) daily bulk and post-placement samples at 28 days, and (f) verification boreholes at 28 days.

Along with the increase in strength, the permeability drops from day 7 to day 28 by about two orders of magnitude as shown by tests results of the daily bulk samples (Fig. 6d). The geometric means of the permeabilities of the daily bulk samples and of the post-placement samples are $2 \cdot 10^{-8}$ and $7 \cdot 10^{-9}$ cm/sec, respectively. With a geometric mean of $6 \cdot 10^{-8}$ cm/sec the average permeability of the verification borings (Fig. 6f) is almost one magnitude higher. When comparing the permeability values obtained from the different tests, the following points should be considered: (i) There may be a scale effect, as the lab test is performed on a small specimen and the field test averages the material properties over the entire wall height. (ii) Many assumptions made to calculate the field permeability using the Hvorslev method do not apply as discussed above. (iii) The structure of the material created by the CSM mixing tool may differ from the structure resulting from manual sample preparation. Despite the agreement of the geometric means, there is only a minor correlation between the permeability values of post-placement samples and the permeability values obtained for the same panel by falling head borehole testing.

The post-placement sampling had the potential to link the test results of lab-cured bulk samples to the results obtained for core samples and in this way to provide information about the *in-situ* properties of the wall. Figure 7(a) has the UCS results obtained from verification core samples plotted versus the results of post-placement samples taken at the same location (same panel, depth ±3 feet). The wide scattering of the results—represented by a correlation coefficient of only 0.25—demonstrates that the testing of bulk samples cannot replace the testing of the actual wall.

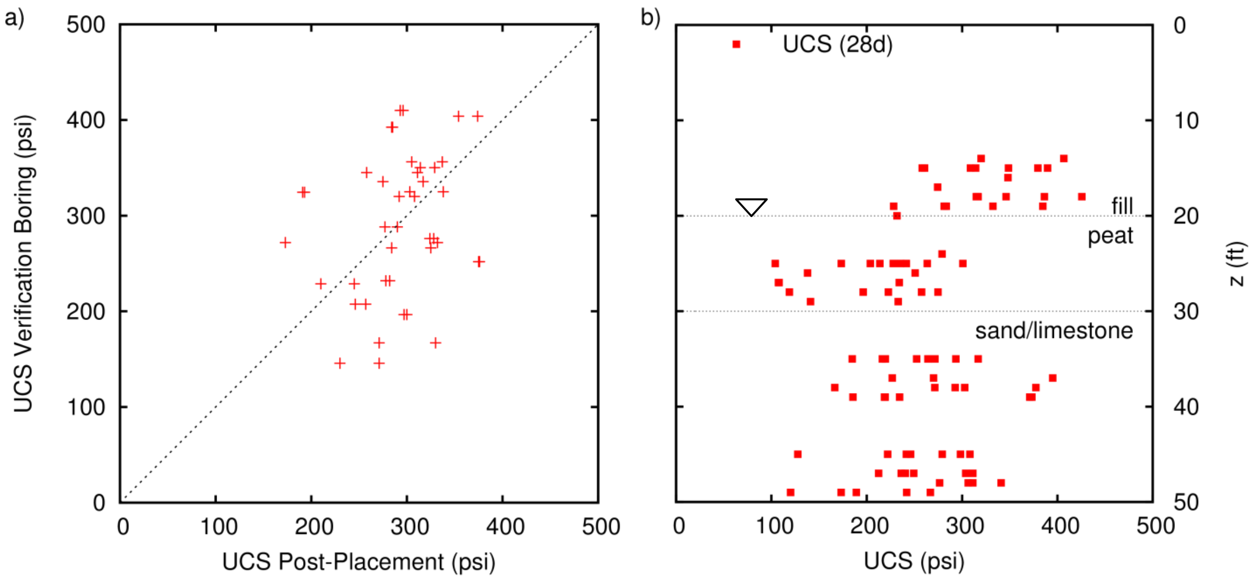

Figure 7: (a) Comparison of unconfined compressive strength results between bulk samples and core samples, and (b) profile of unconfined compressive strength of core samples.

The impact of the *in-situ* soil and groundwater conditions on strength is plainly visible in Fig. 7(b). The plotted data comes from the verification core samples, and the indicated soil profile is simplified. The water table is located approximately at the top of the organic layer. The highest UCS values are obtained in the fill. The soil is in an unsaturated condition, which leads to a lower initial water/cement ratio. As the fill is additionally very permeable, there is more water filtering out of the mix resulting in an even lower water/cement ratio. The lower water/cement ratio in turn causes a higher strength. The lowest strength is found in the organic layer. In the organics the initial water content is much higher, and less water filters out of the mix, keeping the water/cement ratio high in the mix. Additionally, the humic acids present in the ground water in this organic layer could have a strength-reducing effect. In the permeable, saturated sand and limestone layers below, strength is less than in the unsaturated fill but higher than in the less permeable peat. This illustrates the impact of curing conditions as described already by other authors (e.g. Bellato et al. 2013).

Summary and Outlook

Cutter Soil Mixing was utilized by BAUER to install a cutoff wall up to 84 feet deep at the Herbert Hoover Dike. The CSM method was proven to be successfully adaptable to the challenging existing ground conditions like interbedded rock layers, easily adjustable wall depths and very demanding wall performance criteria. This included the replacement of unsuitable organic soils.

Since the cut-off wall was installed into predominantly permeable strata, filtration out of the fresh mix had a substantial impact on the final wall properties. For this reason the results of lab-cured bulk samples and of tests performed *in-situ* cured wall differ substantially and show only a weak correlation. As the value of the test results obtained from bulk samples is limited in permeable soils, the benefits of this testing becomes questionable.

BAUER was awarded and successfully executed four out of a total of nine task orders issued for the Herbert Hoover Dike Rehabilitation Reach 1 project. BAUER is currently installing various short cut-off wall sections underneath or adjacent to new culverts that are being reconstructed. This demonstrates that Cutter Soil Mixing is a competitive method to install a high quality cut-off wall product.

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