Cut-off wall construction using Cutter Soil Mixing: a case study

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Cut-off wall construction using Cutter Soil Mixing: a case study

Cutter Soil Mixing (CSM), a deep soil mixing method, was used to rehabilitate the Herbert Hoover Dike, Florida by installing a cut-off wall. After an introduction to the method including remarks on its advantages and limitations, the rehabilitation project and its background are presented. The paper describes the necessary approach to apply Cutter Soil Mixing under the specific site conditions. Finally, results obtained from an extensive testing program are discussed.

Herstellung einer Dichtwand mittels Cutter-Soil-Mixing: Ein Fallbeispiel. Das Bodenmischverfahren Cutter-Soil-Mixing (CSM) wurde bei der Instandsetzung des Herbert-Hoover-Deichs in Florida zum Einbau einer Dichtwand eingesetzt. Das Verfahren einschließlich seiner Vorteile und Einsatzgrenzen wird vorgestellt und der Hintergrund des Deichsanierungsprojekts erläutert. Der Aufsatz beschreibt das Vorgehen, welches für den Einsatz des CSM-Verfahrens unter den speziellen Randbedingungen der Baustelle notwendig war. Zum Schluss werden die Ergebnisse des umfangreichen Versuchsprogramms diskutiert.

1 Introduction

Cutter Soil Mixing (CSM) is an advanced deep soil mixing method and, with more than 150 completed projects worldwide, it has become very popular, especially for cut-off walls in construction, rehabilitation and upgrading of dams and dikes. The sophisticated CSM equipment allows the mixing of natural ground with a cementitious material in order to economically install high quality vertical structures.

After hurricane Katrina had brought the hazard of dike failure to public attention in 2005, the US Government executed a nationwide risk assessment of dikes. As a result, Herbert Hoover Dike in Florida (not to be mistaken with Hoover Dam damming the Colorado River) was found to be in need of repair. The Herbert Hoover Dike Rehabilitation project was initiated by the US Army Corps of Engineers (USACE), the agency in charge of the US waterways. The installation of a cut-off wall into the existing dike is one of the key measures to improve its safety.

Bauer Foundations Corp. (BFC), Florida-based subsidiary of Bauer Spezialtiefbau GmbH, is one of the contractors, which are qualified for this large scale and long term cut-off wall project. BFC proposed to use the CSM method for wall installation and was awarded a first task order in 2008, which forms the subject of this paper.

2 Cutter Soil Mixing

2.1 Deep soil mixing

Cutter Soil Mixing is an alternative method of deep soil mixing where the soil is mixed in situ with cementitious binder slurry by mixing tools. This creates a mortar-like material with the soil particles becoming the aggregates. The soil-cement mortar lacks the uniform composition, in particular of the aggregates, of conventional mortar or concrete and due to natural limitations, the well-defined conditions which apply to concrete production.

Thus one of the major advantages of deep soil mixing, in this case the CSM method, is to save the transport and purchasing of aggregates. The mass of excavated material and spoil that needs to be treated, transported and hauled and dumped off site is – depending on the ground conditions – also significantly reduced. That makes the method not only environmentally friendly but also economic, as it shows a much higher performance than a two-phase cut-off wall or even a secant pile wall, where the soil has to be excavated in a first step and the excavation has to be filled in a second step, often under water or a supporting fluid.

However, not all kinds of soils are equally suitable for use as aggregate in deep soil mixing. Coarse-grained soils like sand and gravel perform best, but fine-grained soils like clays and silts lead to a lower strength with same cement content or demand a higher cement content for the same target strength. Organic soils are deemed to be principally unsuitable because of their negative effects on the course of hydration when dispersed in the soil-cement mortar, leading to reduced strength, especially at an early age. Therefore the proportion of unfavorable soils in the mix needs to be limited, and the application of deep soil mixing is not usually allowed in ground conditions with organic content. A high groundwater velocity in coarse gravel is another factor to consider thoroughly before using the in-situ deep soil mixing method. As a main principle it can be stated that laboratory trial tests or even full-scale tests under realistic conditions are best to find adequate measures to achieve the required properties of the finally installed soil-cement element.

2.2 Construction method

Based on the experience gained with the in-house developments of trench cutters and deep soil mixing with continuous flight augers (Mixed-In-Place, MIP), Bauer started to develop a technology in 2003 to combine both methods, called "Cutter Soil Mixing". While in trench cutting, the bentonite slurry is used to transport the excavated material out of the trench in addition to its function in supporting the trench, with Cutter Soil Mixing (CSM), cementitious slurry is pumped to the actual location of the CSM tool. The CSM tool essentially consists of two wheels, the gearboxes driving the wheels, shear plates and a slurry nozzle (Figure 1). The in situ soil or rock is cut by the CSM wheels. The slurry is discharged from the nozzle between the wheels and is mixed with the soil by the CSM wheels turning against the slurry flow. The cutting or mixing teeth push the soil particles through the shear plates creating a kind of forced mixer.

A panel is installed in the following steps (Figure 2):

- Positioning of the CSM tool at the specified panel location.
- Penetration to the final depth. The matrix is broken and the soil is liquefied by addition of liquid. For slow penetration speeds or large depths, bentonite slurry or water (in clayey soils) is used (two-phase system). In the case of higher penetration speeds and/or small depths, cementitious slurry can be used since the risk of the mix starting to set during installation is less with shorter panel production times (one-phase system).
- Withdrawal of the CSM tool. Cementitious slurry is added and mixed with the soil. For the two-phase system, the total amount of cement is mixed into the soil in this step. For the one-phase system, only the difference between the calculated cement mass and the mass already mixed in during penetration is added. In either case, the mix is further homogenized.
- Steel beams can also be inserted into the freshly mixed wall panels if the wall is to function as a retaining structure.

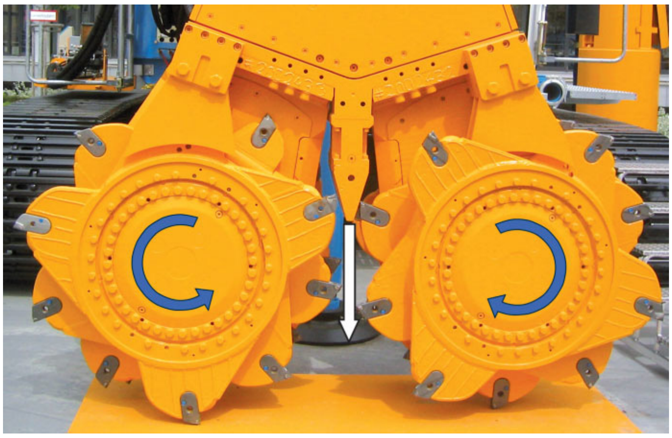

Fig. 1. CSM tool showing slurry flow (white arrow) and direction of rotation of the cutter wheels (blue arrows) [1].
Bild 1. CSM-Werkzeug mit Illustration von Suspensionsfluss (weißer Pfeil) und Drehrichtung der Fräsräder (blaue Pfeile) [1].

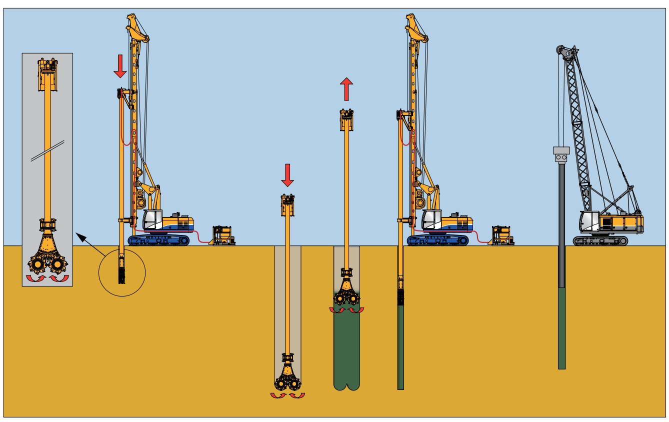

Fig. 2. Procedure of panel installation [1].
Bild 2. Arbeitsablauf bei der Herstellung einer Einzellamelle [1].

The panels can be installed either in a fresh-in-fresh or in a hard-in-hard sequence (Figure 3). Fresh-in-fresh means that each secondary panel (S) is cut in the gap between the most recently produced and still wet primary panels (P). Subsequently, the next primary panel is installed (sequence P – P – S – P – S – ...). When the hard-in-hard sequence is used, first a number of primary panels are produced and subsequently the gaps are filled, over-cutting the already set primary panels (sequence P – P – P – ..., S – S – S – ...).

2.3 Construction equipment

At the moment, two types of cutter head are available. The smaller BCM 5 creates panels of 2.4 m length and a thickness of 550 to 1000 mm. With the larger BCM 10 cutter head, 640 to 1200 mm thick and 2.8 m long panels can be installed. Different types of cutter wheels with different types of cutting teeth are available to adapt the method for different types of ground. The cutter head is either mounted on a rigid Kelly bar or to a guide frame as with trench cutters. The use of Kelly bars with circular shape enables the tool to be turned around the vertical axis by up to 90 degrees, which provides some flexibility e. g. at the corners of excavations. The maximum depth achievable with this Kelly bar is 21 m. The heavier structure of a rectangular Kelly bar cannot be turned, but allows lowering the tool down to a depth of 43 m. When mounted on a rope suspended guide frame, a maximum depth of 50 m can be

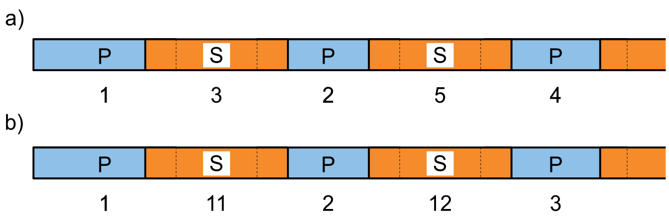

Fig. 3. Construction sequences of continuous walls with primary (P) and secondary (S) panels: a) "fresh in fresh", b) "hard in hard".
Bild 3. Herstellungsreihenfolge durchgängiger Wände mit Primär- (P) und Sekundärlamellen (S): a) „frisch-in-frisch", b) „hart-in-hart".

achieved. An even greater depth of 60 m is possible using the so-called Quattro-Cutter, which consists of two rope-suspended BCM 5 cutter heads, one facing downwards and one facing upwards.

2.4 Construction materials

The materials used in Cutter Soil Mixing are cementitious binder, which is typically a mixture of ordinary Portland cement (OPC), ground granulated blast-furnace slag (GGBFS), bentonite for stabilization and water, and possibly also chemical admixtures like plasticizers and retarders. Polymer additives can also be used, both to increase viscosity and decrease fluid loss.

The mix design should produce a mix achieving the required mechanical and hydraulic properties like strength, stiffness and permeability. The composition of the cement (bentonite) slurry used and its dosage strongly depend on the in-situ ground conditions (stratigraphical sequence, soil types, their densities and moisture contents, chemistry of soil and groundwater) and the purpose of the designed geotechnical structure. Does it function as a cut-off wall, a retaining structure or a foundation? What design strength at what age and what maximum permeability have to be provided? Additionally, a key factor is the quantity of water needed to lubricate the soil to achieve sufficient workability (consistency). Workability in the fresh stage has a strong impact on the quality of the hardened soil mortar. Therefore the mix design should be determined in the laboratory prior to construction despite some deviations from practice. Since the CSM method is applied under natural environmental conditions, the client and contractor should agree that the effective mix, which in fact is surrounded by more or less water-saturated soils of certain permeability, might vary from the theoretical mix complying with production data. This is mainly influenced by water loss from the fresh mix into the surrounding soil, which may be unavoidable due to head pressure in the liquid stage. If considerable amounts of water are lost, the mix might not be stable enough to retain its water sufficiently, and the mortar level would subside. But if a section with less solids or lower density is to be avoided, the mix design ought to be reviewed to gain a more stable final soil-cement mortar. This is usually an empiric process because the complex interaction of different soil properties, actual consumption of slurry needed and slurry composition cannot be easily predicted. This means that a remarkably higher spread of the in-situ properties of the soil-cement mortar already has to be accepted at the design stage.

2.5 Application, advantages and limitations

Cutter Soil Mixing – like other methods of deep soil mixing – can be used for soil improvement, installation of cut-off walls and also for retaining walls if subsequently reinforced. A compressive strength up to 15 MPa for retaining walls and a permeability in the magnitude of $1 \cdot 10^{-8}$ m/s for cut-off walls can be achieved within an economic product range.

In additional to the advantages shared with other deep soil mixing methods (cf. Section 2.1), the CSM method provides further advantages:

- The method can cope with many soil types including rocks since harder soil formations can be penetrated, broken down and mixed. Even fine-grained soil can be homogenized as the cutter wheels together with shear plates act as a kind of forced mixer.
- A high degree of verticality of wall panels is achieved by counter-rotating horizontally aligned cutter wheels.
- The cutter principle ensures construction of clean and trouble-free panels and joints, even between wall panels of different construction age.
- The method is environmentally friendly as no vibrations are induced during construction and as the construction process is comparatively quiet.
- Small base units can generate a high daily output and very deep panels.
- By producing rectangular panels, the entire wall section can be considered for structural design and permeability.

Clays of high plasticity and very hard rock formations are unfavorable soil conditions. The method cannot be directly used in organic soils.

3 Project background

Since Lake Okeechobee as well as the Herbert Hoover Dike are little-known abroad, both are briefly described.

3.1 Lake Okeechobee

Lake Okeechobee is a freshwater lake in south central Florida, USA (Figure 4). The lake covers approx. 1,900 km^2, which corresponds to twice the area of Berlin. It is exceptionally shallow for a lake of its size, with an average depth of only 3 m. [5]. The lake is fed mainly from areas north and west of the lake, e.g. by the Kissimmee River.

Lake Okeechobee is the main source of water for the Everglades (dark areas south of Lake Okeechobee in Fig. 4), and thus of eminent importance. Large parts of this globally unique ecosystem are well described as “River of Grass“. It is a very shallow, but tens of kilometers wide river which is completely overgrown with grass. It is estimated that 11,000 species of seed-bearing plants and 400 species of land or water vertebrates live in the Everglades [4].

South and south-east of the lake (reddish in Figure 4), and hence between Lake Okeechobee and the Everglades, is the Everglades Agricultural Area with an annual production of mainly sugar cane, but also citrus fruit and winter vegetables worth 1.5 billion USD. The lake is also an important source of drinking water for 6 million people in the South Florida metropolitan area (Miami, Fort Lauderdale, and West Palm Beach) on Florida’s south-east coast.

3.2 Herbert Hoover Dike

Due mainly to land reclamation, the population south of Lake Okeechobee increased quickly at the beginning of the 20th century. Local government and residents built up the lake’s natural embankments. In 1926 and 1928, the

Fig. 4. South Florida satellite image map [7].
Bild 4. Südflorida, Satellitenaufnahme [7].

south shore of the lake was struck by hurricanes. The winds caused the lake's water to overflow the shallow embankments and resulted in massive flooding with a loss of about 3,000 lives.

After this, a larger dike was built on the south shore by the USACE in the 1930s to prevent a repetition of this kind of disaster. During two more hurricanes in 1947 and 1948, the dike worked to protect lives but massive flooding occurred again. To improve the protection of people, their property and the agricultural industry, the dike was raised and enlarged to encircle the complete lake as well as parts of the inflows. The total length of the dike is now 230 km with an average height of 9 m. After completion of construction in 1960, the dike was named Herbert Hoover Dike in honor of the president who personally visited the site and authorized funds for its construction in the 1930s.

3.3 Ground conditions

The following description of embankment fill and subsurface relates to the conditions encountered in task order 2 between Port Mayaca and Canal Point (see Section 4). Figure 5 shows a typical cross section of the embankment including the soil profile.

Embankment construction was carried out using dipper and hydraulic dredges, which created a navigable channel parallel to the dike. During the first phase of construction, the fill material was placed hydraulically. When the embankment was raised and widened, the materials were placed mechanically. The fill material is a heterogeneous mixture of all the components of the natural lake ground: loose to dense, fine to medium, clean to silty or clayey sands with lesser contents of limestone gravel, cobbles and shell. The primary minerals of the sand are quartz and carbonate. Exceptionally, pockets of cobbles and boulders can be found in the embankment [6]. Furthermore, organic soils were used in the embankment as well.

Typical dimensions of the embankment are a crest width of 4 m, a base width of 75 m, a lakeside slope of 1:6 (V:H), a landside slope of 1:3, and a crest height above ground of approx. 7.5 m [2].

The top of the natural ground consists of organic materials. This is mainly peat, but soft organic silts, partly sandy and partly clayey, are also common. The dark brown to black color distinguishes this material from the grayish embankment fill and from the underlying layers. The thickness of this layer varies between 0 and 4 m.

Below the peat there is a heterogeneous layer which can be considered to be decomposed limestone. The layer is partly made up by clay, silt and sandy clay and silt. But it can also consist of sand and shell. It is followed by a hard limestone layer. The thickness of this layer averages 2.5 m, but can be up to 6 m. Its permeability varies in a wide range but is generally high. A loss of drill fluid in this layer was recorded several times during ground exploration. The unconfined compressive strength of the limestone is in the magnitude of 10 to 17 MPa [6].

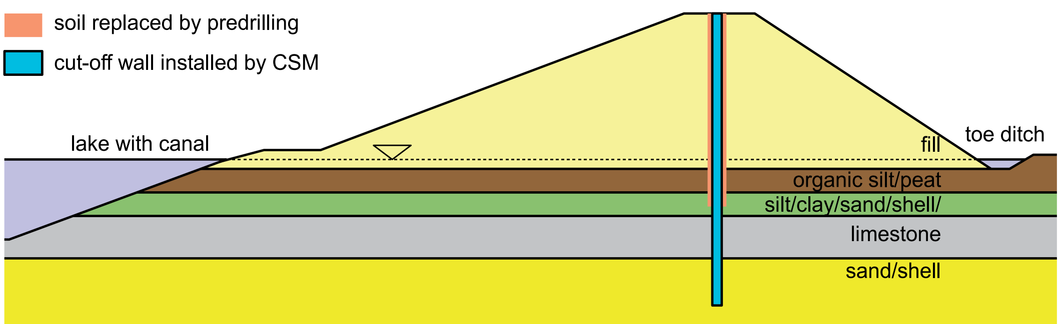

Fig. 5. Generalized soil profile.
Bild 5. Verallgemeinertes Baugrundprofil.

Underneath the limestone, layers of quartz sand, shell or mixtures of both are found. This densely packed layer can also be characterized as highly permeable. In some areas, a second rock layer up to 1.5 m thick was encountered embedded in this layer. The properties of this limestone layer can be considered similar to the upper limestone layer.

3.4 Geotechnical problem and solution

When it was first constructed, the only purpose of Herbert Hoover Dike was flood protection. Under this condition the lake level is subject to seasonal changes, but corresponds to the ground water table on the landside. Hence there is little flow through the embankment and the dike is not hydraulically stressed. The water level only temporarily rises after heavy rain, since inflow can be up to four times the outflow capacity. The lake was permanently maintained at a higher level during the 1970s to secure the water supply of the Everglades Agricultural Area during seasonal droughts. This led to a permanent flow through the embankment during this time.

The temporary as well as permanent hydraulic stress the dike has been exposed to during its eight decades of existence have damaged its internal structure. The damage was most clearly revealed during two nearly back-to-back high water events in the 1990s, when numerous sink holes, seeps, pipes and boils were observed (Figure 6). While these problems were subsequently addressed with interim remedial measures, they demonstrated the need for a thorough rehabilitation. The installation of a cut-off wall into the existing dike was chosen as the preferred measure to improve the safety of the dike [2].

4 Cut-off wall construction

Task order 2 for cut-off wall installation as part of the Herbert Hoover Dike Rehabilitation project was awarded to Bauer Foundations Corp. by the USACE in 2008. The task order covers more than 5 km of dike between Port Mayaca and Canal Point at the east shore of Lake Okeechobee (Figure 7). The contract comprises 75,000 m^2 of cut-off wall with a specified wall depth of 17 or 20 m.

Since it was a performance-based contract, neither means nor methods were prescribed, but acceptance criteria for the final product were specified instead. Important requirements were:
- continuity and homogeneity of the wall,
- a minimum wall thickness of approx. 45 cm,
- 28-day unconfined compressive strength (UCS) between 0.7 and 3.5 MPa and
- a 28-day permeability less than $1 \cdot 10^{-8}$ m/s

Fig. 6. Damage to the dike: a) sinkhole formation in crest; b) heave of downstream toe and c) piping at downstream toe of dike; and d) saturation of landward toe and embankment slope (from [2]).
Bild 6. Deichschäden: a) Sackung im Bereich der Deichkrone, b) hydraulischer Grundbruch und c) Piping am landseitigen Deichfuß sowie d) Aufweichen von Deichfuß und -flanke auf der Landseite (aus [2]).

Fig. 7. Aerial photograph of task order 2 including working platform (Photo: Mark's Photo).
Bild 7. Luftbild des Loses 2 mit Arbeitsplanum. (Foto: Mark's Photo).

The testing necessary to prove the compliance of the finished wall with the criteria is discussed in section 5.2.

4.1 Construction sequence

Construction was carried out in four basic steps: (1) platform construction, (2) pre-drilling, (3) wall installation and (4) dike restoration.

1. Since construction was carried out from the top of embankment, a platform was needed to provide sufficient work space for the CSM and drilling rigs as well as for all the support and material flow. The working platform was built centered on the cut-off wall alignment. During production, all rigs stood on one side of the wall alignment and the opposite area was used as a supplementary road. Before the platform material consisting of gravelly sand was dumped and compacted in layers, the top soil was stripped and piled and a silt fence (an approx. 0.5 m high fence protecting waters from soil particles contained in stormwater runoff) was installed.
2. The mixing of adjacent layers to form a homogeneous soil-cement mortar is in principle more or less restricted to the diameter of the mixing tools, i.e. CSM wheels. Therefore any extremely unsuitable organic material in form of an existing peat layer or organics contained in the embankment fill has to be replaced by a suitable granular material. The replacement was executed by a specific "pre-drilling" procedure which is described in detail below.
3. After pre-drilling the wall alignment, the cut-off wall was installed using the CSM method. This process is also described below in a separate section.
4. After wall acceptance by the client, the embankment was restored. The platform material was removed and reused for platform building (step 1). The intention was to establish a more or less continuous process of platform removal behind the operation and platform building ahead of the operation to save platform material. The stockpiled top soil together with the organic material put aside and stockpiled during step 2 was used to restore the original shape of the dike. Dike restoration was finished by seeding grass using hydroseeding.

4.2 Pre-drilling

As stated above, the organic material of the peat layer and embankment fill was unsuitable for deep soil mixing. Since the CSM method is not able to vertically distribute unsuitable material in order to homogenize the material over depth with a tolerable amount of organics, the organic material had to be removed from the wall alignment in a process further described as "pre-drilling".

The removal of organics was done by first generating a wall of non-organic backfill similar to a secant pile wall. This wall consisted of an alignment of overlapping columns with an average replacement depth of approx. 12 m.
Pre-drilling of a borehole consists of the following actions:

1. Excavation of borehole by Kelly drilling. The casing was drilled down to the top of the limestone layer at final excavation depth. The soil profile of each borehole was logged by a geologist.
2. The excavated soil was separated into non-organic and organic material. The operator looked at each soil-loaded auger and decided whether it contained a substantial amount of organics. The material was then dumped on different piles on either side of the drilling rig depending on the operator's decision. The geologist supervised the operator in his decision-making.
3. The non-organic material was blended with imported fine sand by running both materials over a screening machine.
4. The blended material was dumped into the open casing using a funnel for backfill.
5. The material containing organics was stockpiled and reused later for dike restoration, avoiding the need to haul it off site. This environmentally friendly measure saves additional transport and disposal.

Most of the time, pre-drilling was carried out by two teams. Each team used a Bauer BG 28 drilling rig with two sets of casing and supporting machinery like front loaders, skid steer loader and telescopic handler (Figure 8).

As the CSM method is sensitive against organics, the CSM wall quality crucially depends on the proper and clean execution of pre-drilling. Therefore, a quality con-

Fig. 8. Pre-drilling operation using two BAUER BG28 drill rigs (in front).
Bild 8. Vorbohren mit zwei BAUER BG28 Bohrgeräten (vorn).

trol (QC) procedure was developed to address numerous sources of error during the complete pre-drilling process, consisting of production planning, surveying, executing and reporting.

4.3 Cutter Soil Mixing (CSM)

The cut-off wall was installed using a BCM 5 cutter head (Figure 9) mounted on a RTG RG 25 S base rig via a rectangular Kelly bar. This unit was assisted temporarily by an additional BG 28 rig also equipped with a BCM 5. The RTG RG 25 has a slight advantage of faster positioning since it features the parallelogram kinematic linkage system. Additionally, this rig was able to do the penetration and withdrawal for a panel depth of 17 m in one run without grabbing the Kelly bar at different heights. Both the rigs feature the on-board monitoring and controlling system B-Tronic, which enables – amongst other features – simple control of the verticality and the pumped slurry volume by depth during production as well as the documentation of the production process with respect to quality control.

A wall thickness of 64 cm was chosen to ensure the final wall dimensions. The panels were installed in a single phase, thus using the same cement/bentonite slurry for penetration as well as withdrawal. Most of the slurry was mixed in during penetration to liquefy the soil and generate a well workable mix. The remaining volume of slurry was pumped during withdrawal. The volume pumped during penetration is subject to some variation with depth, since the operator´s main attention during penetration is the verticality of the panel and temperature of the tools, and since slurry sometimes has to be used to ease the cutting process in the hard layer. But because the volume pumped by depth is recorded and visualized by the B-Tronic system, the operator can smooth this out during withdrawal and produce a uniform slurry distribution with depth.

Fig. 9. CSM cutter head BCM 5 finishing a panel.
Bild 9. CSM-Fräskopf BCM 5 beim Abschluss der Herstellung einer Lamelle.

The speed at which the tool is lowered into and pulled out of the ground controls the mixing time. The slower the penetration and withdrawal speed are chosen, the longer the soil is subjected to mixing and the better the homogeneity of the mix as represented by size of soil lumps and slurry distribution. Since well mixable coarse grained soils prevail at the site, the tool was moved relatively fast. Depending on the hardness of the rock, penetration was slower in the limestone layer.

The wall was constructed fresh-in-fresh with the secondary panels installed immediately after the adjacent primary panels. In this way, the secondary panels are partly cut into the not yet hardened primary panels and a jointless, continuous wall is created.

Even under the prevailing conditions of quite permeable coarse grained soils in the embankment fill and subsoil layers, the addition of slurry results in an increase of volume in the panel. Additional volume is added to the panel by the Kelly bar during penetration, so a small trench was excavated by a mini excavator before panel installation to provide space for the overflow. A part flowed back into the panel during withdrawal due to the extraction of the Kelly bar's volume.

The slurry used consisted of water taken from Lake Okeechobee, slag cement, type II Portland cement, bentonite and retarding agent. Since the panels were installed in a single phase, the mix could not be allowed to set during panel installation until the CSM tool was completely out of the ground. This was one of the reasons for the use of slag cement in the mix design. The slag is also beneficial for the few cold joints created after weekend breaks. Since the slag causes the mix to harden slowly during the first days, it allows the panels installed before and after the break to "grow" together. This effect is amplified by the rough joint surface created by the cutter wheels cutting in the old panel. The bentonite was used to increase the viscosity of the mix as the soils are mainly coarse-grained.

Two colloidal batch mixers, a MAT SCC-20 and a MAT SCC-40, were used to mix the slurry. Both mixers were assembled with two water tanks and two silos in a fixed setup in the yard. First, the water was mixed with the bentonite and stored in one of the tanks for one day to hydrate the bentonite. The next day the bentonite water was taken and mixed with the cements. Several batches were accumulated in an agitator tank until the needed amount for one panel was produced. Subsequently, the slurry was pumped into a concrete truck and hauled to the CSM unit. There it was again dumped into an agitator tank which was mounted on a trailer. The CSM rig was fed from this agitator tank by an eccentric screw pump, which was remotely controlled by the CSM operator.

5 Testing

An extensive testing program was carried to monitor and control the production process and also to check the final product. The major part of the testing program was specified in the USACE contract and was related to the mix and to the wall.

5.1 Slurry testing

Internal testing was also performed to monitor the entire process of materials delivery, slurry production, storage and transport and to ensure the quality of every single panel. Samples were retained of every delivery of cements and bentonite.

The slurry was tested for density, Marsh time and temperature in the usual way directly after production and before being pumped into the concrete truck. The same parameters were checked again when the slurry was temporarily stored in the agitator tanks waiting to be used by the CSM rig. This procedure covers most production and transport related problems, helped the mix plant operator to check his work and to detect problems such as water in the concrete truck after a weekend of heavy rainfall. Additionally, a slurry sample was retained for each shift to qualitatively check the curing process of the slurry. The slurry volume was measured with a flow meter on the base rig and recorded with the B-Tronic. The total volume of two panels per shift was double-checked with a second flow meter installed on the slurry trailer.

5.2 Contract-based testing

The client required the taking of wet samples cured under lab conditions as well as the drilling of boreholes into the cured wall to verify the finished product. While the testing of the wet samples was only done for monitoring, the acceptance of the finished product by the client depended only on borehole testing.

Those so-called verification borings were drilled around day 25 after installation into the wall approximately every 60 m, alternating between the center of a primary panel, of a secondary panel and of the over-cut between primary and secondary panel. The borehole diameter was 122 mm, the core diameter 84 mm. Figure 10 shows a typical core obtained. For each of the verification holes, a drilling log including a detailed description of the core was prepared. Additionally, a video log was created by scanning the borehole with a down-hole camera. Both logs were used by the client to assess the acceptance criteria homogeneity and continuity of the cut-off wall. Four core samples were taken at different depths of the borehole and tested at day 28 for UCS.

Furthermore, a falling head borehole test was carried out on day 28. Based on the assumption of a hole extended in uniform soil (case 8 in [3]), the fall of water in a given time of 30 min had to be used to calculate a value of permeability. This assumption does obviously not hold for the wall surrounded by soil with permeability several magnitudes higher. Additionally, due to the unavoidable deviations during drilling, the boreholes are not necessarily in the center of the wall. Hence the calculated permeability is questionable from a scientific point of view and cannot be directly compared to the results of permeability tests in the lab. However, the permeability value obtained can be seen as a normalized water loss and helps to compare falling head tests carried out on boreholes of different depth and diameter. Additionally, this test is a very good integrity check.

There were two kinds of wet samples. So-called daily bulk samples were taken every day before and after noon alternating at depth levels of 6, 9, 12 and 15 m below top of dike. Additionally, three so-called post-placement samples were taken from one panel in the vicinity of each of the verification borings at depth levels of 6, 12 and 15 m. All sampling activity was done during the day shift for safety reasons. To take both kinds of samples from the just finished panel, a heavy sampling device (Figure 11) was lowered into the mix to the planned depth. Then the sam-

Fig. 10. Core of a verification boring.
Bild 10. Bohrkern aus einer Abnahme-Bohrung.

Fig. 11. Sampling device filled with fresh soil-cement mortar.
Bild 11. Probennahmegerät mit frischem Bodenmörtel.

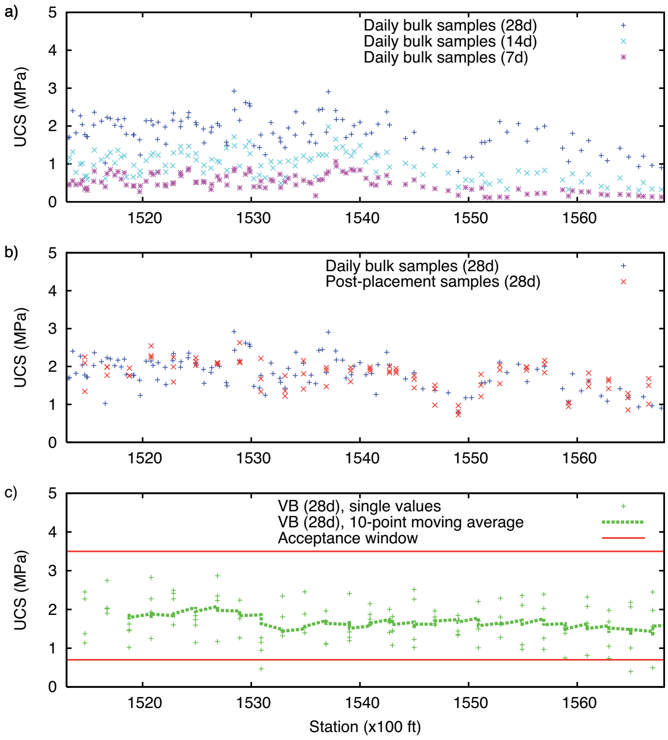

Fig. 12. Unconfined compressive strength against station: a) of daily bulk samples at 7, 14 and 28 days of hydration, b) of daily bulk and post-placement samples c) of core samples at 28 days.
Bild 12. Einaxiale Druckfestigkeit aufgetragen über die Station: a) von Probezylindern im Alter von 7, 14 und 28 Tagen, b) von verschiedenen Probezylinder nach 28 Tagen und c) von Kernproben nach 28 Tagen.

pling device was lifted causing two trap door-like flaps at the bottom to close. The wet mix material obtained was used to prepare cylindrical samples in plastic molds of 152 mm height and 76 mm diameter and closed with plastic lids. The cylindrical samples were stored for three days at the site in an air-conditioned trailer at 23 °C and then transported to the lab. In the lab, the samples continued to cure at 23 °C in water-saturated air.

Permeability and strength of the daily bulk samples were determined in the lab after 7, 14 and 28 days on one sample each. For the post-placement samples, permeability and strength was tested at day 28 one two samples each.

5.3 Selected test results

Figure 12 shows UCS results plotted versus station for the northern 1.7 km long part of the task order. The strength evolution obtained from the daily bulk samples can be clearly seen in Figure 12a. The mix gains strength by time and shows on average 25 % of the 28 day strength after 7 days of curing and 50 % after 14 days. Since daily bulk and post-placement samples are taken and cured in exactly the same manner, both show very similar strength at day 28, cf. Figure 12b. The results of both the samples vary between approx. 1 and 3 MPa averaging at 2.1 MPa. As the entire section was carried out using only one mix design, this variation results mainly from the variation of the ground.

The results of the verification borings plotted in Figure 12c show a slightly higher variation and average 1.8 MPa, and thus lower than the bulk samples. The differences can be attributed to the different curing conditions. While the water is contained in the plastic molds, the mix can drain in situ. Furthermore, the mix on site is exposed to the humic acid of the peat layer to a much greater extent. As Figure 12c clearly depicts, the 10-point moving average keeps well in the middle of the range given by the acceptance criteria. Although not necessary under the contract, even all single values fall within the range, most likely due to the refilling of quite homogeneous soil before deep mixing.

Figure 13 shows permeability results plotted, also against station. The permeability drops from day 7 to day 28 by approximately two orders of magnitude (Figure 13a). While there is an inverse relation between strength and permeability, the variation of permeability is somewhat larger than of strength and supposedly caused by test related problems. This is supported by the deviations between daily bulk and post-placement samples around station 1470 (cf. Fig. 13b). The geometrical mean of daily bulk samples and post-placement samples is $2 \cdot 10^{-10}$ and $7 \cdot 10^{-11}$ m/s, respectively. With a geometrical mean of $6 \cdot 10^{-10}$ m/s the average permeability of the verification borings is almost one magnitude higher. Comparing all permeability results three points need to be considered:

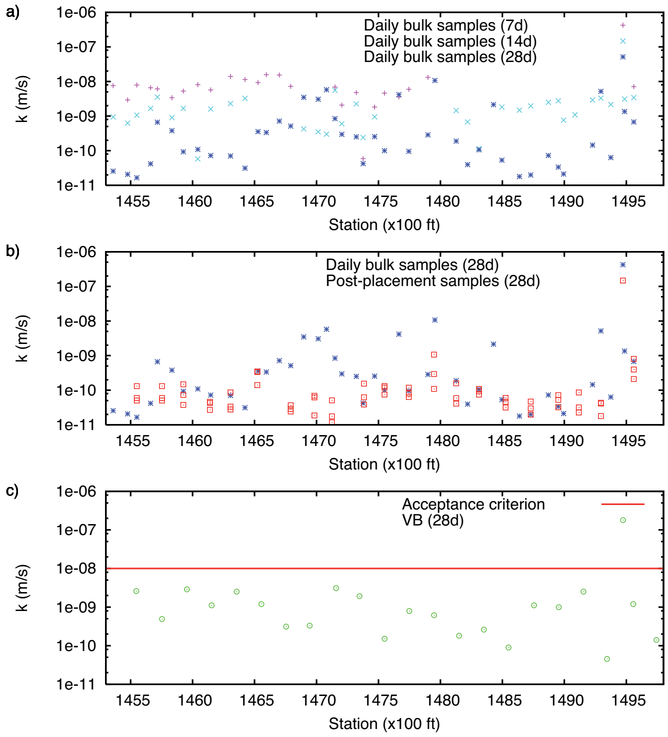

Fig. 13. Permeability against station: a) of bulk samples after 7, 14 and 28 days of hydration, b) 28-day permeability of bulk samples and c) 28-day permeability of core samples.
Bild 13. Durchlässigkeit aufgetragen über die Station: a) von Probezylindern im Alter von 7, 14 und 28 Tagen, b) von verschiedenen Probezylinder nach 28 Tagen und c) von Kernproben nach 28 Tagen.

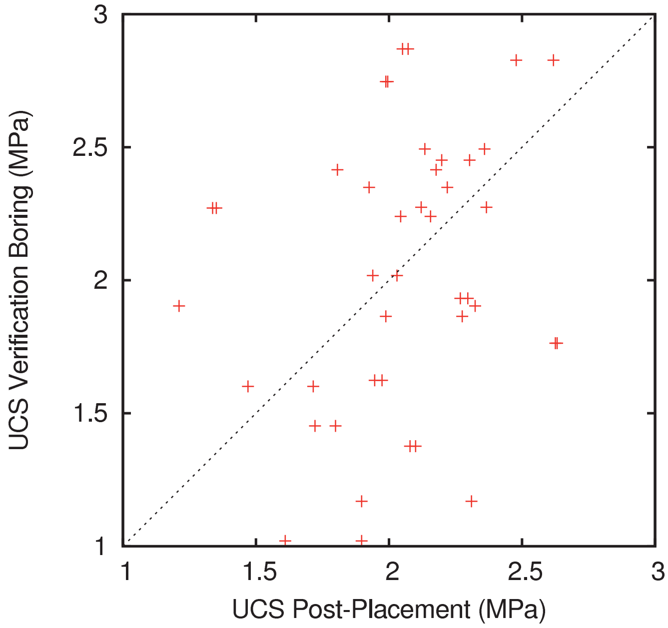

Fig. 14. Comparison of unconfined compressive strength results between bulk samples and core samples.
Bild 14. Vergleich der einaxialen Druckfestigkeiten von gesondert hergestellten Probezylindern und von Kernproben.

1. the different nature of the test (lab test on a small specimen vs. field test averaging the properties over the entire wall height),
2. the inapplicable assumptions made to calculate the field permeability as discussed above and
3. the different structure of the material (structure created by CSM vs. structure resulting from sample preparation including compaction by vibration).

Although the agreement of the geometrical means is relatively good considering (1) through (3), only a very weak correlation was found between the permeability values of post-placement samples and the permeability values obtained for the same panel by borehole testing.

The intention of the post-placement sampling was to link the test results of bulk samples to the results obtained for the finished wall. In this way the bulk samples could

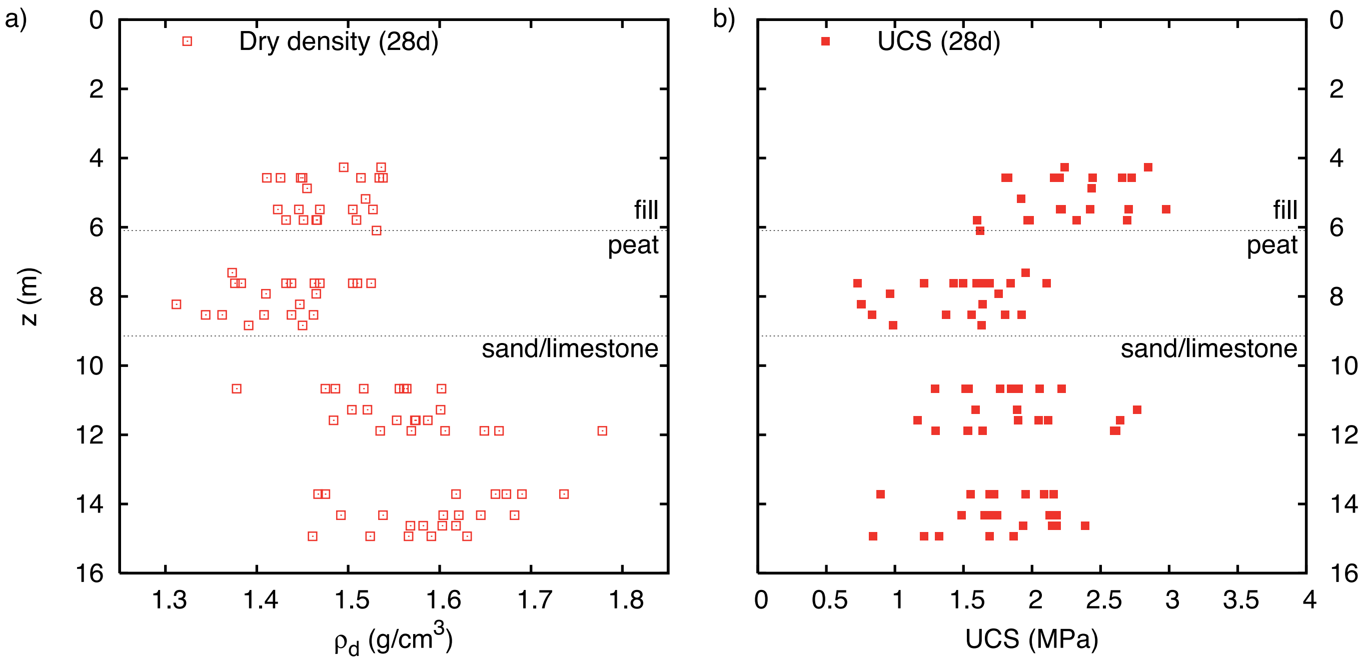

Fig. 15. Depth profile of a) dry density and b) unconfined compressive strength of core samples.
Bild 15. Verteilung der a) Trockendichte und b) der Druckfestigkeit von Kernproben über die Tiefe.

provide information about the in-situ properties of the wall, and thus help to check the quality of the final product. The UCS results obtained from verification core samples are plotted against the results of post-placement samples taken at the same location (same panel, depth ±1 m) in Figure 14. The wide scattering of the results clearly shows that testing of bulk samples is unfavorable for the assessment of the quality of the final wall.

To demonstrate the impact of different ground conditions, the depth profiles of dry density and unconfined compressive strength obtained from the verification core samples are plotted in Figures 15a and 15b, respectively. The soil layers are also indicated in both the figures in a very simplified manner. The water table is located approximately at the top of the peat layer. Dry density is lowest in the peat layer and highest in the sands and limestone below. This is supposedly caused by differences in water loss. While water can easily drain out of the fresh mix into the surrounding sands and limestone and permit the mix to settle, much less water will drain out into the peat layer as it consists to a large extend of less permeable organic silts, and thus will prevent a larger compaction of the mix in this layer. Considering all permeable layers, there are slight indications that the water loss and hence the dry density increases with depth.

The strong impact of the in-situ soil surrounding the wall can also be seen regarding strength. The highest strength is obtained for the fill, since the soil is unsaturated and permeable in this layer and hence there is less water in the fresh mix resulting in a lower water/cement ratio. The lowest strength is found in the peat layer, as there is less water loss and hence a higher water/cement ratio. The humic acids could have a reducing effect too. In the permeable, saturated sands below, strength is less than in the unsaturated fill but higher than in the less permeable peat.

6 Summary and outlook

The paper demonstrates that Cutter Soil Mixing (CSM) was a very suitable method to install a cut-off wall within Herbert Hoover Dike. This deep mixing method succeeded even under demanding ground conditions like interbedded rock layers and for challenging wall performance criteria. However, since organic soils are problematic for deep mixing, a peat layer had to be replaced beforehand. Even considering this additional measure, the CSM method was economical.

BAUER Foundations Corp., USA was awarded two out of three new cut-off wall task orders released in 2010 in the framework of the Herbert Hoover Dike Rehabilitation project. This underlines the competitiveness of the method and the satisfaction of the client with the product, and thus with the method as well.

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