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Rehabilitation measures with several construction methods at dam and dike projects in the United States

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Intro

The rehabilitation of existing dams, dikes and levee systems presents multiple challenges when considering the varying geological conditions of the sites, technical specifications and required qualifications which result in project-specific solutions for seepage barriers. Individual project-specific technical solutions vary based on the required depth and width of the seepage barrier and site logistics (access roads, platform dimension etc.). This paper discusses the application of different sustainable foundation techniques and construction methodologies which only a specialist foundation contractor with relevant experience can offer. The successful completion of challenging projects is possible only by combining safety, quality, and sustainability while ensuring the long-term safety of existing dams and dikes/levees. This paper describes various construction methods and technologies adopted at the East St. Louis Levee (Illinois) where a cut-off wall was installed with the Diaphragm wall method, using self-hardening slurry and Jet Grouting technologies, and at Herbert Hoover Dike (Florida), executing a cut-off wall deploying Cutter Soil Mixing (CSM) and Jet Grouting. At Teller Dam (Colorado) the cut-off wall was constructed using the Secant Pile Wall and permeation/TAM grouting solutions.

1. Background

Due to the current equipment available and the several construction methods, cut-off walls can be installed in any type of ground condition and up to 150 m depth to provide a reliable, durable, and impermeable system which ensures efficiency, durability, stability, and safety for the project. Thus, the cut-off wall makes rehabilitating the existing structure that bit easier. Cut-off walls convert the existing ground conditions to meet your design requirements, at the location of your choice. The ability to install safe walls in remote areas enables you to meet the environmental and social requirements of dams, dikes or levees, in line with efficiency and durability, as well as other performance specifications both extending and enhancing the life span of the structure, as required by design and intended purpose.
As part of dam safety programs worldwide, dam, dike/levee owners, municipal and state authorities and private parties conduct regular reviews of all their structures. Although the condition of a dam, dike or levee may not have changed since it was built, reviews of its purpose or design could identify a need for upgrades to increase capacity or to enhance life span and dam safety, which may be compromised due to hydraulic conditions or during major earthquakes. Other existing barrier systems, for example those constructed with conventional grouting methods, and in particular geology like Karst or alluvial/colluvial sediments over time often fail to make the grade. Bauer has great expertise in the design and execution of sealing and soil improvement solutions (for both rehabilitation and new projects concerning dams, dikes, levees and tailings facilities). Our core competencies include various construction methods, technologies, or a combination of methods/techniques. Project-specific requirements for special equipment are covered with solutions developed by the Bauer Group. The experience gained over many years with regards to the construction materials used and developed and the integrated design solutions required for certain projects, ideally complement our overall competence in contributing to durable solutions. The successful completion of our work (as a contribution) to (ensure) client satisfaction is based on our knowledge of digitalization in civil engineering, the ISO 9001 standard, and the associated standards and norms.
Likewise, the quality management is based on a (project-specific) quality management plan tailor-made for the project, to ensure the agreed quality of the work. Our digitization tools and monitoring capabilities are supporting this quality assurance, all aimed at improving our services. A carefully planned, certified, and implemented HSE management system accompanies the planning and production processes.

2. Projects

Based on relevant news, existing dams and dikes/levees will be rehabilitated and upgraded in the United States during the next 20 years. Projects we have recently been involved in are described below.

2.1 East St. Louis Deep Cut-off Wall Project – Illinois

The East St. Louis levee system is located in St. Clair and Madison Counties, Illinois, along the left descending bank of the Mississippi River and provides flood protection to approximately 250,000 residents and over $4.5 billion in economic value. The system is aged and requires rehabilitation. The United States Army Corps of Engineers (USACE) devised and designed the East St. Louis cut-off wall to be installed in the Metro East Sanitary District levee segment, one of the levee segments that form the East St. Louis system (see figures 1 a & b).

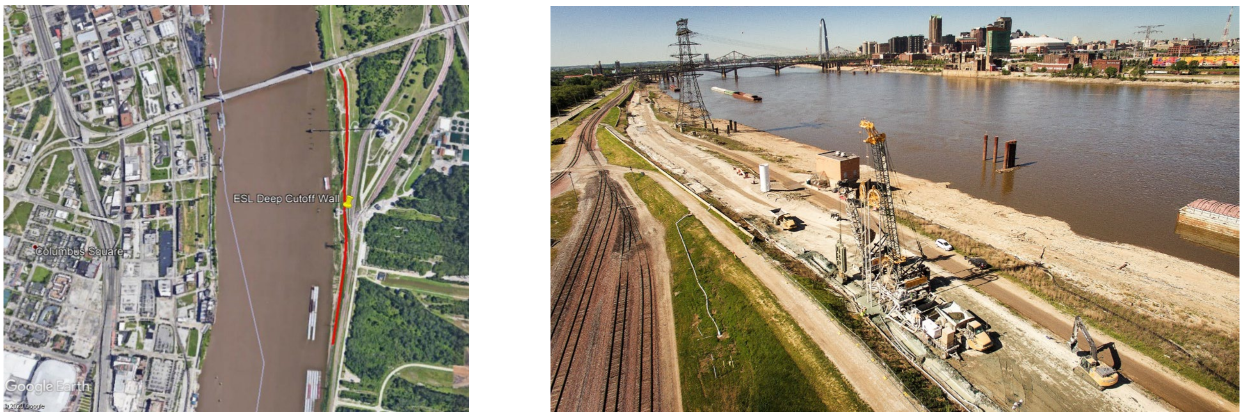

Figure 1 a & b: East St. Louis Deep Cut-off Wall project location (aerial-view & site at Mississippi River)

The cut-off wall was 1,350 meters long, with a minimum thickness of 60 cm, embedded into rock, and with a maximum design depth of over 43.5 m. The scope of work also included the following main items: a thorough Quality Control / Quality Assurance program; the installation of a clay cap at the top of the cut-off wall; nine inclinometers, in sets of three to monitor any movement of the surrounding soils that could signal a potential collapse of the excavation trench; restoration; sodding. The contract was awarded to BAUER Foundation Corp. (BFC) in November 2019. Additional scope of work was awarded to BFC in May 2021, which included the installation of another 50 m of cut-off wall.

Project Design

The design provided for the installation of a cut-off wall through alluvial and outwash soils, comprised of sand, mostly, and clay, silt, gravel, and cobbles, and was embedded in limestone (see figure 2).

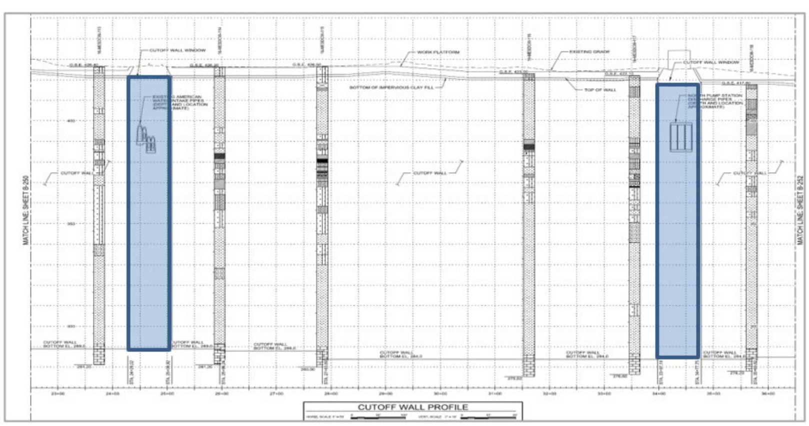

Figure 2: Cut-off wall profile with stratigraphy

The prescribed panel method consisted of overlapping primary and secondary panels, each no more than 9.0 m in length. The maximum allowed vertical deviation of each panel was 0.5 percent of its full depth.
The additional cut-off wall was designed as a combination of “panel method” and jet grouting method (Fig. 3).

Cut-off wall installation
The original 1,350-m-long cut-off wall was installed by the diaphragm wall method using the single-phase process, which requires that a self-hardening slurry is used as the excavation fluid. The slurry is left in place to cure, once panel excavation is complete, and thus becomes the cut-off wall’s final backfill material. BFC designed the self-hardening slurry to meet the specified stringent requirements for unconfined compressive strength between 0.35 and 1.80 MPa and maximum hydraulic conductivity of $1x10^{-6}$ cm/s.

The additional 50-m-cut-off wall had the target to treat two 25-m-long openings (Windows) located along the original cut-off wall alignment, represented by the two blue areas in Figure 2. The Windows were due to the presence of vital underground utilities, passing through the wall alignment. One of the utilities serves the purpose of flood control, while the other one supplies water to the surrounding areas. The cut-off wall was installed by a combination of panel method and jet grouting (Figure 3).

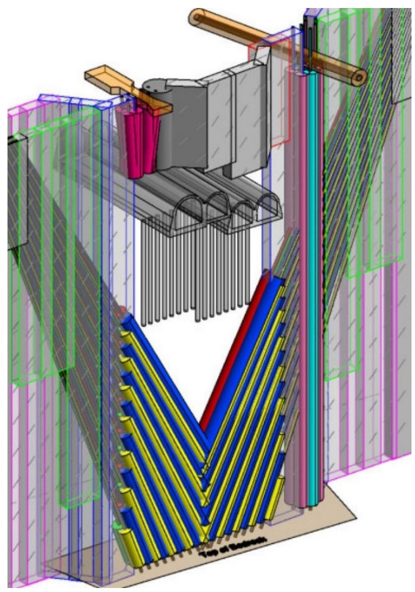

Figure 3: Cut-off wall at one of the Windows

Construction equipment
Diverse and numerous pieces of equipment were required for the installation of the cut-off wall.
Panel Method Cut-off Wall Construction Equipment
BFC determined that a combination of hydraulic clamshell grab (Bauer DHGV) and cutter Bauer BC 40 trench cutter, both mounted on Bauer MC 96 cranes was the best solution for the installation of the panel method cut-off wall. The cutter was equipped with a portable desanding unit.
The batching plant was fitted with five mixers (three Bauer CMS 45 for the preparation of self-hardening slurry and two Bauer SKC 30 for the batching of bentonite slurry), tanks for water storage and bentonite hydration, vertical and horizontal silos for bentonite and binder powders, insulated and heated containers where additives were stored, and two trailer-mounted 500 kW generators. The batching plant complex was enclosed in an insulating structure due to the winter condition in the area.

Jet Grouting Method Construction Equipment
For the installation of the jet grouting columns a Klemm KR 720 drilling rig was used.
The rig was fed by a plant which included high-pressure pumps, slurry mixers, and vertical and horizontal silos.

Figure 4: Grab and cutter

Figure 5: Jet grouting rig

Quality control

Construction of the cut-off wall was completed in April 2022 to the full satisfaction of the owner. The 265 panels comprising the original cut-off wall did not require any remediation work. Nor did any of the additional panels installed at the two windows.

The cut-off wall far exceeded the required minimum thickness set by USACE at 60 cm. This was demonstrated by, among other things, drawings produced by the QC team that showed horizontal elevation cuts of the wall generated in 3.0 m vertical intervals, which also demonstrated the continuity of the cut-off wall. The average hydraulic conductivity of the cut-off wall, tested on wet grab samples, was two orders of magnitude lower than the required hydraulic conductivity of $1x10^{-6}$ cm/s.

The average unconfined compressive strength was within the 0.35 to 1.8 MPa range, and no specimen was either below 0.2 MPa or above 1.9 MPa, as required by the specifications. All 22 verification borings drilled along the wall confirmed the continuity of the wall and proved its homogeneity (Figure 6).

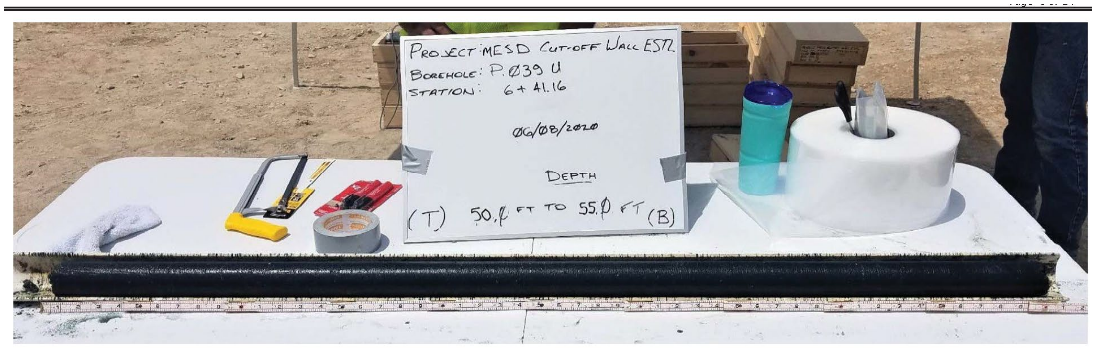

Figure 6: Verification borings – core sample

The jet grouting barrier met all specification requirements as well. The total of just over 160 overlapping columns produced a curtain which reached the minimum required width of 76 cm.

All wet grab samples tested at least one order of magnitude lower than the required hydraulic conductivity of $1x10^{-5}$ cm/s. The continuity of the jet grouting barrier was proven by a 3D model of the installed columns and confirmed in the field by eleven verification bores, all drilled at the center of a cluster of three columns.

2.2 Herbert Hoover Dike, Task Orders 1, 3, & 5 - Florida
Situated in southeast Florida at Palm Beach and Hendry Countries, Lake Okeechobee is a 1,890 km² freshwater lake, which is the largest in Florida and second largest in the US. Everyone in south Florida relies on Lake Okeechobee and the water conservation areas (WCAs) to replenish and recharge drinking water and irrigation supplies. In the early 1900's the original levees were constructed in order to help reduce the risk that the lake overflows.

Even after the original levees were constructed, hurricanes and severe weather events still caused the lake to overflow. The US Army Corps of Engineers have since been active in making continuous improvements to what has now become Herbert Hoover Dike (HHD). In its current state the Dike is still susceptible to seepage and therefore potential erosion. This is why the US government has commissioned multiple cut-off wall projects around the lake in order to mitigate excessive seepage and control erosion.

Bauer have been involved in cut-off wall projects on the Herbert Hoover Dike since 2008 and have worked both directly with the USACE and general contractors.

In the latest and final phase of the dike rehabilitation, BAUER Foundation Corp. was contracted by the U.S. Army Corps of Engineers, to construct a cut-off wall along the southwestern section of the dike. Divided into five sections, spanning approx. 56 kilometers. BAUER Foundation Corp was awarded three of the five available contracts - Task Orders 1 and 3, and Task Order 5. The scope included the installation of 384,475 m² of underground cut-off wall and jet grouting installation for connection to existing structures, Civils works including platform construction, restoration, sodding and Asphalt, and Verification borings and Lab testing.

Subsurface Conditions
Figure 7 shows a simplified embankment cross section and soil profile. The approximately 7.6-m-high embankment consists predominantly of loose to dense, fine to medium, clean to silty or clayey sands. A layer of organic materials up to 3.7 m thick was encountered at the top of the natural ground. These materials are mainly peat and organic silts. Below the organics there is often a layer of decomposed limestone, which mostly consists of clays and silts, but can also consist of sand or shell. In some parts, a hard cap rock is encountered within this layer.

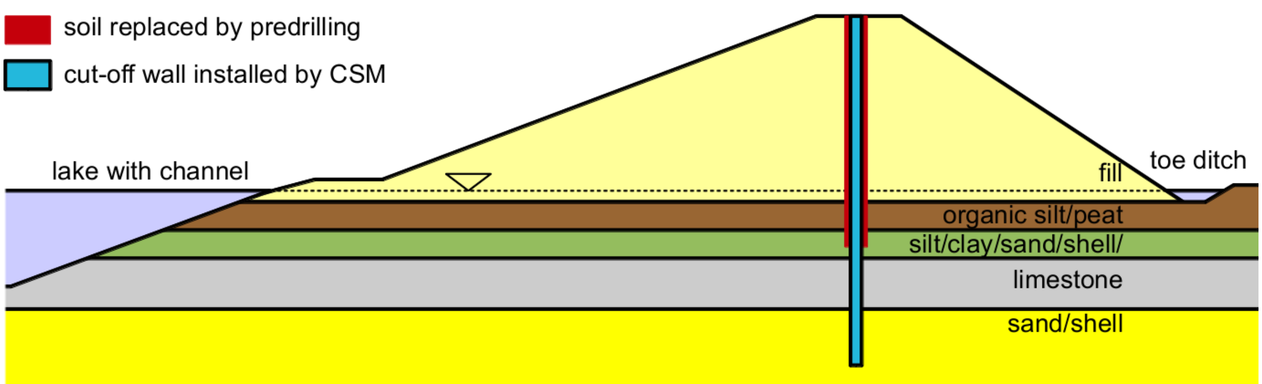

Figure. 7: Idealized soil profile (from Arnold et al. 2011).

Below are interbedded layers of hard limestone and sands. The hard limestone is typically highly permeable. The densely packed and highly permeable sand layers consist of quartz sand, shell, or mixtures thereof. For a more detailed description of the subsoil conditions please refer to Arnold et al. (2011) or Arnold (2015).

Construction methods / Techniques
Bauer used the cement deep soil mixing method of Cutter Soil Mixing (CSM) to install the wall to depths between 17 to 26 m. The CSM panels were installed with a thickness of 640 mm. To facilitate soil mixing with the CSM, the organic soils were replaced with materials suitable for soil mixing by means of a series of cased, Kelly-drilled replacement columns (Figure 8). Typically, two Bauer BG 28 were used to produce the replacement columns and one RG 25 with a BCM 5 tool with a footprint of 2.4 m x 0.64 m were used for the soil mixing.

The two construction stages at HHD

1. Replacement of unsuitable organic materials with non-organic backfill.
2. Installation of CSM cut-off wall

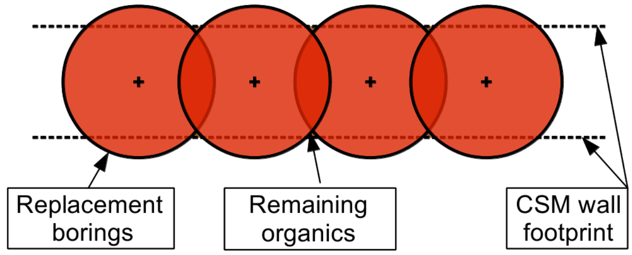

Figure. 8: Two construction stages at HHD – schematically only

At the connection to existing structures Bauer used the Jet Grouting (JG) method to maintain a continuous cut-off between the interface of the structure and the CSM cut-off wall. During the jet grouting process, the soil surrounding the drill string is eroded by a high energy fluid jet and mixed with a self-hardening cement suspension. The Jet Grout columns were installed with a diameter of approximately 1.2 m using a 1-phase (single fluid) system.

Figure. 9: Cut-off wall construction

The CSM construction sequence is as follows (Figure 10):

1. Positioning of the cutter head in the wall axis. The construction of a guide wall is not required.
2. The mixing tool is driven into the ground at a continuous rate. The soil matrix is broken up by the cutting wheels and at the same time a fluid is pumped to the nozzles, set between the cutting wheels, where it is thoroughly mixed with the loosened soil. Adding a compressed airstream can improve the breaking and mixing process in the downstroke phase. The direction of rotation of the wheels can be varied at any time. The rotating wheels and cutting teeth push the soil particles through vertically mounted shear plates that have the effect of a compulsory mixer. Penetration speed of the cutter and the volume of cutting fluid pumped in are adjusted by the operator to optimize the absorption of power and to create a homogeneous, plastic soil mass which permits easy penetration and extraction of the machine. Typical speed of penetration is about 20 – 60 cm/min.
3. After reaching the design depth, the mixing tool is slowly extracted while cement slurry is continuously added. Homogenization of the liquefying soil mixture with the fresh cement slurry is ensured by the rotation of the wheels.

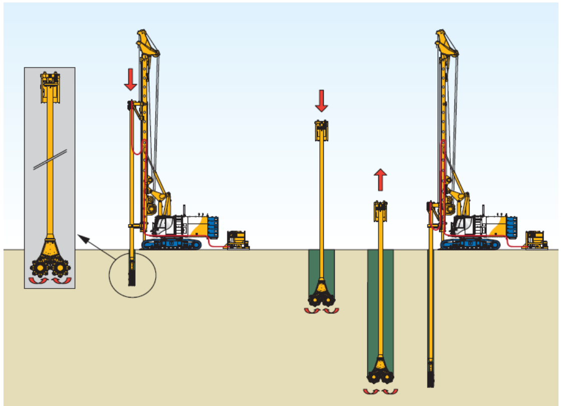

Figure 10: Construction sequence CSM.

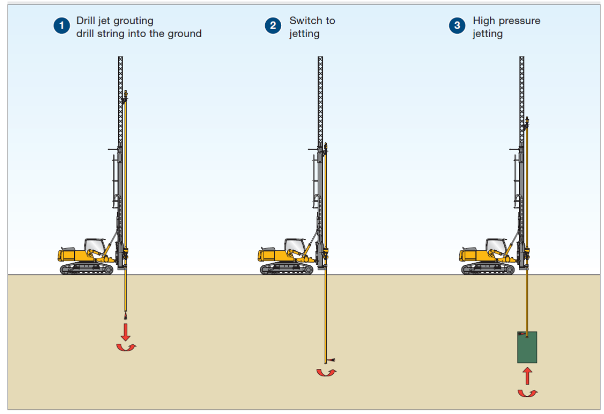

Figure 11: Sequence JG using the 1 Phase method.

The Jet Grouting construction sequence is as follows (Figure 11):

1. A string of jet grouting rods is drilled into the ground to the required depth by a rotary drilling rig. The lower end of the drill string is fitted with a nozzle holder and a laterally mounted jet grouting nozzle.
2. Jetting fluid is pumped through the jet grouting nozzle at high pressure 400 to 600 bar. This produces a high-energy "cutting jet" that erodes the soil from its natural position and mixes it with the binder slurry. The diameter of the column is determined by the density and type of soil as well as the jet grouting parameters.
3. By rotation and simultaneously retracting the jet grouting drill string, the cutting jet creates a tightly spaced helix in the soil, resulting in a column-shaped space filled with binder suspension and soil. The binder causes this mixture to set and solidify, as a result of which load bearing jet grout columns are formed.

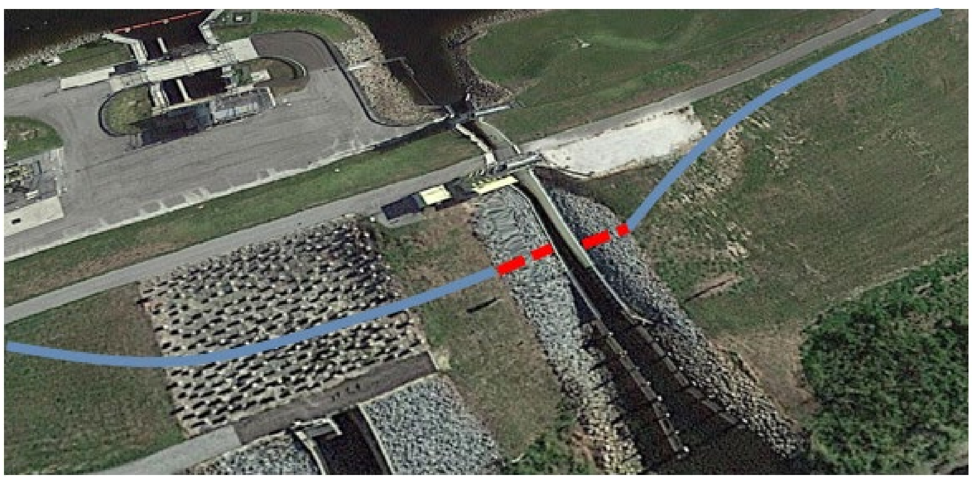

Figure 12: Jet Grouting locations TO 1.

Quality Control

Several parameters were monitored and tested for quality control and verification purposes, including in-situ sampling carried out by both the wet grab method and coring. In some instances, inclined coring was utilized whereby multiple elements can be captured. Post-coring and an in-situ permeability test were performed, in addition to visual verification via the use of an optical televiewer and CCTV.

Cutter Soil Mixing and Jet Grouting were successfully utilized by BAUER to install a cut-off wall up to 26 m deep at the Herbert Hoover Dike Rehabilitation project.

2.3 Teller Dam - Colorado

The Teller Dam at the Turkey Creek River is located within the U.S. Army post Fort Carson south of Colorado Springs in Colorado. The remediation works are coordinated by the U.S. Army Corps of Engineers (USACE). The prime contractor, Komada LLC, commissioned BAUER Foundation Corp. with the execution of the specialist foundation engineering works

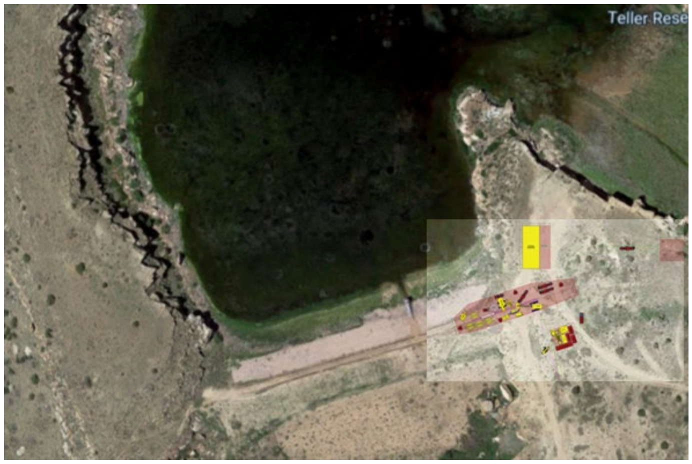

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Figure 13: Location of the project.

The cut-off wall works included the execution of approximately 1,189 m² secant pile wall and 1,175 m² of grout curtain treatment at the left abutment (Figure 13).

The aim of the cut-off wall is to intercept potential seepage pathways that could contribute to internal erosion of dam material along the dam and abutment contact. The cut-off wall consists of two sections, a secant pile wall through the left end of the dam and abutment and at the abutment contact, and a grout curtain to further extend the interception of seepage pathways at the left abutment.

The cut-off wall has been divided in three different Technique Areas (TA) based on soil profile characterization (Figure 14)

- TA-1: through the embankment and 1.5 m into the Glencairn shale,
- TA-2: through the embankment and sloping abutment contact - primarily sandstone - and 1.5 m into the Glencairn shale,
- TA-3: through the sandstone abutment and 1.5 m into Glencairn shale.

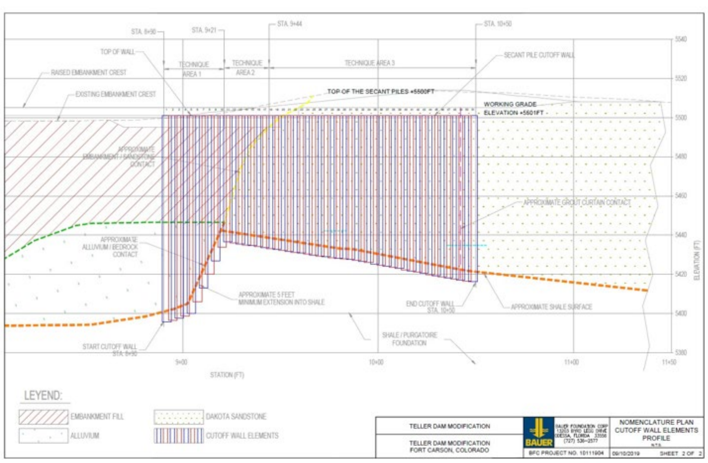

Figure 14: Left abutment - Secant pile wall layout

The bedrock encountered during the cut- off wall installation is a mixture of Glencairn shale and Dakota sandstone, with rock strengths (UCS) exceeding 100 MPa.

The secant pile wall and grout curtain total length is approximately 106 m, reaching a maximum depth of 36.5 m.

The secant pile wall comprised of piles with a diameter of 1,500 mm, constructed with a BAUER BG 39 in combination with a casing oscillator for the temporary segmental casing installation. The pile execution had to follow tight verticality requirements; a minimum pile overlap, and minimum continuous cut-off wall thickness had to be guaranteed throughout the entire pile length, considering the challenge of a very steeply angled soil- rock interface.

Secant pile cut-off wall installation (Figure 16) was carried out with a Bauer drilling rig using deep temporary segmental casing up to the top of the rock in TA-1 and TA-2 (cased holes), and temporary surface casing in TA-3 (uncased holes). No drilling fluids were used as excavation support, but it required water to control temperature of the drilling equipment during rock excavation. Therefore, no risk of hydraulic fracture, erosion, filter/drain contamination, heave, or other mechanisms during drilling operations were considered.

Figure 15: Roller core barrel / Cross cutter /Cleaning brush

According to the specification, three different methods for verticality measurements: Drilling Inclination System (DIS), Rope Inclination System (RIS) and Prad Sensor (PRAD) had to be used to confirm the required cut-off wall parameters. To verify water tightness, verification boreholes were cored between two adjacent piles allowing Closed Circuit Television (CCTV) videos, Optical Televiewer (OPTV) images, and permeability tests based on falling head tests were conducted.

Figure 16: Secant pile wall construction

Fig. 17: Grout curtain installation

The actual grout curtain installation (Figure 17) included drilling or coring of the embankment soil, bedrock sandstone, and 1.5 m embedment into shale using a Klemm 806. All primary drill holes were cored and referenced as exploratory holes in the specifications. Secondary, tertiary, and quaternary elements were drilled utilizing a down-the-hole water hammer system. Primary elements were cored using a Boart-Longyear HQ3 triple-tube

wireline coring system. The HQ3 coring bit produces a 96-mm hole with 63.5-mm cores. All grouting elements were drilled using the W70 hammer from Wassara.
The grouting was executed using inflatable packers supported by automated grout plants and a grout buggy. Several mix designs were preloaded into the user interface allowing the operator to easily select and mix the desired mix design for the grouting operations. Grouting works included real-time computer monitoring, single, and double packer grouting considering the upstage grouting method but also the downstage grouting method in specific cases. Lugeon testing and OPTV surveys were executed to locate and identify potential rock fissures.

4. Summary and Conclusion

For more than 35 years, BAUER Spezialtiefbau GmbH, together with its subsidiaries, has been successful in the field of design and execution of specialist foundation services, including cut-off walls for dams, dikes, and levees. The many years of experience and the successful implementation of the existing innovative know-how are impressively demonstrated by the work carried out by our valued employees, the successfully implemented projects and satisfied clients.

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The Authors

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M. Baltruschat graduated as Diploma Geologist (equivalent to B.S. and M.Sc.) from Technische Universität in Berlin (Germany) in 1994. He has been with BAUER Spezialtiefbau GmbH since 1995 as site and project manager, tender manager and head of two specialist departments. Since 2005, he is a senior project manager and tender manager in the field of dam, dike and mining projects worldwide.

B. Harris holds a Bachelor of Science in Civil Engineering. Bryn started his career in the specialist foundation industry in the United Kingdom 18 years ago, having started in the field and progressing through the tendering and commercial teams, Bryn moved to Canada in 2012 to become Commercial Manager for Bauer Foundations Canada. Over the last 10 years with Bauer, Bryn has been responsible for Commercial Management and has worked as part of the project management team in the execution of major projects in Canada, Bangladesh, and the USA. Bryn now holds the position of Vice President – Operations for BAUER Foundation Corp.

M. Bertoni is a Preconstruction Manager for BAUER Foundation Corp. Originally from Italy, where he practiced as a Professional Geologist, he moved to the USA in 2008. In the over 14 years he has lived in the States, he was assigned to several projects, where he had the opportunity to familiarize with various construction techniques and work with very experienced and knowledgeable people.

C. Bou Sleiman has a Bachelor and Master of Engineering in Civil and Environmental Engineering from the Lebanese American University. He has been an employee of Bauer since 2008 with project execution experience on various different specialist foundation techniques and in countries including, the Philippines, Qatar, the United Kingdom and the USA. He currently holds the position of Operations Manager in BAUER Foundation Corp. USA.