

The Remediation of Buckeye Lake Dam, Ohio: Deep Mixing as an Interim Risk Reduction Measure and Key Component of Final Design

Daniel P. Stare, P.E.¹, George Filz, Ph.D.², Donald A. Bruce, Ph.D., C.Eng.³

¹ Principal Geotechnical Engineer, Gannett Fleming, Inc., 207 Senate Avenue Camp Hill, PA 17011, dstare@gfnet.com

² Virginia Tech, Charles E. Via Professor, Assistant Department Head, Civil & Environmental Engineering Department, Director of the Center for Geotechnical Practice and Research, filz@vt.edu

³ President, Geosystems L.P., PO Box 237 Venetia, PA 15367, dabruce@geosystemsbruce.com

ABSTRACT

Rehabilitation of Buckeye Lake Dam in central Ohio presented significant logistical and technical challenges given the history of the site, limited access and the proximity of private residences to the work. Covering almost 200 years, Buckeye Lake has a rich and varied history of industry and recreation. Presently a State Park administered under the Ohio Department of Natural Resources, the seepage, stability and hydraulic performance of the existing embankment dam was deemed unacceptable necessitating rehabilitation of the structure. Flanked by private residential and commercial properties at the downstream dam crest, construction of the new seepage barrier and new dam necessitated selection of appropriate construction methods and close coordination with the public. After presenting a brief history of the site, this paper focuses primarily on the different deep soil mixing methods utilized to construct the seepage barrier as well as the use of additional deep soil mixing downstream of the seepage barrier to construct a composite gravity dam structure.

INTRODUCTION

Constructed in the period from 1825 to 1837 and then known as Licking Summit Reservoir, Buckeye Lake Dam formed a feeder lake for the Ohio and Erie Canal system. Situated on a high plateau in a historically marshy area, the location provided a natural site for impoundment of water and for feeding the canalways to the north and south. Subsequent domination of freight transport by the railroads in the mid to late 1800's resulted in abandonment of the canal and appurtenant structures. Beginning in the early 1900's, the resulting 2,800-acre lake was primarily utilized for recreation for those living in central Ohio and beyond. Most recently, and as illustrated in Figure 1, the area has seen significant development inclusive of construction of several hundred private residences on and within the historic 4.1-mile-long dam embankment.

In the 1960's, notable high pool events necessitated heroic efforts on the part of the State of Ohio - Department of Natural Resources and USACE Huntington District to prevent failure due to overtopping and piping. Reconstruction of the original principal spillway and the construction of an auxiliary spillway in the 1990's provided additional hydraulic capacity for the structure.

However, seepage outbreaks and upstream slope instability continued to occur, and the hydraulic capacity remained inadequate resulting in predicted overtopping even under sub-PMF conditions.

In 2015, the Ohio Department of Natural Resources sought a long term solution to the dam deficiencies. An alternative contract delivery method was used as well as a two phase approach to provide interim risk reduction and construction of a new dam. Deep mixing was the principal seepage risk reduction measure during the interim phase completed in mid-2016. The second phase, which includes constructing a gravity dam section using deep mixing methods immediately upstream of the existing embankment, is presently under construction.

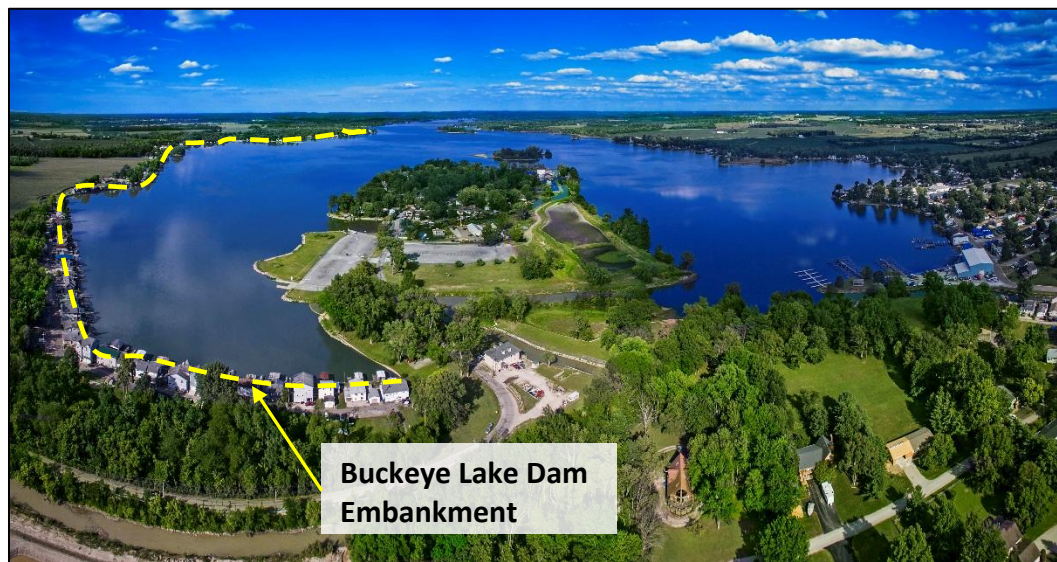


Figure 1: Aerial Photograph of Buckeye Lake

Included within the paper is a discussion of the two different types of deep mixing employed for the interim phase where approximately 860,000 square-feet of cutoff wall was constructed in 74 days. The strengths and weaknesses of the methods are presented. Design concepts for the permanent gravity structure, of which deep mixing will be the principal means of construction are also presented.

EXISTING CONDITIONS

As originally constructed, the maximum 12-foot high dam embankment consisted of fine-grained soils reportedly obtained from local excavations. On the upstream side of the embankment, a masonry retaining wall was constructed in about 1832. Various phases of sheet piling were installed upstream of sections of the existing masonry walls starting in approximately 1948. Prior to this most recent remediation, the upstream shoreline consisted of masonry retaining walls along the southern third of the dam, and steel sheet piling along the remainder.

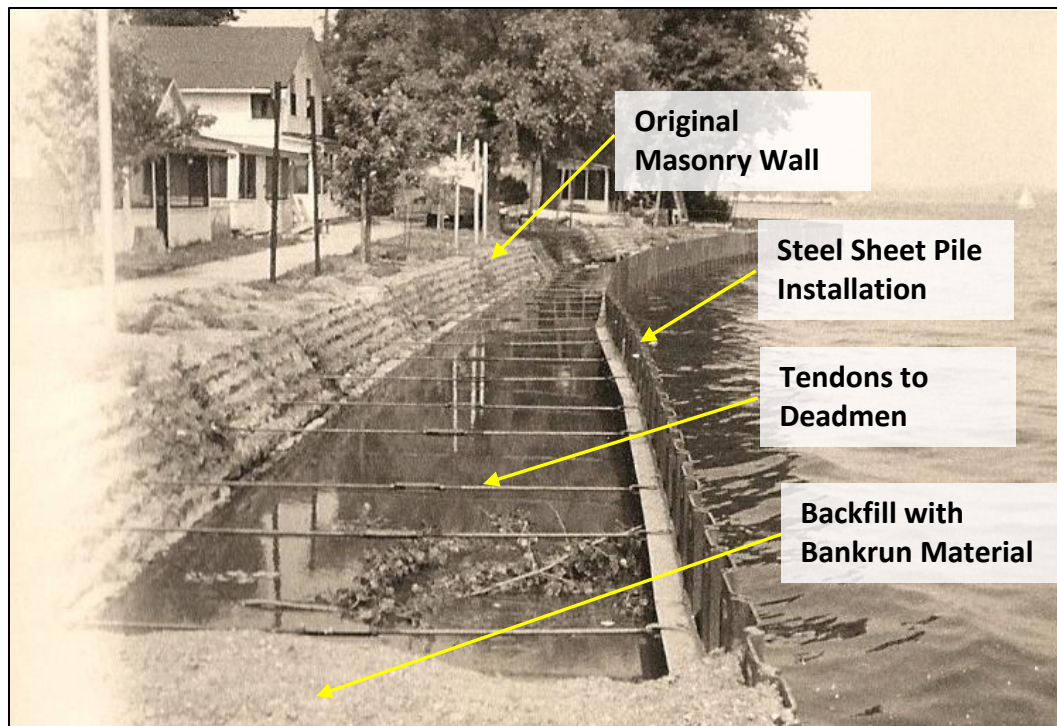


Figure 2: Circa 1960 Steel Sheet Pile Installation Upstream of Masonry Wall

Prior to construction of the cutoff wall, conventional earthmoving equipment was utilized to place the stability berm immediately upstream of the existing dam. The berm materials consisted of bank run soils obtained from nearby commercial quarries. This material was glacial in nature and classified as poorly graded sand in accordance with the Unified Soils Classification System. Rip-rap on the upstream slope of the stability berm completed the minimum 30-foot wide surface upon which deep soil mixing would be conducted.

Native soils were present below the bottom of the stability berm. While the depositional environment of the site is complicated by the glacial history of the area, a general stratigraphic profile of the native materials is as follows:

- Surficial Lake Sediments – Recent lake sediments 1 to several feet in thickness and typically consisting of sands and silts with moderate organic content.
- Lacustrine Soils – Fine-grained soils deposited by glacial lakes, typically 10 to 30 feet in thickness, and having frequent sandy stringers.
- Fluvial/Alluvial Soils – Higher energy glacial deposits of sand and gravel with various fine-grained stringers, typically 10 to 30 feet thickness.
- Glacial Till – Very dense silt with gravel extending to bedrock.
- Bedrock – Reported to be sedimentary in nature and approximately 100 feet or more below the ground surface.

With a cutoff wall extending to a depth of 43 feet, the materials within the mixed zone consisted of the stability berm materials and all of the above soils. Bedrock was not encountered during the work.

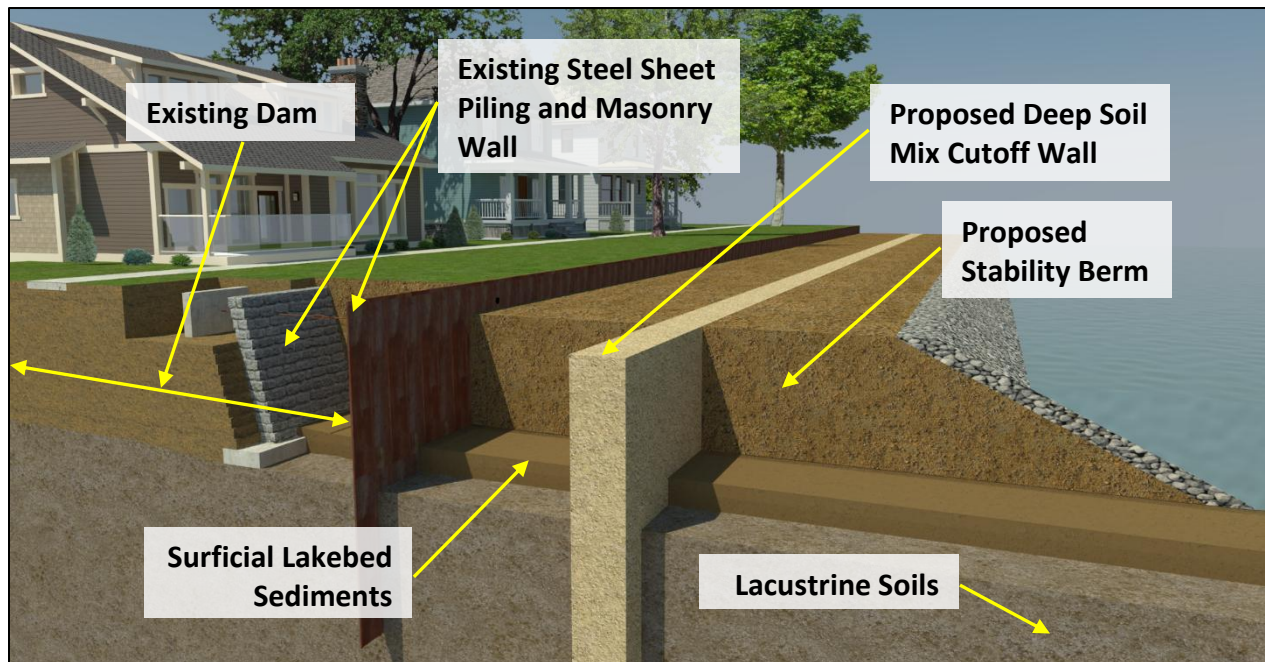


Figure 3: Typical Conditions

INTERIM RISK REDUCTION

The principal Failure Modes for Buckeye Lake Dam were determined to be unacceptable seepage performance, instability, and overtopping. Using a two-phase approach, seepage and stability risks were to be mitigated during the first, Interim Risk Reduction (IRR) Phase I, while overtopping risks are to be mitigated in the next phase, Phase II, through construction of a gravity structure immediately upstream of the existing embankment and downstream of the soil mix cutoff wall.

Access constraints for construction on and downstream of the existing embankment dam necessitated the construction of a temporary access in the form of a berm along the shoreline of the existing dam. This 30-foot wide berm served a dual purpose. While not only providing access for construction, the berm also buttressed the existing shoreline features which included a masonry retaining structure along approximately the southern one-third of the dam, and flat steel sheet piling along the remainder of the dam. A photograph of the stability berm and proximity to adjacent residences is included as Figure 4.



Figure 4: Stability Berm Construction

The schedule for implementation of IRR Phase I was aggressive with construction starting in November 2015 and ending in June 2016. Approximately 400,000 cubic yards of imported fill were required for construction of the stability berm and approximately 860,000 square-feet of cutoff wall were required to complete the seepage barrier.

Deep mixing was the selected seepage barrier construction method for the cutoff wall. Various other cutoff wall construction methods were evaluated including a cement-bentonite diaphragm wall and steel sheet pile. However, deep mixing presented the best overall economy and minimal risk to the existing structure and adjacent residences. The following performance-based specification requirements were established for the cutoff wall:

- Minimum continuous width of 24-inches
- Minimum depth of 43 feet below berm surface
- Minimum unconfined compressive strength of 100 pounds per square inch
- Maximum in-situ permeability of 1×10^{-7} centimeters per second

Two contracts were awarded for construction of the 43-foot deep soil mix cutoff wall. Raito of Hayward, California was awarded approximately 58% of the work, while Dewind One-Pass Trenching of Zeeland, Michigan was awarded the remaining 42%. Raito utilized conventional wet rotary shaft mixing methods while Dewind utilized the chain mixing method. Both methods are discussed in detail below.

WET ROTARY SHAFT METHOD (WRSM)

Wet rotary shaft mixing consists of rotation and vertical penetration of the mixing tool and simultaneous injection of a cement slurry. Given the required geometric constraints of the cutoff wall, Raito selected a multiple shaft mixing system whereby three columns were constructed simultaneously. The mixing rig was oriented such that the tracks straddled the proposed wall alignment and mixing occurred on the trailing side of the rig travel direction. Spoils handling was also conducted on the trailing side of the mixing equipment.

Mixing shafts were spaced at 24-inches on center, and diameter of the mixing tools was approximately 39-inches. The resulting minimum wall width at column overlap was

approximately 31-inches assuming no deviation of the columns during construction. Simultaneous construction of the three columns resulted in a soil-mixed element approximately 6 feet in length.

Mixing equipment provided by Raito (Figure 5) consisted of a diesel powered crawler piling rig with an electric top drive. A hoist coupled to the top drive unit provided for vertical movement of the top drive and integral mixing shafts along the mast. Twin 90 kilowatt electric drive multiple pole motors coupled to gear boxes provided the rotational energy to the mixing shafts. This allowed mixing to occur at approximately either 20 rotations per minute (RPM) or 40 RPM. Various instruments were provided on the mixing rig to monitor tool depth, mast inclination, shaft rotation speeds, penetration rates, and grout injection rates.



Figure 5: Raito Wet Rotary Shaft Mixing Equipment

The binder slurry consisted of a cement-bentonite slurry, which was batched at a centralized batch plant and pumped to the mixing operation. Batching and mixing was conducted using an automated high-shear plant equipped with load cells. After batching, the binder slurry was pumped via three separate piston pumps to each of three separate delivery lines routed to the mixing rig. Each delivery line was monitored separately by individual flowmeters.

After initially starting with work with a slightly higher cement factor, Raito completed the vast majority of the project with the following binder slurry mix design:

- In-Place Cement Factor: 278 kg/m^3 (467 lbs/CY)
- Bentonite Dosage: 18.5 kg/m^3 (31.2 lbs/CY)

- Slurry Water to Cement Ratio: 1.7

Raito provided an electronic quality control monitoring system for both mixing rig and batch plant. Grout batch components were weighed or measured individually and recorded for each batch. A quality control report was provided for each element and included target slurry volume and penetration rates, and measured mixing tool advancement rate, RPM, mast inclination and energy index.

CHAIN MIXING METHOD (CMM)

The chain mixing method differs significantly from conventional rotary mixing methods given the type and orientation of the mixing equipment. In the rotary shaft methods the mixing tool is advanced vertically and mixing is incrementally performed at deeper depths as the mixing process progresses. Chain mixing utilizes a vertical bar with a mixing chain running its entire length. Rotation of the chain along the bar much like a chainsaw provides the mixing action. Once inserted into the ground to the desired depth (Figure 6), the rig trams horizontally pulling the bar and rotating the mixing chain. Mixing is performed continuously from top to bottom of the over the length of the bar as a result.



Figure 6: Dewind Onepass Rig – Bar/Chain Entry on Left, Mixing Position on Right

The specific rig provided by Dewind consisted of an excavator base with a custom drive unit and mixing bar/chain. Diesel engines provided the mixing power by direct coupling to the mixing chain through a transmission. The total combined power of the mixing engines was approximately 1,600 horsepower. Typically mixing was conducted at full engine RPM and in high gear. This resulted in an estimated chain speed of approximately 14 feet per second.

Portland cement was used as the binder in the mixing process. Bulk trucks pneumatically delivered cement directly to a hopper on the rig and a calibrated auger feed system conveyed dry cement from the hopper to the mixing chain immediately below the ground surface. At approximately mid-depth of the bar, a water delivery port was located to deliver pumped lake water directly to the trench at-depth. While dry cement is delivered via this specific system, it should not be considered a dry mixing method given the simultaneous delivery of water and aggressive mixing action of the chain.

The target mix design utilized by DeWind consisted of the following:

- In-Place Cement Factor: 240 kg/m^3 (404 lbs/CY)
- Slurry Water to Cement Ratio: 1.03 (calculated based on weight of materials injected)

The mixing process was controlled by monitoring of the cement auger feed rotations, water usage by flowmeter, and tram speed of the mixing rig. Using these parameters, the contractor was able to calculate in-place cement factor and water to cement ratio. Additionally, the consistency of the spoils was monitored to ensure they were adequately fluid to facilitate enhanced mixing action. An inclinometer was provided on the rig to monitor inclination of the bar/chain in the upstream/downstream direction. Rig tram speed was closely monitored as it directly correlated to the mixing energy applied per unit of volume of mixed material.

METHOD COMPARISON

While with each mixing method came unique capabilities as well as complexities and challenges, both the chain mixing method and wet rotary shaft method proved successful on the project. Design for future deep mixing is underway to construct a soil-mixed buttress immediately downstream of the cutoff wall and upstream of the existing dam. Lessons learned from the Interim Risk Reduction phase will prove valuable in subsequent phases of this project.

As discussed below, the WRSM and CMM are evaluated with respect to various categories of capacity and performance. The evaluations provided are based upon the experience of the authors at Buckeye Lake and other projects where these deep mixing methods were utilized.

Geometry

The WRSM provides for the ultimate in flexibility when it comes to the geometry of the proposed elements. Given the vertical penetration of the mixing equipment, the geometry is limited only by the imagination of the designer. The WRSM allows for construction of acute angles in walls, isolated foundation elements, varying depth among elements, and elements of various diameters if one so chooses. The drawback to such flexibility is continuity between elements as discussed below.

The CMM is ideally suited for long lengths of relatively straight walls at the same depth. Given the limited capability to articulate the bar and chain, turning a “hard” corner is not possible without removing the equipment from the ground and starting a new trench at a different alignment. The practical limit for a radius in the wall using the specific equipment provided at Buckeye Lake was approximately 30 feet. What the CMM lacks in geometric flexibility is offset by the assurance of wall continuity.

Continuity

Continuity is defined as contact between adjacent constructed elements, and this contact or intersection meeting the design requirements of the cutoff. Often the issues of minimum continuous wall width and the potential for a “window” in the cutoff are of concern. With the WRSM, or any method where continuity is not inherently ensured, these issues must be considered by the designer and the designer must have an understanding of the realities of work layout and monitoring resolution of the instruments used in the layout and control process. Certainly the contractor will attempt to minimize their costs by minimizing the number of elements to construct, and they are undoubtedly entitled to do so on a performance-based contract. This is achieved by maximizing the spacing of the elements, which minimizes overlap between adjacent elements. In principle and on the ground surface all may appear fine, but the true concern is what happens at-depth when deviations occur. Tolerances and resolution must be considered for all equipment used to layout and control the work such as survey equipment, inclinometers or instruments used to measure mixing tool deviations, the calibration of the instrument, resolution compatibility between an instrument and the display of the instrument data, etc. Monitoring must also be performed at the appropriate locations, preferably on the mixing tools, rather than on the rig mast. Errors can compound, and with no ability to visually or consistently verify continuity, realistic assumptions must be made such that continuity is ensured.

Continuity is strong aspect of the chain mixing method. Given mixing occurs over the entire vertical face of the advancing tool, and presuming that binder dosing occurs without error, it can be assumed the wall is continuous from bar/chain entry to exit of the trench.

Homogeneity

Both WRSM and CMM have their positive aspects with respect to homogeneity. WRSM mixing energy, typically expressed as a blade rotation number, and binder dosage can be varied with depth allowing for application of increased mixing energy and binder contents at identified problematic soil layers. While some vertical mixing of materials occurs with WRSM, it is typically considered to be minimal for all practical aspects, therefore the consistency of the resulting columns can vary over their depth.

Homogeneity is key feature of the CMM. While binder content and mixing energy cannot be varied with depth, the mixed materials are exceptionally homogeneous. The speed of the mixing chain coupled with the prevalence of teeth on the chain impart significant mixing action.

Materials within the trench are effectively mixed twice as the both the front and back of the chain advance through the trench.

Spoils Management

At Buckeye Lake both WRSM and CMM required separate spoils management activities. The equipment used is similar in that a medium size excavator performs this function on the trailing sides of the mixing equipment. One distinct difference is the need to pre-excavate and subsequently backfill after mixing tool withdrawal on each element with the WRSM. This activity, and spoils management in general in the immediate vicinity of freshly mixed elements, presents a high likelihood for contamination of the elements with unmixed materials. Practically speaking, on a constrained site the WRSM requires additional working area to effectively manage spoils.

With the CMM, spoils management is typically only necessary to preserve a clear pathway for service equipment at the trailing end of the rig. Given the bar/chain cannot be retrieved without complete rotation/removal of the bar from the trench, routine service is conducted with the bar/chain oriented in the mixing condition and from the trailing side of the machine. Only catastrophic failure to key components necessitates bar/chain removal. No pre-excavation or backfill is required for the CMM, and spoils are typically left in-place until adequately solidified for removal by conventional excavation.

CONCLUSIONS

Both the CMM and WRSM proved successful at Buckeye Lake Dam and have historically proved successful at other projects. With each method come unique capabilities as well as complexities and challenges that may or may not be suitable for specific projects. Future work at Buckeye Lake Dam will entail additional mixing to construct a buttressing gravity section immediately downstream of the prior constructed cutoff wall, as well as soil mixed pile elements located at the downstream side of the buttress for foundation support. Both methods are inherently suitable for the proposed future work.