ASCE 1994 Annual Convention & Exposition
Civil Engineers-Champions for the Global Environment
Atlanta, Georgia
October 9-13, 1994

A Deep Soil Mix Cutoff Wall At Lockington Dam, Ohio

Andrew D. Walker[1], M. ASCE

Abstract

The Miami Conservancy District built five flood control dams after the catastrophic flood of 1913 in Dayton, Ohio. Lockington Dam was one of these five hydraulic fill structures. The Ohio State Department of Natural Resources (ODNR) issued new regulations in 1981 requiring that design flood for class I dams be considered equal to the Probable Maximum Flood (PMF). Flood routing studies performed for the PMF calculated inflow indicated that the reservoir rose to the crest of the dam. Therefore, the existing dam core required extending to the crest level to maintain dam safety. The extension was constructed using a deep soil mix soil-cement cutoff wall. This paper will describe the cutoff wall from conceptual design through to construction, including alternates considered, construction methods and data obtained, both prior to and during construction.

While Deep Soil Mixing (DSM) has been used on contaminated sites as a method of containment and for dam foundations to decrease the risk of liquefaction, Lockington Dam represents one of the first applications as a conventional cutoff on an existing dam.

Introduction

The largest single project under construction in the United States in 1919 was the flood control works of the Miami Conservancy District. Started in 1918, the five flood control dams and 73 miles of levees which made up the project, would not be completed until 1921 (ENR, 1994).

Work was initiated in response to ten major floods which had inundated Ohio's Miami Valley at various times over the previous century, claiming more than 1,000 lives and causing more than $100 million in property damage. Historically,

[1]Project Manager, Geo-Con, Inc., 4075 Monroeville Boulevard, Monroeville, PA 15146

this project saw the first ever use of electrical draglines on a large construction contract.

Power shovels excavated raw materials from the pits which were then mixed with water to form a slurry and pumped by dredge pipes to the dams. The water gradually drained and the dam rose in layers of impervious clay in the center, providing the waterproof core, with sand and gravel forming the dam shell. this use of hydraulic fill, while not a first, was one of the largest such applications ever recorded.

One of the five structures, the twenty-one meter high Lockington Dam, is located on Loramic Creek, a tributary of the Great Miami River, north of Piqua, Ohio. The 1,950 meter long dam is founded on Cedarville limestone bedrock with a combined central low level outlet and emergency spillway (Figure 1). No permanent reservoir exists upstream of the dam as it is operated purely as a flood control project with storage only occurring when the upstream runoff exceeds the capacity of the outlet structure.

Figure 1. Aerial View of Lockington Dam

The central impervious core was built to about 4 meters below the dam crest which corresponded, at that time, to the maximum reservoir level for the Official Plan Flood (OPF).

Site Geology

Test pits were excavated in the summer of 1991 to augment boreholes sunk in 1983 as part of the original preliminary studies. This site investigation indicated that the general geological succession in the upper 6 meters of the dam consisted of:

- A medium dense grey moist gravelly sand to sandy gravel classifying as an SP to SM to a GW to GO material, 1.5 to 4.3 meters deep. Mostly gravel was encountered in the west side of the spillway with mainly sand encountered on the east side. As mentioned, this material was probably placed by pit run hydraulic methods. The absence of significant fines in this upper layer indicated that no attempt had been made to obtain finer grained fill for this upper zone. Based on the Unified Soil Classification, this material has a permeability ranging from 10 cm/sec (GW) to 3 x 10^{-3} cm/sec (SM). Falling head permeability tests in this strata indicated permeabilities as high as 4 x 10^{-2} cm/sec.

- A loose brown silty sand to soft sand silt, wet to saturated in layers classifying as SW-SM to ML, 1 to 2 meters thick. This material appears to be the start of the core material. Test pits indicated a heterogeneous material, with thin layers of sand and gravel within the wet silt and fine sand layers. This layering is typical of hydraulic fill placement.

- A soft brown wet to saturated sandy silt to silty clay below the bottom of the above layer to the dam foundation, classifying a ML to CL, 1 to 8 meters thick. This material is the clay core and appeared to be somewhat finer than the layered strata above.

Design Considerations

Lockington Dam is classified as a Class 1 structure by the Ohio Department of natural Resources (ODNR). Accordingly, under regulations issued in 1981, the design storm for the structure is considered equal to the Probable Maximum Flood (PMF).

Hydrologic studies performed in 1982, 1988 and 1990 indicted that the PMF would exceed the Official Plan Flood (OPF) producing reservoir storage levels higher than the design storage level. It was evident that the dam fill material overlying the core would transmit a significant amount of seepage under PMF conditions.

The client’s consulting engineer, Harza of Chicago, estimated that during PMF reservoir storage conditions, the reservoir water level would be 1.2 meters below the crest for more than two days and 4.3 meters below the crest for more than one week. The resulting seepage through the upper core could produce potentially unstable conditions leading to a sliding or piping failure of the dam.

It was recommended that a cutoff be constructed in this permeable zone, extending at least one meter into the existing core material, thus assuring the safety of the dam during a PMF event.

A major consideration in cutoff selection was the potential for drying out and cracking of the wall with time. The upper part of the dam had remained above the highest reservoir level for over 70 years. With the sand and gravel having a moisture content of around 3.5 percent, a significant loss of moisture from the wall with time was anticipated.

A further requirement for the cutoff was an intimate contact at the spillway abutment walls that bisect the dam near its midpoint.

Cutoff Alternatives

A number of techniques were studied for forming the cutoff wall including:

- Open excavation and replacement with compacted clay material.
- Steel sheetpile cutoff.
- Pre-cast concrete panels.
- Soil-bentonite slurry wall.
- Jet grout curtain.
- Soil mixed cutoff wall.
- Cement-bentonite slurry wall.

Detailed costings indicated that the latter three methods were the most economical. The narrowness of the crest at twenty four feet, and the length of the dam, dictated remote mixing for a soil bentonite wall. A cement bentonite wall was therefore the favored slurry wall option. The slurry wall design incorporated a full depth HDPE liner to maintain wall integrity should possible desiccation of the backfill occur with time. This was a genuine concern, given that the cement bentonite backfill consists of 90% water which is stabilized by the use of bentonite. As explained later, this is not a problem for a soil mixed wall, where the water solids ratio of the soil-cement-bentonite is low.

A major advantage of the soil mix wall technique was that there was no excavated soil for disposal, or a need for remote mixing operations, with all the mixing taking place in-situ.

Accordingly, the bid package allowed contractors to bid either an auger mixed soil-cement wall and/or a conventional cement-bentonite slurry wall.

The price received from Geo-Con, Inc., for the soil mixed alternate was ten percent lower than the slurry wall and met all requirements of the specification, thus Geo-Con was awarded the contract. Interestingly, the price differential was very close to the cost of the supply and installation of the HDPE liner specified for the slurry wall.

Deep Soil Mixing

Pioneered in Europe and Japan, the Deep Soil Mixing System has made dramatic progress in the United States in the last few years with the completion of many successful projects involving a wide range of applications (Ryan and Jasperse 1989; Reams, Glover and Reardon 1989).

A specific American evolution of the technique has been site remediation of hazardous wastes where, for instance, high soil disposal costs are eliminated, nevertheless, the list of major structural walls and cutoff applications on clean sites continues to grow (Jasperse and Miller 1990). The Lockington site is, to the author's knowledge, the first use of Soil Mixing in the United States to raise the core of an existing dam.

Deep Soil Mixing equipment consists of a DSM rig and a grout plant. The base machine for the rig is a 175 tonne crawler crane fitted with a set of leads. The leads guide a series of four hydraulically driven, overlapping mixing paddles and auger flights (Figure 2).

Figure 2. DSM Augers

The auger flights are 0.9 meters in diameter. As the hollow-stem augers penetrate, a slurry is injected through their tips. The flights break the soil loose which the paddles then blend with the grout. As the augers advance to greater depth, the mixing paddles continue to mix the soils. When the design depth is reached, the mixing shaft rotation is reversed and the mixing process continues as the shafts are brought to the surface.

An overlapping pattern of primary and secondary strokes is used ensuring a continuous wall, as at Lockington, or full coverage for block treatment (Figure 3). Depending on soil conditions, DSM can extend to over 30 meters in depth.

The DSM technique is also used to construct earth retaining structures. Bending resistance in the wall is created by installing vertical H-Beams within the soilcrete columns immediately after mixing, normally at 1.4 m centers, thus forming a structural waterproof wall. This is an attractive solution for supporting deep excavations in urban areas especially when a high groundwater table is present.

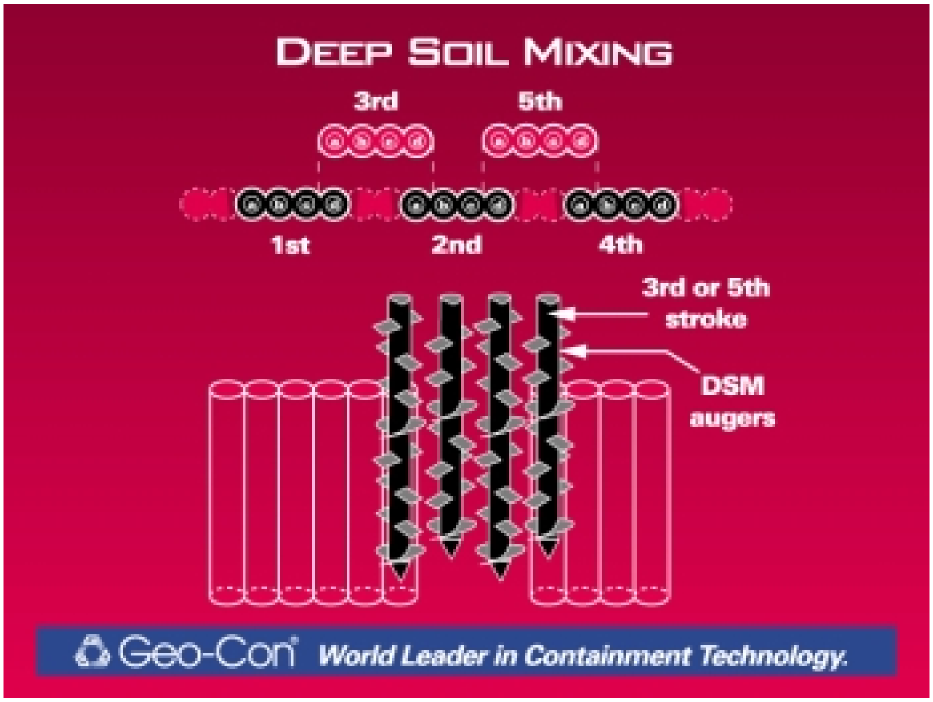

Figure 3. Overlapping Construction

Backfill Mix Design

The contract specification called for an in-place wall permeability of 1×10^{-6} cm/sec and a cement content of the soilcrete (soil and grout mixture) of not less than 6% by weight of soilcrete.

In addition, a mix design developed from bench scale testing was to be submitted prior to start of work to demonstrate that these properties were attainable. This procedure is standard for soil mixing projects where it is relatively straightforward to model in the laboratory the final wall composition using soil samples recovered from site.

An extensive laboratory test program was therefore developed with the following objectives:

1. Characterize the proposed materials.
2. Test and develop a workable cement-based grout suitable for soil mixing.
3. Develop and characterize trial grout-soil mixtures which span the expected range of material properties.
4. Perform unconfined compressive strength tests and hydraulic conductivity tests on the proposed grout-soil mixtures.
5. Recommend a proportioning of materials which will provide a grout-soil mixture with a maximum hydraulic conductivity of 1×10^{-6} cm/sec.

In total, 12 different grout soil mixtures were made during the program. Defining cement content by weight of soilcrete is impractical as soilcrete density varies depending on the soil bulk density and is only known once samples have been cast and density measured. On site, the procedure is to add a certain volume of a fixed proportioned grout to each soil mixed shaft volume. This was the approach adopted in the laboratory with the grout to soil ratio by volume set at an empirical value which was the minimum required to allow satisfactory auger penetration.

The cement and bentonite contents of the grout were varied to assess the effect on the soilcrete properties, with cement/water ratios by weight ranging from 14% to 33%.

Unconfined compressive strengths were obtained as per ASTM D1633 while hydraulic conductivity testing was carried out using triaxial (flexible wall) permeameters as per ASTM D-5084. Tests were performed using an average hydraulic gradient of 15 and a confining stress of 345 kN/m^2 to model actual wall service loads. Samples were moist cured for durations between 14 and 21 days prior to testing.

All samples tested met the specified permeability of 1×10^{-6}cm/sec and , as anticipated, a general increase in strength was observed with increased cement/water ratio.

Normally for cutoff barriers, the residual permeability is the primary consideration; but for the Lockington project, the cement content was determined to be of equal importance. It was felt that a grout of higher cement content would provide greater erosion resistance should overtopping of the dam occur. Conversely, from past experience, it was known that increasing cement content could compromise permeability, probably due to the more open lattice structure produced by cement hydrations having a higher permeability than that of bentonite and soil. This correlation has been demonstrated clearly in the past for neat cement grouts (Littlejohn 1982) but due to the present small database, has not as yet been clearly proven or S-C-B mixes.

Desiccation tests were carried out on samples 1A and 4A, which appeared the most favorable from the initial tests. Samples were set in beakers surrounded by moist gravel and left for two weeks without humidity control. Moisture contents reduced fourfold to between 7% and 8% with no sample deterioration observed. As a more extreme test, the specimens were oven dried, and again showed no deterioration, the samples remaining monolithic with no visible cracks.

Given the emphasis placed on strength, the high strength Mix 1A was ultimately selected as it also met the other requirements of the specification.

Construction

Construction took place over a seven-week period during the harsh winter of 1993, with work often taking place in sub-zero temperatures. Nevertheless, the work proceeded as planned with only a few days lost to weather with production peaking at 650 m^2 per shift. A total of 6,200 m^2 of wall was installed down to a maximum depth of 6.5 m. No penetration problems were experienced by the drill rig which had a rated output of 67,000 Nm torque, developed from a 450 kw powerpack; and excellent mixing was achieved.

The first work on site was to construct a 1 m wide by 1 m deep trench on the wall centerline to act as a containment for the residual material displaced during mixing. This quantity was around 20% of the wall volume.

In order to overcome the narrowness and length of the site, the grout plant was erected just east of the central spillway for construction on the west side and then re-erected on the east abutment for mixing on the east side. The restricted width of the spillway bridge also necessitated teardown and re-erection of the crane after completion of the west section of the work. Even so, pumping distances for the grout were over 900 m which was accomplished by the use of four Moyno L-10 grout supply pumps, one for each auger.

The crest was just of sufficient width for the Manitowoc 4100 crane on which the drill rig and powerpack were mounted, with the complete unit supported on crane mats to spread the high equipment load (Figure 4).

Figure 4. DSM Unit in Operation

The block treatment at the spillway wall to provide a watertight connection was built using the jet grout system (single jet). Before the last soil mix shaft adjacent to the wall had reached its final set, the jet grout monitor was inserted to the base of the block using a conventional hydraulic-driven tracked drill rig. Jet grout columns were then formed to connect the soil mix wall to the concrete face of the wall. The grout jet at a pressure of 20.7 MN/m^2, scoured the concrete face and simultaneously cut into the last soil mix column as it was rotated. The same grout mix as for the DSM work was used in the jetting with the monitor raised at 1.5 m per minute.

This method produced a much better seal than could have been achieved by some form of mechanical cleaning of the wall followed by column remixing.

Quality Control

The specification required a very thorough QC program to include procedures to check the verticality, depth, and alignment of the wall, and the grout proportions and application rates, to ensure the highest standards of workmanship.

The verticality and alignment of the wall was achieved by two controls. A laser provided a line onto a target on the DSM auger shaft for horizontal alignment, while verticality was monitored by two measurements made on the mast. These were the pitch and the roll. Two servo accelerometers within a fixture on the leads continuously outputted the angle to a display in the operator's cab.

At the grout station, bentonite slurry and cement slurry were mixed separately before being mixed to produce the final bentonite-cement slurry in a 3.8 m^3 lighting mixer. Slurry densities and viscosities were taken by mud balance and marsh cone respectively to monitor batch control.

The amount of grout injected in each DSM stroke was controlled by the DSM technician using automatic flowmeters, one for each grout pump. The grout flowmeters also allowed adjustment of pump speeds to be made between individual augers. This is helpful when redrilling previously drilled columns for overlapping, or to aid penetration in difficult areas. It was soon found at Lockington that these features were not needed due to the very consistent rate of penetration and the system was changed to one single-instrumented L-12 pump.

In addition, extensive sampling of the wall was required to verify compliance with the specification. The uncured mixed-in-place column was sampled using a specifically designed tube, following completion of a specific DSM stroke. The tube was closed by a pneumatic device at the designated depth and the sample brought to the surface.

Samples were taken every shift for permeability and unconfined compressive strength testing.

The primary intent of obtaining higher strengths was achieved, with a few slightly lower compressive strengths in thick zones of ML and CL material where possibly no vertical blending with coarser soils took place. Even so, these lower values were comparable to typical cement-bentonite slurry wall strengths. As predicted, some permeability values were slightly higher than the 1×10^{-6} cm/sec which was originally targeted.

Furthermore, the soilcrete strength will continue to increase over an extended time period with the gain in strength from 4 days to 28 days of around 100% for this project reflecting previous experience which has recorded strengths still increasing up to 5 months after mixing (Ryan and Jasperse 1989).

As a final measure, a 5 m by 5 m test panel was excavated to investigate the degree of mixing. The wall exposed was continuous and well blended having the consistency of a firm clay, after a two-week cure period.

Closing

As the older water retaining structures in the United States continue to age and deteriorate, there will be a growing need to remediate and upgrade these structures to meet new regulations and factors of safety.

The project at Lockington is a good example of a recently introduced innovative technology, namely Deep Soil Mixing, providing the best solution both technically and economically, to the specific problems of an existing dam.

DSM was the only method that could provide a low permeability wall with good resistance to erosion and desiccation, all verifiable properties of a soil-cement-bentonite cutoff, and still overcome difficult physical site constraints, through mixing all materials in-situ.

Furthermore, the use of preconstruction laboratory testing accurately predicted the in-situ properties of the wall which were subsequently confirmed by an extensive post-construction testing phase.

Appendix

REFERENCES

ENR, January 3, 1994.

Jasperse, B. M. and Miller, D. A., "Installation of Vertical Barriers Using Deep Soil Mixing", Hazmat Central '90, Rosemong, Illinois, 1990.

Littlejohn, Dr. G. S., Design of Cement-Based Grouts, Conference on Grouting in Geotechnical Engineering, New Orleans, Louisiana, 1982.

Reams, D., Glover, J., and Reardon, J., Deep Soil Mixing Shoring System to Construct a 60 mgd, 40-ft Deep Wastewater Pumping Station, KOR Engineering, 1989.

Ryan, C. R. and Jasperse, B. M., "Deep Soil Mixing of the Jackson Lake Dam", ASCE Geotechnical and Construction Division, Special Conference, June, 1989.

Keywords

Hydraulic Fill Dam, Core Raising, Soil-Cement Cutoff Wall, Deep Soil Mixing