

Soil Mixing and Slurry Trench Cutoff Walls for Coal Combustion Residue Sites

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CONFERENCE: 2019 World of Coal Ash – (www.worldofcoalash.org)

KEYWORDS: Slurry walls, in situ mixing, vertical barriers, soil-bentonite, shear walls

ABSTRACT

The closure of coal combustion residual (CCR) sites is occurring at an ever-increasing pace. Some of these sites may require ground water corrective action while other sites may require improvement of the stability of storage dikes, dams or embankments. For these situations, the well-established ground improvement technologies of in situ soil mixing and slurry trench cutoff walls may be appropriate. This paper describes considerations for the application of in situ mixing and slurry trenching to CCR sites and presents case studies where these technologies have been implemented. In situ mixing involves the use of augers to blend the subsurface materials with additives, usually cement, to greatly increase the shear strength and reduce the compressibility of the treated subsurface material. Configurations include linear walls oriented perpendicular to the axis of the dike resulting in shear walls for improved dike stability and block mixing of CCR to improve in situ strength, handling characteristics, or environmental leachability. Slurry trenching can be used to install cutoff walls with soil-bentonite and cement-bentonite being the most common. Cutoff walls can be deployed upgradient to prevent clean ground water from entering the CCR site, downgradient to reduce off site contaminant transport and circumferentially to create a closed ground water system beneath the site. Case studies in this paper include soil mixed shear walls, embankment foundation elements installed using slurry trenching with self-hardening backfill, and soil-bentonite and cement-bentonite cutoff walls installed for groundwater control.

INTRODUCTION

The shift away from coal coupled with the coal combustion residuals (CCR) rule have led to closures and planned closures of CCR sites. Closures of CCR sites typically require consideration of the nature and extent of any ground water contamination issues, dike/embankment stability under both static and earthquake loading conditions, and final closure requirements. It is the purpose of this paper to consider the application of soil mixing and slurry trench cutoff walls, both tried and

proven technologies, in the context of CCR site needs. The paper is organized in a way to first identify the types and methods of construction of various slurry trench cutoff walls and the techniques and configurations of in situ mixed soils. Potential needs at CCR sites and the category of solutions available are then discussed. With this framework established and the available techniques discussed, case studies are presented.

SOIL MIXING AND SLURRY TRENCH CUTOFF WALL TECHNIQUES

Soil-Bentonite Slurry Trenches

The terms slurry trench and slurry cutoff wall are widely recognized to refer to the installation of non-structural walls using long, continuous slurry supported excavations (Evans 1993). The slurry trench installation method refers to construction practices that utilize an engineered fluid, generally consisting of some mixture of bentonitic clay and water, to hold open the sidewalls of an excavation, thereby permitting the excavation of deep and narrow trenches without the need for other conventional excavation support systems. Slurry trench cutoff walls have been employed at thousands of sites across the United States and internationally in a variety of applications. Applications include containment of contaminated groundwater at contaminated sites, control of groundwater for excavation dewatering at uncontaminated sites, and at dams, levees, and embankments to improve stability otherwise degraded by seepage.

In the installation of soil-bentonite (SB) slurry trench cutoff walls, the trench is excavated under slurry followed by a distinct backfilling step wherein the slurry is displaced by a mixture of soil and slurry (see Figure 1). This is sometimes referred to as a two-step or two-stage slurry trench installation. Most slurry trenches are excavated with backhoe excavators which can be modified to dig up to 30 m deep. Deeper depths are possible with clamshell excavators. SB cutoff walls are the most common type of non-structural slurry trench. These walls were sporadically used in the United States between the 1940s and 1970s after which their use became commonplace.

SB backfill is most commonly made from suitable materials excavated from the trench and may be blended using a variety of equipment. Most commonly, backfill is mixed in batches of backfill alongside the slurry trench using small excavators and/or dozers. The resultant mixture looks like wet concrete (i.e. moderate to high slump) and is normally placed in the trench with the equipment used for mixing. The mixture is placed in a semi-fluid state which allows it to flow into the trench and displace the trench slurry. Once the backfill operation is complete, the SB backfill consolidates slightly under its self-weight, ultimately behaving as an extremely soft clayey soil. For most applications, the most important property of the SB backfill is low hydraulic conductivity. Typically, SB backfill has a hydraulic conductivity in the range of 10^{-6} to 10^{-8} cm/sec. Environmental projects often require a permeability less than 1×10^{-7} cm/sec, but a levee or dewatering project may require a permeability less than 1×10^{-6} cm/sec. Either value is achievable with the right mix of materials. SB backfill has low strength and will remain soft (in the range of 0 to 15 kPa) for the life of the barrier, but this is nearly always sufficient to maintain a vertical cut through the wall for subsequent installation of utilities and other light structures. The most important variables in a SB mix design are bentonite content and grain size distribution of the base soil. In general, SB backfill performs well when

exposed to pure phase contaminants or impacted groundwater due largely to the fact that most of the matrix is composed of inert soil particles (Ruffing et al. 2018).

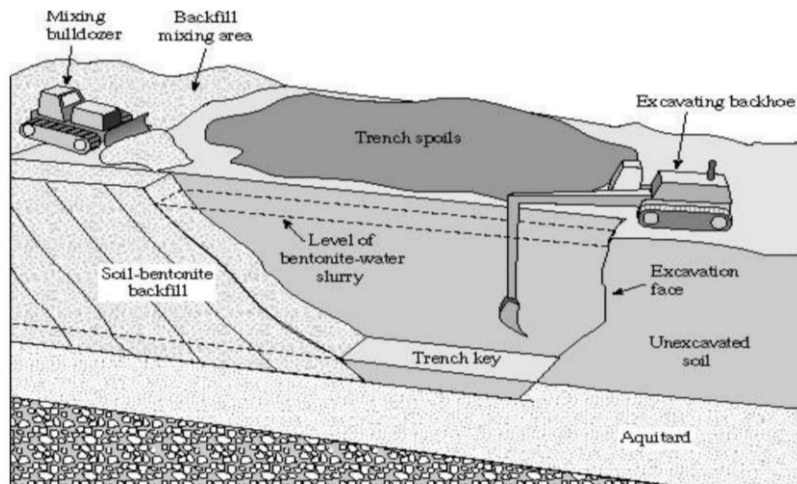


Figure 1 SB Slurry Trench Cutoff Wall Schematic (LaGrega et al. 2010)

Self-Hardening Slurry Trenches, a.k.a Cement-Bentonite or Slag-Cement-Bentonite

Cement-Bentonite (CB) slurry trenches represent a smaller and more specialized type of slurry trench installation method used in the US since the early 1970s. In Europe and many other international locations, CB walls are the more common barrier wall choice. In this method, the wall is excavated through a slurry typically consisting of water, bentonite, ordinary Portland cement, and granulated ground blast furnace slag cement. The trench slurry hardens in place, normally with an initial set occurring overnight. The hardened CB slurry serves as the final barrier wall. CB installations do not require a separate backfilling operation, and it's for this reason that this technique is sometimes referred to as one-step or one-phase slurry trench construction.

CB walls are excavated using hydraulic excavators and/or clamshell excavation equipment, the same equipment used for other slurry trench installations. At the slurry plant, ordinary Portland cement, or some combination of ordinary Portland cement and granulated ground blast furnace slag, is added to the bentonite slurry. The viscosity of the mixed slurry is designed to be in the fluid range during the excavation process. The slurry is then pumped from the mix plant to the excavation. Once the excavation is completed to full depth, the bottom is cleaned and the process moves on. The slurry stays in the trench and is allowed to set. Typical CB slurry will attain a butter-like consistency overnight and a clay-like consistency after fully hardening.

The properties of interest for most CB slurry walls are strength and permeability. CB slurry has a relatively high water content, and because of this, there are more water-filled voids than in a SB backfill. Despite the higher void ratio, typical permeability values that are similar to SB backfill, generally less than 1×10^{-7} cm/sec after a month of curing if the mixture includes slag. Without the addition of slag, permeability values are one to two orders of magnitude higher. CB can take months to fully harden, and long-term tests have shown CB permeability gradually decreases (improves) over long timescales, measured in years. CB material generally attains 75% of its ultimate strength after 28 -

56 days of curing and close to 100% after 90 days of curing. The addition of blast furnace slag typically results in a higher strength, lower permeability material, but it takes much longer to achieve the final properties with properties shown to improve out to 6 months and beyond (Opdyke and Evans 2005). Chemical compatibility is also an important factor when designing containment systems for impacted groundwater. CB is particularly well-suited to resisting certain oils and petroleum products, and thus, it is often preferred on sites with heavily contaminated groundwater.

Bio-Polymer Slurry Trenching

Bio-polymer (BP) slurry trenching is a method used to install high hydraulic conductivity vertical barriers. The goal on these projects is to form deep permeable zones that can serve as toe drains in dams, recovery trenches for contaminated groundwater, deep French drains, permeable reactive barriers (PRB), permeable absorptive barriers (PAB), leachate collection trenches, and other types of active groundwater control structures. BP trenching is similar to conventional slurry trenching with bentonite-water slurry except that a biodegradable polymer slurry is used instead of a bentonite slurry. The BP slurry serves to eliminate dewatering and/or shoring. The BP slurry stabilizes the trench walls as the excavation and backfill are completed below the groundwater surface. After excavation, the trench can be backfilled with a variety of permeable materials such as sand, gravel, and particulate treatment media. In bio-treatment schemes, the bio-polymer slurry can actually increase the reactivity of the media. Depending on the project goals, BP slurry trench drains (or BP Drains) may be equipped with wells, filter fabrics (costly and not always recommended), liners (e.g. HDPE), sumps, horizontal pipes, and a variety of other features. When construction is complete and the trench is backfilled with the permeable material, the slurry is biodegraded to water and a small amount of precipitate thereby the trench becomes an active drain. Installation of a BP Drain may require the use of long stick attachments, tremie pipes, end stops, special weights, and other tools.

In Situ Soil Mixing

The term soil mixing loosely refers to any construction approach used to mix soils with or without a reagent additive. In the fields of geotechnical and environmental construction, the term often refers to methods of soil mixing performed *in situ* for the addition of a cementitious reagent, most commonly Portland cement. The concept for soil mixing originated in the US, but much of the early technological development took place in Europe and Japan until the technology was reintroduced into the US market in the 1980's. The most common use of soil mixing in the environmental market is for in situ stabilization/solidification (ISS) of wastes. Soil mixing is used in the geotechnical market for the installation of rigid elements for bearing capacity and slope stability improvement, for installation of low hydraulic conductivity cutoff walls, and for excavation support systems.

There are many equipment configurations and processes that can be used for the successful completion of soil mixing, but the goal is almost always the efficient creation of a soil-reagent mixture with improved properties relative to the soils alone. The most common type of soil mixing used on environmental sites is single auger soil mixing using a large diameter (typically 1 to 4 m in diameter) tool with cutting edges, mixing paddles, and grout ports. The auger is drilled into the ground as a fluid grout is pumped

through the hollow shaft and out the grout ports. The grouting fluid acts as an aid to drilling and is mixed into the soil column creating the soil-reagent mixture. The term deep soil mixing (DSM) often refers to the use of multi-auger soil mixing rigs that can be used to install linear elements such as for vertical cutoff walls. DSM auger configurations are specific to each contractor, but typically include 3 or 4 relatively small (1 to 1.2 m) diameter augers spaced evenly apart. For stabilization/solidification of a soil mass, very shallow soil mixing, typically less than about 5 m, can be performed using excavator buckets with or without rotary blending tools (think: large rototiller). These methods are more primitive than some of the other approaches but can be performed at a significantly reduced cost. Another method of soil mixing for the installation of linear elements is chain trenching (Evans and Garbin 2009). This type of soil mixing is completed using essentially a large chainsaw mounted on a tracked chassis.

Soil mixing may be used for a variety of purposes, including creating structural elements for foundations and retaining walls, soft soil improvement, installation of groundwater cutoff walls, and in situ treatment of contaminants. It may also be used with specialized cementing and chemical reagents for waste treatment, sludge stabilization/solidification, lagoon stabilization, in-situ chemical oxidation (ISCO), and in-situ chemical reduction (ISCR). Soil mixing is often a preferred remediation tool on contaminated sites due to the limited handling of the contaminated soils, the high strengths (350 to 1400 kPa unconfined compressive strength UCS) and low permeability ($\sim 5 \times 10^{-7}$ cm/s) values that are achievable, and because the method is less susceptible to variations in surface topography and soil consistency.

SOIL MIXING AND SLURRY TRENCHING APPLICATIONS FOR CCR

The slurry trenching and soil mixing construction techniques described above can be used for a variety of applications on CCR sites, including hydraulic cutoffs, shear walls, in situ solidification and drainage trenches. In this section of the paper, each of these applications is described and their potential uses on CCR sites is explored.

Hydraulic Cutoffs

Cutoff walls on CCR sites can be deployed to cutoff subsurface groundwater flow. The cutoff walls can be deployed completely around the facility, in up-gradient locations or in down-gradient locations depending upon the site-specific conditions and project goals. For example, an up-gradient cutoff will prevent uncontaminated up-gradient groundwater from entering the site where it could potentially then become contaminated. Also, the up-gradient cutoff wall may result in the lowering of the groundwater levels within the site. A cutoff wall completely surrounding the site provides the added benefit of substantially reducing the rate of contaminant transport from the site. The cutoff walls are effective in reducing flow in both homogeneous conditions and conditions where there is localized zonal flow. Hydraulic cutoff walls can also be installed for seepage control in CCR dams or embankments and, as such, result in improved stability. Finally, hydraulic cutoff walls can be installed to facilitate CCR dewatering projects by providing perimeter groundwater control or to segment large storage facilities into more manageable areas.

The most applicable construction methods for installation of hydraulic cutoff walls include both slurry trenching and in situ soil mixing. Typically, a SB slurry trench cutoff wall is the most economical but there are many cases where the slag-CB wall or in situ mixed wall are appropriate choices.

Shear Walls

Shear walls are structural elements that are installed perpendicular to and beneath or in front of embankments and dams to improve the stability of the structure. Shear walls can be particularly effective in increasing the factor of safety during earthquake events that cause liquefaction of the foundation soils. In this situation, the reduction in shear strength of the foundation soils is compensated by the shear strength of the non-liquefiable shear walls. Shear walls are also used for mine tailings and CCR storage retrofits to increase storage capacity by enabling the raising of the dam/embankment. Shear walls are also used to bring the facility into compliance with current standards for static slope stability.

Shear walls, by definition, require substantial shear strength and therefore only methods that use cementitious agents in their construction are applicable. Slurry trenching using the one stage method of slag-CB is an appropriate technology for this application. Similarly, in situ mixing methods where cementitious materials are added to and mixed with the subsurface soils are also appropriate.

In Situ Solidification/Stabilization or In Situ Treatment

In situ solidification/stabilization (ISS) is a common means of contaminated site remediation to reduce the impact of the contaminants on the surrounding soil and groundwater. ISS is a process by which the in situ soils are mixed with reagents, such as lime or cement, to effectively solidify the mixed mass. In this way, the solidified mass has increased shear strength, reduced hydraulic conductivity and reduced leachability. The most common reagent used in this application is Portland cement. The application of ISS results in a reduction in the impact of contaminants upon the environment by reducing groundwater flow through the contaminated area and, in most cases, through chemical reactions between the reagent(s) and the contaminants that reduce the contaminant mobility. Note that for most ISS projects, the contaminants are still in the subsurface environment but their ability to migrate is substantially impeded.

In situ treatment (IST) is a specific application of ISS wherein the reduced impact goal is accomplished through contaminant mass reduction. The most common methods of IST are in situ chemical oxidation (ISCO) and in situ chemical reduction (ISCR). Although ISCO and ISCR projects can and are sometimes completed with direct injection methods, soil mixing is often preferred because reagent distribution is assured independent of subsurface conditions. Given the nature of the chemical contaminants found at CCR sites, IST is likely to have limited usefulness at these sites.

Since ISS and IST require the mixing of reagents in a soil mass (rather than along a linear wall alignment), in situ mixing is the appropriate technology in these applications. Where in situ mixing with augers is used, the auger choice is a single large diameter auger and not a series of smaller diameter in-line augers.

Drainage or Collection Trenches and Permeable Reactive Barriers

Deep drains, collection trenches, and PRBs have numerous potential uses at CCR sites. Like vertical cutoff walls of low hydraulic conductivity, these drainage systems can be deployed around, upgradient, or downgradient for the collection of groundwater. Downgradient groundwater, if contaminated, can be treated ex situ before discharge into an appropriate surface water body. Drains and collection trenches can also be used to facilitate dewatering of CCR materials. PRBs are normally applied over a limited area given their high cost. PRBs are often deployed in conjunction with a low permeability vertical cutoff wall that serves to funnel contaminated ground water to the PRB treatment zone, hence the term “funnel and gate” to describe these systems.

It is desirable to maintain the hydraulic conductivity of the formations in which drainage trenches and PRBs are installed. As a result, biopolymer slurry trenching is the only available construction technique for these applications.

CASE STUDIES

The following case studies highlight applications of soil mixing and slurry trenching as construction solutions that have been applied to CCR sites.

Soil Mixed Shear Walls for Embankment Stability Improvement

As part of a coal fired power plant shutdown, one of the ash management pond embankments at the site required structural improvement. In this project, embankment stability was jeopardized during the design earthquake due to the liquefaction potential of the foundation materials. To remedy this situation, in situ soil mixing was used to install shear walls at the toe of the embankment. The project included 150 individual shear walls at an average depth of 10 m deep and a maximum depth of 15 m. Each wall consisted of four or five overlapping elements with each element consisting of four columns constructed using a single stroke of the four-auger DSM drill rig. In order to ensure intimate contact with the underlying bedrock an additional single auger drill rig was used to re-drill the individual DSM columns that did not contact with the rock. This re-drilling was completed immediately after the four-auger mixing while the soil-mix was still fresh. At this site, Portland cement was added to and mixed with the soils to increase the shear strength of the soil such that the improved zone constituted a shear wall. The project required that 90% of samples exceeded target unconfined compressive strength (UCS) of 1900 kPa (275 psi). One project challenge of note was the narrow work platform resulting from the limited space between the storage pond and an adjacent creek. Figure 2 shows an active shear wall installation at this case study site along with the limited work platform width.



Figure 2. Deep soil mixing for shear wall installation at toe of ash pond embankment

Slag-CB Walls for Embankment Foundation Support

A dike failure at a coal ash management facility, resulting in significant community impact, necessitated the design of subsurface reinforcement beneath the reconstructed embankment and remaining containment cells. The typical design configuration included continuous inboard and outboard walls with a connecting shear walls as shown on Figure 3. The connecting shear walls were installed perpendicular to the inboard wall lateral wall segments and were designed to withstand shear loads. In some segments, the shear walls extended beyond the outboard perimeter wall to form a buttress to the outboard wall. Each segment had different treatment widths and area-replacement ratios to economically account for differing applied stresses obtained from failure analyses along the alignment.

The shear walls were installed using the self-hardening slurry trench installation method. The slurry was made using granulated ground blast furnace slag cement, ordinary Portland cement, and bentonite-water slurry. The proportions of the mixture were developed during an extensive laboratory testing program that evaluated over 70 candidate mixtures. Multiple mix recipes were used in production segments to accommodate different design needs with the cured CB slurry reaching a UCS of 1400 to 2800 kPa (200 to 400 psi).



Figure 3. Typical foundation wall design layout

The shear walls were installed down to a local bedrock formation with depths ranging from 14 to 20 m. In total, the walls installed at this site have a combined length of 19 km (12 miles). The project totaled 428 m³ (560,000 cubic yards). In units typical of vertical cutoff walls (area = length x depth), the project totaled 351,000 m² (3,780,000 ft²) making this the largest self-hardening slurry trench installation in the US.

One of the primary challenges during construction was a need to perform concurrent design and construction. This required close coordination between the Contractor and Designer to ensure smooth transitions between phases. In addition to the concurrent design/construction challenges, the excavation was performed through a difficult stratigraphy, including 15 feet of highly liquefiable coal ash. This necessitated extra care and caution during the excavation and work platform construction.

Soil Bentonite Slurry Trench Cutoff Walls Around Ash Management Ponds

Soil-bentonite cutoff walls have been installed through levees at multiple power plants for groundwater flow control. Two such examples include 1700 m² (18,000 ft²) and 3600 m² (39,000 ft²) walls at two different sites. In both cases, the cutoff wall was installed through existing levees to reduce seepage and improve dike stability. In both cases, due to the depths greater than 9 m, a 40 metric tonne excavator was used with a custom long stick. Challenges on these projects included excavation along a narrow corridor with nearby adjacent utilities for much of the project's alignment. This slowed production and resulted in a need for remote backfill mixing over much of the project's alignment. A photograph of the excavation and backfill mixing at one of these sites is shown as Figure 4.



Figure 4. Soil-bentonite cutoff wall installation at coal fired power plant

Self-Hardening Slurry Trench Cutoff Walls in Ash Management Pond Embankments

Self hardening, cement-bentonite and slag-cement-bentonite walls, have been successfully used as hydraulic barriers for improving coal ash storage facilities numerous times. Two such examples include 1950 m² (21,000 ft²) and 3700 m² (40,000 ft²) walls installed to depths of 9 to 12 m. In both cases, the hydraulic cutoff walls were installed through embankments to minimize seepage and improve stability. In these applications, the self-hardening method was selected so that the cutoff wall would have an unconfined compressive strength greater than 200 kPa (30 psi) to support access roads and for stability of the structure. Project challenges included the narrow work platforms and in one case an adjacent railway that required daily coordination. Figure 5 shows the slurry trench installation at one of the sites and illustrating the narrow work platform.



Figure 5. Self-hardening slurry trench installation in coal ash storage facility dam
In Situ Soil Mixing for In Situ Stabilization / Solidification of Coal Ash (Maine)

Not sure I have enough info for this, will look if we have room

SUMMARY

This paper has reviewed the commonly used techniques for construction of vertical barriers including SB and slag-CB slurry trench cutoff walls as well as in situ mixing methods. The paper identified CCR site uses of these vertical barriers including control of ground water flow and contaminant transport, shear walls and stabilization/solidification for control of contaminant transport. After review of the techniques and their applications, several case studies were presented illustrating the use of slurry trench cutoff walls and in situ mixing used to meet the site-specific needs at CCR sites. In summary, there are many applications for soil mixing and slurry trench cutoff walls at CCR sites.

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