Between Covers and Liners
The Varied Roles of Vertical Barriers

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ABSTRACT:
Federal Coal Combustion Residual (CCR) Rules define the final cover system requirements for closing CCR surface impoundments in place and the requirements for surface impoundment liner systems (although most existing surface impoundments are unlined). Cover systems are effective solutions for isolating CCR and controlling infiltration, but lateral groundwater flow between the cover and liner (if one exists) may leave owners unsure of the optimum closure approach to mitigate potential future impacts of this flow. The need for lateral groundwater control is often achievable with a “vertical barrier,” which must be determined based on thorough evaluations of groundwater, structural, and chemical conditions. The engineering and construction industries have led the way in developing techniques to design and deploy vertical barriers, while environmental engineers and regulators have worked together to understand what vertical barriers can realistically achieve. Vertical barriers can provide an array of characteristics, such as structural-to-hydraulic manipulation systems to meet site conditions and project requirements. Three major types of vertical barriers are implanted barriers, remotely mixed and backfilled barriers, and mixed-in-place barriers. Each type has inherent quality considerations, and their installation techniques have constructability requirements and limitations. A six-step decision framework helps owners to select the appropriate vertical barrier system based on such roles as hydraulic control (e.g., reducing, directing, collecting, and/or treating liquid flow), hydraulic conductivity and seepage reduction, constituent reduction time, chemical compatibility, and contracting approach. A properly selected system can reduce groundwater flow and improve water quality outside CCR surface impoundments as part of a comprehensive corrective action.
INTRODUCTION:

Coal combustion residual (CCR) surface impoundment cover systems are effective solutions for isolating CCRs and controlling infiltration. Most surface impoundments do not have liner systems; however, some have a naturally low hydraulic conductivity (i.e., low-permeability) aquitard beneath them, or natural hydraulic conditions that can help reduce CCR contact water release vertically. Furthermore, horizontal migration at many sites requires additional measures to mitigate CCR-related contaminants of concern (COCs) in groundwater outside surface impoundments.

Owners often desire to reduce long-term operation and maintenance (O&M) (e.g., pumping and active groundwater treatment) while mitigating future releases. Lateral groundwater flow between the cover and the liner system (if one exists) may leave owners unsure of the optimum closure approach. Lateral groundwater control, commonly known as a “vertical barrier,” can help owners achieve their mitigation goals.

Vertical barriers are engineered structures, usually less than 1 meter (3 feet) thick, with hydraulic, structural, and chemical functional characteristics. The functional characteristics are dictated by remediation objectives identified in a conceptual site remediation model (CSRM). These remediation objectives can be met by matching the functional characteristics to appropriate installation techniques and materials while considering relevant site conditions.

The three major types of vertical barriers are implanted barriers, remotely mixed and backfilled barriers, and mixed in-place barriers. Each has its advantages, disadvantages, and ranges of effectiveness. A six-step decision framework, considering such factors as barrier type, application, installation techniques, and materials, is used to select the appropriate vertical barrier type. Aside from myriad regulatory requirements, the decision framework establishes a “roadmap” for owners, regulators, and stakeholders, and helps experienced project teams to methodically identify a feasible solution to mitigate CCR-related COCs in groundwater.

VERTICAL BARRIER TYPES:

The three most common vertical barrier types (implanted barriers, remotely mixed and backfilled barriers, and mixed-in-place barriers) can be described by how they are constructed. The types share some common characteristics and installation techniques.

The three barrier types are defined as follows:

- **Implanted Vertical Barriers.** These barriers are formed by directly implanting manufactured material into soils and weathered rock, or in an excavation. Implants include steel, composite or vinyl sheet piling, sealed interlock sheet piling, and geomembranes. The inherent quality of implanted elements is usually the highest because of their manufacture under controlled conditions.

- **Remotely Mixed and Backfilled Vertical Barriers.** These barriers are formed in trenches in existing soil and weathered rock that are then backfilled with an
engineered backfill. These barriers are often considered to potentially have an intermediate level of quality because the backfill mixing is directly observable, but not in its in-place form.

- **Mixed-in-Place Vertical Barriers.** In-place soils, weathered rock, and water are mixed with reagents in-place to form an engineered backfill. These barriers are often considered to potentially have the lowest quality because they are the least observable.

The reagents used in the remotely mixed and mixed-in-place vertical barriers may include materials such as manufactured clays (bentonites, attapulgite, and specially formulated/modified bentonites), cementitious and pozzolanic materials (Portland cement, cement kiln dust, reactive lime, reactive fly ash, silica fume, and ground granulated blast furnace slag), and admixtures (polymers, hardeners, set retarders, pumping aids, etc.). During installation, the backfill is a watery mixture of soils and reagents that cures and sets with time to yield the required hydraulic, structural, and chemical characteristics. The roles that barriers can provide are a combination of their characteristics, as described below:

- The manipulation of hydraulics by redirecting flows to or around features, reducing flow/flux\(^1\) out of the surface impoundment or facilitating removal, or injection of liquids, while maintaining those characteristics under the expected loads
- The enhancement of, and compatibility with, structural characteristics of the existing/planned ground, while maintaining those characteristics under expected stresses and strains
- The ability to maintain hydraulic and structural characteristics under expected environmental/chemical conditions, and occasionally the manipulation of water chemistry, by providing a zone where favourable chemical conditions exist to mitigate water quality through treatment or re-speciation of COCs

**INSTALLATION TECHNIQUES:**

Common installation techniques range from conventional to increasingly specialized for site-specific challenges. Years of development have refined these techniques with procedures to narrow the inherent quality differences between the types of vertical barriers. Careful design and installation and the use of appropriate quality control procedures are key to providing quality vertical barriers. Following are installation techniques for vertical barriers.

**Conventional Trenching and Backfilling**

In conventional trenching, a trench is excavated with sufficient dewatering to provide acceptable hydraulic conditions to safely advance a trench in soil and weathered rock. After the trench is excavated to the desired depth, implants or engineered backfill are

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\(^1\)“Flows” refers to the quantity per unit time (cc/sec). “Flux” refers to the mass transfer of a chemical per unit time (mg/sec) and is relevant to potential environmental impacts.
placed in the trench to form barriers. Conventional trenching includes open trenching or the use of temporary excavation support systems such as trench-boxes, sheet piling, and large-diameter caissons that are evacuated and then backfilled.

**Slurry Trenching**

Slurry trenching techniques replace temporary excavation support systems with a high-viscosity liquid, such as bentonite or biopolymer slurry, along with acceptable hydraulic conditions to safely advance a trench in soil and weathered rock. After the trench is excavated to the desired depth, backfill is gently placed in the trench to displace the slurry while maintaining the engineered backfill characteristics. Low- or high-permeability backfill can be placed in a trench excavated under bentonite or biopolymer slurry, respectively.

As an alternative to backfilled trenches, cement can be added directly to the slurry to form mixed-in-place, cement-bentonite barriers. Segments can be connected to form linear and gently curved vertical barriers. The equipment requires level or benched work areas to contain the slurry and can be adapted to work in spaces as narrow as 12 meters (40 feet).

**Displacement and Replacement**

The displacement and replacement technique entails inserting a solid object in the ground and placing backfill in the resulting void that forms as the solid object is removed. The most applicable method is the vibrated beam method, where a void is formed by vibrating a heavy steel I-beam into soil and weathered rock. After the I-beam reaches the desired depth, it is extracted, and the void is filled with grout to form individual segments that result in the required characteristics when the grout is cured. Vertical barriers are formed by overlapping the individual grouted segments. The equipment can install continuous complex shapes and typically requires level open spaces adjacent to the barrier alignment about 15-meters-wide (50 feet) to operate.

**Grouting**

Grouting entails injecting a liquid containing reagents (grout) under pressure into soil, weathered rock, and rock to modify existing characteristics. The pressures applied and the grouts available can produce various barriers with a range of characteristics. The grout can be engineered to withstand environmental conditions (i.e., chemical compatibility) during construction and over the long term.

Grouting techniques include the following:

- **Void grouting** is the filling of voids in soil and rock with viscous high solid grouts.
- **Permeation grouting** is the slow injection of low viscosity (i.e., watery) grout into small voids and permeable seams in soil or rock.
- **Jet grouting** is the use of very high pressures to inject grout to erode soils and weathered rock and mix them in-place to form columns or panels.
- **Compaction grouting** is the injection of stiff cement or lean chemical grouts to displace or compress existing soft soil and weathered rock resulting in pockets of engineered grout and compacted native materials.
Chemical grouting and other grouting media are also available. Grouting equipment can install continuous complex shaped barriers in three dimensions, typically require small spaces to operate, and can accommodate moderately steep slopes.

**Soil Mixing**
As the name implies, soil mixed barriers are constructed by mixing existing soil and weathered rock with reagents. Mixing requires considerable power and durable equipment that is selected based on soil type and depth. Mixers include excavator or crane-mounted mixing heads, such as rotating drums and soil augers, which are advanced into the ground so that soils and weathered rock are loosened. Grout is added to the soils as they are loosened to produce the required backfill at the desired depth. The equipment can install continuous complex shapes and typically requires level open spaces adjacent to the wall alignment about 15-meters-wide (50 feet) to operate.

**One-Pass Trenching**
A specialty machine, such as a Dewind One-Pass machine, cuts into the existing soil and rock with what is essentially a large chainsaw to form a trench filled with loose materials. As the machine moves along the alignment, it mixes water and reagents with the loosened soil and rock to form the engineered backfill. With added equipment, the machine can simultaneously remove trench cuttings, install an implant, and backfill the trench with cuttings. This equipment can also place a perforated pipe in the backfill at a predetermined depth to remove or inject water, or to inject reactive media to treat groundwater. The equipment can install continuous linear or curved barriers that can operate in spaces as narrow as 4.5 meters (15 feet) (i.e., the tops of CCR surface impoundment dikes/berms).

**DECISION FRAMEWORK:**
Figure 1 illustrates the six-step decision framework that allows owners to select the appropriate vertical barrier system based on such roles as hydraulic control (e.g., reducing, directing, collecting, and/or treating liquid flow), hydraulic conductivity and seepage reduction, constituent reduction time, chemical compatibility, and contracting approach. The framework is intended to be used by owners and experienced project teams. The framework identifies general considerations and decisions, which can be adjusted to meet project-specific objectives due to site complexities and regulatory requirements.
The decision framework is best explained in the context of the following example project:

**Example:** A 1-square-kilometer (247-acre) CCR surface impoundment is located in a hilly region of the Appalachian Mountains, in an old west-to-east sloped valley that drains to a Class B river. Natural groundwater levels, before the impoundment was constructed, were a couple meters (several feet) below ground surface and followed the topography with flow, ultimately discharging to the river. Native saprolite becomes denser with depth, and resistivity studies for an adjacent unconstructed expansion confirmed auger refusal (i.e., bedrock) 9 to 15 meters (30 to 50 feet) below predevelopment grades. The bedrock is massive, without fractures, and is considered an aquitard to vertical groundwater flow. The east side of the impoundment is retained by an earthen dike of compacted native saprolite that is incised into bedrock and sits about 200 meters (700 feet) west of a river. The dike is up to 15 meters (50 feet) tall. A perimeter road encircles the impoundment and runs along the top of the dike. An old vitrified clay underdrain system beneath the CCR and dike has been plugged, but seepage around the pipes enters the river. The groundwater table surface in the CCR is near its almost level ground surface, which is bounded by the perimeter road. The phreatic surface west of the impoundment is within 1 meter (3 feet) of ground surface, and outside the perimeter road, it drops radially from the CCR and flows eastward.

The sluice line enters the impoundment at the northwest corner, and removal of standing water is required at the eastern side during and following heavy rain. An existing gravity drain at the eastern edge can be retrofitted to continue pump-free water removal to an existing treatment system. The owner desires to reduce leakage, water management, and treatment, and ultimately CCR COCs in the pore water entering the river where significant dilution is ongoing.

**Step 1: Develop a Conceptual Site Remediation Model**

Vertical barriers must reduce either seepage rates or the flux of CCR-related COC releases to mitigate potential impacts. Vertical barriers combined with appropriate hydraulic conditions usually mitigate contaminant releases to levels associated only with chemical diffusion through the barrier.

A Conceptual Site Remediation Model (CSRM) defines the remediation elements needed to meet project goals. A qualified team of engineers, hydrogeologists, regulatory specialists, and owners develops the CSRM based on site-specific information and experience. CSRM development begins with preliminary hydrogeologic, structural, and chemical evaluations that identify general hydraulic, structural, and chemical requirements. Consideration of site conditions optimizes constructability.
Preliminary Hydrogeologic Evaluation

This evaluation consists of a water balance that accomplishes the following:

- Quantifies water flows into and out of the surface impoundment.
- Identifies questions that may arise, such as: Is the cover so permeable that the water it allows into the impoundment exceeds what can flow out through a low-permeability perimeter barrier, such that pumping from inside the impoundment is required to prevent the infiltrated water from over-topping the vertical barrier? Does the barrier back up water outside the barrier by blocking its flow? (Example: A low-permeability western vertical barrier can result in frequent/ongoing flooding upgradient (i.e., west) of the impoundment.)
- Identifies the range of hydraulic forces that will be applied to the barrier. (Example: The eastern vertical barrier will produce a differential hydraulic head as high as 10 to 20 meters (33 to 66 feet), which adds load to the dike and hydraulic pressure on the barrier.)
- Identifies the hydraulic characteristics that the barrier must provide. (Example: A low-permeability vertical barrier around the entire impoundment is needed to reduce flow of CCR-impacted water from within the impoundment, and a water diversion system may be needed west of the impoundment.)

Preliminary Structural Evaluation

This evaluation describes how the vertical barrier must work within its structural system: the strain compatibility of the barrier with surrounding materials, the barrier’s influence on dike stability, and site-specific considerations (e.g., alignment and the barrier’s need to improve dike strength). (Example: The old dike is marginally stable now. Adding heads to the barrier will increase loads, which will make the dike less stable. Therefore, the barrier needs to contribute to the dike’s stability to produce acceptable conditions.)

Preliminary Chemical Evaluation

Materials used in the vertical barrier must withstand site conditions (e.g., provide environmental resistance) for some period. Therefore, the site’s geochemistry must be understood considering what the barrier must withstand. (Example: Only CCR was disposed of in the surface impoundment.) “Passive” barriers manipulate flow or enhance existing strengths; “active” barriers contribute to the reduction or alteration of CCR-related COCs.

Preliminary Site Conditions Evaluation

This evaluation considers various site characteristics, including:

- Vertical barrier alignment, topography, and depth
- Existing soils and rock type, character, variability, and excavatability
• Obstructions, including overhead and underground utilities and potential buried debris
• Site access, wetlands, and facility operational considerations
• Existing and planned infrastructure
• Locally available soils and reagents
• Environmentally sensitive areas
• The barrier wall’s place in the overall construction sequence

(Example: The former drain bedding allows seepage containing CCR COCs to discharge to the river, the top of the dike is only approximately 15 feet wide, and the depths needed to reach the underlying bedrock range from 9 to 15 meters [30 to 50 feet] below predevelopment grades.)

These preliminary evaluations are followed by more in-depth analyses that will further develop the CSRM.

Step 2: Determine Vertical Barrier Functional Characteristics

The CSRM is advanced by developing a preliminary conceptual design that refines the understanding of the vertical barrier’s primary and secondary functions. As in Step 1, the functions include hydraulic, structural, and chemical. Step 2 helps owners to choose between such things as a low permeable barrier that is self-supporting and stands up to site chemistry or a permeable barrier that enhances water mitigation and is self-supporting.

Step 2a: Identify Hydraulic Functions

Hydraulic functions include hydraulic conductivity (permeability), thickness, and vertical extent. The water balance must be refined and quantified. The rate at which water flows through the ground and barriers is termed “seepage rate” and is quantified using Darcy’s Law. However, the flux rate of COCs through a barrier is often more important than seepage rate, as described in Step 2c. (Example: Modeling shows that the preferred cover system allows more water in than is flowing out through the barrier and therefore pumping from within the impoundment during post-closure will be required. Therefore, an alternative cover to reduce infiltration will be considered and a cost analysis performed.)

Another vertical barrier hydraulic function is its vertical extent, including top elevation and depth. The top elevation may need to be set to prevent floodwater from entering the closed surface impoundment, set to limit pumping if the cover infiltration exceeds the outward seepage, or limited by the top elevation of an impoundment dike. When a low-permeability layer is not present at depth (e.g., a natural or constructed liner), the barrier
may be able to extend sufficiently deep to limit diffusion/mixing and adequately reduce the flux (see Step 2c). Where the barrier can extend down to a liner or natural aquitard, a 0.6- to 1-meter- (2- to 3-foot) deep key is typical and often adequate. Groundwater modeling may be needed to quantify the vertical extent of this key and the estimated seepage/flux rates. Occasionally, in fractured or vuggy rock/soils, localized supplemental grouting may be required to establish adequate seepage/flux control. 

(Example: Modeling shows that three options exist on the west side: the west side top elevation needs to be 2 meters (7 feet) higher than existing ground, a groundwater diversion system needs to be installed to mitigate water as it backs up against the barrier, or the cover could be extended 50 meters (165 feet) to the west to reduce infiltration. A cost analysis will be performed. Hydraulic modeling and testing show bedrock to have an effective hydraulic conductivity below $1 \times 10^{-8}$ centimeters per second (cm/sec), and no faulting is documented at the site.)

**Step 2b: Identify Structural Functions**

Structural functions include strength and strain compatibility. When the primary function of the vertical barrier is strength, section modulus (cubic centimeters [$cm^3$] or cubic inches [in$^3$]) and material yield stress (kilopascal [kPa] or pounds per square inch [psi]) are used to describe the barrier requirements (e.g., sheet piling and steel-reinforced concrete walls formed in excavations using slurry trenching techniques). When strength is a secondary function, unconfined compressive strength (UCS) is used (kPa or psi) to describe a barrier’s strength.

A qualified geotechnical engineer should assess barrier strength requirements. Brittleness is usually influenced by strain compatibility. A high Portland cement content barrier may become brittle and be subject to cracking, where a barrier with bentonite would be less likely to experience these effects. The addition of bentonite helps the barrier to have higher strains at peak strength and allows a degree of “self-healing” should small cracks develop. However, a low Portland cement, high bentonite barrier may excessively squeeze/deform, reducing its thickness. (Example: The eastern half of the vertical barrier will be required to add sufficient strength to the dike so that the factors of safety meet requirements by achieving a UCS strength of 500 to 1000 kPa [73 to 145 psi].)

**Step 2c: Identify Chemical Functions**

Chemical functions include environmental resistance and site chemical manipulation. CCR surface impoundments tend to contain water with inorganics (e.g., arsenic, barium, beryllium, cadmium, chromium, lead, and mercury). Fuels and solvents can be problematic if they exist, so different barrier types and materials may be needed.

“Environmental resistance” is a vertical barrier’s ability to resist degradation when exposed to environmental conditions. Environmental resistance should first be evaluated using literature sources and supported by field screening and laboratory testing because of the complex chemistry at most sites.
A screening test is recommended to assess potential incompatibility of site soils, groundwater, and candidate mix water with common reagents such as bentonite and Portland cement. Bentonite is susceptible to cation exchange, which can degrade bentonite hydraulic characteristics if the hydration sequence is incorrect or if mix water contains incompatible ions. Cement hydration can be negatively affected by pH, organics, and certain inorganics. A good reference is “Guide to Improving the Effectiveness of Cement-Based Solidification/Stabilization” (1997). ASTM D7100, *Standard Test Method for Hydraulic Conductivity Compatibility Testing of Soils with Aqueous Solutions* permeates a test specimen with site water to simulate years of barrier exposure to site water in a shorter amount of time (Example: The owner requires that the vertical barriers last 30 years, so long-term compatibility testing is necessary.)

Chemical manipulation includes changing chemical concentrations downgradient of barriers through changes in flux. The flux is used to estimate times and concentrations related to achieving a target concentration at a monitoring location by adding the flux rate of individual COCs through the barrier to other water sources beyond the barrier (i.e., infiltration) and dividing those flux rates by the seepage rate beyond the barrier. Geochemical modeling is required to account for complexities.

Chemical alteration can also be achieved with permeable reactive barriers, for which the existing and desired inorganic species need to be identified to inform candidate media selection usage rates and effectiveness. USEPA-542-R-97-004 provides some fundamentals related to in-situ treatment of metals. (Example: The owner has requested that only hydraulic control be provided; however, discussions related to COC flux have begun.)

Chemistry is often a secondary consideration because the primary COCs in CCR surface impoundment fluids are inorganics. The concentrations of inorganics found in these fluids are usually insufficient to cause major compatibility concerns; however, site-specific testing is recommended.

**Step 3: Identify Relevant Site Conditions**

Site conditions are important in vertical barrier design. Relevant site conditions may be considered in two major categories: physical and construction conditions. Input from an experienced team, including engineers, geologists, site personnel, regulatory experts, and contractors, is required. Following are some of the most relevant site conditions.

**Physical Conditions**

Physical conditions include horizontal (plan view) barrier alignment, topography, and depth; existing soils and rock characteristics; overhead and underground utilities, structures, and potential buried obstructions; a consistent water source; locally available materials; and spoils management. Additional considerations include the following:
• Alignments with tight turns, limited access, and steep grade changes will limit installation techniques. Most techniques require a temporary working platform to facilitate operations, as well as support areas and materials handling/processing areas. (Example: The perimeter road was built for tractor trailer access for maintenance and general site access.)

• The topography and maximum depth and the number and magnitude of changes need to be understood early in the process, with a reasonable degree of certainty, through accurate profiling along the alignment. With slurry trenching, bedrock is confidently identified, while with one-pass trenching it may be more challenging or impossible to identify bedrock, requiring more predesign data to confidently identify the bedrock position.

• Soil and rock characteristics, including types, densities, fines content, and excavation difficulty, need to be understood and quantified. For mix studies and equipment selection, the average relative proportions of the various material types and their ranges need to be understood through development of a detailed profile for each barrier. (Example: Pinnacles in the bedrock surface exist. Supplemental geophysics and explorations are underway to assess bedrock excavation difficulty and to inform key depth determination.)

• Overhead and buried utilities, debris, and other obstructions can wreak havoc during barrier installation if not considered when selecting the installation technique. In areas where these obstructions cannot be removed, specialty equipment, such as grouting techniques, may be required to install segments of the barrier. If several crossings exist, it may be economical to add a jet-grouting operation instead of relocating multiple utilities. The potential for obstructions such as historical river debris, large cobbles, and boulders should also be identified if encountered or expected and clearly communicated in contract documents.

• Availability of a consistent water source is often required for vertical barrier installation and should be identified, tested, and used in screening and mix studies. (Example: The nearby river has adequate flow and was used for testing, and a withdrawal permit can be obtained in adequate time so as not to delay construction.)

• Proximity to economical soil borrow sources and reagents, such as alternative cementitious materials, should be identified when preparing cost estimates and materials used in mix studies. If the site is close to a cement facility, it may be more economical to use more cement, cement kiln dust, or non-American Concrete Institute (ACI) spec materials to optimize backfill cost by reducing more costly reagents. (Example: A nearby papermill produces fly ash and lime.)
Spoils disposal volumes can represent considerable costs for many vertical barrier installation techniques, so knowing where trench spoils can be located and the cost of disposal are often important considerations when costing a conceptual design. The volume of spoils is measured relative to excavation volume. Installation of a cement-bentonite barrier may produce 100% spoil, a backfilled slurry trench may produce 30% to 50% spoil plus periodic slurry disposal, in-place mixing may produce 10% to 30%, and sheet piles typically produce little to no spoil.

Construction Conditions

Other conditions include project-specific Quality Assurance/Quality Control (QA/QC) and work sequence:

- QA/QC requirements vary for each type of vertical barrier, but some aspects are shared between installation techniques. Particularly important are knowing the importance of the hydraulic, strength, and chemical characteristics, which generally dictate their required measurement accuracy and frequency. Inherent limitations of the barrier type can be overcome through appropriate QA/QC testing before and during installation. Engaging an experienced team, including an experienced contractor, is recommended.

  It is important to distinguish between QC, which should be completed by the contractor, and QA, which should be completed independent of the contractor. QA is where QC documentation is reviewed, additional/supplemental tests are performed, interfacing with regulators and stakeholders may occur, and construction can be certified. Accurately sampling the barrier directly after it is installed and cured can be problematic and should only be done based on well-informed decisions.

When not regulated, QA/QC is often a “judgement call,” including what can be reasonably assumed based on site knowledge, experience, contractor qualifications, a reasonable number of data points, and what is acceptable to the owner. A report for USEPA, Subsurface Containment and Monitoring Systems: Barriers and Beyond; by Pearlman, 1999 and USACE EM 1110-2-3506 provides guidance on QA/QC for different types of barriers and grouted barriers. As previously mentioned, barrier type can indicate quality and a remotely mixed backfill can be more easily observed, monitored, and tested than a mixed in-place backfill, but placement techniques and site conditions also must be considered. Many specialty contractors use electronic data acquisition to provide real-time documentation of installation quality, which can be supplemented with field and laboratory observation, monitoring, and testing.

Field screening, preliminary mix studies, contractor mix design, and field-scale demonstration should be performed to inform QA/QC and demonstrate suitability of the barrier materials and construction techniques before full-scale installation.
Nondestructive in situ testing techniques, such as large-scale geophysical and smaller-scale hydraulic and vapor tests, also can be implanted. (Example: The owners require a barrier consistent with industry standards of practice. Therefore, a QA/QC program is required along with a field demonstration before full-scale implementation.)

- Work sequencing is often critical to decision making related to design. Installing the vertical barrier early in the CCR surface impoundment closure process can be more cost effective because of the area required for support operations; however, subsequent damage to the wall by other contractors may become problematic from a responsibility and repair perspective, and construction-phase water balance must be considered. (Example: Modeling shows that if the western vertical barrier is installed early, followed by capping and then the easterly vertical barrier, then pumping from within the surface impoundment after closure will be reduced.)

**Step 4: Develop Key Barrier Wall Parameters**

Following Steps 1, 2, and 3, conflicts and cost drivers must be reviewed and reconciled, and the conceptual design finalized. The previously identified functional characteristics should be refined in this step, based on a comprehensive groundwater model and preliminary mix studies that support assumptions. At a minimum, the final conceptual design should include the barrier alignment, topography, depths, and barrier characteristics, including the following:

- Hydraulic characteristics, including permeability to ±0.5 order of magnitude, thickness, and maximum hydraulic heads to ±1 meter (3 feet). (Example: $1 \times 10^{-7}$ cm/sec, width of 0.61 meter (2 feet), maximum head across the easterly vertical barrier of 13 meters (42.6 feet), and 1 meter (3.3 feet) for the westerly vertical barrier with passive water diversion.)

- Strength, including UCS lower-bound to ±70 kPa (10 psi) when cured and intermediate strengths if they impact sequencing; minimum and maximum strains to ±1%; and the relative importance of these strength assumptions. (Example: UCS of 2,750 kPa [400 psi] is needed in the eastern vertical barrier, and enough strength to stand-up, or a minimum of 35 kPa [5 psi], is required of the western vertical barrier.)

- A list of chemicals and concentrations to which the vertical barrier will be exposed, and species if in-situ treatment is needed.

- Work limits, support facilities, screening results, preliminary mix study results, and QA/QC requirements. (Example: No electric power is available at the surface impoundment without extraordinary expense. Portland cement, local reactive fly ash, and bentonite were tested with site groundwater, ash contact water, and river water, with only minor reductions in efficiency evident.)
Preliminary mix studies show that soil-fly ash can achieve the required hydraulic and strength characteristics for the westerly vertical barrier, and soil-slag-cement-bentonite can meet those requirements for the easterly vertical barrier.

Step 5: Select Appropriate Installation Technique(s)

There are a variety of vertical barrier installation techniques. A specialty subcontractor is best suited to install barriers at large industrial projects, such as CCR surface impoundment closures, because their crews typically work on with and therefore specialize in specific technologies. Support operations, such as working platform construction, staging and mixing facility construction, stormwater management, and spoils management, are often most efficiently managed by a general contractor. Additional information that should be considered when selecting appropriate techniques is usually based on site considerations and supported by specialty subcontractor input. Developing a questionnaire for various specialty subcontractors is recommended. The questionnaire should include the CSRM, items identified as potential concerns during Steps 2 and 3, and clearly defined requirements from Step 4.

Sealed Sheet Pile Vertical Barriers

These barriers are formed when steel or vinyl sheet piles are installed to the desired depth and the interlocks are welded and/or a sealant is used to reduce seepage through the interlocks. There are patented systems, such as the Waterloo Barrier®, which uses cold-rolled sheets that have low to moderate strength, and higher strength options where sheets are often welded into pairs and sealed at alternating interlocks with a hydrophilic medium or grout. System-equivalent hydraulic conductivities of $1 \times 10^{-8}$ cm/sec for 0.3-meter (1-foot) thickness are achievable. Non-sealed sheet piling typically has equivalent hydraulic conductivity of approximately $1 \times 10^{-4}$ cm/sec for a 0.3-meter (1-foot) thickness. Installation typically requires a crane and support equipment and a relatively level open area for material storage and installation. Buried obstructions can sometimes be removed but can impede installation, leaving an opening in the barrier and requiring supplemental work. (Example: As an alternative should strength testing be unfavorable, a sealed joint sheet pile barrier may be more economical than building a traditional soil-reagent barrier.)

Slurry Trenching

“Slurry trenching” is a generic term for a specific vertical barrier trenching technique. Barriers installed using the slurry trenching method are common and can be considered a baseline technology for comparison to other techniques. Since the 1940s, slurry trenches have been used in construction to contain and direct groundwater, so the requirements and practices for designing and installing a barrier in a slurry trench are well-established. Depths of up to 60 m (200 ft) are achievable. Slurry trenches are used to form barrier walls by adding cement to the bentonite slurry to form a cement-bentonite barrier, backfilling the trench, or installing implants (e.g., geomembranes and steel reinforcement for walls with moderate structural requirements).
Backfill may be mixed locally or remotely. In local mixing, the wall backfill is mixed by placing trench spoils next to the trench and adding reagents to produce the desired characteristics. Because batches are mixed using predetermined proportions with mobile equipment, highly variable deposits are usually not well suited to local mixing. In remote mixing, the trench spoils are loaded into trucks and hauled to a staging/mixing area. A batch process is employed to mix the backfill by proportioning select excavated soils, bentonite slurry, dry bentonite, and other reagents to achieve the desired characteristics. The batches are tested to confirm that they meet requirements, and then hauled to the trench for placement. Final design properties develop over time as the backfill settles and cures in the trench.

Backfill can be placed in a slurry trench to displace the slurry using one of two basic methods. The backfill can be pushed into the trench displacing the slurry as the backfill settles at its angle of repose. Alternatively, the backfill can be placed using a tremie pipe, where a large-diameter pipe is suspended within the trench from a crane and constantly moved so that the discharge is within freshly placed backfill. The equipment can operate in areas 9 to 12 meters (30 to 40 feet) wide when remote mixing is used, independent of trench depth. If trench-side mixing is used, a width of 3 meters (10 feet) plus the trench width plus the trench depth is often adequate. Two-way traffic is ideal, because it increases productivity.

(Example: For the westerly vertical barrier, cost estimates show slurry trenching to be economical. The barrier is also determined to be constructible within the space available, achieves adequate construction-phase slope stability, and a 1-meter (3-foot) key is possible with available equipment. Because of level grades, trench-side mixing can be performed and excess spoil and slurry can be placed directly in the uncovered surface impoundment. Supplemental explorations will be required of the subcontractor to verify rock surface based on the excavation studies.)

One-Pass Trenching

This technique produces vertical engineered elements using a specialty machine that cuts the soil/rock with what is essentially a large chainsaw inserted in the ground and moved along the wall alignment at a slow, controlled speed. To form a vertical low-permeability hydraulic barrier, the machine simultaneously mixes in-place soils with reagents and water to form the engineered backfill. With some modifications, the machine can also be used to install implanted barriers (i.e., geomembranes). Using a displacement method, sand/gravel and even piping can be installed for water removal and injection. One-pass trenching produces barriers in-situ and without an open excavation, or an excavation supported by slurry, making it a more inherently stable method than slurry trenching. Mixing reagents can be added dry or wet, depending on equipment involved, which may be a consideration when bentonite hydration or reagent curing are affected by site geochemistry. Trenches are usually 0.6 to 1 meter (2 to 3 feet) wide, and spoil production typically runs up to 30% of total trench volume. Depths up to 46 meters (150 feet) are achievable.
Support equipment and labor are used to remove trenching spoils and deliver mixture materials to the trenching equipment. Many companies offer electronic data acquisition/logging to record real-time documentation of the installation characteristics, supplemented with sampling and laboratory testing of mixed materials.

(Example: For the easterly vertical barrier, a one-pass trencher is better able to access the narrow dike, can cut into and mix the materials along the alignment, will require dry materials storage areas, achieve adequate construction-phase slope stability, can bisect the old pipe and form the wall through it, and can achieve the required 3-foot-deep key. The one-pass equipment, for a modest added mobilization cost, can be used to limit the need to dewater along the alignment. For the upgradient groundwater diversion, a combination of ditches and a high-hydraulic conductivity interceptor trench installed with one-pass trenching is cost-effective to divert and redistribute the upgradient groundwater. The redistributed groundwater will increase groundwater elevations outside large portions of the barrier; therefore, much of the wall will experience inward flows, greatly reducing COC fluxes leaving the surface impoundment.)

Deep Soil Mixing Technique

Deep soil mixing is a common technique for vertical low-permeability barriers. Like one-pass trenching, this technique relies on in situ cutting and mixing to form the barrier. A specially outfitted crane or excavator advances large augers into the ground along the barrier alignment. Supported by the crane or excavator arm, a rotating mixer head with augers and grout injectors travels in and out of the ground, and the augured interval forms a reasonably homogeneous mixture of in-situ soils and grout.

The advantages of deep soil mixing relative to the basic slurry trench technique include reduction in the volume of soil to be disposed of and greater stability during construction. This technique does not accommodate underground utilities or obstructions well, and the alignment (plumbness) of the augers can be problematic in dense soils with large cobbles or boulders at depth. Depths of 30 meters (100 feet) are achievable, and spoil production typically runs up to 30% of total trench volume, depending on soil types and reagent/water addition rates.

Grouting

Grouting does not require a trench or full disturbance of the subsurface. Instead, vertical or horizontal barriers are formed in situ and at the required depth intervals. This technique is applicable to vertical low-permeability barriers and structural barriers. While several types of grouting are available, jet grouting is most applicable to barrier installations. Other applicable grouting techniques include chemical grouting, permeation grouting, displacement, and compaction grouting, which are selected based on formation permeability. The USACOE’s Grouting Technology engineering manual (EM 1110-2-3506) is a great reference and is recommended for use when considering grouting techniques. In particularly challenging geologic areas with underground utilities, grouting methods may be used to effectively seal otherwise inaccessible zones or to
supplement or repair barriers installed using other techniques. Grouting techniques are generally more expensive than slurry trenching, one-pass, and soil mixing, but can overcome limitations the other techniques cannot. Grouting techniques can also be used to build barriers where space limitations are tight, alignments are non-linear, and only deep isolated areas require sealing. For environmental remediation applications, jet grouting can be considered for construction of an artificial liner.

**Jet Grouting**

Jet grouting employs a high-pressure jet of grout along with water/air to construct subsurface vertical or horizontal barriers. The equipment is comparable in size to a typical excavator, so it can be deployed on moderately steep slopes and in relatively tight spaces. The high-pressure jets erode and mix the soil with the grout. The grout is often a blend of reagent and water that is mixed in place with the soil to form distinct elements, such as vertical columns, vertical panels, or level disks (to form liners) with engineered characteristics. The elements can be overlapped to form continuous barriers. Sizes depend on soil characteristics and depth. Depths of 45 to 90 meters (150 to 200 feet) can be achieved, and discrete depths can be targeted.

Table 1 summarizes the installation technologies and applicable vertical barrier types.

**Table 1: Installation Technologies and Applicable Vertical Barrier Types**

<table>
<thead>
<tr>
<th>Installation Technique</th>
<th>Vertical Barrier Types</th>
<th>Vertical Barrier Types</th>
<th>Vertical Barrier Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Trenching</td>
<td>Implanted</td>
<td>Remotely Mixed and Backfilled</td>
<td>Mixed in Place</td>
</tr>
<tr>
<td>Slurry Trenching</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>One-Pass Trenching</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Deep Soil Mixing</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Grouting</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

**Step 6: Select Engineered Backfill Type**

Backfill selection is a multi-step process involving chemical compatibility testing, preliminary mix studies, final mix studies, and possibly a field-scale demonstration. As mentioned in Step 2c, chemical compatibility, including literature studies, engineer/contractor experience, and field/laboratory studies, should be performed during conceptual design development to identify compatible materials. During this phase, a preliminary mix study should be performed using representative soil samples, potentially available reagents, and water sources to estimate needs for costing purposes and simulating the above-identified techniques. Final mix studies should be required of the installer, which will be responsible for the mix’s performance. On large
jobs, and to supplement and inform QA/QC testing, a field-scale test section can be built away from the final alignment once an installer is selected and on-site.

This text focuses on vertical hydraulic barriers because low permeability is most likely to be the primary function of barriers at CCR surface impoundments. Wall backfill types are somewhat interchangeable among installation techniques and consist of similar reagents. The primary selection criteria are based on hydraulic, structural, and chemical barrier functions. The wall backfill typically contains a mixture of materials that can include soils (excavated and/or imported), water, and reagents (identified previously). Table 2 shows the permeability and strength reasonably achievable with the various backfills and the typical associated installation techniques. (Example: The two installation techniques of slurry trenching and one-pass trenching are compatible with the full range of backfill types.)

**Soil-Bentonite Backfills**

Soil-bentonite backfills are formed by blending soil with a bentonite grout and/or powdered bentonite and possibly additional water, typically to reduce hydraulic conductivity. Various bentonite types including American Petroleum Institute 13A Section 9 or 10 or lesser-grades may be used. For remote mixing applications, on-site and imported soils can limit bentonite addition if the soil fines contents are optimized (usually at least 30% is needed). This type of backfill can be applicable in situ, where granular native soils with enough fines exist and minimal heads are predicted across the vertical barrier because the backfill remains in an uncured state and can erode under high hydraulic gradients/velocities. Strengths are often low and dependent on the soils used. Where liquefaction and soil creep may be a problem, this may not be the most desirable wall backfill. However, this can be an economical solution where the barrier is not required to carry much load, such as at a level site with strong/dense clayey soils. These backfills are plastic and not typically subject to stress-induced cracking.

**Soil-Cement Backfills**

Soil-cement backfills are formed by blending soil with a cement. Typically Type I/II Portland cement is used to increase strength, and workability is adjusted by adding water. Other reagents such as slag, cement kiln dust, lime kiln dust, polymers, and proprietary additives may be used as cost savings measures or simply to bulk up the mix to maintain the fines content in the desired range. Water is added to produce a workable mix, with some installation techniques requiring a pumpable mix. This type of backfill can be mixed and placed in an open excavation, or the core of an embankment can be formed as a vertical barrier. This can be an economical solution where the wall is not required to have low hydraulic conductivity and can be engineered to have moderate strengths, but it can be brittle unless fibers of other additives are used. (Example: The saprolite, when mixed to form a vertical barrier with either method, will produce enough fines. A mixed soil-fly ash can provide sufficient strength and hydraulic
characteristics for the westerly vertical barrier, as demonstrated in the preliminary mix study and engineers’ experience.)

**Cement-Bentonite Backfills**

Cement-bentonite backfills are most often formed in bentonite slurry trenches. The trench length is limited, and cement is added to the bentonite, which cures in place. These materials are used most often when unsuitable soils exist, when mixing space is limited, and when short segments are needed to accommodate sloping topography. A clam-shell, instead of a conventional excavator, can be used for short segments.

**Soil-Bentonite-Cement Backfills**

Soil-bentonite-cement backfills are formed by blending a bentonite grout and/or powdered bentonite, cement, and water to reduce hydraulic conductivity and achieve strength. Including cement to the base soil-bentonite mix produces a mix that will cure to a semi-rigid to rigid material based on cement content. Adding cement to a certain point is beneficial, with excessive cement content increasing strength and reducing strains at peak strength. This approach results in a brittle backfill, so limiting cement addition can be an important part of QC.

**Soil-Slag-Cement-Bentonite Backfills**

Soil-slag-cement-bentonite backfills are formed like other soil-reagent backfills; however, some of the cement is replaced with slag. The slag is typically a graded ferrous granulated ground blast furnace slag (GGBFS), which is available as a commercially produced material at limited facilities in the United States. The combined interaction between GGBFS and Portland cement during the hydration process is advantageous because additional and beneficial calcium silicate hydrate is produced at the expense of the unfavorable excess calcium hydroxide produced by hydration of cement. The addition of slag produces a backfill that can achieve lower hydraulic conductivities and higher late-time strength than pure Portland cement with similar durability. *(Example: The saprolite, when mixed to form a vertical barrier with either method, will produce enough fines. A mixed soil-slag-cement-bentonite can achieve sufficient strength and hydraulic characteristics for the westerly vertical barrier, as demonstrated in the preliminary mix study and engineers’ experience.)*
### Table 2: Installation Technologies and Applicable Backfill Types

<table>
<thead>
<tr>
<th>Applicable Backfill Types</th>
<th>$K_1^{1}$ (cm/sec)</th>
<th>UCS$^2$, (psi)</th>
<th>Conventional Trenching</th>
<th>Slurry Trench</th>
<th>One-Pass Trenchers</th>
<th>Deep-Soil Mixing</th>
<th>Grouting$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil-Bentonite</td>
<td>$1 \times 10^{-7}$</td>
<td>Up to 5</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
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<tr>
<td>Soil-Cement</td>
<td>$1 \times 10^{-7}$</td>
<td>Up to low 100s</td>
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<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Cement-Bentonite</td>
<td>$1 \times 10^{6}$</td>
<td>Up to low 1000s</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil-Bentonite-Cement</td>
<td>$1 \times 10^{-7}$</td>
<td>Up to low 100s</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Soil-Slag-Cement-Bentonite</td>
<td>$1 \times 10^{-9}$</td>
<td>Up to high 100s</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
</tbody>
</table>

Notes:

1. $K_1 = \text{hydraulic conductivity, centimeters per second (cm/sec).} \text{Reductions are possible based on site soils and additives used. Based on Pearlman, 1999.}$

2. UCS = Unconfined Compressive Strength, pounds per square inch (psi). 1 psi = 6.9 kPa.

3. Grouting includes the backfills shown plus chemical grouts such as polyurethane.

**CONCLUSION:**

CCR impoundment closures often include cover systems, which are effective solutions for isolating CCR and controlling infiltration, however there may be lateral groundwater flow that can be effectively controlled with a vertical barrier. The three most common vertical barriers are implanted barriers, remotely mixed and backfilled barriers, and mixed-in-place barriers. Each barrier type was summarized and their quality considerations, installation techniques, constructability requirements, and limitations were discussed. The authors introduced a six-step decision framework to support selecting an appropriate vertical barrier system based on hydraulic control (e.g., reducing, directing, collecting, and/or treating liquid flow), hydraulic conductivity and seepage reduction, constituent reduction time, chemical compatibility, and contracting approach. Through following the decision framework, design teams and owners can be confident that an appropriate vertical barrier meeting hydraulic, structural and chemical requirements has been selected.