Soil Bentonite Slurry Trench Cutoff Walls: History, Design, and Construction Practices

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ABSTRACT

Slurry trench cutoff walls have been widely used for over 70 years to control groundwater flow, seepage through dams and levees, and contaminant transport. In the US, soil-bentonite (SB) slurry walls are frequently the best and most economical vertical barrier to stop the horizontal flow of groundwater and minimize contaminant transport. This paper reviews the development of SB cutoff walls from both a construction and design standpoint. Lessons learned regarding trench stability, the type of bentonite, the makeup of the backfill, specifications, quality control, interface connections, longevity, hydraulic conductivity, state-of-stress, and compatibility with contaminants are presented. Items of particular importance in specifications including viscosity of the fresh slurry, viscosity of the in-trench slurry, unit weight of the slurry, slump, gradation, and hydraulic conductivity of the backfill are discussed. Guidance for quality control testing in both the lab and field are provided including recommendations regarding stresses for testing. The paper provides summary opinions regarding the limitations of SB slurry walls. Issues that require special consideration are identified and include excessive depth, limited available working platform width, excessive underground or overhead obstructions, artesian ground water conditions, layers of extremely weak soil, and rock or boulders in the soil profile.

INTRODUCTION

A soil-bentonite (SB) slurry wall, or trench, is constructed using bentonite slurry to keep the trench open while the excavation is performed continuously to the full design depth. Excavated soils are mixed and amended as required at the ground surface and placed in the trench as a semi-fluid backfill that displaces the slurry forward as the excavation progresses. This is sometimes referred to as a two-step slurry trenching process and this process produces the SB cutoff wall. A photo of the process is presented in Figure 1 and a schematic is presented in Figure 2.

Figure 1. Photograph of slurry trench excavation from NSF Research Site at Bucknell University (photo courtesy of Geo-Solutions, Inc.)

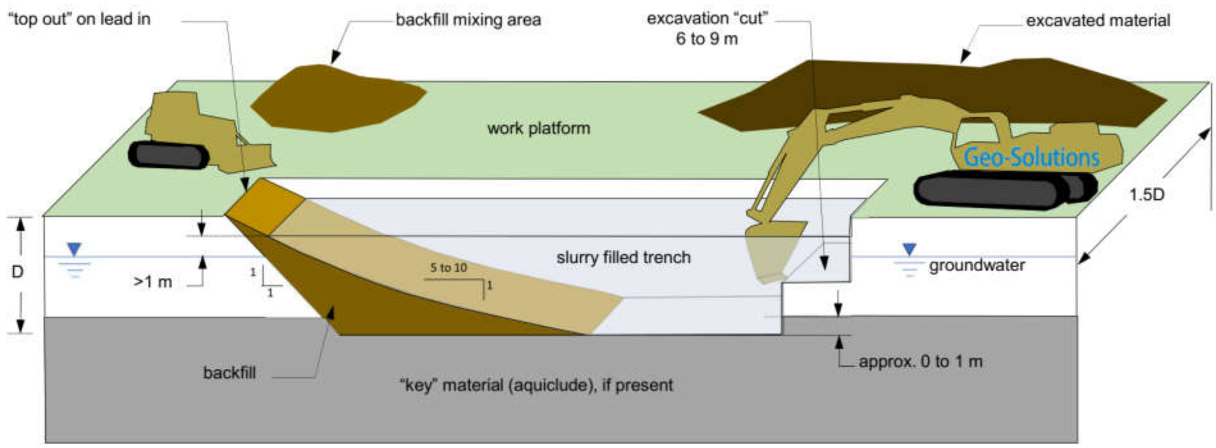

Figure 2. Schematic (cross-section) of slurry trench construction (courtesy of Geo-solutions, Inc.)

There are other versions of slurry walls, e.g. structural elements like diaphragm walls or semi-structural self-hardening walls like cement-bentonite (CB) or slag-cement-bentonite (SCCB), but only SB cutoff walls are discussed in detail this paper. Another variation of the two-step slurry trenching process is soil-cement-bentonite (SCB) wherein cement is added to the SB backfill. This type is also not discussed in detail herein. Some in the industry reserve the term "slurry wall" for structural elements constructed in panels and backfilled with reinforced concrete and use "slurry trench" for SB, CB, SCCB, and SCB wall installations. This paper uses the slurry wall and slurry trench terms synonymously. The terms slurry wall and slurry trench are sometimes incorrectly used to refer to in situ mixed walls. Those other forms of cutoff walls with similar final properties that are formed by mixing soil without excavating it, e.g. deep soil mixing (DSM), cutter soil mixing (CSM), and chain mixing methods (CMM) and are not discussed here.

This paper is a modification and extension of the article "70 years of soil-bentonite slurry walls" written by Chris Ryan for GeoStrata magazine which was published in the June/July 2021 issue (Ryan 2021).

HISTORY OF SB CUTOFF WALLS IN US PRACTICE

By most accounts, the first SB slurry trench cutoff wall was built in Long Beach, CA in 1949/1950 (Xanthakos 1979, Jefferis 1997, Ryan 2021). This SB wall was constructed continuously with a bucket excavator. The process was patented around that same time by Charles Toll of Industrial Equipment Company, the predecessor company of Inquip Associates. Sherard (1963) describes a 10-ft wide, eighty-foot deep wall built with a dragline under the Wanapum Dam on the Columbia River in Washington sometime around 1958.

As the early patent expired, there was increased use of the SB technology in the 1970's. For example, the Mobile District of the United States Army Corps of Engineers (USACE) specified the use of these walls to help with dewatering of the excavations for several locks built as part of the Tennessee-Tombigbee Canal project (Winter 1976). The replacement of draglines with extended long-stick hydraulic excavators greatly improved production and lowered costs (Ryan 2021). By the late 1970's, long stick excavators combined with clamshells for depths beyond the excavators reach were becoming common. Figure 3 shows this configuration with an excavator digging to 16 m followed by a clamshell digging the remainder of the trench to 22 m. The backfill in this project is being mixed along the trench with a bulldozer. The slurry wall was installed to surround a deep excavation in sand below the water table and was one of the early projects demonstrating the efficacy of SB slurry walls in cutting off groundwater flow. This project was also the project that began a long professional relationship between authors Ryan and Evans extending over the last 40-plus years. Advances made in the understanding of stability of slurry trenches (Nash 1974) and increases in the availability of literature on the subject (Clough 1973, Xanthakos 1979, D'Appolonia 1980) also helped to increase the application of this technique. Slurry walls then became common in the geotechnical marketplace in the 1970's and 1980's. They were used for stabilizing levees, extending the cores of dams to depths below the ground surface and dewatering large excavations.

Figure 3. Photo of SB slurry wall construction showing long stick excavator, clamshell and bulldozer backfill mixing

SB slurry trench cutoff walls were also quickly applied to solve environmental containment issues after and concurrent with their adoption and acceptance in the geotechnical market. The first applications of slurry walls for the containment of hazardous wastes were in the late 1970's with rapid expansion of their use in the 1980's. As an example of an early project, a SB cutoff wall was used at a site to contain contaminated groundwater at a phosphate plant in Cofield, NC in 1980. About the same time, a 4 km long SB slurry wall (with a leachate collection system) was installed around a landfill site in eastern Baltimore County. Ten years later, the US EPA designated the site as "No further remedial action planned" and 40 years later the site is monitored by the Maryland Solid Waste Division. Since the early applications in the 1980's, SB slurry walls have been used for containment of a wide variety of wastes at hundreds of contaminated sites, including many Superfund sites.

For a sense of the size of the US market, the authors have collectively been involved with the installation of well over 2,000 SB walls in the United States (US) in geotechnical and environmental applications.

INTERNATIONAL USE

Interestingly, SB slurry walls, although widely used in the US, are not widely applied overseas. The US has adopted a number of related European-led technologies including slurry wall techniques, like concrete diaphragm walls and CB walls, and Japanese-led in situ mixing technologies, DSM and trench remixing deep (TRD). Conversely, SB slurry wall technology has not been widely adopted outside of the US. There are a few cases where, with support of US firms, these types of walls have been built in other countries. In general, however, there is very low acceptance and utilization of this technology overseas, especially relative to the applications in the US. The authors believe that there are a number of factors causing this, as identified below.

- Space: Sites overseas tend to be more constricted, with less room to do things like mixing alongside the trench. This makes SB walls less economical.
- Product control: Engineers and constructors alike overseas prefer the final product or backfill to be more precisely controlled than is possible with SB slurry walls. CB is made in a mixing plant and is therefore seen as an engineered product that offers greater control of quality. While the concept of using the soil dug from the trench, amending it and putting it back in the trench may seem less reliable than a mixing plant, the authors note that in situ soil mixing techniques also mix soil but arguably with less homogenization of the soil than slurry wall techniques.
- Trench Stability: There are concerns about stability of long trenches under slurry. There is even still lingering belief that long slurry supported trenches are impossible. These concerns and beliefs limit the allowable installation procedures (e.g. panel installations with clamshells vs. longer trenches with long stick excavators), if the technique is selected at all.

In addition to these technical considerations, it is clear from studies of other technological developments that the development and adoption of different technologies for similar applications is shaped by social and political circumstances within the environment in which the development occurs (Mackenzie 1993). Additional discussion comparing one international market (UK) versus US slurry wall practice can be found in Evans and Dawson (1999).

LIMITATIONS OF SB SLURRY WALLS

In general, the SB slurry trench cutoff wall is the most cost-effective technology to make a barrier for control of lateral (horizontal) groundwater flow. That said, every technology has limitations, so it is useful to identify the limitations of the SB technology. The following list identifies issues that might by themselves, or in combination, cause the selection of a different method for the entire barrier or at least a segment of it.

- Excessive depth: Costs tend to increase with depth, especially when the trench is deeper than approximately 90 ft, the depth at which the excavation tool switches from an excavator to a clamshell. However, slurry trenching has been demonstrated for deep applications, as evidenced by the deepest circumferential slurry wall, to date, at 56 m (Ruffing and Evans 2016) as shown in the photos in Figure 4.
- Limited work platform width: Costs increase if the backfill cannot be mixed alongside the trench. While there are numerous projects where the backfill has been mixed remotely, transportation of excavated soils to the mixing area and transportation of backfill back to the trench adds to the project cost.
- Obstructions: Excessive natural or manmade underground or overhead obstructions will all add to the cost. This is a consideration for all cutoff wall technologies.
- Trench stability: Conditions that may cause marginal stability, e.g. artesian groundwater conditions or layers of very weak soil, will increase cost or may make the installation impossible.
- Difficult excavation conditions: Rock or boulders in the profile are difficult to excavate economically. Rock can be pre-drilled or blasted. Some boulders can be removed during excavation. Others may require pre-drilling, or chiseling/drilling through the slurry. Rock at the bottom of a profile may be more economically sealed with another cutoff wall technique, like grouting.
- Voids in the profile: Cavities in a profile due to open-graded cobbles or limestone need to be considered when making the cutoff wall installation approach selection. These conditions, which may lead to rapid slurry loss in the trench, can be particularly consequential for deep projects where there is a substantial volume of "open" slurry filled trench.

Figure 4. World's deepest circumferential slurry wall, constructed to a depth of 56 m (185 ft) deep. On left: with backhoe (background) and clamshells (foreground), on right showing final embankment adjacent to a flooded Ohio River for a 100 ft deep hydroelectric plant excavation (photos courtesy of Geo-Solutions Inc.)

TRENCH STABILITY

There are a number of methods for the calculation of the stability of excavations supported by slurry, as described by many (e.g. Nash and Jones 1963, Morgenstern and Amir-Tahmasseb 1965, Xanthakos 1979, Tsai and Chang 1996, Filz et al. 2004, Fox 2004). These calculations are generally over-conservative. They will often predict failure at a point in the process when the trenching begins and the trench is filled with fresh slurry even though the trench is perfectly stable. At this point the density of this slurry will be at its lowest. Once the slurry is in the trench, mixing of formation fines with the slurry raises the density of the slurry. Field experience with thousands of installations in the US reveals few failures under static conditions. As an illustrative example, the authors have seen slurry walls successfully installed through dikes constructed of clean sand adjacent flowing water with less than one meter of differential head between the slurry and the water surface. The fact is that most soil has components of strength, including capillary tension, that are ignored in calculations of long-term stability, but are significant in the temporary situation.

However, there are situations that present risks that should not be ignored:

- a layer anywhere in the excavated profile with artesian head conditions,
- inadequate differential head between the trench slurry and the local groundwater level at any point in the trench profile—usually around one meter of slurry head over the groundwater table is adequate for installations using bentonite slurry,
- layers of open graded materials or voids in the excavated profile,
- higher ground adjacent to the wall, for example, where the wall is being installed next to an embankment or dike or on a step on a hillside,
- very soft, low-permeability soil or highly organic soil like peat in the profile, and
- excessive loading like very heavy equipment operations, vibrations, or soil stockpiles adjacent to the open trench.

Slurry trenching may still be feasible if one or more of these conditions are present, but these conditions must be considered in the design and construction planning.

BENTONITE TYPE

In the US, the predominant type of bentonite sold is sodium bentonite. Manufacturers may add polymers or other materials to increase the "yield" of the bentonite, that is, how much bentonite powder it takes to make a given amount of suitably viscous slurry. Most of the bentonite used in slurry trenching is referred to as 90-barrel yield and there are two versions of this, a so-called "natural" product with minimal additives meeting Section 10 of API 13A and a lower grade bentonite with some additives meeting Section 9 of API 13A. The authors' experience is that there is not a detectable difference between the two materials for use in the slurry that stabilizes the trench, nor in the backfill that forms the final product. Unless project-specific bench scale or pilot testing shows otherwise, it is not necessary to specify the "natural" product (Section 10). Further, the specification of "high-yield" bentonite products is not recommended. Using a high yield bentonite results in fewer bentonite particles in the final backfill.

For environmental projects where groundwater is contaminated, compatibility studies during the design phase are recommended to ensure there are no undesirable slurry-groundwater interactions. The authors' experiences with these studies suggest that standard bentonite (Section

9) will work in most conditions for both stabilizing the trench and for reducing the permeability of the backfill. For particularly contaminated groundwater, a modest increase in the bentonite content in the slurry may be warranted to ensure properties are maintained during excavation. When this slurry is combined with a correctly graded backfill soil, compatibility issues with the final SB material are rare. Bench scale compatibility studies are always recommended to ensure these generalities apply to the specific situation.

BACKFILL

As documented over 40 years ago, SB backfill is generally best created from a well-graded mixture of sand and fines (D'Appolonia 1980). In general, the fines content will contribute most to the low permeability of the barrier, and clay fines work better than silt fines. Fines content can be as low as 15% (or possibly less if the target hydraulic conductivity is greater than 1×10^{-7} cm/s) and as high as 50% or more in most backfill designs. Backfill design should take maximum advantage of the in situ soil profile, and therefore be site specific. It is important to minimize the amount of additional soil and/or bentonite that is added to the blend. When achievement of a low hydraulic conductivity is critical or when contaminants are present or will contact the wall in the future, design mix studies should always be conducted. In almost every case, there is a blend of materials that can achieve what might be considered a standard maximum hydraulic conductivity for SB of $\leq 1 \times 10^{-7}$ cm/sec. That is not always the case for walls containing cement, CB, SCCB, or SCB. It is particularly important that the backfill mixture contain low plasticity silt and clay fines for environmental sites. While the high swelling capacity of bentonite is essential to the SB technology, the swelling is also reversible in the backfill under certain groundwater chemistry conditions. As a result, for backfill that will be in contact with contaminated groundwater, it is recommended that the low hydraulic conductivity be accomplished through the use of relatively inert silt and clay fines rather than by increasing the bentonite content. A backfill amended with fines rather than more bentonite is more likely to result in a compatible cutoff due to the less reactive nature of the fines compared to bentonite. It is important to note here that the hydraulic conductivity is stress dependent (Ruffing et al. 2010) and the magnitude of the influence is dependent upon the grain size distribution of the backfill (Evans and Huang 2016).

IMPORTANT SPECIFICATIONS

SB specifications generally cover the following technical areas (Ryan and Day 2003):

- properties of fresh, as-mixed, bentonite-water slurry,
- properties of in-trench bentonite-water slurry,
- mixing and placement properties of the backfill, and
- physical properties of the as-placed backfill.

The following properties, usually included in the specifications are important to trench stability, constructability, and long-term performance:

- Viscosity of fresh, as-mixed, bentonite-water slurry: While the viscosity of the slurry is not usually important in and of itself, it is a quick indicator of the quality of the slurry and is measured in a Marsh funnel. The viscosity of the mixed slurry can be adjusted so that, when added to the trench, the freshly added slurry can be used to adjust the viscosity of the slurry in the trench.

- Viscosity of in-trench slurry: A minimum for stability is usually considered to be approximately 40 seconds as measured using a Marsh funnel. The maximum viscosity measured in the field on in-trench slurry can as high as 120 seconds Marsh or more. Should the slurry in the trench become too thick, the slurry can impede the proper flow of backfill being placed into the trench. The viscosity in the trench can usually be reduced by replacing heavier trench slurry with fresh slurry or by removing solid particles via desanding (added cost).
- Unit weight of the slurry in the trench: There is a point, somewhere around a slurry density of 13 to 15 kN/m^3 (85 to 95 pcf), where it becomes difficult for the mixed backfill to displace the slurry properly. It is best to specify the difference between the in-trench slurry density and the backfill density, with 2.3 kN/m^3 (15 pcf) being a commonly acceptable differential. To clarify, the backfill density should be greater than the slurry density to ensure proper backfill placement (i.e., slurry displacement).
- Backfill slump: This is normally specified in the range of 50 to 150 mm (2 to 6 in). The backfill must be semi-fluid so as to flow into the trench and displace the in-trench slurry. A stiffer backfill (towards the lower end of the range of acceptable slump values) will have a steeper slope in the trench reducing length (and time) of open, slurry supported, trench.
- Backfill gradation, with particular attention to fines content: If possible, specifications should require the reuse of excavated soils found at the project site. A minimum fines content of somewhere around 15% is usually necessary to meet hydraulic conductivity specifications of $\leq 1x10^{-7}$ cm/s. Well-graded backfill is less compressible resulting in less surface settlement during consolidation and higher in situ stresses, resulting in lower hydraulic conductivity, as compared to a poorly graded backfill. Well-graded backfill is also likely to be more resistant to increases in hydraulic conductivity on sites with contaminated groundwater.
- Backfill engineering properties: Specifications should include details as to hydraulic conductivity requirements and means and methods used to determine the hydraulic conductivity including the effective stress for laboratory testing. For SB walls with cement added, unconfined strength is normally also specified.

LIMITATIONS OF SPECIFICATIONS

The ASTM specifications for test methods on bentonite slurry follow very closely to the related specifications from the American Petroleum Institute (API) testing methods. Considering that API is concerned about slurry performance in very high-pressure applications in deep and small diameter holes, some of the API tests are not as relevant to the relatively wide and less deep SB slurry wall projects. For example, in a deep drill hole such as those for which the API specifications were written, excessive filtration (slurry loss into the surrounding formation) can lead to a build-up of a filter cake on the sides of the drill hole that may eventually impede the return flow of drilling fluids which would effectively end advancement of the drill hole. In the case of the SB slurry walls, excessive thickness of the filter cake has no negative impact and may actually contribute to both trench stability and low hydraulic conductivity of the cutoff wall.

The inappropriate application of specifications that do not relate to the safety or quality of the completed SB slurry wall can result (and have resulted) in unnecessary disputes, lost time, and economic losses. The following are several examples of irrelevant specifications that are sometimes incorrectly included with project specifications for SB cutoff walls.

- Fresh slurry filtrate loss: Filtrate loss is primarily an indicator of the quality of the bentonite product and/or the water used to mix the slurry. In most cases, high filtrate loss is more of an economic issue for the Contractor (more slurry will be needed or higher bentonite content per unit slurry). High filtrate loss of the fresh slurry does not affect safety or long-term properties of the wall. Evidence of this comes from other slurry trenching techniques like CB or polymer trenching where filtrate loss is not measured (or losses are very high) and trench stability is maintained without issue. There are no doubt different mechanisms of stability in those approaches, but the fact remains that strict filtrate loss requirements for bentonite slurry used in SB wall construction serve little or no purpose in controlling the short-term stability of the trench or the long-term performance of the wall.
- Sand content of in-trench slurry: The limitation of sand content in slurry likely derives from limitations in sand content of bentonite-water slurry used in concrete diaphragm walls where it is an important item to be specified. Historically, when sand content of slurry in SB projects has been specified, the values have been in the range of 10% to 30%. These numbers may be attainable without excessive cost on some projects, but not all projects. More importantly though, there is never any reason to specify these limits on sand content for a SB slurry wall. Increasing sand content correlates to an increase in trench slurry unit weight. Control of the unit weight is relatedly a more direct and better way to control solids content. Another concern with excessive sand content is the separation of the sand and slurry, allowing settlement of the sand at to the bottom of the excavation, which could create lenses of sandy particles. Thin lenses like this undoubtedly exist in most SB cutoff walls, but there are no documented cases of the detection of excessive flow through a cutoff wall containing lenses. A detailed investigation of sand lenses on one particular project showed the lenses have hydraulic conductivity values essentially at or less than $1x10^{-7}$ cm/s (Evans et al. 2004). This is presumably due to the fact that the sand is surrounded by the bentonite slurry in these lenses. The same study found that sedimentation at the bottom of the wall was coarser than that higher up on the backfill and this sediment was considerably more permeable. Excessive sedimentation is most likely to occur overnight when work stops and can be detected with normal depth soundings and cleaned out, if needed and feasible.
- In-trench slurry filtrate loss: Specification of in-trench slurry filtrate loss has no rational basis and it has created havoc on projects where it has been enforced (Ruffing et al. 2016, Ryan 2021). If specified (incorrectly), the specification is typically a maximum of 20 to 40 ml in the standard filter press test. This is not appropriate to specify for many reasons, but notably because it is beyond the control of the Contractor to modify and has no possible relationship to stability of the trench or final quality of the wall. As an illustrative example, other types of slurries, like CB and polymer slurries, have much higher in-trench filtrate losses and those slurries perform the intended trench stability function without consequence.

LONGEVITY

There is no reason to think that slurry walls have a finite design life. They are composed of an engineered blend of natural, mostly inert, soil components and there is little evidence that their properties change over time. In the case of certain chemicals, there can be some reduction in the effectiveness of the bentonite although this reduction is finite and bench scale tests can be used to evaluate the magnitude of these effects. In almost every case, slight increases in inert fines content, bentonite quantity, or other design mix changes can be used to compensate for any potential degradation. There are no documented cases where SB cutoff walls have failed over time, but published studies defend the long-term efficacy. For example, an early 1980's project included a 4 km long SB wall surrounding a solid waste landfill built in a former sand and gravel quarry in eastern Baltimore County Maryland. Monitoring wells outside of the SB wall revealed such low levels of contamination that the site was classified by the USEPA as "No Further Remedial Action Planned" (Maryland Department of the Environment, 1992).

Despite the experiential evidence that these walls have and will continue to behave as intended for long periods of time, longevity of an SB wall is still an important consideration that is often overlooked (Ruffing et. al 2018). The design life should be considered for all projects, i.e. performance is not infinite, nor should it be assumed to be so. In addition, the consequences of failure should be considered in the subject application. Once an understanding of the long-term needs is developed, the long-term behavior needs to be considered. One method of assessment is running contaminated waters through a sample in a long-term permeability test. Experience and research have shown that exchanging around 3 pore volumes (PV) through a triaxial permeability test specimen is adequate to model long-term effects on a particular SB design mix that is exposed to a chemical contaminated water. Other assessments of longevity may include thought exercises to consider what, if anything, would be expected to change over the design life. At this stage, the designer should consider physical changes in and around the wall (stress, strain conditions), geochemical changes in the groundwater, environmental compatibility of the backfill, and the Owner's risk tolerance.

SUMMARY AND CONCLUSIONS

In the US, SB slurry walls remain the most used and most cost-effective method for the lateral control of groundwater flow. After thousands of applications, it is clear that these walls tend to function as intended, but each design and specification must be developed in consideration of the site-specific conditions. Simply applying an old specification from another project may not work out as hoped. This paper provides some insight into important components of SB slurry wall design and quality control for the reader to consider in deployment of this technique.

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