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Soil-Bentonite Slurry Trench Cutoff Wall Longevity

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ABSTRACT

Soil-bentonite (SB) slurry trench cutoff walls are widely used for subsurface containment of contaminants and groundwater control. In many cases, particularly for environmental containment applications, the walls are intended to serve as a permanent barrier with a life expectancy measured in decades. The compatibility of these barriers with the environment is considered during most design studies but a comprehensive review of the longevity of these walls is absent from the literature. This paper identifies key longevity issues, summarizes published literature to date and describes the current practice related to the longevity of soil-bentonite slurry trench cutoff walls. Principle issues potentially affecting long-term performance include compatibility between the backfill and the groundwater, impact of wetting/drying in the zone of the fluctuating water table, long-term property changes due to secondary compression of the backfill, potential for desiccation of the near-surface zone of the barrier wall and the potential for hydraulic fracturing due to the relatively low state of effective stress. The paper concludes with the authors' summary opinions and suggestions for future research.

INTRODUCTION

Soil-bentonite (SB) slurry trench cutoff walls are used in both short and long-term applications to control groundwater flow and in long-term applications to control contaminant migration. The most common short-term application is for the control of groundwater into excavations for time periods measured in weeks to months. Typical long-term applications are in dams and levees and around contaminated sites with sustained performance timespans measured in years to decades. For long-term applications, the longevity of SB walls is of critical importance. While the issue of compatibility between SB backfill and contaminants has been well studied in the laboratory, the examination of the broader system longevity (i.e. service life or design life) is lacking.

Why is SB longevity important? The question of longevity has arisen numerous times in the authors' collective discussions about SB cutoff wall design and construction with industry stakeholders. Further, the National Academy of Engineers report assessing the performance of surface and subsurface engineered barriers (NAE, 2007) found that medium- and long-term performance concerns include property changes due to chemical incompatibility, desiccation above the water table, cracking, and chemically-induced deterioration. Research has also been conducted to assess individual parameters related to the properties of SB and how those properties change over time, but the individual studies lack connection and no summary design life implications have been presented. An overall understanding of the longevity of SB barrier systems is important because SB cutoff walls have historically been and continue to be widely implemented in the US and abroad for the containment of impacted groundwater or improved performance of water control features, e.g. dams and levees. Given the severe potential impacts associated with a failure of one of these structures, an understanding of the longevity and design life is important for the preservation of life and property.

The principle purpose of this paper is to identify critical issues surrounding the longevity of SB cutoff walls including identification of, as yet, unanswered questions about their performance and to provide an overview of longevity considerations for site-specific designs. The authors acknowledge that a complete discussion of SB cutoff wall longevity is not possible within the context of a short paper. However, given the lack of publications addressing this topic, the authors feel that an overview paper is a worthwhile contribution.

The literature addressing the longevity of SB cutoff walls, or even more generally vertical barriers and cutoff walls, is limited. This is probably due in large part to the distinctiveness of each wall with performance affected by site-specific factors, including variability in the geology and geochemistry, performance objectives, and potential failure consequences. For this reason, the design life of a barrier should be determined on a case-by-case basis. However, three questions are relevant for this general discussion of longevity:

1. What range in design life have Owners and Engineers assumed in the design and construction of existing cutoffs? On what basis was the existing design life selected?
2. What research has been done to assess SB longevity and what additional research is needed to improve the understanding of SB longevity?
3. Based upon the current knowledge of SB systems, for given site and subsurface conditions, what is an appropriate design life for SB cutoff walls and what site-specific factors should be considered in the selection of an appropriate design life?

LITERATURE REVIEW

The authors drew upon their collective knowledge of the SB cutoff wall design and construction processes to develop a literature search to identify existing research about this topic. The initial literature search was performed to find resources about the design life of cutoff walls or vertical barriers. This initial search effort found that the service life of sheet pile barriers is expected to be 50 to 75 years (USACOE 2012). Another study noted the average age of USACOE managed dams in the US of 53 years and went on to say that 77% of these structures are considered high hazard (Paul 2013). Finally, one study (Iowa SUDAS 2013), included a statement that "Slurry trench cutoff walls are reported to have a long service life and short construction time…". In summary, this initial search effort reinforced the authors' understanding that the design life of vertical barriers, specifically SB cutoff walls, is rarely discussed in the literature. The scant information available indicates that cutoff walls, specifically SB cutoff walls, are expected to behave as intended for "long" periods of time and that, if compared to another commonly used vertical barrier system, sheet pile cutoffs, should be designed to have a service life of 50 to 75 years.

Informed by the findings of the initial literature review, a broader literature review was conducted using a number of targeted keyword search strings selected to identify issues associated with SB cutoff wall longevity. An early paper (Tallard 1984), addresses placement techniques and chemical additives suggested to improve the longevity of SB walls, indicating that this topic has been a consideration since the earliest uses of SB walls in the US in the 1970s and 1980s. Another early study, (McCandless and Bodocsi 1987) addresses the potential for defects in these walls due to physical and chemical stresses and discusses the possible self-healing properties of SB, postulating that defects would close due to the overburden pressure squeezing the soft, compressible SB backfill back together. Other studies, published in the late 1990s, included papers that discussed the effects of freeze-thaw (Kraus et al 1997), the benefits of adsorptive additives for diffusive transport reduction (Prince and Evans 1998), and the compatibility of DNAPLs and sodium bentonite (McCaulou and Huling 1999). Studies from 2000 to 2010 included one discussing the compatibility of bentonite with acid mine drainage (Kashir and Yanful 2001), the variability in k in SB walls due to chemical interactions and wet/dry cycles (Britton, Filz, and Little 2005), and a case study review of 30 installed seepage barriers (Rice and Duncan 2009). Finally, the most recent document uncovered in this search details an assessment of the long-term durability of SB cutoff walls used for containment of ground contamination through long-term hydraulic conductivity evaluation of model SB backfills in the laboratory (Takai et al 2016).

This literature review summary is not meant to comprehensively address all publications related to SB longevity topics, but rather to highlight that a targeted search using keyword strings hand selected by active SB practioners yields limited results. In addition, this literature search exercise highlights that no comprehensive study addressing SB longevity has been completed and that while there is relevant information about this topic presented in various papers, no one source provides an overview of the findings.

The objectives of the remainder of the paper are to 1) summarize the current practice for SB design life selection, 2) identify technical issues to be considered in the consideration of design life and 3) identify areas of needed research.

SB CUTOFF WALL DESIGN SERVICE LIFE – CURRENT PRACTICE

Specifications often include language indicating that a cutoff or barrier should be expected to behave as intended over the "service life" of the structure or facility. However, few specifications clearly identify what that service or design life actually is. In the authors' experience, a service life of 15, 30, 50, and even "hundreds" of years are indirectly inferred or directly mentioned. That said, there is no industry consensus and little published information to support these numbers. Further, there are no clear and commonly adopted assessment mechanisms to determine if or how the completed barrier meets or fails to meet the service life expectations.

The design life of the SB cutoff wall is often selected consistent with the design of the system in which the cutoff wall is a component. For example, a dewatering project may require the cutoff wall to function for a period of a few months to a few years. In contrast, in a seepage control application, such as a dam or levee, the cutoff wall may be expected to function for 50 to 100 years. Environmental control projects may demand a design life of 30 years, consistent with closure regulations. In some applications, even longer design lives may be needed for the containment of impacted groundwater because of the half-lives of the contaminants. Design lives of selected structures, drawn from the authors' experience, are presented on Table 1.

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Table 1. Representative design lives for various SB cutoff wall applications

Application	Design or Service Life
Dewatering for excavation stability	3 months to 3 years
Dam or levee rehabilitation	50 to 100 years
Environmental site closure	15 to 30 years
Permanent environmental protection	10s to 100s of years

If a design life is specified or implied, there is no consistent design approach to determine if the SB wall will meet or has met expectations. The most common design approach to assess long-term cutoff wall performance was developed for environmental sites and is often referred to as compatibility testing.

Compatibility Testing: ASTM provides guidance for components of “compatibility testing” which generally includes qualitative assessment of the compatibility of bentonite (or alternative barrier clay) with the site groundwater. One of the most common assessment tools is long term permeability testing using the site groundwater as the permeant (ASTM D7100-11). To illustrate one component of the practice common for environmental sites, the long-term performance of the SB cutoff wall is hypothetically evaluated using long-term permeability testing conducted on a laboratory created “model” backfill using the impacted groundwater as the permeant. In this testing, it is common to attempt to model 15 to 30 years of performance as measured by steady hydraulic conductivity throughout the design period. For this discussion, consider the two numerical examples shown on Table 2.

Table 2. Example full scale performance calculations for SB in environmental applications

	Example 1		Example 2	
	Laboratory	Field	Laboratory	Field
k (cm/s)	$1x10^{-7}$		$5x10^{-8}$	$1x10^{-7}$
i (cm/cm)	25	1	25	1
A (cm^2)	40	929	40	929
Q (cm^3)	2 PVDs		3 PVDs	
t	40 days	23 years	120 days	23 years

In Example 1, the laboratory mix exhibits the same hydraulic conductivity as the field mix. Using “normal” laboratory testing parameters, it would take 40 days to complete a laboratory experiment with two pore volume displacements (PVDs) at a gradient of 25 and this would represent approximately 23 years of field performance at a field gradient of one. Little is written on safety factors for hydraulic conductivity design but the authors believe laboratory studies should target a backfill hydraulic conductivity that is at least a half an order of magnitude lower than the target field hydraulic conductivity in order to account for differences in mixing uniformity between the laboratory and field. In addition, for soil-bentonite backfill, it is commonly assumed that hydraulic conductivity equilibrium is achieved after three pore volumes of permeant have passed through the sample. Laboratory studies on SB with organic permeants show this is a reasonable assumption (Evans et al 1985). Example 2 in Table 2 shows that it would take 120 days of laboratory testing to model 23 years of performance of a $1x10^{-7}$ cm/s (field permeability) barrier. Note that, in both cases, the laboratory gradient is 25 times the field gradient.

Many factors affect the results of laboratory tests performed over long durations including, microbial growth in the sample and permeation lines, clogging of the sample and permeation lines, fine particle movement within the sample, secondary compression of the sample, and testing apparatus incompatibility with the permeant (Evans and Fang 1988). Testing and research laboratories have methods for combatting these issues, but these issues introduce uncertainty in the results of the tests none-the-less. In addition to the problems associated with long-term testing, the Engineer rarely has the time or budget needed to perform a comprehensive, long-term, and multi-variable testing program. For this reason, it is common in the industry to evaluate SB backfill mixtures for use in controlling contaminated groundwater flow by performing long-term permeability testing until 2 PVDs have been achieved or for a period of 2 months, whichever is shorter. The Engineer must then use the information collected to assess long-term performance of the barrier material based on these limited results.

Permeating backfill is further complicated by the nature of the contaminants and their solubility in water. For example, non-aqueous phase liquids (NAPLs) are particularly challenging. As one may expect from their name, NAPLs have a low solubility in water. Components of NAPLs will dissolve in water, but the solubility limit concentration will be low in comparison to the NAPL itself. Light NAPLs (LNAPL) consist of liquid contaminants that are lighter than water. Dense NAPLs (DNAPL) consist of liquid contaminants that are heavier than water. LNAPLs tend to have a lower viscosity than water and will therefore be the first component of the permeant to pass through the sample and will pass through the sample at a faster rate than water. Since LNAPLs tend to pass through the sample quickly, this may mitigate detrimental effects on the SB backfill seen in laboratory testing. This can result in a false sense of security for two reasons: 1) since the LNAPL passes through the sample quickly at the high laboratory gradients, the actual amount of field performance time that is modelled is generally much less than one might expect based on calculations of field performance assuming a water like permeant, and 2) the LNAPL in the lab has little effect on the mix because the contact time is limited and therefore any chemical changes that would take place are limited. In the field, the LNAPL source will likely be comparatively much larger and flow may be concentrated on a small portion of the cutoff wall (likely near the GW surface) which could therefore have a much larger effect on the performance of the barrier as a contaminant containment feature. DNAPLs tend to have a much lower viscosity than water. Standard procedures for long-term permeability testing require a bottom-up permeation approach with the contaminated permeant being pushed from the bottom of a bladder accumulator. In many cases where a DNAPL is present in the permeant, the DNAPL clogs the pores of the samples making the sample appear to be nearly impermeable. As with LNAPLs, this is not representative of the field and the results of long-term permeability testing with DNAPLs present in the permeant can easily be misinterpreted to the detriment of predicting actual full scale barrier performance. Modified laboratory procedures can be used to attempt to assess DNAPL impact on barrier wall materials, but the results are limited in that the tests really only assess the aqueous byproducts of the NAPL, not the effect of the pure NAPL itself.

As with the example about NAPLs described above, other contaminant types present unique challenges that require specific in-depth knowledge of the behavior of those contaminants. In addition, most impacted sites have a range of contaminant groups and each may require special considerations.

Contaminant Transport through SB walls: Current practice regarding the design and construction of vertical barriers is overwhelmingly based upon evaluation of hydraulic conductivity only. However, a low hydraulic conductivity is not sufficient to ensure that a vertical barrier will provide effective long-term containment of pollutants. In order to evaluate a vertical barrier in terms of its ability to function as an effective geoenvironmental containment barrier, it is also necessary to examine the contaminant transport mechanisms and how those relate to properties of the barrier material. For example, diffusion has been shown to be a significant, if not dominant, mode of contaminant transport through clay barriers in typical waste containment applications (e.g., Shackelford 1990). Despite the widespread recognition of the influence of diffusion, only a limited number of studies have been conducted to investigate the influence of diffusion on the migration of contaminants through SB materials (e.g., Khandelwal et al. 1997, Prince et al. 2000, Krol and Rowe 2004). In addition, these studies are only theoretical investigations or laboratory studies on model SB backfills.

The utilization of clay barriers for long-term *in situ* geoenvironmental containment also has given rise to the consideration of contaminant attenuation and membrane behavior as significant mechanisms for sustainable performance (e.g., Daniels et al. 2004, Inyang and Galvao 2004, Yeo et al. 2005). Clay barriers with enhanced attenuation capacity offer the potential for sustaining effective containment over more prolonged periods (e.g., see Evans and Prince 1997, Shackelford 1999). Research has demonstrated that membrane behavior is possible in SB cutoff wall backfills, and that this behavior may result in enhanced waste containment performance (Henning et al. 2006).

Based on the above, the primary issues of practical significance related to contaminant transport through SB cutoff walls are:

1. the significance of contaminant attenuation and semi-permeable membrane behavior in constructed SB backfill materials;
2. the potential for amendment of actual SB backfills to provide more sustainable attenuation capacity and membrane behavior; and
3. the influence of variability in contaminant transport properties on field-scale performance of SB cutoff walls.

Evaluation of as-constructed backfill materials is critical, since the performance of such materials may be considerably different than the performance of model backfills. For example, Henning et al. (2006) recovered samples of two SB backfills recovered from cutoff walls constructed in Delaware and New Jersey and tested these samples for the existence of membrane behavior. Both of the field backfills classified as sands (i.e., SC and SP-SC) and consisted of locally excavated soil mixed with 3% to 4% bentonite by dry weight. While the results of this study showed that both of the field backfills exhibited membrane behavior, the magnitude of the membrane behavior was lower than that previously reported for model backfills prepared in the laboratory (Yeo et al. 2005). The difference in behavior is attributed, in part, to lower percentages of added clay in the studied as-constructed backfills relative to model backfills.

Despite research indicating benefits to long-term performance, membrane behavior is rarely considered in practical design and few, if any, full scale barriers have been installed with sorptive additives that can enhance membrane behavior.

RECOMMENDATIONS FOR DESIGN / SERVICE LIFE OF SB CUTOFF WALLS

In the absence of site-specific knowledge that would indicate otherwise, these authors believe a design life of 5 to 25 years for environmental cutoff barriers or 25 to 75 years for barriers used in geotechnical applications is reasonable. However, engineers engaged in the design of SB cutoff structures need to design the walls used on their projects to achieve appropriate design lives by using their knowledge of the site, the construction technique(s), and an understanding of the current state-of-research to impart an appropriate factor of safety. There are two key takeaways here; 1) it is not appropriate to assume that an SB cutoff wall will behave as intended into perpetuity or even over very long timespans relative to other engineered structures, e.g. "hundreds" of years, unless factors influencing longevity have been thoroughly considered, and 2) it is not appropriate to ignore the determination of a useful lifespan of a barrier prior to installation. Ideally, an evaluation protocol would be set in place at the time of construction to consider the effectiveness of the wall after the service life has been exceeded. All indications are that in many cases these walls will continue to behave as intended long after the recommended service life has been exceeded, but it's important to evaluate this assumption on a periodic basis.

TOPICS FOR SB CUTOFF WALL LONGEVITY EVALUATION

In practice, SB vertical cutoff wall systems are employed in a variety of applications, for multiple purposes, in varying geologic conditions with varying geochemistry, and there is no guarantee that the assumptions made at the time of bid / construction will be accurate as time progresses. Selection of the site-specific service life should be based on an evaluation of the main factors contributing to the SB wall longevity, including:

Physical Changes: Are the stress / strain conditions in the wall expected to change? If so, how will this impact the wall's behavior? Are there extenuating circumstances that could impact the wall, e.g. seismic or extreme flooding events? Will the wall be subject to drying stresses which could alter the hydraulic conductivity and/or cause cracking? If so, how can these factors be accounted for?

Geochemical Changes: Could there be conditions in the groundwater that will cause a change in the wall properties over time, e.g. changes in salt concentrations? If so, what are the expected effects of these changes and how can these effects be accounted for?

Environmental Compatibility: Is the SB cutoff wall compatible with the expected contaminants? If so, how long will it take to achieve chemical equilibrium in the pore water in the SB wall and are there any expected changes in the wall's performance as equilibrium is being achieved or after equilibrium is achieved? Does the contaminant matrix include particularly challenging constituents, e.g. NAPLs, that warrant specific consideration?

Other: There are many other factors to consider in the selection of the effective service life, including probability of loss of life, long-term public health impacts, likelihood of property damage, Owner risk tolerance, design and construction cost/schedule, regulations, and community perception. Most of these issues have little connection to tangible design, but must be considered.

ADDITIONAL RESEARCH

Additional research is certainly needed to fill gaps in the collective understanding of the behavior of SB cutoff walls, specifically to determine whether the current understandings of behavior, which are based primarily on laboratory studies on model backfills, compare to the actual behavior of constructed cutoff walls at the field scale. The authors feel that future research should be specifically focused on four goals:

1. to investigate the field scale variability in the properties of SB cutoff walls, specifically hydraulic conductivity, with time and depth;
2. to investigate the longevity/sustainability/durability of SB slurry trench cutoff walls in their *in situ* environment;
3. to investigate the susceptibility of SB cutoff walls to external forces, e.g. seismic events, groundwater chemistry changes, contaminants in groundwater, desiccation, and the potential consequences; and
4. to investigate the *in situ* contaminant transport properties of SB slurry trench cutoff walls.

In order to achieve these goals, specific research objectives will need to be identified, which may include:

1. characterization of the vertical and horizontal variability of physical properties (e.g., grain size distribution, water content, and plasticity) and engineering properties (e.g., strength, compressibility, and hydraulic conductivity) of as-built SB cutoff walls;
2. assessment of changes, if any, in physical and engineering properties as a function of time;
3. assessment of the state-of-stress, and its effect on hydraulic conductivity, as a function of both depth and time;
4. collection of field samples from as-built walls for laboratory testing to examine changes in properties over time and, thus, estimate barrier performance; and
5. assessment of the horizontal and vertical variability in contaminant transport properties (i.e., diffusion, attenuation, and membrane efficiency) and the potential for enhancement of these properties.

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