Final Draft: final version available in proceedings of DFI45 conference

DESIGN AND SPECIFICATION CONSIDERATIONS FOR ENVIRONMENTAL CUTOFF WALLS

Daniel Ruffing, P.E., M.ASCE; Geo-Solutions, Inc., 1250 Fifth Ave., New Kensington, PA 15068 USA, 724-335-7273, druffing@geo-solutions.com
Jeffrey Evans, Ph.D., P.E., D.GE, F.ASCE[2]; Bucknell University, Dept. of Civil & Env. Eng., One Dent Drive, Lewisburg, PA 17837 USA, 570-577-1112, evans@bucknell.edu

ABSTRACT

Vertical cutoff, or barrier, walls are an integral part of environmental site remediation efforts. Vertical barriers are commonly deployed to limit the influx of clean ground water and/or to control the off-site migration of contaminated groundwater. The level of detailed design consideration devoted to the vertical cutoff wall component varies widely from project to project and generally decreases with decreasing size and complexity. For those projects receiving minimal design effort, conservative design decisions can lead to unnecessary costs or unanticipated conflicts between the various design considerations. In this paper, the authors discuss several important design and construction aspects of vertical cutoff walls requiring particularly careful consideration during the design phase of the project. These design and construction considerations include the need for and extent of excavation for a key, project target hydraulic conductivity, the use of statistical allowances in the specifications, filter press testing, sand content of in-trench slurry, cleaning of the backfill slope, measurement of stress and strain, the additional of slag in cement-bentonite cutoff walls, and longevity of cutoff walls.

Keywords: slurry walls, soil-bentonite, vertical barriers, cutoff walls

INTRODUCTION

Vertical cutoff or barrier walls are a common and important component of environmental site cleanups. The most common method of installing these walls on environmental sites is via the slurry trenching technique with either a soil-bentonite (SB), soil-cement-bentonite (SCB), or a self-hardening cement-bentonite (CB) backfill. Since the level of design effort for these walls is based on the size and complexity of the overall project, the level varies considerably and is often minimal for smaller projects. This is unfortunate and often results in unnecessary cost and schedule. Minimal design effort may also result in overly conservative specifications meant to cover risk for design or construction team members counter to cost effectively achieving the project goal(s). This paper includes discussions about a few important topics related to cutoff wall design and construction that are often overlooked or given little focus. Practical advice related to the design and construction of cutoff walls is provided for each topic, particularly as it relates to the design and construction of cutoff walls that will be installed via slurry trenching. However, some of these recommendations are applicable to all cutoff wall types for all applications (environmental or geotechnical) and some may be applicable to a wider range of construction techniques.

SCOPE AND PURPOSE

Many previous papers over the last forty years have addressed considerations for design and construction of cutoff walls with various levels of focus on specific construction techniques (D'Applonia 1980, Jefferis 1981, Evans et al. 1985, Ryan 1987, Evans 1994, Opdyke and Evans 2005). By way of introduction, shown on Fig. 1.a. is a schematic of the excavation, backfill mixing along the trench, and backfilling of a soil-bentonite (SB) slurry trench cutoff wall. Figure 1.b. is a photo of an SB cutoff wall showing excavation with both a backhoe and a clamshell for depths beyond the reach of the backhoe. Also shown on Fig. 1.b. is backfill mixing along the trench with a tracked bulldozer.

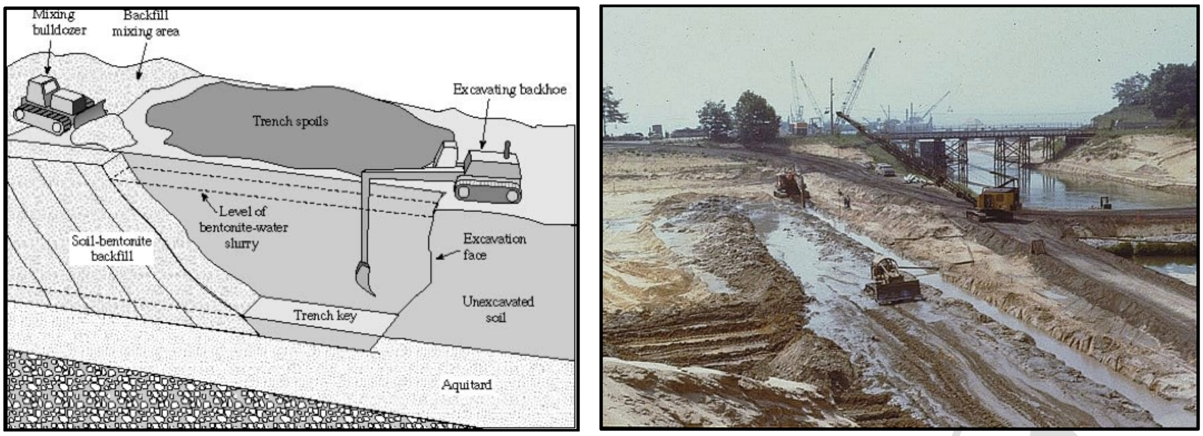

Fig. 1. a. Schematic of the excavation and backfill of a SB cutoff wall (LaGrega et al. 1994). b. Photo of the excavation of a SB cutoff wall using both backhoe and clam shell, backfill mixing is with a tracked bulldozer

This paper assumes the reader understands the background knowledge contained in the above citations, or similar, and is geared towards practitioners that are regularly engaged in the design and/or construction of cutoff walls. The guidance and points of consideration presented in this paper are largely drawn from the opinions of the authors derived from experience and research in the field of cutoff walls. The reader is encouraged to use this paper as a trigger for additional thought and research on the topics presented. Although the paper is focused on cutoff walls, even those that are unfamiliar with cutoff wall design or construction, may find some of the considerations applicable to design and construction of other components of their projects.

In this paper, references are made to three contract parties, Owner, Engineer, and Contractor. The Owner is meant to be the party that is ultimately responsible for the project costs and often has separate contracts with the Engineer for the project design and the Contractor for the construction. The Engineer (or Designer) is the party that is primarily responsible for the design of the overall project and the Contractor is the party that is tasked with the construction of the cutoff wall. As there are many other contractual arrangements, the reader is encouraged to consider the details in this paper in light of their particular contractual arrangement and adjust recommendations as needed for their specific situation.

DESIGN AND SPECIFICATION CONSIDERATIONS

Excavation key and refusal

Depending on the detailed purpose and design function of a cutoff wall, there may be a need for the wall to extend into or through a low permeability layer or even competent rock. This is not always the case as there are situations where the wall was designed and constructed as a "hanging" wall (e.g. McLay 1987), i.e. the bottom is not tied to a lower permeability layer so, in a section view drawing, the wall appears to be suspended (hanging) in a higher permeability soil layer. In a related manner, cutoff walls are not always circumferential, i.e. flow is allowed around the ends. With regard to the need for a "key" into a layer of lower permeability, in theory it may only be necessary to make contact with the underlying low permeability layer. As a result, there are site-specific cases where simply excavation to the top of the low permeability layer will achieve the objective(s). Engineers can also factor the presence of windows along the bottom of the wall, i.e. gaps between the bottom of the cutoff wall and a lower permeability confining unit, into the design. Windows beneath the wall can be accommodated by increased inboard pumping (Ruffing and Evans 2014) or by using alternative construction techniques to eliminate the window (e.g. permeation grouting). There are many other considerations in the determination of the need for or details of a key that a Designer should consider, e.g. the cost of water management and treatment. In any case, the Designer must determine what is necessary to ensure the wall functions as intended, including accounting for design and construction uncertainty, without being unnecessarily expensive or overdesigned.

In the evaluation and determination of the necessity or extent of any key, it's important to consider that conventional excavation equipment is not suited for excavation into competent rock. Depending on how the material is bedded and the overall strength of the rock, excavators may be used to excavate into weathered or soft rock. However, even excavation into softer rock materials that are excavatable is generally slower than excavation through soil layers and therefore there will be cost impacts associated with this key. For example, consider a 15 m (~50 feet) deep cutoff wall including a 0.9 m (3 feet) key into soft rock or a hard soil layer, such as a dense glacial till. In this case, the 0.9 m (3 feet) key would likely make up 10% to 15% of the overall cost despite it being only ~5% of the excavation. As the key layer gets deeper and/or thicker or the refusal language in the contract gets more conservative (more time to achieve refusal), the cost impact becomes more severe. If the layer is not excavatable and a key is specified, this may necessitate a change in methods or the addition of pre-drilling or other equipment like chisels. In all cases (pre-drilling and/or chiseling) these additions will add significantly to the overall cost, on the order of 50% to 200%. Beyond the cost impacts, there will be schedule and site logistics impacts associated with key excavations.

Given the cost and schedule implications, it is incumbent on the Engineer and Owner to understand that decisions about whether to include a key or how to include the key into the project may eliminate construction approaches and generally increase the cost of the project. In some cases, a large key into very competent material is necessary and as long as the contract fairly specifies the requirement and the Engineer / Owner understand the cost impacts of the decision, Contractors should have no problem finding a way to install the designed product. In their decision process, the Engineer / Owner should consider the purpose and function of the wall in the context of ramifications of failure (or even what "failure" is) and relate those back to cost, schedule, methodology, and long term operation restrictions. For Engineers and Owners that are unfamiliar with cutoff wall guidance documents, a commonly referenced industry guidance document, the NAVFAC guidespec (UFGS-02 35 27, 2010), briefly addresses this issue in Section 3.3.1 "Confining Stratum Excavation":

"NOTE: If the confining stratum is a competent low permeability bedrock, a very small penetration into the bedrock may be satisfactory. High costs may result by requiring a 600 mm (2 foot) key into competent bedrock. Remove this paragraph if not required in the project."

The main takeaway is that a key into rock or a low permeability layer is not always needed and, when a key is needed, the extent (depth) should be limited to avoid unnecessary cost and schedule impacts. Slurry trenching offers a distinct advantage here because the key material can be confirmed from observation of trench cuttings which may reduce the need for a more conservative key in instances where the material cannot be confirmed. Further, for the delineation of risk, all specifications should include a refusal clause to define the maximum foreseeable level of effort. The refusal specification must be developed in the context of the need for the key and the expected cost impacts. If the wall is being tied into or seated upon a very competent rock material, these is no need for an extensive period of time to determine whether practical refusal of the equipment has been achieved. In the absence of a defined need for a more conservative refusal criterion, the authors recommend:

Refusal shall be achieved after 5 mins [up to 15 mins in extreme cases] of effort over a 6 m (20 ft) long [up to 9 m (~30 ft) long] excavation cut or irregular observations of the machine behavior indicative of refusal, e.g. excessive ground vibrations or shaking.

The Engineer has the option to specify the minimum machine size for application of the refusal specification, but this sort of prescriptive specification can lead to increased cost due to availability of the specified equipment.

Target hydraulic conductivity

In this portion of the paper, the bases for the selection of the design, a.k.a. target, hydraulic conductivity are examined. For environmental containment, designers and regulators (e.g. US EPA) often specify a value of $1x10^{-7}$ cm/s although occasionally higher values are specified, e.g. $1x10^{-6}$ cm/s. The suspected origins of these specified values are examined and a rational approach to the specification of hydraulic conductivity is presented.

Soil-bentonite (SB) vertical cutoff wall technologies came into use in the 1970s, were increasingly applied to environmental containment in the 1980s, and are widely used for multiple purposes today. Simultaneously, cement-bentonite cutoff walls with slag (slag-CB) found increasing use in the UK and throughout Europe (Ryan 1987, Jefferis 1997, Evans and Dawson 1999). Like many criteria, the lower bound value of $1x10^{-7}$ cm/s was originally technology driven. That is, conventional SB walls could consistently be constructed such that the target backfill hydraulic conductivity of less than $1x10^{-7}$ cm/s, as measured using laboratory tests conducted on bulk field samples, could be achieved. Similarly, it was demonstrated that CB walls could also achieve $1x10^{-7}$ cm/s as long as the mix included the appropriate balance of Portland cement and granulated ground blast furnace slag (Jefferis 1981). Hence the origin of the standard, like many standards, was based upon what was practical. As it turns out, this value of $1x10^{-7}$ cm/s also results in a reduction of flow through the wall to negligible amounts which makes contaminant transport largely diffusion controlled. With diffusion-controlled contaminant transport, lower values of hydraulic conductivity would have a negligible impact on the performance of the wall in an environmental application.

Design of vertical barriers for environmental containment must also address the issue of compatibility between the contaminated subsurface and the cutoff wall materials. As just discussed, the $1x10^{-7}$ cm/s hydraulic conductivity target value also results in contaminant transport that is largely diffusion controlled. This is important in the context of the fact that, for systems with a slight inward gradient, the lowest hydraulic conductivity achievable is not always the optimum hydraulic conductivity to minimize total contaminant flux (Devlin and Parker 1996). That is, in the case of an inward gradient, a slightly greater inward flow resulting from a slightly higher hydraulic conductivity can work to counter the outward diffusive flux. There have been numerous studies of both SB and CB cutoff wall compatibility beginning in the 1980s in parallel with studies of clay liner systems (Evans et al. 1985, Jefferis 1993, Garvin and Hayles 1998, Evans and Opdyke 2006) and there is a generally good understanding of the compatibility behavior of cutoff walls. Importantly, mechanisms of compatibility and the contaminants of concern are very different for SB walls than for slag-CB walls. In SB walls, hydrated bentonite is an important component of the low hydraulic conductivity and reversal of the bentonite swelling may negatively impact the hydraulic conductivity. Conversely, the bentonite is initially important in slag-CB walls to minimize bleed and result in the formation of a uniform mixture, but after set and cement curing, the bentonite is de-structured and its components become part of the hydrated cement structure (Mitchell and Soga 2005, Evans et al. 2020).

Cutoff wall practitioners must also recognize that hydraulic conductivity of SB is stress dependent. Ruffing et al. (2010) found a significant decrease in hydraulic conductivity for a field mixed sample having both a high fines content and a relatively high bentonite content as shown on Fig. 2.a. The magnitude of the stress dependency is dependent both the bentonite content (Fig. 2.b.) and upon the grain size distribution of the base soil used to prepare the backfill (Evans and Huang 2016). This behavior needs to be coupled with the recognition that the backfill stresses within the trench are less than geostatic and can be quite low depending upon the cutoff wall depth and backfill compressibility (Evans and Ruffing 2019, Evans et al. 2018).

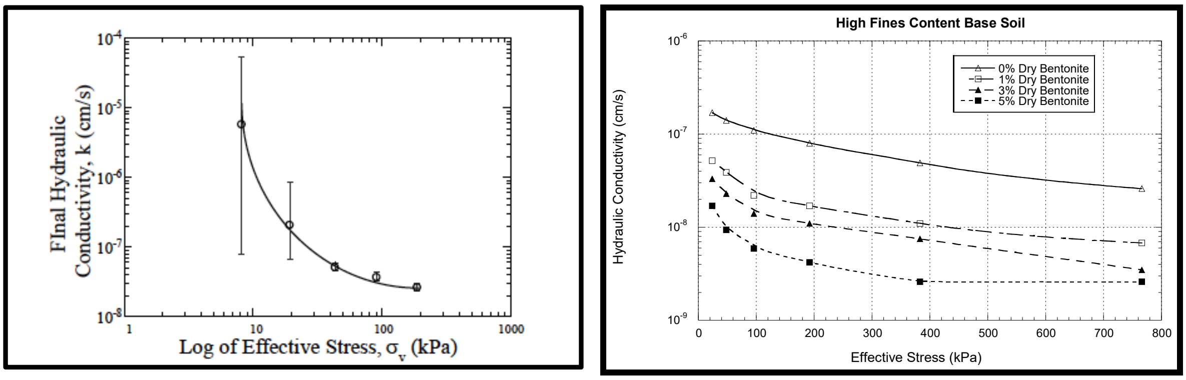

Fig. 2.a. Impact of effective stress on the magnitude and variability of hydraulic conductivity (Ruffing et al. 2010) b. Impact of bentonite content and effective stress upon the hydraulic conductivity of a high fines backfill (Evans and Huang 2016)

Because of the potentially large impact of effective stress on hydraulic conductivity, laboratory hydraulic conductivity tests should be conducted at stresses similar to those stresses that can be reasonably assumed to exist in the trench. If the testing laboratory procedures and equipment are not suitable for testing at low stresses, then the hydraulic conductivity results from tests conducted at higher stresses may need to be adjusted upward via an appropriate factor of safety developed to account for this known stress dependency.

Based on the discussions above, the selection of the target hydraulic conductivity should be made in the context of the contaminant compatibility and site contaminant transport objectives. In the absence of site-specific information that would allow selection of a more refined value, a good rule of thumb for the target is an order of magnitude lower than the surrounding soils. This will generally ensure flow occurs around the wall rather than through it. In the selection of the target hydraulic conductivity value, the wall configuration and bottom details must also be considered. If the wall is a hanging wall or is not circumferential, the hydraulic conductivity only needs to be low enough to force flow below or around as one or both of these flow paths will control the overall wall function. The target value should be selected with an appropriate factor of safety included based on design uncertainties but also considering the fact that the Contractor will add conservatism in the selection of the mix design and during implementation to minimize contractor risk. In many cases the Contractor's risk allowance will include a FS of approximately 5 because Contractor's commonly target half an order of magnitude lower than the design hydraulic conductivity. Finally, the selection of the target value should also be made in the context of limitations of proposed verification testing. For example, a safety factor may be needed to account for laboratory testing results of field mixed samples that generally result in lower measured values than any form of field testing.

Specifications & statistical allowances

Cutoff wall specifications on environmental sites are often not given an appropriate level of consideration, particularly on small sites or on sites where the cutoff wall is a small component. For instance, it is not uncommon to see an unedited version of a specification that was taken from an online source or guide specification in the project documents issued for bid. This approach is inappropriate and ultimately can be costly to the project. In order to avoid unnecessary cutoff wall costs or inadequate performance, all specifications must be reviewed in the context of the site-specific project objectives and constraints to ensure the specification is not overly restrictive or, more concerning, missing key information needed to ensure the end product meets the intended function.

In the development of the specifications, it's always prudent to build in reasonable statistical allowances to account for the inevitable variability of test results and to avoid unnecessary issues. This expected variability is particularly important in the context of the evaluation of the overall factor of safety and how various parties, Owner, Engineer, and Contractor, generally add to the FS as the project develops.

This becomes even more important when key design parameters, e.g. hydraulic conductivity, are selected with no basis other than certain values are common in the industry. As noted in the discussion above, minimum hydraulic conductivity values of 1x10^{-6} cm/s or 1x10^{-7} cm/s are often specified when a much higher permeability would accomplish the site objectives based on overall wall function, existing geology, and/or site-specific features. In these instances, it's at least prudent to understand the level of conservatism (or lack thereof) in the selection of these values and acknowledge that conservatism in a statistical allowance in the specification. For instance, instead of specifying "< *1.0x10^{-7} cm/s*", something like "*the geometric mean hydraulic conductivity must be less than or equal to 1x10^{-7} cm/s with no single value greater than 1x10^{-6} cm/s*" meets the project need without being unduly conservative or opening the project to conflict between the Contractor and the Owner/Engineer As an example of conflict that is likely to arise for the specification of "< *1.0x10-7 cm/s*", consider what happens when just one test result comes back at 2x10^{-7} cm/s. A single value at 2x10^{-7} cm/s would have little impact on the overall wall performance, but the project team would have to deal with a "failing" or "non-conforming" product due to an unnecessarily prescriptive specification. These sorts of allowances do little or nothing to reduce the overall FS, but can be very handy in avoiding conflicts and change orders during construction or the unnecessary need to replace a portion of the wall with no technical benefit. Another key point in this discussion is to notice the difference in significant figures between 1x10^{-7} cm/s and 1.0x10^{-7} cm/s and to recognize the need to include "*or equal to*". These may seem like trivial differences, but even small differences like this can have a large impact in assessing the construction and leave opportunities for cost or schedule issues. For instance, a value of 1.44x10-7 meets the requirements of a "*less than or equal to 1x10-7 cm/s*" specification, but not a "*less than 1.0x10-7 cm/s*" specification. Unless there is an absolute need to specify the more restrictive criteria (note: these instances are rare), it's always best to leave as much flexibility in the target parameters as possible. Another way to consider this issue is to consider statistical distributions of a value around the mean. If a single value is specified (e.g. 1x10-7 cm/s), what must the mean be such that 100% of the measured values are less than the specified value?

Filter press testing

The filter press test was developed and is employed as a means to evaluate the ability of a bentonite-water slurry to form a filter cake between the slurry and the formation. In a separate paper (Ruffing et al 2016), the applicability of filter press testing, particularly on slurry from the trench, was addressed. Although it is widely understood that the filter press test tells an incomplete story of filter cake development, requirements for this test on in-trench slurries persist. As presented in the reference publication, this often results in unnecessary conflict during construction and may actually be counter to the overall goals. This is particularly relevant for soil-cement-bentonite (SCB) cutoff walls because the calcium in the cement can significantly alter the properties of the slurry when the two come in contact within the trench. As an initial specified quality control (QC) measure, only the fresh bentonite slurry from the mix plant or circulation/holding ponds should be tested to confirm sufficient hydration prior to placement in the trench.

Sand content of in-trench slurries

For non-structural barrier walls, the topic of this paper, strict criteria for maximum sand content is an unnecessary specification when considered in isolation. If sand content and filter press testing of in-trench slurries are included in the specification, the information should be collected for reference only and the results should be considered in the context of all QC data to ensure the complete data set is telling a compelling story that the cutoff wall is being constructed in a manner consistent with the overall objective(s). For example, in one project (Evans et al. 2004) measured sand content values were as high as 40% (compared to the specified maximum of 15%) and yet the specified density difference of 13 kN/m^3 (15 pcf) between the backfill and the slurry was maintained and subsequent coring and testing showed no detrimental performance resulting from the high sand content.

Slope cleaning

Proper profiling of the backfill slope is arguably one of the most important, if not the most important, aspects of a QC program for a SB or SCB cutoff wall. This process allows for the identification of soil settlement on the backfill slope from coarse particles falling out of suspension or from sidewall spalling. However, the results of the profiles must be reviewed in the proper context. For instance, data shows that sand/slurry lenses on the backfill slope may have a permeability that is equal to or lower than the backfill (Evans et al. 2004). In this case there is no need for concern. If something of concern is observed, it must be dealt with according to the capabilities of the available equipment. For instance, shallow environmental walls (less than 90') are almost exclusively installed with excavators. These machines cannot be safely used to clean the backfill slope or to investigate an observed anomaly in the profile.

The specification needs to reflect expected equipment and include other means of preventing these issues or dealing with them, should they arise. For instance, the toe of the backfill slope should be kept as close as practical to the excavation cut, for instance within 6 to 12 m, to allow the excavator to drag sediments down the backfill slope by normal action of the excavation process. Also, the trench should not be allowed to sit undisturbed for long periods of time, typically specified as less than 48 to 72 hours. Finally, during the design phase, the Engineer should consider whether an anomaly of a certain size even matters. If not, appropriate wording should be included in the specification. If so, maybe conventional excavators aren't enough for the subject project, but at least the specification will reflect the Owner and Engineer's understanding of the cost implications of their decision to include a more stringent requirement.

Measurement of Strength and Strain

Most practicing geotechnical engineers understand that there are various methods of measuring strength and strain at failure and that the results are dependent upon the test method and boundary conditions. For instance, is the strength being measured in an unconfined or confined condition and, if confined, at what stress? Also, what is the applied strain rate to failure and how does that impact the measurement of strength and strain in terms of the influence of pore pressure dissipation? Unfortunately, in practice, it is not uncommon to see undrained methods, such as the unconfined compression strength (UCS) test, specified for situations that should necessitate a drained test with a slow failure rate. This may be due to a lack of understanding of the subtleties of laboratory testing or due to cost and timing considerations. In some cases, the strength should be measured using multiple methods, especially during the bench scale testing, with the various results applied to different failure cases, e.g. undrained results applied to evaluation during an earthquake and drained results applied for evaluation of long term ground movement potential. For full scale QC, it is appropriate to use simple and fast tests like the UCS test as long as the results are compared to an appropriate target. In any case, it's important to consider how a measurement is to be taken and how that influences the achievable results in the context of the specific material being tested.

Addition of Slag in Self-Hardening Walls or Plastic Concrete

For those in the cutoff wall industry, it is widely known that the replacement of some portion of the Portland cement component of a mix with granulated ground blast furnace slag results in improved properties; lower hydraulic conductivity, higher sulfate resistance, and higher strength (Jefferis 1981, Opdyke and Evans 2005). However, this detail may not be commonly known to practitioners that are not regularly engaged with cutoff walls. Also, even experienced practitioners sometimes neglect the timing of development in these mixes. Even though mixes containing slag tend to outperform mixes containing only Portland cement, it often takes much longer to achieve final properties. For instance, many consider Portland cement mixes to have achieved their final properties after 28 days of curing. This is an obvious extension from the concrete industry where 28 days is a common acceptance point. For mixes containing only Portland cement, the 28-day mark is a good measurement point as most mixtures have achieved near final properties by that time and it allows evaluation of the product in a reasonable amount of time. The 28 day data for mixes containing slag tells an incomplete and misleading story. For mixes containing slag, improvement occurs well beyond 28 days and the improvement is significant. For instance, the ultimate hydraulic conductivity of a mix containing slag is often an order of magnitude lower than the 28-day result. Since it's difficult to wait months or years to assess a component of the project, the selection of a 28 or 56 day data point could instead be based on the expected property development post measurement. Ideally this expected improvement would be selected based on trends developed from a site -specific bench scale or pilot study, but it could also be based on information in reference publications showing expected long term improvement (e.g. Coughenour et al. 2018). By not accounting for the long term improvement of mixes containing slag, a specification to achieve properties at the standard 28 day mark will lead to an unnecessarily conservative mix and, in some cases, may actually result in a product that is counter to the intended product (e.g. ultra-high strength and brittle vs. medium strength and more ductile).

Competing Properties

In the development of specifications, care should be taken to avoid competing objectives with specific consideration given to the material specified. For instance, higher strength self-hardening cutoff materials, CB or slag-CB, generally have a lower strain at failure. If a high strain at failure is needed, e.g. in earthquake prone areas, this may limit the achievable strength or may necessitate a switch to a more expensive cutoff wall backfill like plastic concrete.

Longevity

Given that cutoff walls in both environmental and geotechnical applications are intended to behave over long periods of time, longevity should be given attention during design. Unfortunately, due to a variety of factors, this important consideration is often ignored or only partially assessed. At the very least, the cutoff wall designer should consider the design life of their wall and what factors may contribute to changes in the wall over that time period. Detailed assessment of the longevity of a wall may be beyond the scope of design for smaller walls, but this topic deserves some level of attention on every project. Although this issue is very complex and hard to assess, there are publications available that address components of the topic and provide points of consideration (e.g. Ruffing et al 2018).

CONCLUSIONS

Subtle, but significant, issues associated with the design and specification of slurry trench cutoff walls have been identified and discussed. These issues include excavation refusal, keying into layers of low hydraulic conductivity, specifying and measuring hydraulic conductivity, statistical measurements in specifications, use of the filter press, sand content in the slurry, cleaning of the backfill slope, measurement of stress and strain, the use of slag in CB mixtures, the need to balance the design mix to reflect competing desirable properties, and cutoff wall longevity. Recommendations are provided for these issues that will assist in producing a quality vertical cutoff wall that meets the needs of the project while minimizing costs and the potential for conflict during construction. Extensive references are provided that expand upon many of the topics identified in this paper.

ACKNOWLEDGMENTS

The financial support of the National Science Foundation (Grant No. 1463198) for the construction of an instrumented, full-scale SB slurry trench cutoff wall is greatly appreciated.

REFERENCES

Coughenour, N., Ruffing, D.G. and Evans, J.C., 2018. Lessons learned: self-hardening slurries in slurry trenching, Proceedings of the 71st Canadian Geotechnical Conference and the 13th Joint CGS/IAH-CNC Groundwater Conference, Edmonton, Canada, September 23-26.

Devlin, J. F., & Parker, B. L., 1996. Optimum hydraulic conductivity to limit contaminant flux through cutoff walls. Groundwater, 34(4), 719-726.

D'Appolonia, D.J., 1980. Soil-bentonite slurry trench cutoff walls, J. Geotech. Eng. Div., ASCE, 106(4), 399-417.

Evans, J.C., Fang, H. Y., and Kugelman, I. J., 1985. Containment of hazardous materials with soil-bentonite slurry walls, Proceedings of the 6th National Conference on the Management of Uncontrolled Hazardous Waste Sites, Wash., D. C., Nov., pp. 249-252.

Evans, J. C., 1994. Hydraulic conductivity of vertical cutoff walls, Hydraulic Conductivity and Waste Contaminant Transport in Soils, *ASTM STP 1142*, D. E. Daniel and S. J. Trautwein, Eds., American Society for Testing and Materials, Philadelphia, pp. 79-94.

Evans, J. C. and Dawson. A. R., 1999. Slurry walls for the control of contaminant migration: a comparison of United Kingdom and United States practices, ASCE Specialty Conference on Geo-Engineering for Underground Facilities, ASCE Geotechnical Special Publication No. 90.

Evans, J. C., Trask, J. M. and Frank, R. L., 2004. Lessons learned from the Macon County slurry wall, Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering, NY, NY April 13-17.

Evans, J. C., & Opdyke, S. M., 2006. Strength, permeability, and compatibility of slag-cement-bentonite slurry wall mixtures for constructing vertical barriers. In 5th ICEG Environmental Geotechnics: Opportunities, Challenges and Responsibilities for Environmental Geotechnics: Proceedings of the ISSMGE's fifth international congress organized by the Geoenvironmental Research Centre, Cardiff University and held at Cardiff City Hall on 26–30th June, pp. 118-125. Thomas Telford Publishing.

Evans, J.C. and Huang, H., 2016. Hydraulic conductivity of soil bentonite slurry walls. ASCE Geo-Chicago 2016 Sustainability, Energy and the Geoenvironment, ASCE GSP 271, pp. 548-557.

Evans, J. C., Yang, Y.-L., and Ruffing, D.G., 2018. Vane shear tests to evaluate in situ stresss State of a soil-bentonite slurry trench wall, Proceedings of the 8th International Congress on Environmental Geotechnics, Hangzhou, China, October 28 to November 1.

Evans, J. C., & Ruffing, D. G., 2019. Stresses in soil-bentonite slurry trench cutoff wall. In ASCE Geo-Congress 2019, March 24-27, Philadelphia, PA

Evans, J.C., Larrahondo, J.M. and Yeboah, N., 2020. Role of bentonite in slag-cement-bentonite slurry trench cutoff walls, under review, ASCE J. of Geotechnical and Geoenvironmental Engineering

Garvin, S. L., & Hayles, C. S., 1999. The chemical compatibility of cement–bentonite cut-off wall material. Construction and Building Materials, 13(6), 329-341.

Jefferis, S.A., 1981. "Bentonite-cement slurries for hydraulic cut-offs", Tenth International Conference, International Society for Soil Mechanics and Foundation Engineering, Stockholm, Vol. 1, pp. 425-440.

Jefferis, S.A., 1993. "In-ground barriers," In: Contaminated Land – Problems and Solutions, ed. T. Cairney, Blackie A+P, London. Pp. 111-140.

Jefferis, S.A., 1997. "The origins of the slurry trench cut-off and a review of cement- bentonite cut-off walls in the UK," Proceedings of the International Containment Technology Conference, St. Petersburg, FL, pp. 52-70.

McLay, D., 1987. Installation of a cement-bentonite slurry wall using the vibrating beam method—a case history. In Proc., 19th Mid-Atlantic Ind. Waste Conf, pp. 272-82.

Mitchell, J. K., & Soga, K., 2005. Fundamentals of soil behavior (Vol. 3). New York: John Wiley & Sons.

Opdyke, S. M. and Evans, J. C., 2005. Slag-cement-bentonite slurry Walls," ASCE J. of Geotechnical and Geoenvironmental Engineering, Vol. 131, No. 6, pp. 673-681.

Ruffing, D. G., Evans, J. C., and Malusis, M. A., 2010. Prediction of earth pressures in soil-bentonite cutoff walls," ASCE GeoFlorida 2010 Advances in Analysis, Modeling and Design GSP 199, pp. 2416-2425.

Ruffing, D. G., and Evans, J.C., 2014. Case study: Construction and in situ hydraulic conductivity of a deep soil-cement-bentonite cutoff Wall. ASCE GeoCongress: Geo-Characterization and Modeling for Sustainability, GSP 243, pp. 1836-1848.

Ruffing, D.G., Evans, J.C. Spillane, V.A. and Malusis, M. A., 2016. The use of filter press tests in soil-bentonite slurry trench construction. ASCE Geo-Chicago 2016 Sustainability, Energy and the Geoenvironment, ASCE GSP 271, pp. 590-599.

Ruffing, D.G., Evans, J.C. and Coughenour, N., 2018. Soil-bentonite slurry trench cutoff wall longevity. International Foundations Congress and Equipment Expo, March 5-10, 2018 pp. 214-223.

Ryan, C.R., 1987. Vertical Barriers for Pollution Control, Geotechnical Practice for Waste Disposal '87, ASCE Geotechnical Special Publication No. 13, pp. 182-204.

United States Army Corps of Engineers, 2010. Guide specification for construction: soil-bentonite (S-B) slurry trench, UFGS-02 35 27.