SLURRY WALLS FOR GROUNDWATER CONTROL:
A COMPARISON OF UK AND US PRACTICE

By Jeffrey C. Evans1, Member, ASCE and Andrew R. Dawson2 and Shana Opdyke3

Abstract: In both the UK and the US, low permeability, vertical barriers (slurry walls) are widely used in systems designed and constructed for the control of groundwater such as in to temporary excavations. These vertical barriers may result in more economical dewatering for larger and/or more complex underground excavation projects than dewatering wells, the conventionally used alternative. In the US, soil-bentonite slurry wall technology is the predominant method for the construction of these low permeability barriers. In contrast, slag-cement-bentonite slurry wall technology is the most widely employed method in the UK. These barriers are made with water, cement, and granulated ground blast furnace slag. This paper presents an examination, comparison, and assessment of each of these practices. It is concluded that slag-cement-bentonite techniques could readily be adopted by US designers and contractors. Permeability data developed in the US using US sourced ingredients are presented which show that a mixture of about 20% cementitious material to 80% slurry (where the cementitious material is about 25% Portland cement and 75% slag) results in a barrier having a hydraulic conductivity less than 1x10^-7 cm/s. Evidence points to a current trend towards the increased use of slag-cement-bentonite cutoffs in the US.

INTRODUCTION

In both the United Kingdom (UK) and the United States (US), low permeability, slurry trench cutoff walls are widely used for the control of groundwater flow into excavations below the water table. Cutoff walls have also been used to control ground water flow into and out of reservoirs, water flow through small dams and levees, and to maintain ground water levels beneath structures (Day, 2002). To construct such ground water cutoffs, soil-bentonite slurry wall (SB) technology is the most-widely employed method in the US. However, in the UK, slag-cement-bentonite (Slag-CB) slurry wall technology is used virtually exclusively in similar applications. The current trend in geotechnical engineering is to consider and sometimes use the UK-style slurry trench cutoff techniques here in the US. This trend is supported by recent data demonstrating that the UK style slurry trench cutoff wall material formulations can be replicated in the US with similar results to those achieved in the UK.

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GENERAL DESCRIPTION OF METHODS

Important aspects of the US and UK practices are summarized on Table 1 (Evans and Dawson, 1999) and discussed in the paragraphs which follow.

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>US PRACTICE</th>
<th>UK PRACTICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier composition</td>
<td>Soil-bentonite (SB)</td>
<td>Slag-cement-bentonite (CB)</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>&lt; 1x10^{-7} cm/s</td>
<td>&lt; 1x10^{-7} cm/s after 90 days</td>
</tr>
<tr>
<td>Solids content (Mv/Mt)</td>
<td>~ 70%</td>
<td>~20%</td>
</tr>
<tr>
<td>Unconfined compressive strength</td>
<td>~0</td>
<td>&gt; 100 kPa @ 28 days</td>
</tr>
<tr>
<td>Strain to failure</td>
<td>plastic</td>
<td>brittle</td>
</tr>
<tr>
<td>Time dependency</td>
<td>Consolidation: rapidly</td>
<td>Initial set: within one day</td>
</tr>
<tr>
<td></td>
<td>(within a few days)</td>
<td>Complete hydration reactions:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 days or more</td>
</tr>
<tr>
<td>Construction Stages</td>
<td>Two phase</td>
<td>One phase</td>
</tr>
<tr>
<td>Excavation Equipment</td>
<td>Backhoe, clamshell</td>
<td>Backhoe, clamshell</td>
</tr>
<tr>
<td>Depth (typical)</td>
<td>20 m</td>
<td>15 m</td>
</tr>
<tr>
<td>Width (typical)</td>
<td>0.75m</td>
<td>0.6m</td>
</tr>
<tr>
<td>Length (typical)</td>
<td>&gt; 1 km</td>
<td>&lt; 1 km</td>
</tr>
<tr>
<td>Working space needed</td>
<td>Large for slurry plant &amp;</td>
<td>Small for slurry plant &amp;</td>
</tr>
<tr>
<td></td>
<td>backfill mixing</td>
<td>excavation spoil disposal</td>
</tr>
<tr>
<td>Material assessment</td>
<td>Hydraulic conductivity,</td>
<td>Hydraulic conductivity,</td>
</tr>
<tr>
<td></td>
<td>compatibility during</td>
<td>strength, strain at failure</td>
</tr>
<tr>
<td></td>
<td>design</td>
<td></td>
</tr>
</tbody>
</table>

US Soil-Bentonite Slurry Trench Cutoff Walls

SB slurry trench cut-off walls are constructed by first excavating a trench using a slurry to maintain trench stability and then displacing the slurry by placing soil-bentonite backfill. Thus, it is a two-phase process of excavation and backfill. In the first phase (excavation), a narrow trench (0.5 to 1.5m) wide is excavated, usually with a backhoe while trench stability is maintained by the slurry consisting of bentonite (about 5%) and water (about 95%).

Once the desired depth has been reached, the slurry in the trench is displaced by a soil-bentonite backfill (the second phase) consisting of a mixture of soil, bentonite-water slurry, and occasionally dry bentonite. This backfill is made from either material excavated from the trench, imported materials or some combination of the two.

The hydraulic conductivity of soil-bentonite, as measured in the laboratory, is typically between 1x10^{-7} cm/s and 1x10^{-8} cm/s. While not typically specified or measured, other characteristics of SB backfill include no unconfined compressive
strength, high plasticity with very high strains at failure (greater than 20% or even strain hardening), and a high solids content (typical about 70%).

UK Slag-Cement-Bentonite Cutoff Walls

Slag-cement-bentonite slurry trench cutoff walls are constructed in a single phase using equipment similar to that used in the US. The slurry is left to cure (harden) in the trench and forms the permanent cutoff wall. Slag-cement-bentonite slurry is commonly made of bentonite-water slurry (about 75% to 80%) mixed with the cementitious material (about 25 to 30%). In the slag-cement-bentonite mixtures, the cementitious material is approximately 20% to 25% Portland cement with 75%-80% granulated ground blast furnace slag. An example mix proportion used on a project in the UK (Barker, et al. 1997) is:

- 35 kg/m³ bentonite
- 120 kg/m³ ground granulated blast furnace slag
- 30 kg/m³ ordinary Portland cement
- 934 l water.

The hydraulic conductivity of slag-cement-bentonite, as measured in the laboratory on cured samples, is typically less than 1x10⁻⁷ cm/s. Other properties of the slag-cement-bentonite material include a moderate unconfined compressive strength in the range of 100 to 1000 kPa (BRE, 1994), a low to moderate strain at failure (typically less than 2% in an unconfined compression test), and a low solids content (about 20% solids and 80% water).

It is important to note that walls of cement-bentonite have been constructed in the US for many years. The primary difference is that the cementitious material is ordinary Portland cement without slag replacement. Importantly, the resulting hydraulic conductivity is higher (1x10⁻⁵ cm/s to 1x10⁻⁶ cm/s). The UK practice of using slag as a partial cement replacement was adopted following studies by Jefferis (1997) that demonstrated lower hydraulic conductivity could be achieved.

DESIGN CONSIDERATIONS

US Design Practice for Soil-Bentonite Walls

Used in dewatering applications, the primary design consideration for SB is low hydraulic conductivity. A hydraulic conductivity of 1x10⁻⁷ cm/s is often a standard although for many dewatering applications, the flow through the wall may be minimal for a hydraulic conductivity of 1x10⁻⁶ cm/s. These results are readily achieved for SB with appropriate materials and construction technique. The hydraulic conductivity of SB is very stress dependent (Evans 1994) and designers need to specify the effective consolidating pressures used in laboratory testing for hydraulic conductivity. Since SB has no unconfined compressive strength and is an extremely plastic material, there is not generally a performance requirement for stress-strain behavior.

UK Practice for the Design of Slag-Cement-Bentonite Walls

For the control of ground water flow, performance requirements for Slag-CB are typically low hydraulic conductivity and stress-strain behavior (Privett, et al. 1996).
Similar to US practice, a maximum hydraulic conductivity of $1\times10^{-7}$ cm/s is often specified. Due to the time rate of curing that is characteristic of cementitious materials, the time of testing will greatly influence the results. Designers normally choose a curing time of either 28 or 90 days but the hydraulic conductivity continues to decline over time. Since Slag-CB walls include cementitious materials, to minimize the possibility of cracking, the strain at failure (usually a minimum of 5%) had often been specified. Current design practice typically omits a strain at failure criteria or specifies a value of 2 or 3%. The effective confining pressure must also be specified since the strain at failure is stress dependent (the higher the confining pressure the higher the strain at failure). The trade-off for mix designers is that altering the mix for increased flexibility tends to increase hydraulic conductivity. A minimum strength of 50 kPa is included in the draft UK national specification (Doe and Jefferis 1996a).

CONSTRUCTION: MATERIALS AND METHODS

Slurry preparation

Slurry preparation procedures are similar for both SB and Slag-CB. In the UK, bentonite-water slurry is mixed in a high-speed colloidal shear mixer and an additional 4-8 hours of hydration time is required. The cement and slag are added to hydrated slurry in a separate mixer in the UK. In the US, colloidal shear mixers are used without additional hydration time. In the US, if low shear energy mixers are used, hydration ponds or tanks are employed to permit adequate hydration time.

Excavation

SB and Slag-CB barrier walls are excavated using similar techniques. Backhoes are typically used for excavations to depths of 15m or so and crane mounted clamshells are used for greater depths. Since the slurry for a SB project is composed of bentonite and water and does not set, excavations can be stopped at any depth and continued later (the next day for example). Slag-CB slurry hardens and therefore the excavation to the trench base must be completed within the working day or the mix must be altered with set retarding agents to delay the hardening.

In SB projects, the excavated soils are often reused to make the backfill. In Slag-CB projects, the excavated materials are typically wasted or used as site fill.

Backfill

Backfill meeting the design requirements including slump and grain size distribution is placed in the trench in a manner to avoid entrapment of slurry or segregation of coarse fraction. Since the Slag-CB is left in the trench to harden, no displacement of construction slurry is necessary.
PERFORMANCE

US Practice

For the two-phase SB construction methods, field quality control measures are essential to insure the homogeneity of the constructed barrier. While much has been written on this topic (Spooner 1984, Evans 1991, Evans 1993), the focus here is relative to the comparison of UK and US practices. The most commonly asked question is: How does one insure that the SB backfill completely displaces the excavation slurry? While it is not possible to send inspectors into the trench, backfill quality and continuity is controlled by 1) prohibiting placement of backfill directly into the slurry and 2) a comprehensive program of soundings of the backfill and excavation surfaces ensures the displacement. In this way, the backfill can be expected to displace the slurry and form a homogeneous barrier. The most common defect in SB walls is inadequate key form either poor design or construction quality control. Sources of construction defects in SB barriers also include improperly mixed backfill, entrapped sediments at the bottom of the trench, and entrapped slurry pockets in the backfill (LaGrega, et al. 1994).

Documentation of material properties is routinely done using laboratory testing of field mixed samples taken just prior to their introduction into the trench. Mixed samples of SB would be tested in the field for slump and sampled for laboratory tests including grain size distribution, moisture content and permeability. In some projects, a field laboratory is established for this testing. In situ testing is rarely routinely undertaken. In case of dispute, in situ testing (with limited success) and/or in situ sampling and laboratory testing may be conducted.

UK Practice

For single-phase construction needed for CB, the continuity of the barrier is more easily insured. The physical passing of the excavation bucket through the trench section demonstrates the trench continuity, and the slurry hardens in place. Samples are taken from various depths of the trench to check that any settling of coarse fraction from the slurry prior to slurry set does not result in a material at the bottom of the trench that is substantially more permeable than the remainder of the trench. It is implicitly assumed that the trench remains stable while the slurry hardens and any further sedimentation after sampling does not result in a material of greater permeability.

Documentation of material properties is routinely done using laboratory testing of field mixed samples. Mixed samples of Slag-CB are obtained from various locations within the trench, allowed to set in the field and then cured and tested in the laboratory in strength and permeability tests. For example, on a recent project 3 km long and 7 m deep, 76 consolidated-undrained strength tests at 14 days, 81 permeability tests at 28 days, 71 strain at failure tests at 90 days and 77 unconfined compression tests at 28 days were conducted (Barker et al. 1997). Like the US practice, in situ testing is rarely routinely undertaken but in case of dispute, in situ testing and/or in situ sampling and laboratory testing may be conducted. While in situ testing may initially appear to be a more reliable way of assessing the hydraulic conductivity of the barrier, penetration of the completed barrier is required and in situ testing programs are not without complications of their own (Tedd, et al. 1995a, Tedd, et al. 1995b).
CURRENT TRENDS

For both SB and Slag-CB, research efforts and contractor developments have improved the profession's understanding of each of the techniques and improved our ability to design and construct vertical barriers in the subsurface to control groundwater flow.

Slag-CB Cutoff walls

Early development of slag-CB included studies of strength, strain, and hydraulic conductivity (Jeffers, 1997). Most importantly, the influence of slag replacement upon the hydraulic conductivity was recognized and typical results for samples cured a minimum of 3 months are shown on Fig. 1. Results of preliminary studies to test this relationship for US mixtures similar to UK mixtures (Trietley, 1996 and Veracco and Smith, 1997) are shown as solid square symbols on Fig. 1. These data support the expectation that UK style Slag-CB mixtures are technically feasible in the US as well.

The results of a more recent study shown on Fig. 2 provide further insight into the influence of slag and Type I cement content upon the hydraulic conductivity of samples cured one-month (Opdyke, 2002). Without slag, or even with slag contents of up to 60%, values of hydraulic conductivity are in the range of 1x10^{-5} to 1x10^{-6} cm/s. Slag replacement of greater than 80% similarly has no benefit. The studies also show the benefit of increasing the cementitious material content (Portland cement plus slag) up to 20%. The optimum mixture appears to be a mixture containing 20% cementitious material containing about 70 to 80% slag and 20 to 30% Portland cement.
SUMMARY AND CONCLUSIONS

A summary of the differences and similarities of each of the two techniques is show on Table 1 and advantages and disadvantages of each are summarized on Table 2.

It is concluded that vertical barriers to ground water flow can be readily designed and constructed in the US using Slag-CB methods. The ingredients (Portland cement and slag) and the equipment (excavators and slurry mixers) are readily available. In the US, while SB has been used for the majority of cutoff walls, there is considerable experience constructing CB walls without slag. More recently, there has been an increased use of Slag-CB. Slag-CB is particularly advantageous where a shear strength is required for the barrier an/or there site is such that the area necessary for mixing SB is unavailable or too costly.

Fig. 2 Influence of Cement and Slag on Hydraulic Conductivity (from Opdyke, 2002)
Table 2 Advantages/Disadvantages of US and UK Practices
(from Evans and Dawson, 1999)

<table>
<thead>
<tr>
<th>TYPE</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK-style CB</td>
<td>• Slurry quality readily controlled</td>
<td>• Excavated soil wasted</td>
</tr>
<tr>
<td></td>
<td>• Hydraulic conductivity readily obtained (&lt; 1x10^{-7} cm/s)</td>
<td>• Properties change with time (hydration)</td>
</tr>
<tr>
<td></td>
<td>• Minimal space requirements</td>
<td>• Limited concerns of shrinkage and cracking above water table</td>
</tr>
<tr>
<td></td>
<td>• Design independent of site geology (not independent of contamination)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Better trench stability</td>
<td></td>
</tr>
<tr>
<td>US-style SB</td>
<td>• Process not unduly sensitive to excavation rates</td>
<td>• Hydraulic conductivity sensitive to soil gradation</td>
</tr>
<tr>
<td></td>
<td>• Reuse of excavated material common</td>
<td>• Requires local availability of suitable soil</td>
</tr>
<tr>
<td></td>
<td>• High solids content likely to enhance long-term reliability</td>
<td>• Large construction area needed for backfill mixing</td>
</tr>
<tr>
<td></td>
<td>• Economic on longer/deeper walls</td>
<td>• Short projects difficult due to long backfill slope</td>
</tr>
</tbody>
</table>

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