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SLURRY CUT-OFF WALLS
METHODS AND APPLICATIONS

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ABSTRACT

Slurry cut-off walls are non-structural walls constructed underground to act as barriers to the lateral flow of water and other fluids. Principal applications are site dewatering, pollution control, and seepage barriers in the foundations of water retaining structures. In this paper, the two basic types of trench -- soil bentonite (SB), and cement-bentonite (CB), and the principal kinds of slurry trenching equipment are discussed. There are examples of several recent projects with emphasis on the reasons behind the selection of the particular method.

Slurry cut-off walls normally have permeability in the range of $10^{-6}$ to $10^{-7}$ cm/sec. Recent advances in methods of analysis of slurry cut-off walls for the key factors of permeability and durability have provided much-needed assistance in the design process. The primary purposes of quality control are to check the continuity and depth of the wall, and to ensure a slurry and backfill which fall within workable limits while satisfying design criteria.

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INTRODUCTION

The past five years have seen a veritable explosion in the number of applications of slurry cut-off walls. They are increasingly being used on all types of projects where a positive groundwater cut-off is required. Recent advances in the capacity of excavating equipment and refinements in technique have brought the cost of slurry walls down and they now easily compete economically on projects where well-points or sheeting would have previously been used. The types of walls discussed herein are non-structural; they are relatively impervious but are not capable of supporting bending moments or significant shear stress. Normally, their strength is of the same order as the surrounding ground.

The techniques all involve excavating a trench which is kept filled with slurry, whose primary ingredients are bentonite clay and water, and whose function is to maintain the trench open with vertical sides, even below the water table. The excavation is carried out through the slurry from the ground surface using any equipment capable of the trench widths and depths required. Once the trench is excavated to its final depth, a mixture of soil and bentonite is placed in the trench, displacing the bentonite slurry. This type of construction is called a Soil-Bentonite (SB) slurry cut-off wall.

With a variation on the above technique called a Cement-Bentonite (CB) slurry trench, cement is added to the bentonite slurry just before it is introduced into the trench. The resultant slurry has properties substantially similar to normal bentonite slurry with respect to maintaining the sides of the trench. However, once excavation is complete, the CB slurry remains in the trench, sets up and forms the permanent watertight wall.

The extent and type of quality control on slurry wall projects has varied widely. In some recent cases, specifications have been too brief or incomplete to protect the owner's interests; in others, overly conservative design and excessively rigid specifications on aspects of construction not pertinent to overall performance have led to higher than necessary project costs and sometimes to unnecessary burdens on the contractor. In a later section, design parameters and quality control are discussed and optimal ranges for key indicators are recommended.

CONSTRUCTION METHODS

Trench Backfill

The Soil-Bentonite slurry trench technique has been in use in the United States for about thirty years. Figure 1 shows the excavation for a SB cut-off. On projects where the material excavated from the trench is suitable for use as backfill, the SB system can be economical because of the minimum amount of materials required. After the trench has been excavated under a bentonite slurry, more slurry is mixed with the soil adjacent to the trench (Figure 2). A bulldozer is used to work the material to a smooth consistency and it is then pushed into the trench so that the backfill slope displaces the bentonite slurry forward (Figure 3). Excavation and backfilling are phased to make the operation continuous with relatively small quantities of new slurry required to keep the trench full and to mix backfill.

Cement-Bentonite slurry trenches have been in use in Europe for at least ten years and in the United States for about six years. Figure 4 shows a small CB batch plant. Since the entire trench must be filled with slurry materials and a significant amount of slurry is wasted due to the excavation process and seepage losses through the sides of the trench, the backfill is considerably more expensive than under the SB method. This increased cost is partially offset by the elimination of the backfill mixing operation. However, the CB method can provide the following technical and construction advantages over the SB method:

- The technique is not dependent on the availability or the quality of soil for backfill.
- The CB system is more suitable in trenching through areas with difficult access or not enough room for backfill mixing.
- Because of the cement content, the backfill sets up quickly to a stiff consistency. Trenches may be cut through the wall without sloughing of the backfill. Construction traffic can cross the trench after a few days. There is no significant consolidation with time.
- Since the trench can be constructed in sections with later sections keyed-in by reexcavating a short section, the construction sequence is more flexible to meet site constraints. The long slope of the backfill under the SB system normally requires trenching continuously in one direction.
The major disadvantage of CB compared to SB is in situations where even tiny amounts of seepage are critical, due to its relatively higher permeability. A CB wall is also less resistant to chemical attack of many pollutants. These topics are treated in more detail in a later section.

Given the relative advantages between the two systems, the project requirements should be evaluated to determine the best method to be selected. Where possible, it may be most economical to specify both methods and allow the contractor to bid with the least expensive system.

Excavating Equipment

The primary requirement for the excavating equipment is the capability to excavate a trench of the design width to the required depths within permissible verticality tolerances. A variety of equipment has, in fact, been used. In the following paragraphs, the principal types are discussed, along with their relative advantages.

The hydraulic excavator, or backhoe, has been used on many slurry cut-off wall projects in the United States (Figure 5). The depth limitation of the largest hoes is presently about 18m but new advances in equipment technology will undoubtedly extend this range. The backhoe, because of its fast cycle time, is the most economical means of excavation. Minimum trench widths are controlled by the thickness of the boom. For large hoes, this can mean 80cm or more. The thickness of the wall is an important cost factor for CB slurry cut-offs.

Draglines have been used on projects to depths of about thirty meters. Specially weighted buckets are used to get the power required at depth. Draglines are sometimes the most economical means of excavating below the range of the backhoe; minimum bucket widths are in the range of 2m, ruling out using draglines with CB slurry due to high material costs. To reach the deeper depths, very large draglines are required and mobilization can be expensive.

The clamshell bucket rigs which were originally developed for cast-in-place concrete slurry walls have been applied to slurry cut-off trenching. These buckets may be cable-mounted or attached to a rigid sliding kelly bar (Figure 6). They may be powered by mechanical means (cables) or by hydraulic cylinders operated by a remote power supply. These rigs have a maximum range up to 80m and can be used with buckets as thin as 40cm. Their production is much lower than other methods, so unit costs for excavation are higher.

Another technique more recently introduced into the United States from Europe involves driving a beam into the ground with a vibrating pile-hammer while simultaneously jetting with CB slurry to form a "thin wall cut-off". The beam is withdrawn while more slurry is injected under pressure. The beam is driven in overlapping imprints to form a continuous wall. The result is a curtain about five centimeters thick with the additional protection of grouting coarser-grained strata with CB slurry. Given the right soil conditions, production is rapid and the thin wall cut-off uses far less CB slurry than conventional slurry trenching. However, the same narrow width mandates more careful quality control since each square meter of the wall is subjected to one pass of the beam which does not mix the slurry as in the case of slurry trenching. The principal problem of the vibrated beam has been assuring continuity between adjacent passes at depth. Its range is approximately 10-15m, but even within these depths slight deviations may leave "windows" in the wall. Soil profiles with cobbles or boulders are a particular problem and keying into underlying weathered rock or hardpan may not be possible to the extent feasible with excavated slurry trenches. The narrow width of wall makes this type of cut-off less suitable for applications in soil where movements due to settlement, subsidence, etc., can be expected later. Design parameters and quality control for thin-wall cut-offs are specialized topics, not treated in this paper.

APPLICATIONS

There have been several hundred slurry cut-off walls constructed in the U.S. Applications have included dewatering wells for excavations, seepage cut-offs under dikes and dams, and cut-off walls to contain outflow of various liquid pollutants. In general, this type of construction enjoys a number of advantages over competitive systems walls are described. To illustrate the fact that cut-off walls are not necessarily always jobs of major scope and cost, two of the selected examples involve walls where total costs were under $30,000.
Seepage Cut-off under a Dike

In 1979, the city of Jackson, Mississippi gained national attention as the "Easter Flood" of the Pearl River devastated large areas of the city and its suburbs. The Pearl was partially contained by a system of levees. Along a long section on the east side of the river, the levees had held but had been substantially weakened by underseepage which had created numerous boils on the landward side. The levees themselves were constructed of relatively impervious material so the Corps of Engineers decided to improve them by installing a slurry cut-off wall on the river side of the levees (Figure 7) and keying it into the levees with an impervious cap. Figure 8 shows a typical section through the work site.

For this job, the Corps rightly decided on a soil-bentonite trench, since there was adequate room for a mixing area. Most of the material excavated from the trench was suitable as backfill, but it had to have some coarse aggregate added to meet the standard Corps backfill gradation specification. The corps uses a good average backfill mix that incorporated a specified range of fine particles to minimize permeability. They perhaps do not vary their ranges sufficiently to always suit design constraints and locally found soils. For example, on this project, there were to be no loads superimposed on the wall. The addition of imported coarse gradation material to the in situ silty sands may not have been necessary.

The wall was installed to a maximum depth of forty feet and keyed into an underlying silty sand formation. The section treated was about one mile long, the weather was favorable and the work completed in about one month's working time.

Excavation Dewatering

Figures 9 and 10 illustrate the problem that a large southern industrial plant faced with its new addition. The soil profile consisted of about eight feet of rubble fill overlying eight feet of sand over clay. Previous construction had left massive concrete foundations underlying a major portion of the site. The owner wished to use the old foundations to the maximum extent possible while at the same time being able to excavate for new foundations. The groundwater was heavily polluted with caustic wastes and lowering the water table too far would cause the existing wood piles on and near the site to deteriorate. Any water pumped from the ground had to be treated before release. The problem was further complicated by extremely tight access conditions on most of the site and by the owner's need to maintain access across the site.

A soil-bentonite wall was essentially infeasible due to access. Also, the material excavated from the trench consisted of rubble, wood, and organics and was unsuitable as backfill. Fortunately, cement-bentonite was chemically compatible with the high pH caustic groundwater, so a CB cut-off was the obvious choice. There was still the problem of how to penetrate the old foundations at several points which was necessary to completely isolate the site. This was accomplished eventually (Figure 11) by open-cutting along the alignment, breaking out the old slabs with a hydraulic ram, and then backfilling the cut and subsequently installing the slurry trench to the full depth.

Figure 12 shows the trench excavation in progress. Figure 13 shows the hardened slurry. The trench was about seventeen feet deep and, once site preparation work was complete, required ten days to install.

Pollution Control

There have been many applications of the use of slurry cut-off walls for pollution control. All types of municipal, industrial and chemical wastes have been contained. The following example illustrates one of the newest applications, to oily wastes on top of the groundwater table. Most slurry wall cut-offs built for containment purposes require the presence of a clay or rock layer underlying the site to provide an impervious stratum that the cut-off wall can key into. In the case of most petroleum pollutants, they do not mix with water and are borne on the top of the groundwater table and flow laterally until they exit in a stream or wall. It is necessary for the cut-off wall to merely intersect the groundwater table to skim off the oil and contain it. There have been numerous applications of this technique, as idealized in Figure 14, particularly in the State of Michigan where numerous tank farms lie along the shores of the lakes and streams. The selected example shows how one refinery attempted to use steel sheets inserted into a stream to try to contain the pollution (Figure 15). This was mostly ineffectual and required frequent maintenance by vacuum trucks. The slurry cut-off wall was installed along a 1,000 ft. section (Figure 16) in five working days.

Cement-bentonite was used because of limited working room and the time of the year in which the work was done. Mixing soil-bentonite backfill would have been essentially impossible in the sub-freezing weather which prevailed.
DESIGN AND QUALITY CONTROL

Design Parameters

The primary design parameters, in their usual order of importance, are permeability, strength, and compressibility. In the following paragraphs, each is briefly discussed. A fourth parameter, durability, has implicit importance in permanent installation and is discussed in the next section.

Permeability has been the best studied of the design parameters. Laboratory and field studies have repeatedly yielded measured permeabilities in the range of $10^{-6}$ for CB cut-offs and in the range of $10^{-8}$ to $10^{-9}$ for SB cut-off walls. There has been some speculation about the role of the filter cake and how it differs between the two types of trench. The filter cake is the buildup of solids due to water seeping out of the slurry through the walls of the trench. After a certain point, the filter cake is thick enough to preclude further seepage losses. The higher concentration of bentonite in the filter cake is an important factor in bulk permeability or SB cut-off walls (Figure 17). In the case of the CB slurry, the filtrate loss increases dramatically upon the addition of the cement. Some penetration of the cement-bentonite mixture into the more pervious zones may be possible.

With respect to the backfill, research has shown that in the case of an SB wall, the permeability is dependent on the percentage and character of the fines content of the soil blended with the bentonite slurry. The higher percentage of minus 200 sieve particles and the more plastic the fines, the less pervious the wall will be (Figure 18). Twenty to forty percent fines seems to be an ideal range. Permeability may also be decreased by adding additional bentonite to the backfill mix (Figure 19). The permeability of the CB slurry cannot be controlled as easily since addition of bentonite would affect the working properties.

Under most conditions, the only strength requirements for slurry cut-off walls is to attain the approximate strength of the surrounding ground. Either SB or CB walls will satisfy this criterion. The top of the trench is usually covered to prevent the application of wheel loadings or other concentrated loads.

The compressibility of slurry cut-off walls is high in most situations to allow for deformations without cracking. In the case of CB slurry backfill, a normal mix can withstand compressive strains of several percent under in situ stress conditions without cracking. Slight changes in the mix can increase compressibility. The walls can also be designed for maximum flexibility under seismic conditions.

With the SB backfill, the percentage of coarse-grained particles has the greatest effect on both strength and compressibility. As the percentage of coarse-grained particles increases, strength increases and compressibility (crackibility) decreases.

Durability

In any permanent installation of a slurry cut-off wall, the ability of the wall to remain impervious in the underground environment is always an important question. The materials involved are bentonite clay, and soil or cement. In situations which involve clean water, these materials are indefinitely stable and no reduction in permeability is experienced. However, cement is known to be a poor performer in situations where acids or sulphates are present. Soil particles are stable in all but the most extreme acid or basic environments, where they may actually become soluble.

The greatest concern lies with the bentonite, since soil-bentonite walls are usually used in harsh chemical situations because of their lower permeability and better resistance to attack. The pore fluid substitution may lead to a smaller double layer of the partially bound water surrounding the hydrated bentonite or other clay particles, reducing the effective size of the clay particles that clog the pore space between soil grains, and thereby increasing the size of the effective flow channels in the soil skeleton and the permeability.

The permeation time required for the changes associated with pore fluid substitution to be completed is relatively short. Once a sample has been permeated by a volume of pollutant equal to about twice the volume of the pore fluid in the sample, the initial pore fluid has been, for the most part, leached out and the new pore fluid is essentially the pollutant. Sodium readily exchanges with multivalent cations such as calcium, magnesium and heavy metals, and the exchange is typically complete once an equivalent number of ions are supplied by the periment to satisfy the total cation exchange capacity of the bentonite. Once both the pore fluid is substituted and the cation exchange occurs, steady state conditions prevail and the permeability remains constant at a higher value associated with the new pore fluid and the new cation montmorillonite. These points are illustrated by Figure 20 which plots permeability for both bentonite filter cakes and SB backfill as a function of permeation time with a calcium carbonate.
The best approach from a design standpoint where durability is in question is to conduct a test using the materials from the site and the actual leachate. The best test is to mix a sample of soil-bentonite backfill, consolidate it in a tri-axial cell and run a continuous permeability test. The same kind of test can be run on the cake in a filter-press cell. Behavior such as that shown in Figure 20 where a relatively small increase in permeability is experienced followed by a constant reading is indicative of a stable mix.

While every pollutant should be checked, in general, a mix with well-graded SB materials and about one percent bentonite will exhibit small increases in permeability for most pollutants. Where this mix is not sufficient, the addition of more fines, particulary clay fines, or more bentonite will provide a satisfactory solution for practically all cases.

Quality Control

The primary functions of quality control during construction are to:
- Assure continuity of the completed trench to the widths and depths required.
- Control the composition and placement of the backfill to achieve the required design parameters.
- Control the quality of the slurry during construction to minimize the risk of trench failure (in most cases where trench failures threaten adjacent structures).

The continuity of the trench with respect to the required dimensions is relatively easy to control. The excavating equipment should have a minimum width equal to or greater than the width of trench required. Depth is controlled by direct measurement and by observation of materials excavated from the trench. When the wall is excavated by a backhoe, the motions of the machine ensure longitudinal continuity. In the case of a clamshell which digs vertically, primary panels should first be dug and then overlapped by secondary panels. Once this process is completed, a slight sideways movement of the bucket in both directions is used as a final check on continuity before the machine is moved and a new primary panel is dug.

The most important requirement for the slurry during the excavation of the trench can be summarized as workability. If the slurry is too thin, the trench may collapse. If the slurry is too thick, excavation may become difficult and large lumps of soil may become suspended in the slurry. In the case of the SB trench, a very thick slurry may interfere with the backfill process. Experience has shown that an optimal slurry can be attained by controlling a few essential factors: hydration of the bentonite, viscosity, and specific gravity.

Viscosity is the primary test to control the workability of the slurry. The standard test, the Marsh Funnel, consists of measuring the time required for a known volume of slurry to run out of a standard funnel. The ideal range for both SB and CB slurries is in the range of 40-45 seconds. Typical values measured in the trench may range as low as 35 seconds or as high as 80 seconds without causing problems. In the case of CB slurry, the slurry may become so thick as not to pass through the cone, but still be acceptable. The fluctuations may be caused by variations in the slurry being added or changes in the underground environment, or simply settling time. Any specification on workability should recognize and allow for these variations and permit the contractor to add new slurry with the properties required to bring the slurry in the trench back to an optimum value. The continued action of digging will tend to mix the slurry to a homogenous mass.

Specific gravity provides an additional control on workability. The principal application of a specific gravity criterion is to SB slurry cut-off walls. If the mud becomes too heavy, it is difficult to assure good placement of the backfill because the backfill may fold over the heavy slurry, rather than displace it. Experience has shown that as long as unit weights are maintained at least 15 pcf below the unit weight of the backfill mix, the slurry will be easily displaced.

The composition and placement of the slurry trench backfill is a different problem for the SB and CB techniques. In both cases, the amount of bentonite in the original slurry is as required to achieve correct slurry properties. In the case of the CB wall, cement is weighed and added in the correct proportions to the slurry as it is placed into the trench. The SB backfill is composed of suitable soil material mixed with additional slurry to attain a smooth consistency with a slump of 4 to 6 inches; the resultant mix is bladed into the trench. Care is taken to assure that the backfill moves continuously forward in the trench, displacing the slurry and not folding over it.
SUMMARY

Slurry cut-off walls have achieved wide recognition in a variety of applications as seepage barriers for dewatering and pollution control. The two principal techniques, soil-bentonite and cement-bentonite, have different relative advantages, but under some conditions are technically interchangeable. Typical projects involve the prevention of water inflow into excavations, seepage cut-offs under or through dikes, and dams, and underground barriers to prevent lateral flow of polluted water or other fluids.

A design for a slurry cut-off wall should take into consideration whether the wall is for permanent or temporary use, the loadings anticipated, and other construction constraints in selecting the technique to be used and the extent to which the work should be controlled by the engineer. Specifications should take account of the built-in safety factors in slurry cut-offs (e.g. more thickness than required in most cases) and allow the variability in slurry properties normally experienced during this type of work and give maximum flexibility to the contractor in selecting materials, equipment and technique. The economy, convenience and positive control of seepage afforded by slurry cut-off walls will bring them acceptance and application on an increasing number of construction projects in the United States.

REFERENCES


FIG. 3  SCHEMATIC SECTION THROUGH SB SLURRY CUT-OFF

FIG. 1  S-B CUT-OFF WALL EXCAVATION

FIG. 2  MIXING S-B BACKFILL
FIG. 10  SECTION THROUGH SITE TO BE DEWATERED

FIG. 11  DETAIL OF SLURRY CUT-OFF SOLUTION
FIG. 12
TRENCHING UNDER CEMENT - BENTONITE

FIG. 13
HARDENED C-B SLURRY

FIG. 14
SCHEMATIC OF TYPICAL APPLICATION OIL-POLLUTED GROUNDWATER
FIG. 15
OWNER'S PREVIOUS ATTEMPT TO CONTAIN OIL POLLUTION

FIG. 16
SLURRY CUT-OFF WALL ALONG RIVERBANK

FIG. 17 THEORETICAL RELATIONSHIP BETWEEN WALL PERMEABILITY AND PERMEABILITY OF THE FILTER CAKE AND BACKFILL

(k = WALL PERMEABILITY
k_c = CAKE PERMEABILITY
k_b = BACKFILL PERMEABILITY
l_b = BACKFILL THICKNESS
l_c = CAKE THICKNESS)

AVERAGE PERMEABILITY OF WALL k cm/sec

WALL THICKNESS = 80 cm

k_c / l_c = 25 x 10^3 sec
15 x 10^3 sec
5 x 10^3 sec

BACKFILL PERMEABILITY k_b, cm/sec
FIG. 20 EFFECT OF POLLUTANT PERMEATION ON PERMEABILITY OF FILTER CAKE AND SB BACKFILL

(AFTER D'APPOLONIA AND RYAN 1979)