Vertical Barriers in Soil for Pollution Containment

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ABSTRACT

Vertical barriers have evolved over the past fifteen years into a technique that is widely applied to restrict the underground movement of liquid wastes and polluted groundwater. Most applications are slurry cut-off walls, although there are several other techniques such as composite slurry walls and soil-mixing walls which show promise. Vertical barriers are used in applications both for new sites and for remediation of polluted sites. In both cases, the vertical barriers may be only one part of the remedial process and may be combined with other containment systems such as liners, or with remedial techniques such as leachate collection and treatment to provide a complete system.

Experience on a number of projects has provided data that act as a guide for the design of slurry cut-off walls. A key parameter is the quantity of additional dry bentonite added to the backfill blend. Once the blend has been designed to have an acceptable permeability to water, its compatibility with the expected leachate must be checked. For most leachates, a suitable soil-bentonite backfill blend can be designed.

A case study is presented that describes a project where bentonite was determined to be unsuitable as an additive. Attapulgite was substituted for the bentonite and the project successfully constructed.

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INTRODUCTION

Underground vertical barriers are used to prevent the lateral migration of liquid pollutants in the groundwater. In general, underground barriers are variations of the slurry cut-off wall technique, although other specialized techniques have been used and continue to be proposed.

There are on the order of 1,000 installations of underground barriers for groundwater control in the U.S. The earliest ones date back to the 1940's; most have been installed since the mid-1970's. One interesting development has been that the concept of how to design and build these containments has undergone considerable change over the years. The general engineering population has been somewhat slow in the acceptance and use of these techniques, and for the most part is not up to date in the latest design philosophies. It is a measure of the technique's novelty that the ASTM is only now beginning to produce relevant test standards and, at the present time, there is no generally accepted standard of practice.

This paper describes some of the principal methods for forming vertical barriers in soil to prevent the underground migration of pollutants. Both the more accepted slurry cut-off walls and some new variations are reviewed. Conventionally constructed concrete and clay cut-offs are not covered. The design properties of principal concern, permeability and contaminant compatibility, are discussed and some guideline data presented.

METHODS

Soil-Bentonite Slurry Cut-Off Walls

The Soil-Bentonite (SB) technique has accounted by far for most of the installations of vertical barriers in the U.S. It has been in general use since the mid 1970's. The construction methods are described elsewhere (D'Appolonia, 1980; Ryan, 1980; Tallard, 1984) and will not be treated in detail in this paper. In brief, a trench is excavated under bentonite slurry and subsequently backfilled with a blended mixture of soil and bentonite (Fig. 1).

The principal advantages of the SB wall are economy, ease of continuity verification, flexibility in permanent backfill design and the thickness of the wall (which is generally greater than with other methods). In only a very limited number of cases has the design investigation shown that bentonite would be incompatible with an expected leachate. There have been recent examples of alternative materials being substituted for bentonite to overcome this problem. A case study is presented in a later section.

Figure 1: Typical SB Slurry Cut-Off Wall Under Construction

Cement-Bentonite Slurry Cut-Off Walls

The Cement-Bentonite (CB) technique is a less commonly used method, but even so has somewhere in the range of 50-100 installations here in the U.S. The first use in the U.S. was in 1973 at a dam site in Georgia. Once again, the construction method has been well described in other publications (Millet & Perez, 1981; Adaska and Cavalli, 1984; Portland Cement Assoc., 1984). The principal difference from the SB technique is that a cementitious additive is mixed into the slurry, so that the slurry itself sets with no separate backfilling operation required.

CB provides some advantages where access is limited (Fig. 2) , or on jobs where the excavated materials are unsuitable as backfill material (e.g. building rubble). One advantage frequently ascribed to CB over SB is strength and incompressibility. This is somewhat of a misconception since, while it is true that CB will exhibit some unconfined strength, triaxial tests in most cases show that SB may actually be more incompressible and can have a higher modulus. (D'Appolonia, 1980; Millet and Perez, 1981). The principal disadvantages of CB are typically higher cost and higher permeability. The mix is also usually more susceptible to degradation by chemical pollutants than SB.

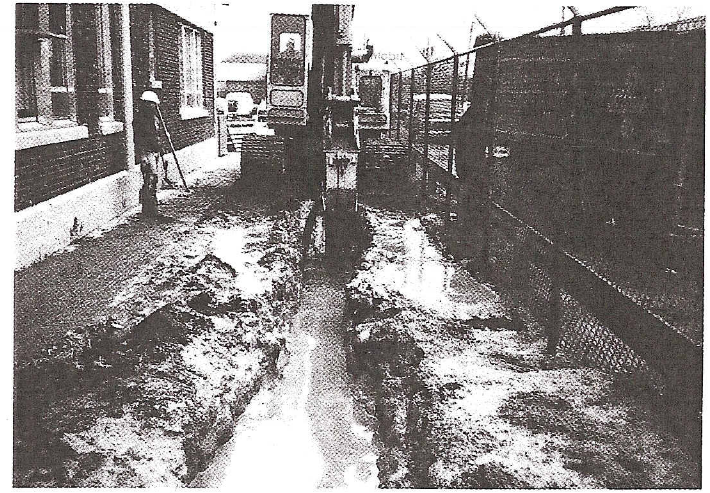

Figure 2: Installing a CB Wall in Tight Quarters

Composite Slurry Wall

The concept of inserting a sheet of material into a slurry wall has been around for some time. There are examples of concrete panels and sheet-piles inserted into both SB and CB walls that go back to the late 1960's. The purposes of composite walls have been generally to provide greater strength for lateral support and, occasionally, a greater degree of impermeability. Recently, there have been several applications of synthetic membrane liners inserted in slurry cut-off walls to provide an extra margin of safety and a more impervious barrier (Figs. 3 & 4). The sheets are generally connected by an interlock joint system, although there have been numerous other types of joining systems used. The toe of the sheet may be imbedded in backfill material or in a special grout or concrete.

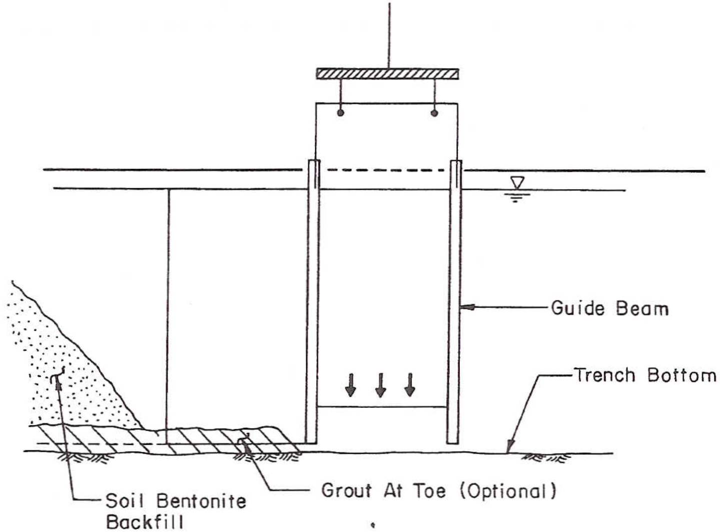

Figure 3: Installation Method for Composite Wall

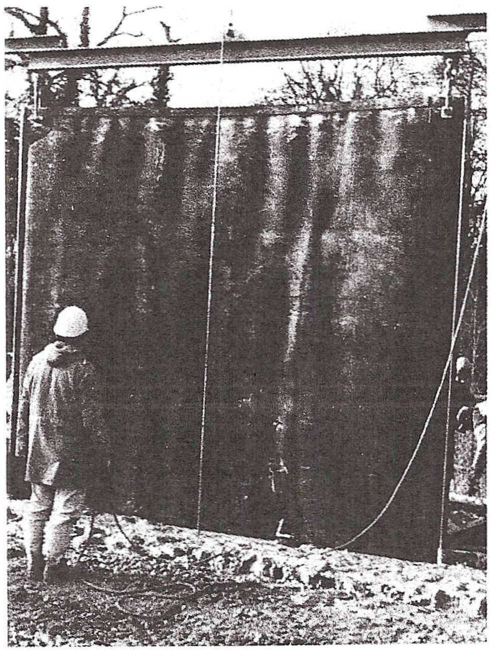

Figure 4: Installation of Composite Wall in Progress (Photo courtesy of Zublin AG)

An alternative system has been proposed using an envelope of synthetic membrane filled with sand (Druback and Arlotta, 1985). This system has yet to receive wide acceptance, since it is particularly difficult to install and creates a problem at the toe of the doubled sheet, in that it is difficult to create a good contact between the sheet and the walls of the trench.

Soil Mix Walls

A technique which has been relatively recently introduced into the U.S. is the soil-mixed wall (SMW). A special auger/mixing shaft is inserted into the ground and rotated while a fluid slurry or grout is injected into the soil (Fig. 5). The result is a column of treated soil. Typically, a multi-shaft unit is inserted, mixing a pattern of either a linear or rectangular shape. In the case of a cut-off wall, the linear arrangement is used with the first shaft redrilling the print of the last segment to achieve continuity (Fig. 6).

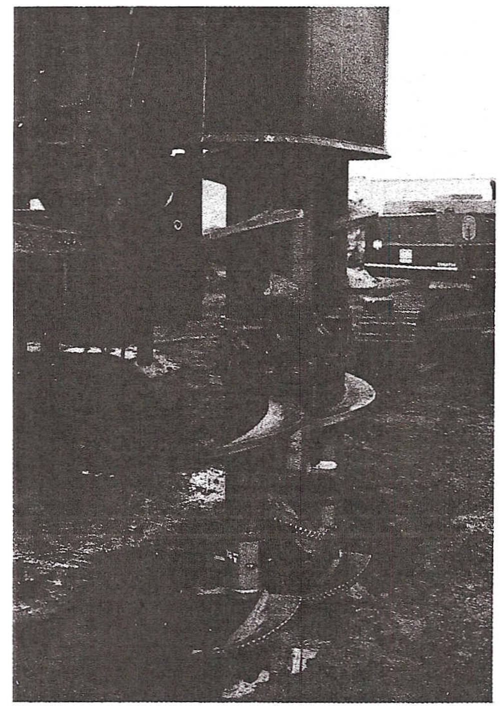

Figure 5: Soil Mixing Method Equipment

The process was developed in Japan and has been used on over a thousand projects there. (Seiko Kogyo, Ltd., 1983). Most of the Japanese applications are for structural retaining walls and incorporate a steel beam inserted into soil mixed with cement grout. The same equipment can be used to mix a bentonite slurry into the soil. On a recent project in Japan, for example, a slurry cut-off wall was installed around a refinery complex; in locations where there was concern that the proximity of above-ground or below-ground structures presented too great a risk, the SMW technique was used, since it did not require an open excavation.

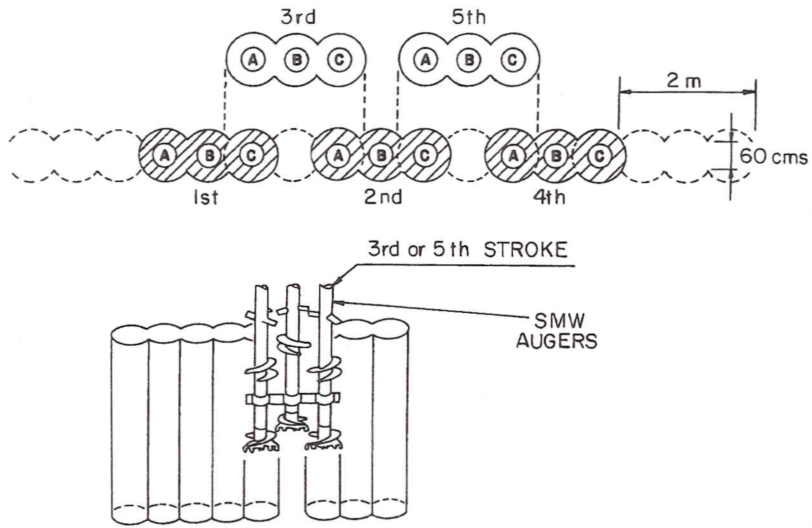

Figure 6: Installation Sequence for SMW Barrier

A disadvantage of the SMW technique as a cut-off wall is that the amount of bentonite that can be added to the soil is limited, since it has to be added in the form of a pumpable slurry. This may lead to higher permeabilities than can be achieved with a soil-bentonite slurry cut-off wall through the addition of dry bentonite. The Japanese have a newer technique, called dry jet mixing (DJM), that adds dry powdered constituents to a soil and mechanically mixes them in a manner similar to the SMW process. The DJM method may have a more limited range of applications in the U.S., since the equipment involved is extremely complex and the range of soils that can be treated is restricted to very soft soils such as sensitive clays and peats. Both techniques are usually more expensive than slurry cut-off walls.

Other Methods

Three other techniques see occasional application as vertical barriers for pollution containment. The first is pressure grouting, where a hole is drilled into the ground and a fluid injected under pressure into the soil or rock to permeate the voids and fissures. With the holes on a close enough spacing, an effective grout curtain can be formed. This technique is best applied in situations where cut-offs in rock formations are required. In the case of soils, permeation of all the voids to form a continuous cut-off is difficult to achieve for most soil types, and almost impossible to verify. Grouting a cut-off in soils is also generally far more expensive than the other techniques listed above. Formation of grouted barriers is a specialized topic not treated in this paper.

The second is a technique known as jet grouting. Once again, a hole is drilled into the ground and a grout pipe placed. With this method, very high pressure small diameter jets of grout are used to blast and displace the soil, thereby mixing it with grout. As the grout pipe is raised, it is rotated and a column of cemented material is formed. Adjacent columns are formed with contact between columns providing a continuous barrier. This is a relatively new technique in the U.S. (Andromalos and Pettit, 1986). While it provides some additional assurances over conventional grouting, since permeation of the soils is not required, it is still very difficult to adequately verify continuity.

The last, and somewhat related technique, is the vibrated-beam wall. A heavy I-beam is driven into the ground with a vibratory pile hammer and then extracted as a cement-bentonite grout is injected into the resulting print of the beam and surrounding soil. The beams are driven in an overlapping pattern to try to achieve continuity. Numerous studies have shown that the resultant grout, particularly when special mixes are injected, achieves a good degree of impermeability (Leonards et al, 1985; Jogis and Bell, 1984). Problems have been experienced on some projects in driving the beam through dense or cobbled soils and in maintaining sufficient verticality of the beam at depth to assure continuity. For this reason, there is some sentiment (Jepsen and Place, 1985; Leach and Miller, 1984) that this technique should not be used on projects where continuity is critical.

APPLICATIONS

Applications of vertical barriers fall into two general categories, new and remedial work (Ryan, 1985). New work generally involves an unpolluted site on which a waste depository or lagoon is to be built. In most cases, current regulations prohibit new contamination of soils, mandating liner systems under new facilities. A slurry wall might be used as a reinforcement and fail-safe device to supplement a liner system (Fig. 7). There have been numerous examples of slurry walls used in both directions: as a dewatering cut-off wall to keep water out during the construction of a landfill; and as a permanent barrier to keep pollution in the landfill area after construction (Civil Engineering, 1984).

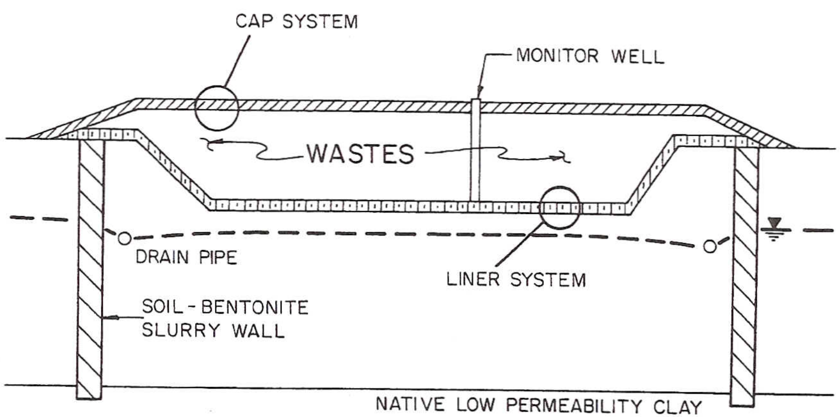

Figure 7: Slurry Wall used in Conjunction with a Liner System

Remedial work represents the bulk of the applications of vertical barriers for pollution control and a significant portion of the slurry cut-off walls recently installed and those proposed. In some situations, where a substantial amount of soil has already been contaminated, or where the contaminant plume underlies factory facilities, for example, underground vertical barriers may represent the only reasonable or economically feasible solution to the problem. Although acceptance by environmental authorities of permanent on-site containment is uneven at best, recent federal publications recognize the appropriate use of slurry cut-off walls in some situations (EPA, 1984). Several of the Superfund sites completed to date have utilized vertical barriers as a component of the site remediation (Waste Age, 1983; Ayres et al, 1983). Even in cases where the ultimate goal is to remove all contamination by pumping, or to excavate for disposal or

thermal destruction, installation of a vertical barrier may serve a useful economic and technical purpose since:

- Migration of the leachate plume is effectively halted while other systems are designed, installed and operated.
- The amount of clean water drawn into the site is dramatically reduced leading to significant savings in pumping and treatment costs.
- In cases where a total cleanup is not feasible, a vertical barrier provides a permanent passive system for containment.

It is fairly common to see slurry walls installed with leachate collection systems just to the inside of the containment (Fig. 8). This design concept is intended to provide a gradient into the site; since water is flowing through the wall towards the site, no water can flow out of the site. This applies to normal water transport mechanisms, described as D'Arcy's law; other transport mechanisms, such as osmotic pressures, ion exchange phenomena etc. may come into play in some cases (Freeze and Cherry, 1979).

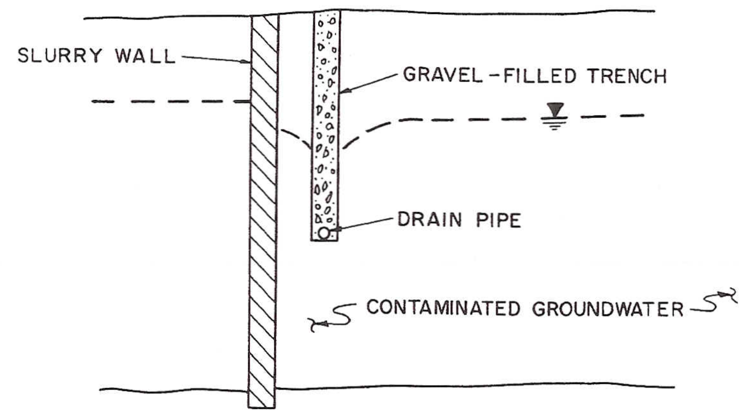

Figure 8: Slurry Wall Used Together With a Leachate Collector

PERMEABILITY

The question of how to measure the permeability of a slurry cut-off wall is one that has caused as much controversy as the related question about compacted clay liners. In both cases, designers generally are currently relying on small scale laboratory tests to arrive at design parameters to apply to large scale constructed facilities. A wide variety of testing procedures have been and continue to be used. The industry appears to be standardizing around a procedure for soil-bentonite backfill that involves placing a remolded sample into a triaxial cell and consolidating it to in situ stresses and then performing the permeability test. CB slurries or grouts are generally allowed to set and cure in a mold and subsequently are tested in a triaxial cell. There is some controversy over the laboratory methods that should be used to arrive at the design permeability, but is small in comparison to the debate over field verification of in-place permeabilities.

Compacted clay liners are somewhat easier to check since they are available at the surface; a number of tests have been developed that seem to represent reasonable models for the field conditions (Day and Daniel, 1985a). Unfortunately, these tests have not always provided consistent agreement with laboratory design parameters (Day and Daniel, 1985b).

Vertical barriers represent a different set of problems since they are not easily visible nor accessible from the surface. One advantage over clay liners, however, is that the vertical barrier components are perhaps less susceptible to the vagaries of the construction process and weather. All of the barrier techniques involve a relatively fluid mixture of materials that is placed into a trench or mixed in place and allowed to set or thixotropically gel. Once these materials are properly mixed and placed, weather is generally not a factor as it would be for construction processes like the compaction required for clay liners. There is also considerable evidence that some of the variation in testing of exposed clay liners is due to the low applied stresses, since a liner is not loaded as long as it is exposed (Daniel, 1985). This problem would obviously not be of much concern in a deep hydraulic barrier.

For all of the above reasons, field permeability verification of SB and CB walls has generally centered around taking samples from the mixed material at the point of placement into the trench before setting or gelling takes place, reconstituting the sample in the laboratory, and testing it using the same procedures used in the design phase.

<u>Soil-Bentonite Slurry Cut-Off Walls</u>

Data from about thirty SB slurry cut-off wall projects where field samples were taken are summarized in Figure 9, demonstrating the relationship between additional dry bentonite and permeability. There is an apparent correlation between relatively minor amounts of bentonite and permeability. Both the average permeability and the

deviation from the average are reduced at increased dry bentonite contents. Designers will generally specify a bentonite content in the backfill mix which includes that which is added as slurry for workability and that which is added dry. The data in Figure 9 are plotted as the percentage of dry bentonite added, since this is normally an easily verifiable quantity. The amount of bentonite added as slurry is normally not measurable in the field, since some comes from the slurry plant, some from the trench during the excavating process, and it even depends on such factors as rainfall. In general, the amount of bentonite added as a slurry is probably in the range of 0.5 - 1.5 percent by weight, although it could be as high as 4.0 percent for a dry clayey soil.

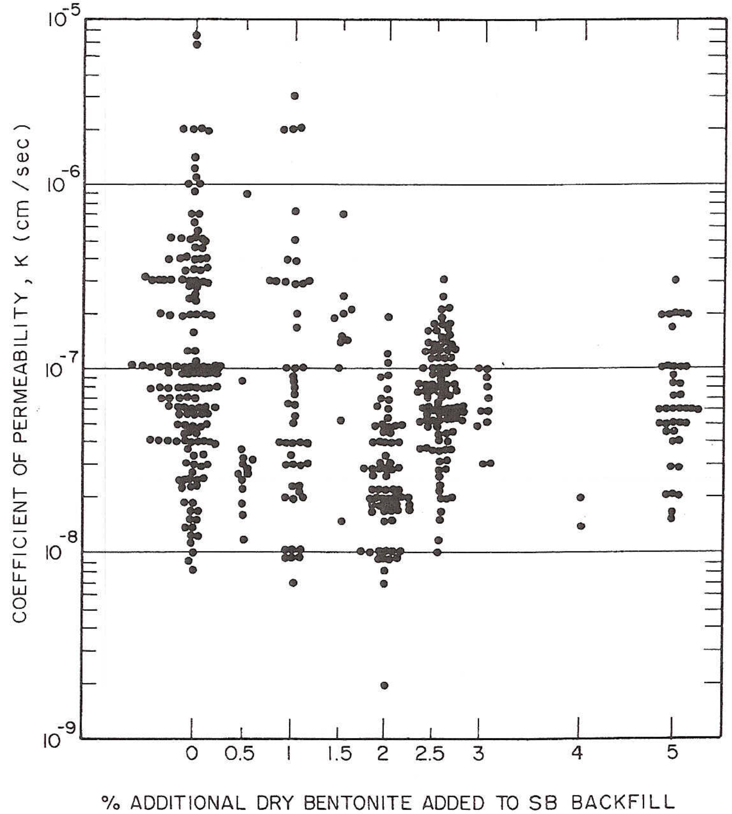

Figure 9: Permeability of SB Backfill vs. Bentonite Content

It would be expected that the type of soil used in the backfill might play a significant role in the final permeability. Figure 10 shows data taken from field-mixed backfill on a number of projects where no additional dry bentonite was added. There is a less significant correlation to permeability for higher fines content, although there seems to be a positive effect of having clay-size fines present. The amount of scatter in the data reinforce the point that it is dangerous to rely on design curves from previous projects. Permeability testing must be done for each case. In general, effective SB backfill should always have sufficient fines in the mix, perhaps 15-20% minimum, to prevent the bentonite particles from being flushed out of the soil matrix by piping.

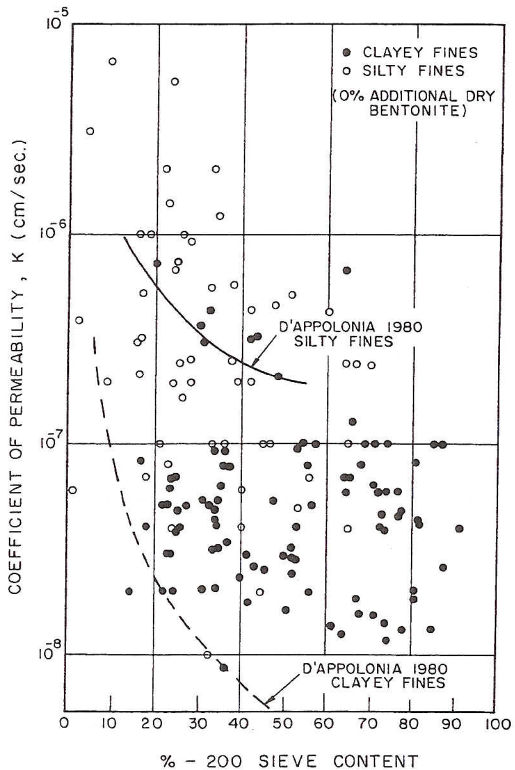

Figure 10: Permeability of SB Backfill vs. Fines Content

Some other general conclusions that can be drawn about SB backfill are as follows:

- There is no ideal grain size range for backfill soils. A wide variety of soils are usable. Pre-job design testing on proposed mixes is essential.

- In cases where the native soils are unsuitable (for example have no fines), rather than importing all new borrow material, it is always easier and more economical to blend in makeup material to correct the deficiency.

Cement-Bentonite Slurry Cut-Off Walls

CB walls, as mentioned earlier, are less frequently applied to waste containments. One reason for this is that the permeability of a CB wall is generally not as good as that of an SB wall (Ryan and Day, 1986). Figure 11 summarizes some data recently presented from different projects; it can be seen that a typical permeability value for CB slurry is in the range of 10^{-6}. It is not usual to obtain results below 1×10^{-6}. Because CB slurry must remain fluid during the construction process, it is generally not possible to add additional components to the slurry to achieve lower permeability.

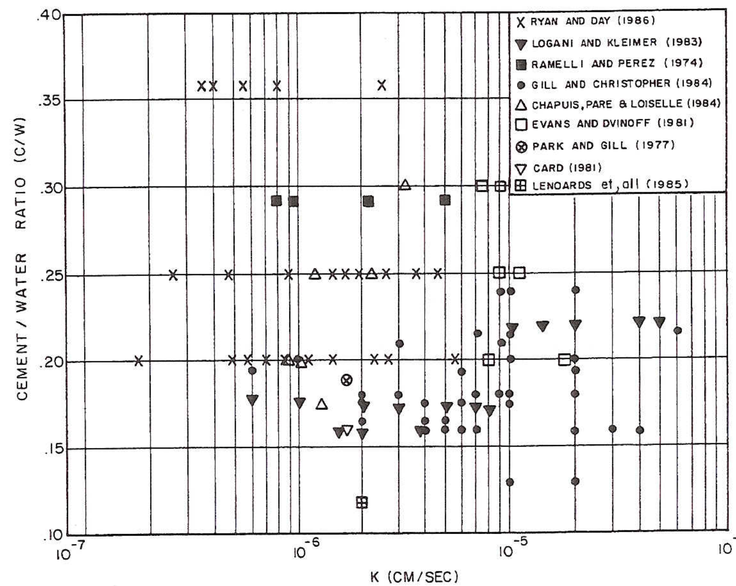

Figure 11: Permeability of Cement-Bentonite Slurry

Large Scale Field Verification Techniques

Beyond the field sampling and laboratory verifications described in the preceding sections, many designers would like to see some type of large scale field verification.

Unfortunately, the permeabilities are so low and the walls are so narrow, that most of the methods that would be easily applicable do not yield good results. Techniques that have been more or less unsuccessfully tried include placing piezometers on both sides or within the wall to run an infiltration test (Bjerrum et al, 1972).

The only large scale field verification which appears to be a reasonably good model and can be relied on for decent results is to construct a containment in the field and run a pumping test. To be valid, the containment should be at least 20-30 meters on a side. Of course, this is an expensive and time consuming process. Only one well-documented test like this has been carried out (Perez, 1974). In that case, the field-measured results were generally consistent with the design parameters obtained pre-job and with field sample verification testing.

COMPATIBILITY

To this point in this paper, the permeability results provided have not included the effects of a leachate other than water. Since most leachates will have some deleterious effect on a blend of materials containing bentonite, another design concern is introduced, that of durability (Alther et al, 1985; Anderson et al, 1985). The behavior of a backfill blend under polluted conditions with respect to permeability and durability is usually summed up by the term "compatibility".

Since most vertical barriers for waste containment are SB slurry cut-off walls, the remarks in this section generally relate to that technique. The usual procedure followed to determine compatibility is to complete the backfill design process with clean water, and then to permeate the proposed backfill design mix with the leachate from the site to see what the effect is. A successful compatibility test will show that a) the increase in permeability is relatively small (a factor of two or three is typical for many leachates) and b) the permeability levels off after a period of time. Given a successful test, a relatively small increase in the amount of additional dry bentonite may serve to counteract the effects of the leachate.

Numerous compatibility tests have been run from which some general conclusions may be drawn:

- For almost all leachates, it is possible to arrive at a reasonable SB backfill design.

- In almost every compatibility test, the increase in permeability of the sample due to the leachate levels off after about two pore volumes have been passed through the sample. It is advisable to verify this in each case with a longer term test.

- On sites that are already polluted, it usually makes good economic and technical sense to use the polluted material from the trench excavation as backfill material rather than importing clean borrow. It solves the disposal problem and usually arrives at the same result, since the wall may eventually be contaminated. Pre-job compatibility tests can be used to verify this.

- Every project that involves a leachate of any consequence should have compatibility tests run. As the case study presented below illustrates, the results can sometimes be surprising.

A Case Study

A recent project for a private client illustrates the design process in a case where bentonite was incompatible with a leachate. The case is presented in summary form since a more complete presentation is planned for a later date.

The site is located at an existing sanitary landfill. In one location, the owner had constructed a lagoon and accepted disposal of a variety of hazardous wastes. The site perimeter was underlain by numerous pockets of refuse and there were an undetermined number of drums containing hazardous waste buried at several locations on the site. The result was a leachate contaminating the local groundwater table. Analyses of some of the monitoring well samples are shown in the following table:

Water Well Analysis

Compound	Concentrations, ppb
Phenolics	18,500 - 26,000
Phenol	8,000 - 74,000
Methylene Chloride	0 - 40
Acetone	2,600 - 5,700
Benzene	190 - 1,100
Toluene	1,300 - 5,200
Xylene and Ethylbenzene	90 - 7,100
Gasoline	13,000 - 65,000

The owner desired to construct a perimeter containment as an interim remediation measure to prevent further off-site discharges while the final site remediation was being planned and executed. A competent continuous clay layer existed at depths from 8-14 meters below the ground surface to act as the lower aquaclude and key material for the slurry cut-off wall.

On first inspection, the concentrations of pollutants present in the leachate appeared to be relatively innocuous, and certainly below single concentrations of similar organic solvents successfully contained by SB walls on previous projects. As preliminary testing commenced, however, it was soon apparent that the combination of chemicals was causing major problems to bentonite. Figure 12 shows cracking that occurred in a simple test where leachate was mixed with slurry and allowed to sit. After unsuccessfully trying different bentonites, including a "contaminant-resistant" bentonite, attapulgite was introduced as the slurry and the backfill additive. Attapulgite is a clay mineral of different structure than bentonite. On a microscopic scale, bentonite is composed

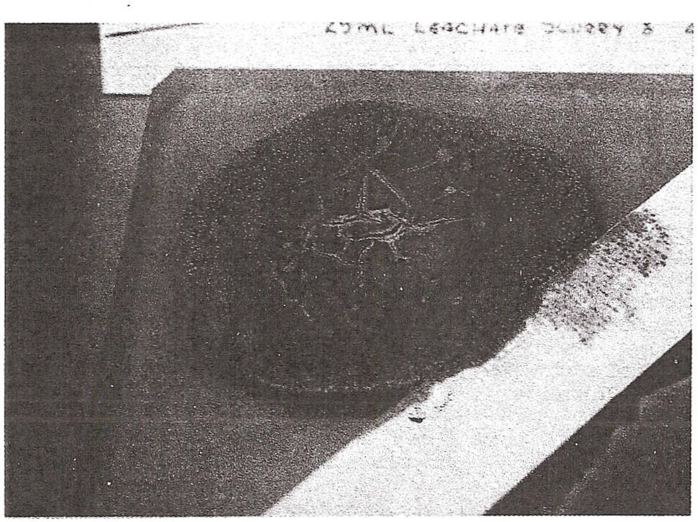

Figure 12: Cracking Test on Bentonite Slurry Showing Cracks Caused by Leachate

of flat plates that swell apart when contacted by water and which can be drawn back together into a collapsed or floculated structure under the action of various chemicals. Attapulgite, on the other hand, is composed of needle-like particles that do not rely on a swelling phenomenon to form a slurry. (Tobin and Wild, 1986). A test with attapulgite (Fig. 13) resulted in no cracking. Furthermore, slurries made of bentonite floculated and fell out of suspension when exposed to the leachate, while attapulgite slurry remained stable (Fig. 14). This had serious implications on the feasibility of excavating a slurry-filled slot at the site; if the slurry were to fall out of suspension during the trenching operation, a major collapse could result. Figure 15 shows the results of compatibility testing for some of the test samples. Obviously, the attapulgite backfill was essentially unaffected by the leachate. An unusual problem with the bentonite backfill was that, with increasing amounts of added bentonite (1.5 - 4.5%), there was an actual increase in the permeability of the blend.

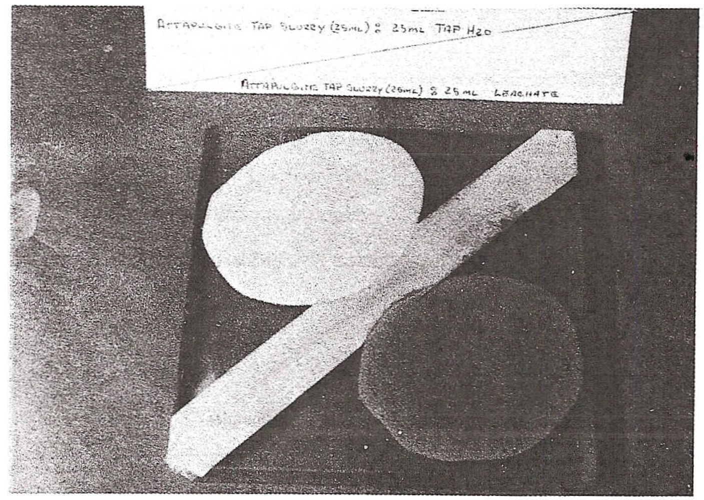

Figure 13: Cracking Test on Attapulgite - No Cracking Caused by Leachate

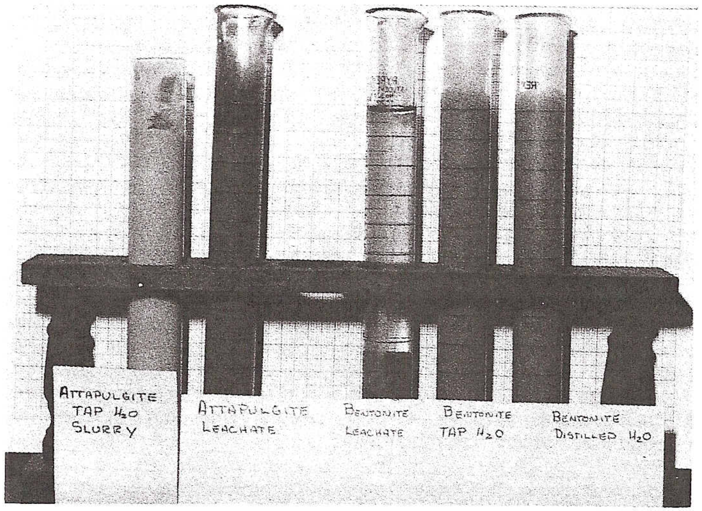

Figure 14: Effect of Leachate on Various Slurries

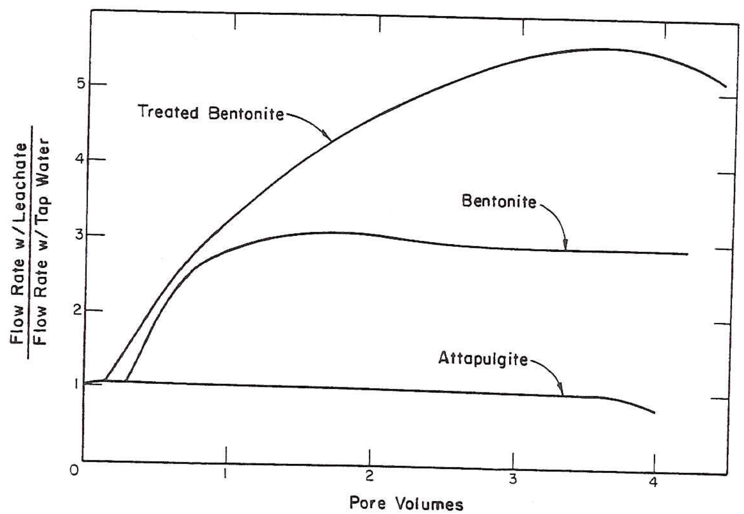

Figure 15: Results of Bentonite and Attapulgite Compatibility Tests

This project was successfully constructed using the attapulgite material in both the trench slurry and as dry clay added to the backfill blend. The use of attapulgite was obviously required in this case but is not generally recommended for any site. Attapulgite has several disadvantages compared to bentonite as a slurry cut-off wall constituent:

- The material is significantly more expensive.
- Because it is less efficient than equivalent amounts of bentonite, greater amounts of material are required in the slurry and backfill, further increasing the expense.
- It is far more difficult to mix into a slurry and to work with in the trench, requiring special construction equipment and procedures that again add to the cost.

CONCLUSION

Vertical barriers have evolved into an essential component in waste containments. While soil-bentonite slurry walls have and probably will continue to be the most widely applied technique, several other variations have been proposed and show promise. Another recent development that should extend the range of slurry cut-off wall applications is the use of alternative materials as the active components in the backfill blend.

The last fifteen years of vertical barrier construction have really seen its evolution from infancy to a well-known and often-applied technology. The next ten years should provide standardized testing techniques, more field verification testing for comparison, and more experience on an interesting array of new techniques and materials.

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MOVEMENT OF NONAQUEOUS LIQUIDS IN GROUNDWATER

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ABSTRACT: Evidence from field sites indicates that when nonaqueous liquids, such as organic solvents and gasoline, are released into the subsurface environment they tend to remain as a separate liquid phase in the form of discrete ganglia and lenses. The presence of the separate phase is often not recognized because water samples may not necessarily be saturated by the contaminants. Therefore, soil sample analysis is essential in defining the extent of the separate phase contamination. The movement of the ganglia of the separate phase can be described using two relatively simple relationships derived from the consideration of capillary phenomena: the Bond Number for gravity driven motion, and the Capillary Number for groundwater flow driven displacement. An analysis of field situations using these relationships shows that lighter than water liquids can be trapped below the water table and that groundwater pumping is unlikely to mobilize the trapped ganglia and lenses.

INTRODUCTION

In recent years increasing attention has been focused on the problem of groundwater contamination by nonaqueous liquids such as organic solvents, gasoline and other petroleum products. This contamination is typically the result of leakage from underground tanks, accidental surface spills, and improper disposal practices. While the problem appears to be most acute in industrialized areas, for example in Santa Clara Valley in California over 100 cases of spills of chemicals and gasoline have been reported since 1980, chemical fumigants used in agriculture and hundreds of thousands of underground gasoline tanks at gas stations also represent relatively widely spread sources of potential contamination.

Table 1 shows the properties of some of the most frequently detected soil and groundwater contaminants at industrial sites in the Santa Clara Valley, California (Olivieri et al., 1985; Cooper et al., 1985a), three chemical fumigants of major concern in domestic groundwater supplies from the agricultural San Joaquin Valley, California (Munnecke and Gundy, 1979; Peoples et al., 1980; Albrecht and Chenchin, 1985), and a

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