7.0 Construction Methods

Once the desired location, configuration, and dimensions of the PRB have been determined, a suitable construction technique must be selected. Conventional and innovative techniques that could be used to install a PRB are discussed in detail in this section and are summarized in Table 7-1. The information in Table 7-1 was compiled from various vendors. The technical and

Table 7-1. Summary of Various Techniques for Barrier Construction

Construction Techniques	Maximum Depth (ft)	Vendor-Quoted Cost[(a)]	Comments
Slurry Wall and Sheet Pile Installation			
Soil-bentonite slurry wall • Standard backhoe excavation • Modified backhoe excavation • Clamshell excavation	 30 80 150	 $2-10/ft^2$ $2-10/ft^2$ $6-17/ft^2$	Requires a large working area to allow for mixing of backfill. Generates some trench spoil. Relatively inexpensive when a backhoe is used.
Cement-bentonite slurry wall • Standard backhoe excavation • Modified backhoe excavation • Clamshell excavation	 30 80 200	 $4-22/ft^2$ $4-22/ft^2$ $16-55/ft^2$	Generates large quantities of trench spoil. More expensive than other slurry walls.
Composite slurry wall Geomembrane barrier	100+ 40-50	NA $38/ft^2$	Multiple-barrier wall. Permeability less than 1×10^{-7}.
Steel sheet piles Sealable-joint piles	60 60	$15-30/ft^2$ $15-30/ft^2$	No spoils produced. Groutable joints.
PRB Installation			
Caisson-based construction	50+	$50-300/ vertical ft	Relatively inexpensive.
Mandrel-based construction	40-50	$10-25/ft^2$	Relatively inexpensive and fast production rate. A 3- to 5-inch-thick zone can be installed in a single pass.
Continuous trenching	25	$5-12/ft^2$	High production rate. High mobilization cost.
Jetting	200	$40-200/ft^2$	Ability to install barrier around existing buried utilities.
Deep soil mixing	150	$80-200 /yd^3$	May not be cost-effective for PRBs. Columns are 3 to 5 ft in diameter.
Hydraulic fracturing	80-120	$2,300 per fracture	Can be installed at deep sites. Fractures are only up to 3 inches thick.
Vibrating beam	100	$8 /ft^2$	Driven beam is only 6 inches wide.

(a) Does not include mobilization cost.
NA = not available.

cost claims for each technology should be verified on a site-specific basis with direct discussions with the vendors of appropriate technologies. Factors that limit and ultimately determine the type of construction method used include:

- Installation depth
- Required reactive cell permeability
- Site topography
- Site access and work space
- Geotechnical constraints
- Soil characteristics (of backfill)
- Disposal requirements of contaminated trench spoils
- Costs.

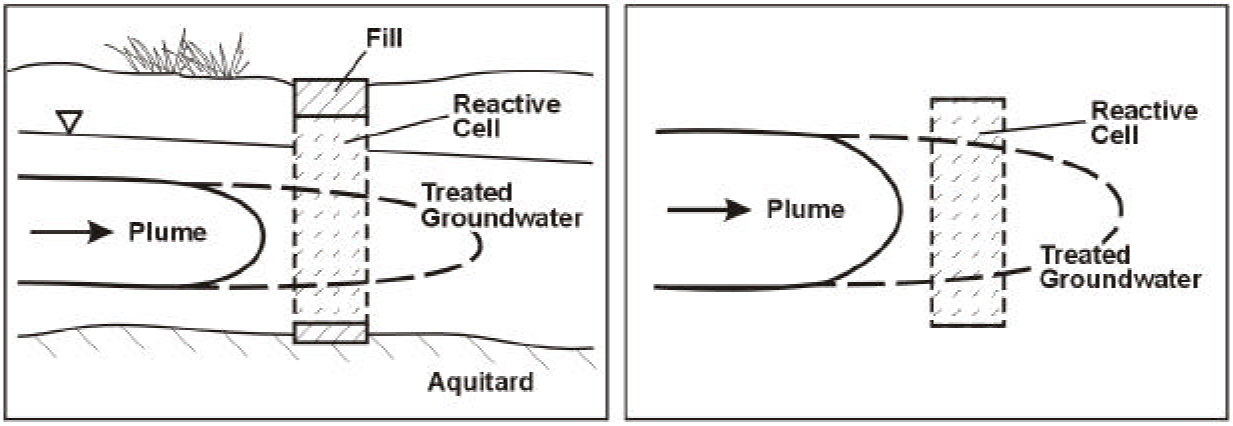
The reactive cell is the portion of the aquifer that is modified to contain the reactive medium through which a contaminated plume will flow. Figure 7-1 shows various arrangements of a reactive cell that may be used depending on site-specific hydrogeologic conditions. In a continuous reactive barrier configuration, the reactive cell runs along the entire width of the barrier. In a funnel-and-gate system, only a portion of the total barrier width is taken up by the reactive cell. For some initial PRB applications, the reactive medium was bounded on both upgradient and downgradient sides by thinner sections of pea gravel in an effort to improve flow and homogenize influent contaminant concentrations. However, in most subsequent applications, the use of pea gravel zones has been eliminated as their benefit appears to be marginal.

7.1 Excavation Methods for Reactive Cell Construction

The reactive cell generally is excavated and completed above the water table to allow for water-level fluctuations and medium minimization, although this process may vary from site to site. Generally, the reactive cell is keyed at the bottom end into the aquitard, unless the PRB has a hanging-barrier configuration. In a funnel-and-gate system, the funnel walls may also be keyed about 5 ft into the aquitard. In the excavation method of installing the reactive medium, it is relatively easier to ensure and verify the desired continuity and thickness of the reactive cell. If the innovative injection techniques discussed in Section 7.2 are used, greater depths are possible; however, ensuring and verifying the desired continuity and thickness of the reactive cell may be relatively more difficult.

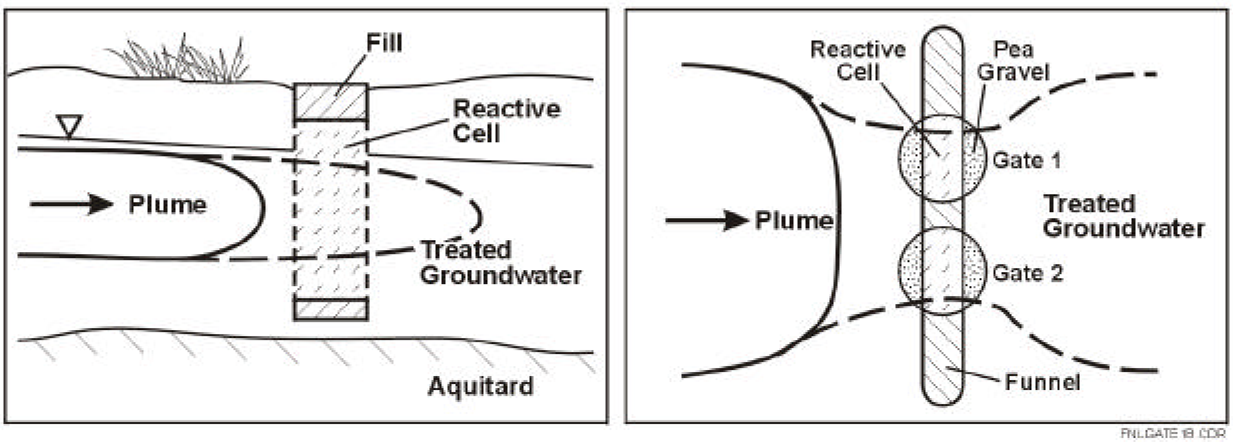
7.1.1 Excavation with a Backhoe

Depending on the design of the PRB, installation of the reactive cell may require the excavation of a trench that will house the reactive medium. Backhoes are the most common types of equipment used for conventional trench excavation. Standard backhoe excavation for shallow trenches down to 30 ft deep is the cheapest and fastest method available. The digging apparatus is staged on a crawler-mounted vehicle and consists of a boom, a dipper stick with a mounted bucket, and either cables or hydraulic cylinders to control motion. Bucket widths generally range in sizes up to 5.6 ft. Because the vertical reach of a backhoe is governed by the length of the dipper stick, backhoes can be modified with extended dipper sticks and are capable of reaching depths up to 80 ft (Day, 1996). Even greater depths are possible if benches can be excavated in which the backhoe can be located, thereby enabling the whole backhoe to sit below



(a) PRB (elevation view)

(b) Continuous reactive barrier configuration (plan view)



(c) Hanging barrier configuration for shallow plumes (elevation view)

(d) Funnel-and-gate system with two gates (plan view)

Figure 7-1. Various PRB Configurations

grade; however, this method can be time-consuming and can require a large area to be excavated to reach the required depth.

To ensure the stability of the trench wall during reactive cell construction, several options may be used. A first option is the cofferdam approach, in which temporary steel sheet piles are driven into the ground along the boundaries of the intended reactive cell prior to excavation and then are reinforced with bracing as the trench is excavated. If required, sheet piles also can be used to temporarily separate reactive medium and pea gravel sections within the trench (Figure 7-2). Dewatering of the trench may be required if sheet piling cannot prevent groundwater seepage

Figure 7-2. Placement of Reactive Iron Media (Suspended Bag) and Pea Gravel (Front-End Loader) into Divided Sections of Trench for a PRB (Courtesy of PRC, 1996)

into the reactive cell. Interlocking or sealable-joint sheet piles (see Section 7.3.1) are better at preventing water seepage from the sides, but water may still seep in from the bottom of the excavation. The temporary sheet piles are removed after the excavation is backfilled with the reactive medium. Generally, the sheet piles along the side of the trench (parallel to groundwater flow) are left in place to prevent short-circuiting of flow. The advantage of using this trench stabilization method is that the walls of the trench are retained even as the trench is being dug. The disadvantage is that some portions of the intended trench, such as the corners, may be difficult to access with a backhoe when sheet piles are present. With any excavation technique, if entry of personnel into the trench is required (for example, to clear out the corners of the trench), special safety measures, such as those for confined space entry, may be applicable. The cofferdam approach has been used at a number of PRB sites, including a DOE site in Kansas City, MO; Watervliet Arsenal, NY; Intersil, CA; two industrial facilities in the States of New York and Kansas; and the Denver Federal Center and former Lowry AFB in Colorado.

Another method of trench stabilization involves the use of a trench box to create void space for the installation of either an impermeable or permeable zone (Breaux, 1996). The trench box can be pre-fabricated aboveground using interlocking sheet piles and inserted into the open trench. After backfilling the reactive cell, the sheet piles are removed. The advantage of this method is that clearing the corners of the intended reactive cell is not a problem. The disadvantages are that the trench must be completely excavated before the box can be installed and temporary sheet piles must be used to maintain trench stability. The trench box approach has been used at some PRB sites, including Warren AFB, WY; Watervliet Arsenal, NY; Canadian Forces Base, Canada; former NAS Moffett Field, CA; an industrial facility in the State of Massachusetts; and a National Aeronautics and Space Administration (NASA) facility in the State of Louisiana.

7.1.2 Excavation with a Clamshell

A clamshell bucket can be used for excavation to around 200 ft bgs. A cable-suspended mechanical clamshell is a crane-operated grabbing tool that depends on gravity for accurate excavation and closure of the grab (Figure 7-3). Therefore, a heavier tool is beneficial.

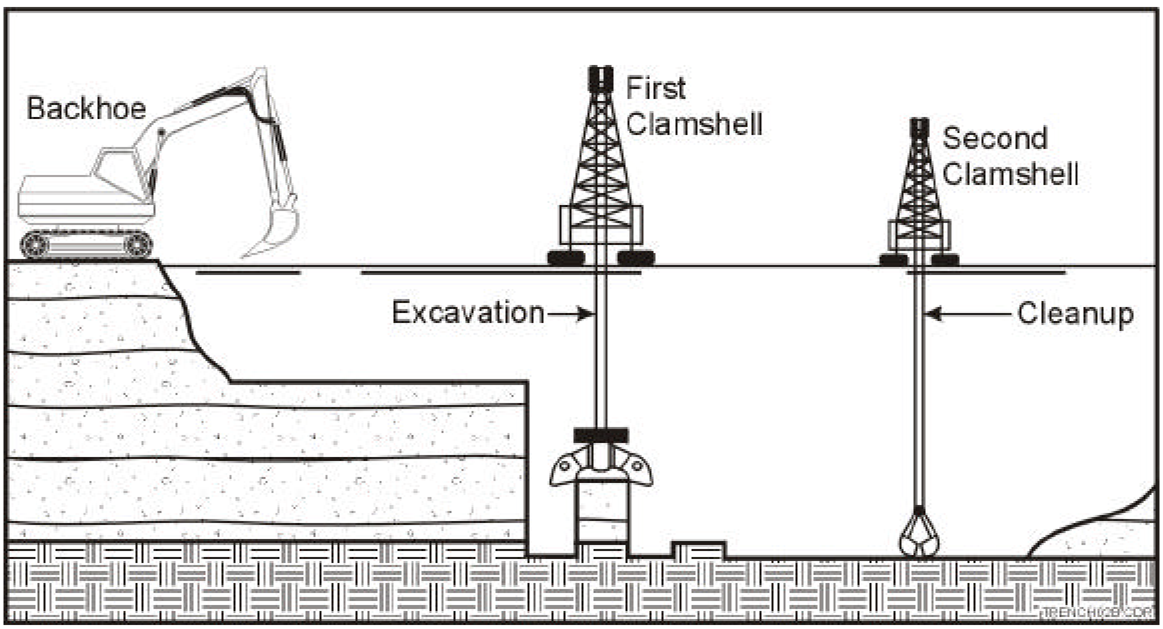


Figure 7-3. Trench Excavation Using a Clamshell and Backhoe

Hydraulic clamshells can be equipped with a kelly bar to help guide and control the vertical line in addition to providing weight. The verticality of the excavation is controlled by the repeated cyclic lifting and lowering of the bucket under gravity. Mechanical clamshells are preferred over their hydraulic counterparts because they are more flexible in soils with boulders, can reach greater depths, and involve fewer maintenance costs. Clamshell excavation is popular because it is efficient for bulk excavations of almost any type of material except highly consolidated sediment and solid rock. It also can be controlled and operated in small and very confined areas as long as the boom can reach over the trench. Clamshell excavation, however, has a relatively low production rate compared to a backhoe. Also, worker safety can become an issue during clamshell excavation. At previous PRB installations, construction sometimes involved sending a person into the trench to clear soil out of regions in the perimeter sheet piles that were not accessible to the clamshell. Clamshell excavation has been used to construct the PRB at the Canadian Forces Base at Borden, Canada.

7.1.3 Excavation with a Caisson

Caissons are load-bearing enclosures that are used to protect an excavation (Figure 7-4), and are a relatively inexpensive way of installing reactive cells at depths inaccessible with a standard backhoe. Caissons may have any shape in cross section and are built from common structural materials. The caissons can be pre-fabricated and transported to the site, or they can be built in sections with each section welded on top of the next as the caisson is driven in at the site. For PRB sites at Somersworth Landfill and Dover AFB, where this technique has been used, the barriers were installed to depths of 50 and 45 ft, respectively, and the caissons were 8-ft-diameter circular cylinders open at both ends. Caissons as large as 15 ft in diameter have been used in bridge construction; however, smaller diameter caissons are more common. In spite of the steel edges at the bottom of the caisson, it does not sink through soil under its own weight because friction along the sides of the caisson is high and can range from 300 lb/ft^2 to more than 1,000 lb/ft^2. At Dover AFB, a vibratory hammer mounted on a crane was used to drive the caisson in. The interior of the caisson was excavated with a large auger to make room for the reactive medium.

Pulling the caisson out may prove to be more difficult than driving it in, especially with the pressure from the reactive iron medium inside. At the Somersworth and Dover AFB sites, a vibratory hammer was used to pull the caisson out at both sites. At Somersworth, the caisson got stuck after it was withdrawn a few feet. Cobbles and/or highly consolidated sediments were thought to be the cause of the impedance. Extraordinary measures had to be taken to dislodge the caisson and pull it out the rest of the way. At Dover AFB, both caissons were withdrawn easily in spite of the presence of an intermediate clay layer. However, the 0.5-inch-thick structural steel material of the caisson, which held up fairly well when the caisson was driven in, started tearing near the vibratory hammer grip when it was being pulled. When the caisson continued to tear despite changing the position of the grip a few times, a 1-inch-thick steel collar was built around the top edge of the caisson. No further problems were encountered. At Dover AFB, the iron medium subsided by about 2 ft when the caisson was pulled out. Part of this subsidence was due to the reactive medium entering the thin annular space left behind by the caisson walls. But some subsidence was probably due to the granular iron itself consolidating under the vibrations from the caisson (Battelle, 2000).

It is difficult to ensure a good seal between the caisson gates and the funnel wall in a funnel-and-gate system because loose iron consolidates into the annular space left behind by the caisson walls. At Dover AFB, interlocks were welded on the two side dividers (Figure 7-5). The first sheet pile of the funnel wall on either side of the gate was guided into this interlock and the joint was grouted to obtain a good seal. Also, during construction of a caisson, some soil compaction can occur along the walls of the caisson that can lower the permeability around the intended reactive cell. If the formation contains a significant amount of cobbles, the caisson may be deflected to an off-vertical position as it is pushed down, or it may even meet refusal. At one previous installation, highly consolidated sediments and cobbles created difficulties in driving in and pulling out the caisson (ETI, 1996). It also may be difficult to drive a caisson to depths greater than about 45 ft.

(a)

(b)

Figure 7-4. (a) Driving and (b) Excavation of a Caisson for Reactive Media Installation

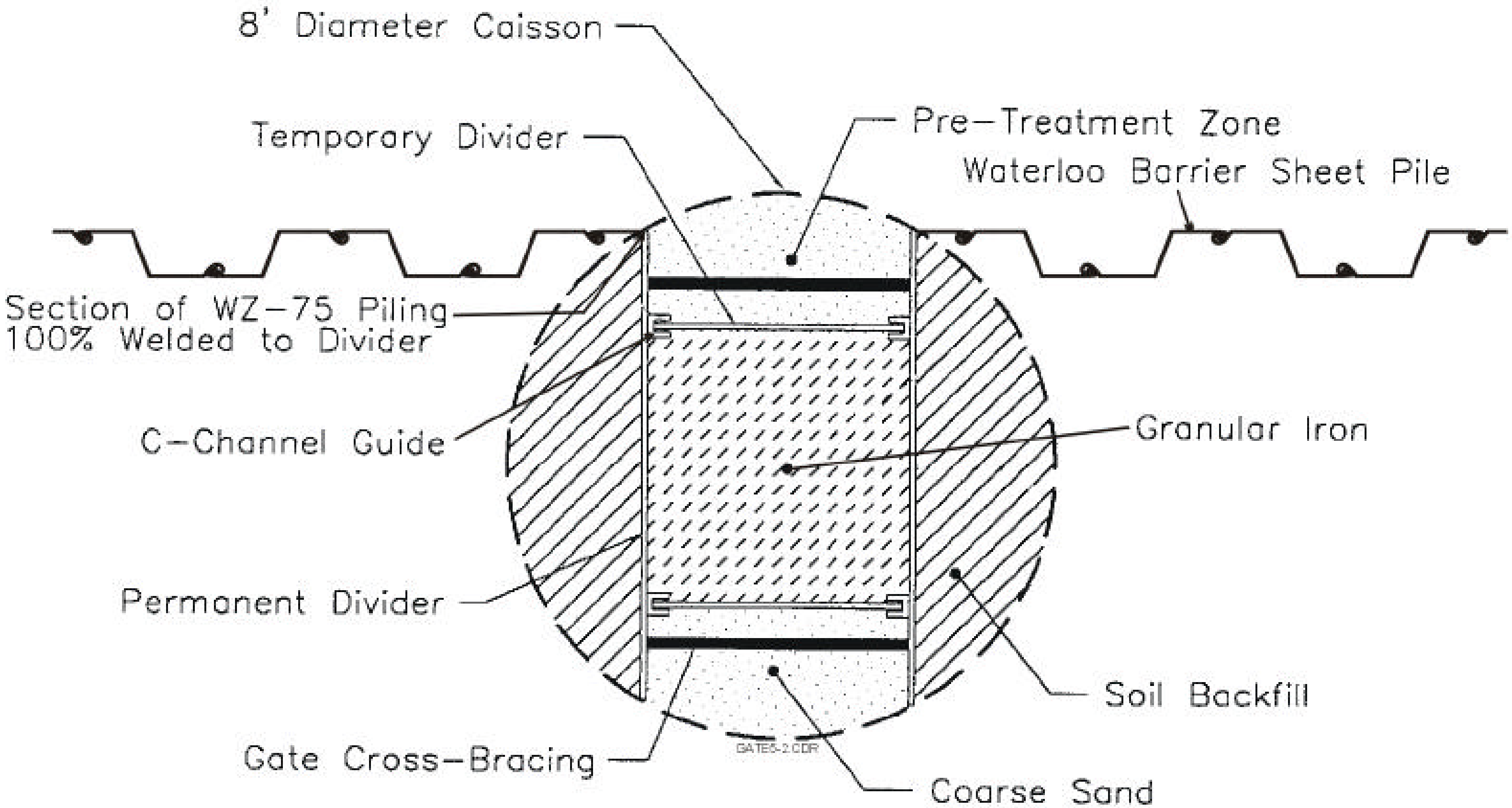


Figure 7-5. Plan View of a Caisson Gate

However, in the absence of such geotechnical difficulties, caissons have the potential to provide a relatively inexpensive way to install a funnel-and-gate system or continuous reactive barrier. One significant advantage of using caissons is that they require no internal bracing. Therefore, the caisson can be installed from the ground surface and completed without requiring entry of personnel into the excavation. It also can be installed without significant dewatering in the excavation. Finally, in a continuous reactive barrier configuration, multiple caisson cells could overlap to form a continuous length of reactive medium.

7.1.4 Excavation with a Continuous Trencher

Although not as common as backhoes or clamshells because of depth constrictions, using a continuous trencher is an option for installing barriers 35 to 40 ft deep. It is capable of simultaneously excavating a narrow, 12- to 24-inch-wide trench and immediately refilling it with either a reactive medium and/or a continuous sheet of impermeable, high-density polyethylene (HDPE) liner. The trencher operates by cutting through soil using a chain-saw type apparatus attached to the boom of a crawler-mounted vehicle (Figure 7-6). The boom is equipped with a trench box, which stabilizes the trench walls as a reactive medium is fed from an attached,

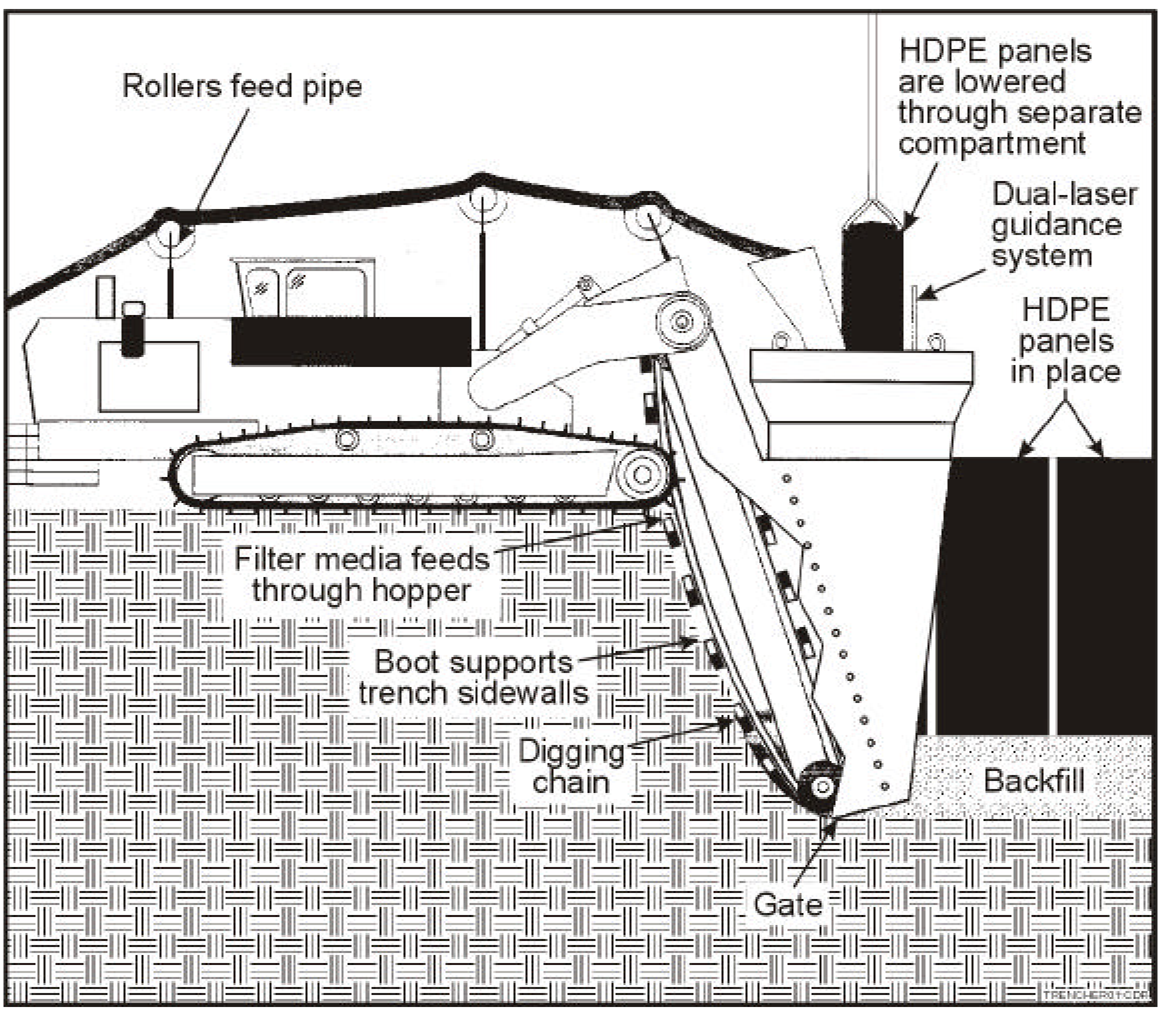


Figure 7-6. Continuous Trencher

overhead hopper into the trailing end of the excavated trench. The hopper contains two compartments, one of which can install media up to gravel-size. The other compartment is capable of simultaneously unrolling a continuous sheet of HDPE liner if desired.

The trencher can excavate in a water-filled trench without having to dewater or install sheet piles to temporarily stabilize the trench walls. Because the boom is positioned almost vertically during excavation, a trench slope is not created and greatly minimizes the amount of generated trench spoils. One other advantage is a fast production rate. At the Elizabeth City, NC site, a reactive cell 150 ft long, 2 ft wide, and 26 ft deep was installed in one day (Schmithorst, 1996). Also, a trencher is ideal for working at sites with constrained working space, and it minimizes soil disturbance to allow for work in sensitive areas. Drawbacks include a shallow depth capability and problems with excavating wet, very unconsolidated materials, which may cause difficulties in bringing trench spoils to the surface. Obstructions such as large cobbles and boulders also can disrupt the sawing process. Quoted costs for this technique are between \$5 and \$12/ft^2 for construction, not including mobilization or reactive medium costs.

7.1.5 Use of a Biodegradable Slurry for Stabilizing a Trench

One variation to the conventional excavation techniques that appears promising for trench-type reactive cell construction is the use of a biodegradable slurry (Owaidat, 1996; Day et al., 1999). This technique was used to install a PRB at ORNL, TN in 1997. A biodegradable slurry, generally made of powdered guar bean, is introduced into the trench as it is excavated (Figure 7-7). The pressure of the slurry helps to retain the walls of the excavation. Granular iron is introduced into the trench through a tremie tube or by displacement over a gradually sloping side wall. The guar gum later biodegrades, leaving the iron behind. One advantage of this method is that no personnel are required to enter the excavation. Also, the continuity or settling of the iron in the trench is expected to be more uniform than in a conventional open trench installation.

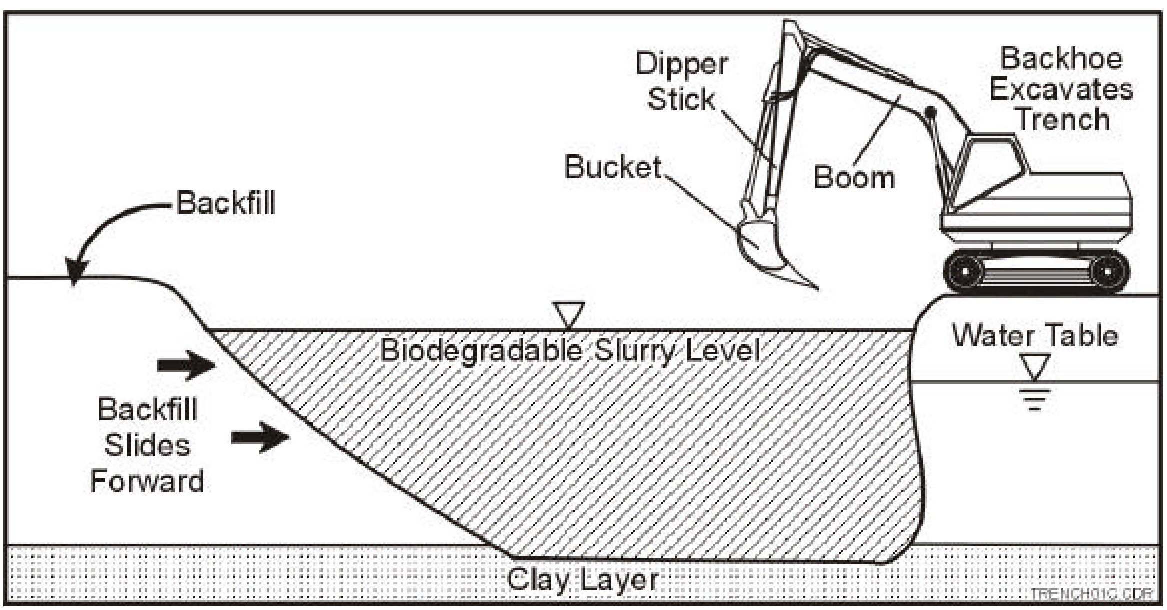


Figure 7-7. Use of a Biodegradable Slurry for Reactive Media Installation

7.1.6 Excavation with a Hollow-Stem Auger

In this method, a hollow-stem auger or a row of hollow-stem augers is used to drill holes up to 30 inches in diameter into the ground. When the desired PRB depth is reached, reactive medium is introduced through the stem as the auger is withdrawn. Alternately, the reactive medium can be mixed with a biodegradable slurry and pumped through the hollow stem. By drilling a series of overlapping holes, a continuous PRB can be installed. This method has been used to construct a 74-ft-wide PRB at a dry-cleaning site in Germany (ETI, 1999).

7.2 Direct Installation of Reactive Media Using Innovative Techniques

The construction methods discussed in Section 7.1 all involve the excavation of a trench to house the reactive medium. The economics of excavation methods are strongly correlated with the depth of the PRB installation: the deeper the excavation, the more costly the effort becomes. Innovative methods that introduce the reactive medium directly into the ground without first excavating a trench are being tested at some sites.

7.2.1 Hydraulic Fracturing

One promising technology for construction of deeper barriers is hydraulic fracturing, a technique that is currently being tested at a site in Cape Cod, MA. First, a series of wells is installed along the length of the proposed barrier. A controlled vertical fracture is initiated through the well with a special downhole tool inserted in each well (Hocking et al., 1998). The fracture can be oriented along the required azimuth and depth. The tool is withdrawn and a packer is installed in each well. An iron-gel mixture then is injected through the series of wells to form a reactive barrier. The propagated geometry of the fractures is monitored in real time to ensure that coalescence or overlap of the fractures takes place as desired. Monitoring is done by introducing electrical energy in the fractures and monitoring it through downhole resistivity sensors.

The gel used is a water-based cross-linked gel. Hydroxypropylguar, a polymer used in the food processing industry as a thickener, typically is used for this application. The viscosity of the cross-linked gel ensures that the granular iron remains suspended during mixing, handling, and subsequent pumping. When the gel degrades, a 3- to 4-inch thick reactive barrier is left behind in sandy soils. Some variability in barrier thickness can be expected if the advancing fracture encounters heterogeneities such as cobbles or consolidated sediments. To some extent this variability can be addressed in the design by injecting a slurry that provides a barrier thickness greater than the minimum required for treatment. Until more field experience is obtained with this technique, at least two parallel fracture reactive barriers may be considered (Hubble et al., 1997).

This technique also may be used for installation of an impermeable barrier (funnel) by injecting a soil-bentonite slurry instead of an iron-gel mixture.

7.2.2 Vibrating Beam

In this technique, an H-beam or mandrel with a sacrificial shoe at the bottom is used. The beam is driven into the ground with a vibratory hammer to create a void space. As the beam is raised, grout is injected into the void space through special nozzles at the bottom of the beam. An impermeable barrier is thus installed by driving at overlapping intervals.

This technique was tested at Cape Canaveral Air Station, FL to investigate its use for installing a PRB (Marchand et al., 1998). In the first test, dry iron was installed in the void space through a hollow mandrel driven with a vibratory hammer. The mandrel was used to create a 45-ft-deep, 4-inch-thick, 32-inch-long void space with each entry. A total of 32 overlapping panels were installed, and no spoils were generated. In the second test, a 36-inch I-beam with a high/low pressure nozzle was driven into the ground. Water was sprayed through the high pressure side of the nozzle to help create the void space. An iron-guar gum slurry was introduced into the void space through the low-pressure side of the nozzle as the beam was brought up. During the installation of 24 panels, approximately 24 tons of soil and 4,000 gallons of liquid were generated.

The vibrating beam technique also was used at a private site in Tifton, GA to install a 400-ft-wide funnel-and-gate sytem.

7.2.3 Jetting

Jet grouting has been used for infrastructure development in Japan and Europe since the 1970s. The technique is being increasingly used in the United States to reduce the permeability of soils for infrastructure development and to place impermeable barriers for remediation. More recently, there has been some interest in substituting the grout with an iron-guar gum slurry to install a PRB at deeper sites. This technique was field tested in a clean site at Dover AFB, DE (Landis, 1998) and in a contaminated site at Travis AFB, CA.

Jet grouting involves the injection of grout at high pressures into the ground. The high velocity jet erodes the soil and replaces some or all of it with grout. Jet grouting systems are classified into three types depending on the delivery mechanism. In a single-rod system, the fluid injected is grout. In a double-rod system, grout and compressed air are injected. The combined effect of the high-pressure grout and air results in a greater percentage of soil being removed and replaced with grout, and the remaining soil-grout mixture is called soilcrete. In a triple-rod system, grout, air, and water are jetted. This triple combination enables an even higher percentage of soil to be removed, and the system can be used for almost complete replacement of the soil with grout. The triple-rod system offers better control over injection rates and results in better quality of soilcrete. Although the single- and double-rod systems can be used in loose sandy soils, the triple-rod system can be used in most types of soil.

If the injection rod is rotated as it is brought up, a column of soilcrete can be installed. A continuous impermeable barrier can be created by installing a row, or multiple rows, of overlapping columns. Alternately, a thin panel of soilcrete can be installed by not rotating the rod. A continuous barrier, sometimes referred to as a thin diaphragm wall, is formed by installing a row of overlapping panels.

It is the triple rod system that is projected as being suitable for installing PRBs. Grout can be used to install impermeable sections or funnel. A slurry made of granular iron and guar gum is used to install the reactive section.

7.2.4 Injection with a Mandrel

In this method, a hollow steel shaft, or mandrel, is used to create a vertical void space in the ground for the purpose of emplacing reactive media. A sacrificial drive shoe is placed over the bottom end of the mandrel prior to being hammered down through the subsurface using a vibratory hammer. Once the void space is created, it then can be filled with a reactive medium in one of two ways. One method uses a tremie tube to simply pour the media loosely down the hole. After a desired depth is reached, the mandrel is extracted, leaving the drive shoe and media. Another way to complete the cell is to install wick drains, geomembranes, or geofabrics in conjunction with reactive media. A 4-inch-thick test barrier with granular iron was installed using a mandrel at Cape Canaveral Air Station, FL (Marchand et al., 1998). The objective of this test was to investigate the injectability of the iron. The ability of the barrier to achieve a reactive cell thickness and continuity that would achieve cleanup targets was not investigated.

Some disadvantages to this technique include the limited size of the reactive cell, which is controlled by the size of the mandrel (typically 2 inches by 5 inches). Therefore, a series of mandrel-installed voids would constitute a reactive cell rather than a single insertion. Because the mandrel is hammered down using a vibratory hammer, it is possible that subsurface obstructions during installation could cause the mandrel to deviate from an intended vertical path. Also, compaction can occur around the individual voids as the mandrel is driven down, thereby lowering the permeability of the soil.

Mandrel-based construction does have some advantages. It is inexpensive ($7/ft^2 including labor and equipment for 45 ft of depth), and no spoils are generated, which minimizes hazardous waste exposure and disposal. Also, reactive media of up to 1-inch particle diameter can potentially be installed.

7.2.5 Deep Soil Mixing

In deep soil mixing, two or three special augers equipped with mixing paddles are lined up in series. These augers penetrate the ground and mix up soil as they rotate (Figure 7-8), and a bentonite slurry is injected simultaneously through a hollow drill stem as the augers retreat back to the surface. An impermeable wall is formed by successive overlapping penetrations made with the deep soil mixer, resulting in a series of hardened soilcrete columns. Typically, 40 to 60% of each soilcrete column is composed of grout.

Depths of up to 120 ft can be obtained using this method, and permeabilities approaching 1×10^{-7} centimeters/second are attainable. This method generally is employed in situations where excavation of contaminated soils is not feasible because only a minimal amount of spoils are brought to the surface. It is best used in soft soils, yet special attention should be given so that injection does not cause hydrofracturing of the soil, which can easily occur in soft soils. Generally, deep soil mixing is less expensive than jet grouting and has a higher production rate. The same technique that has been used to create an impermeable wall has been proposed for use in reactive medium installation.

Although it has never been done commercially, it may be possible to use deep soil mixing to inject a reactive medium for the purpose of creating a reactive cell. However, because deep soil mixing does not completely replace soil with the reactive medium but rather mixes them together, only about 40 to 60% of the reactive medium is present in a completed column. Increased permeability occurs as the soil mixing process fluffs up the soil matrix, yet with time, compaction due to overburdening reduces it (Burke, 1996). The injected reactant could be

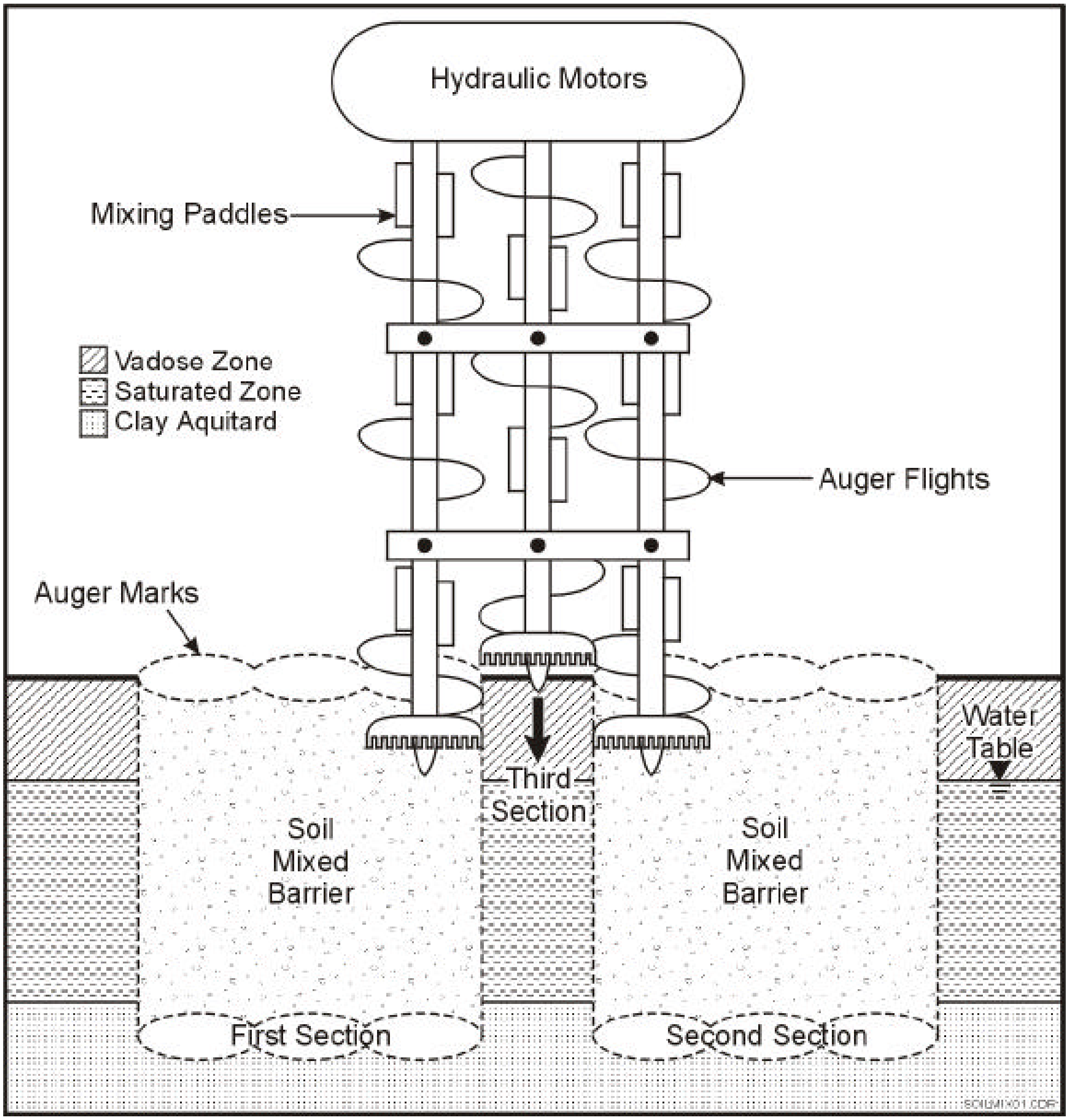


Figure 7-8. Deep Soil Mixing

equivalent to fine sand-sized particles, but would have to be suspended in a revert (biodegradable slurry) to be injected. Because the slurry is injected using piston-driven cylinder pumps, several factors should be considered when deciding on the reactant particle size. The abrasiveness of the reactant can cause considerable wear and tear on the pumps, which can increase O&M costs significantly. Also, the reactant needs to be in suspension if it is to be injected in an efficient manner.

7.3 Construction Methods for the Funnel

The design of some reactive cells may include flanking impermeable walls to aid in directing or funneling groundwater flow toward the permeable gate. The two most popular types of subsurface barriers are the steel sheet pile cutoff wall and the slurry trench cutoff wall. These subsurface cutoffs are either keyed in a confining layer to prevent downward groundwater migration or, less commonly, installed as a hanging wall to contain floating contaminants.

7.3.1 Sheet Piles

Barriers made of a series of steel sheet piles driven into the ground have been used in the construction industry for retaining soil (Figure 7-9). To adapt this technique for remediation applications, where both soil and water movement must be restricted, the University of Waterloo, Ontario has patented a technique for sealing adjoining sheet piles by pouring grout into the joints. Figure 7-10 shows cross sections of a sealable-joint sheet pile barrier. Sheet pile barrier integrity can be maintained to depths of about 50 ft. Beyond this depth, the sheet piles can be driven in, but it is unclear how well the integrity of the sealed joints is maintained. Sheet piles that are about 40 to 45 ft long can be easily transported to the site. Beyond this length, sheet piles must be transported in sections to the site, and then welded together during installation.

Figure 7-9. Sheet Piles Installed Using a Vibrating Hammer

Sheet pile barriers can be installed relatively quickly at most sites. They are especially useful when the barrier must be installed under horizontal space limitations. Because sheet piles are relatively thin and can be driven straight down, this type of barrier was used at the Dover AFB site for the funnel sections because the funnel walls lay in close proximity to subsurface utility lines and a nearby road that needed to stay open during construction. In fact, one of the utility lines was cut and rejoined over the sheet pile wall after the barrier was completed. A 100-ft

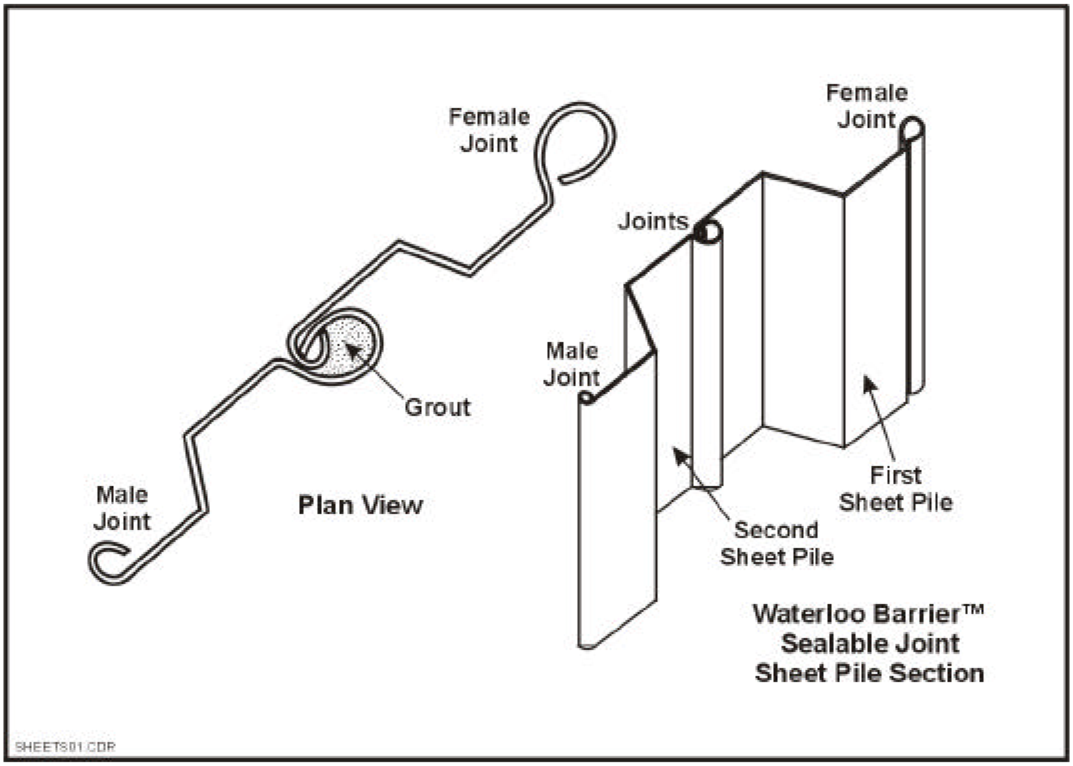


Figure 7-10. Cross Section of Sealable-Joint Sheet Piles (from Smith et al., 1995)

crane with a vibratory hammer was used to drive the sheet piles 45 ft into the ground with a 2-ft key in the aquitard. Another reason for choosing a sheet pile barrier instead of slurry wall at the Dover AFB site was because the sheet pile barrier generates much less spoils. Sheet piles also are useful as dividers when the reactive cell or gate has to be divided into sections to house different media. Sheet piles were used at the former NAS Moffett Field site to form the funnel for the barrier. For the former NAS Moffett Field PRB, sheet piles supported by cross bracing also were used to keep the trench (gate) open after excavation so that the iron medium could subsequently be emplaced.

Some uncertainties remain regarding the integrity of the joint as a sheet pile is being driven. A considerable amount of friction is produced during sheet pile installation and joint flanges could weaken or be damaged, especially if greater depths are desired (Breaux, 1996). Also, the irregular shape of the individual sheet piles and the curved nature of the interlock could create some difficulties during installation. The spaces between corrugations in the sheet piles are not accessible with clamshell excavators, and this has resulted in construction personnel entering the trench to clear away these areas (Myller, 1996). The loose interlocks of connecting piles (prior to grouting) have made it difficult to drive piles in vertically without them pinching together.

As with conventional steel sheet piles, the sealable-joint sheet piles are limited to depths of 60 ft with confidence of maintaining sheet integrity and performance, but the sheets can be installed deeper. Rocky soils and consolidated/compacted sediments can damage sheet piles during installation and limit the types of geologic media through which the sheets can be safely driven.

Using sheet piles may be difficult in a funnel-and-gate system with caisson gates, although the difficulty of obtaining a proper seal between the funnel and reactive cell can be overcome through engineering modifications.

7.3.2 Slurry Walls

Slurry walls are the most common subsurface barrier used for diverting contaminated groundwater. Although slurry walls have been used in a variety of configurations, they are especially suited for installation as a funnel-and-gate system with caisson gates because of the ease with which the seal between the slurry wall and reactive cell can be achieved. They are constructed by first excavating a trench under a head of liquid slurry using either a backhoe or a clamshell, as described in Section 7.1. The slurry, which is usually a mixture of bentonite and water, helps maintain the integrity of the trench by forming a filter cake over the face of the wall. As a trench is excavated, it is quickly refilled with a mixture of cement-bentonite or a selected soil-bentonite backfill.

Careful planning is critical in the design of a slurry wall. Site-specific conditions will dictate which type of slurry wall is appropriate and which is most effective. Permeability, deformability, and performance are important factors that will determine the feasibility and performance life of a slurry cutoff wall. The more common slurry walls constructed are the soil-bentonite slurry wall and the cement-bentonite slurry wall. Another, but less common, type is the plastic concrete slurry wall. These and the composite barrier slurry wall are described in the following paragraphs:

- **Soil-Bentonite Slurry Wall.** Slurry walls comprised of a soil-bentonite mixture are by far the most commonly used cutoff walls for environmental applications. They are the least expensive to install, have very low permeabilities, and are chemically compatible for withstanding various dissolved-phase contaminants. The construction of the wall is fairly straightforward (Figure 7-11). The bentonite slurry is introduced into the trench as soon as excavation begins. Excavated backfill can be mixed with water and bentonite. Once the trench reaches the desired depth and a sufficient length has been excavated, mixed backfill is pushed back into the trench. It is important to ensure that the backfill is uniformly mixed and liquid enough to flow down the trench slope. The backfill should not flow past the trench slope where it could interfere with the ongoing excavation. However, if it does not flow enough, it can start to fold over and create pockets or void spaces of high permeability. It is necessary to have ample work space for adequate mixing of excavated backfill and the collection of unused trench spoils.

- **Cement-Bentonite Slurry Wall.** At field sites that have limited work space for mixing the excavated backfill, one option is a cement-bentonite slurry wall. Construction of the wall involves excavation of a trench under a head of slurry composed of water, bentonite, and cement. Instead of backfilling the trench with mixed soil, as in the case of a soil-bentonite wall, the slurry is left to harden and form a wall with the consistency of a stiff clay. The use of cement-bentonite slurry walls in environmental applications is limited for various reasons. First, these walls are more expensive to install than other slurry walls because a large amount of cement is needed to fill the trench. Also, because the excavated soil is not used as backfill, the wall will

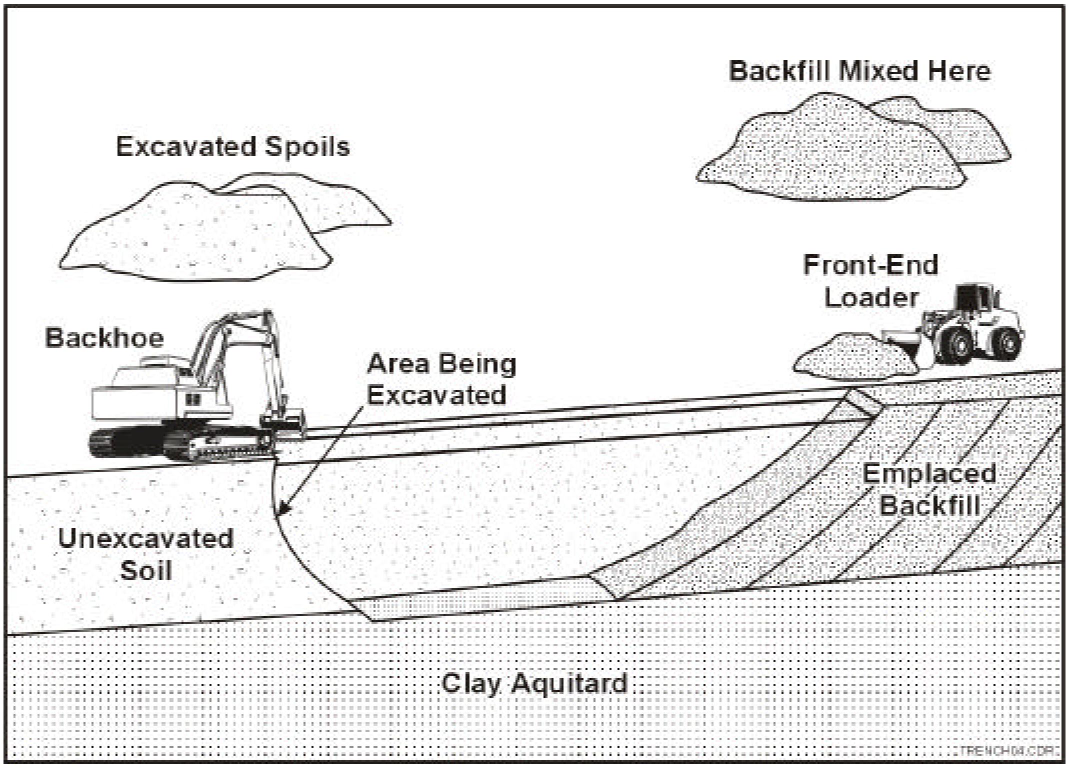


Figure 7-11. Cross Section of a Soil-Bentonite Slurry Trench, Showing Excavation and Backfilling Operations

need to be disposed of at additional cost. Moreover, because the cement-bentonite slurry wall does not contain many solids, the wall is composed mostly of water and therefore has a higher permeability and is more prone to permeation by contaminants. Advantages of the cement-bentonite slurry wall include greater strength and the ability to be installed in areas with extreme topography.

- **Plastic Concrete Slurry Wall.** The plastic concrete slurry wall is composed of a mixture of water, bentonite, cement, and aggregate that hardens to form a wall which has significantly greater sheer strength yet remains flexible. The plastic concrete slurry wall is constructed in paneled sections that are individually excavated under a bentonite slurry. Once a panel is excavated, the plastic concrete is poured with a tremie pipe into the panel to replace the bentonite slurry and is left to harden. The plastic concrete slurry wall is used in applications where strength and deformability are desired. It has a relatively low permeability and, based on limited data, may be more resistant to permeation by contaminants.

- **Composite Barrier Slurry Wall.** This multiple-layer barrier offers three walls of defense, each with increasing chemical resistance and lower permeability. It is composed of an outer 1/8-inch-thick bentonite filter cake, a 1- to 2-ft-thick soil-bentonite, cement-bentonite, or plastic-concrete middle layer, and an inner 100-mil HDPE geomembrane. The HDPE has a permeability of 1×10^{-12} cm/sec. Installation of the composite barrier starts with excavation of a trench under a bentonite and/or cement slurry. Because the slurry maintains trench wall stabilization, excavations greater than 100 ft are possible; however, the difficulty of emplacing the HDPE liner to those depths and the high cost of deep construction has resulted in restricting the use of HDPE to 50 ft depths (Cavalli, 1992). The geomembrane envelope then is installed vertically in sections into the slurry trench by either mounting it onto a detachable and removable frame, pulling it down using weights affixed to the membrane bottom, or "driving" it down using a pile driver. Once the HDPE is in place, the trench can be backfilled on either side of the membrane. The inside of the geomembrane then can be filled with a drainage system in which sampling points can be installed to monitor the performance of the system. Advantages of the composite barrier include a very low permeability, high resistance to degradation, option to install a monitoring system within the membrane, and ability to isolate and repair sections of the wall without removing the entire membrane envelope.

7.3.3 Innovative Construction Methods for PRBs

In addition to the construction techniques that have been used at PRB sites in the past, several techniques have been used in other geotechnical applications and may merit serious consideration for PRBs. Types of innovative construction techniques discussed include jetting, installed hydraulic fracturing, and deep soil mixing (these techniques have been described in Section 7.2 for direct installation of reactive medium in the ground). Because excavation equipment is not involved, these innovative techniques have considerable potential to minimize health and safety issues. However, because these techniques involve specialized equipment, they can be more expensive to operate and maintain than conventional techniques.

7.4 Other Innovative PRB Configurations and Construction Approaches

At some sites, unique PRBs have been designed that are significantly different from typical continuous reactive barrier (reactive cell only) or funnel-and-gate configurations. Some of these innovative PRB configurations are discussed in this section.

At the Rocky Flats Environmental Technology site in Golden, CO owned by DOE, a unique PRB design was used that is akin to a seep collection and treatment system (Rocky Mountain Remediation Services, 1999). The barrier consists of a 230-ft-long, single-membrane HDPE impermeable funnel, an upgradient collection trench (porous media and sump), and two treatment cells downgradient of the HDPE barrier. The 230-ft-long impermeable section is keyed into bedrock that occurs at depths ranging from 10 to 16 ft. Groundwater that collects in the sump is piped to the treatment cells. Both treatment cells contain iron as the reactive medium. Treated water is discharged back to the water table through a French drain on the downgradient side of the treatment cells. The French drain has an overflow line that discharges directly to surface water. This whole process is achieved passively. The Rocky Flats barrier is designed to capture the entire plume and is located within the boundaries of the plume. An excavator was used to create the collection trench. The trench and HDPE barrier are keyed into the bedrock.

CVOCs are destroyed by the iron in the treatment cells, whereas the radionuclides are reduced and deposit on the iron surfaces. The treatment cells are designed to provide easy access so that the reactive medium can be changed periodically. The cells are plumbed so that a water blanket remains above the level of the iron at all times. The water enters from the top and is discharged at the bottom of the cell. Cleanup targets for the CVOCs are based on MCLs. In the most recently reported monitoring round (March 1999), the barrier met all cleanup targets. The barrier appears to be satisfactorily capturing the targeted plume.

Another PRB configuration that is being considered at several DOE sites is the use of replaceable reactive cells. Because PRBs at many DOE sites tend to be designed for remediation of radionuclide- or metal-type contaminants, the reactive medium cannot be permanently left in the ground, as with PRBs for organic contaminants (Korte, 1999). Even after the plume is dissipated, metals sequestered in the reactive medium could re-dissolve in the groundwater flow. Therefore, the reactive medium at these sites must be removed and disposed of at some point. At Y-12 Plant, Oak Ridge Reservation, TN for example, DOE has installed a specially-designed treatment vault to house the reactive medium (granular iron), which makes it easier to retrieve and, if required, replace the reactive medium. The contaminants at this site include uranium and nitrate.

A semipassive variation to a PRB is the GeoSiphon™/GeoFlow™ cell, a system developed by WSRC under a DOE EM-40-funded project (WSRC, 1999). WSRC has filed a patent application for this semipassive technique. In this variation of the PRB, significant natural head differences between two points at a site are used to induce higher flowrates through aboveground or underground reactive media or treatment systems. A siphon, open channel, or pressure flow is used to transport the water from one point to another. The reactive medium or treatment system can be placed at the inlet or outlet of the siphon or pipe, and also can be located aboveground or underground. Two such cells have been demonstrated, one for the treatment of a TCE plume and the other for the treatment of metals (iron, aluminum, nickel, and chromium). Granular iron was used as the reactive medium for TCE, and a combination of limestone, peroxides, and other bases was used as the reactive medium for the metals.

7.5 Construction Quality Control

The effectiveness and long-term performance of permeable and/or impermeable sections of a PRB depends on the level of construction quality control (CQC) that is implemented. For the permeable section (gate or continuous reactive barrier) of a PRB, the CQC issues relate to ensuring that the installed reactive cell provides the designed reactivity and hydraulic performance (porosity and permeability). Construction-related factors may cause the actual performance of the reactive cell to deviate from the design performance and should therefore be guarded against, and include the following:

- Low-permeability silt and clay materials may smear across the influent or effluent face of the reactive cell. Smearing is especially possible when the aquifer is composed of heterogeneous stratigraphic layers that smear during construction activities, such as backhoe or clamshell excavation, sheet pile driving, vibrating beam movement, and caisson driving.

- The soil matrix may densify where structural sections are driven into the ground. For example, during the driving of sheet piles, caissons, or vibrating beams, the soil material that is pushed aside may pack more densely in the immediately adjoining slice of aquifer. Smearing or densification may reduce the overall permeability of the reactive cell, even though the reactive medium inside may be highly permeable. Generally, the probability of smearing or densification is lower in relatively homogeneous sandy aquifers, and the surrounding soil and reactive medium often collapses into the space left by the structural section (e.g., sheet pile, vibrating beam, or caisson) when it is pulled out of the ground across the influent and effluent faces of the reactive cell. Reactive medium placement techniques that do not require excavation, such as deep soil mixing, also may have the potential to create densification.

- Construction fluids or sealants may enter into the reactive cell or aquifer. For example, the grout used to seal the joints between sheet piles may seep into the surrounding aquifer or reactive cell. One CQC measure that can be taken to prevent this seepage is to keep an inventory of the grout poured into each joint and compare the volume of the grout to the volume of the joint. A measure taken at Dover AFB to prevent excessive seepage of grout into the aquifer was to inspect each joint (with a fiber optic camera) to ensure that adjoining sheet piles were aligned well before grouting. The deeper the aquifer, the greater the possibility of misalignment of sheet piles. Similar precautions should be taken during fluid injection with techniques such as jetting.

- Discontinuities in the reactive cell may occur, especially with innovative construction techniques such as jetting or hydraulic fracturing. Discontinuities may cause part of the flow to emerge untreated through the reactive cell. Adequate inspection procedures should be identified and implemented when reactive cell construction techniques are used that do not involve complete excavation and replacement of the aquifer soil with reactive medium. When funnel-and-gate configurations are used, care must be taken that the funnel materials, such as bentonite or cement, do not enter the reactive cell. Permanent dividers (such as structural steel plates) generally are installed between the funnel-and-gate sections to separate the two. Permanent dividers between funnel-and-gate sections or between the lateral edges of a continuous reactive barrier and the aquifer also prevent short-circuiting of flow through the sides of the reactive cell.

- Uneven placement of the reactive medium in the reactive cell may become an issue, even when conventional excavation and refilling techniques are used. If the reactive cell is more than 10 ft deep, it may be desirable to tremie the reactive medium into the excavation, rather than suspend bags of reactive medium above ground and release the reactive medium in an open stream into the excavation. An inordinate amount and distribution of void space in the reactive cell may lead to excessive channeling of flow and exhaustion of the reactivity of the medium along these preferential paths, while leaving the bulk of the medium unused. When using innovative techniques that do not involve excavation of the native soil, such as jetting or deep soil mixing, ensuring an even distribution of reactive medium is even more challenging.

There may not be any foolproof way to completely avoid these construction risks. However, with appropriate tracking and inspection procedures, their occurrence can be minimized and/or recorded for future interpretation of PRB monitoring results. Post-construction monitoring can be conducted to verify reactive cell continuity by measuring field parameters indicative of medium reactivity. For example, lower ORP and DO and higher pH measured spatially along various flowpaths through the reactive cell may be indicative of continuity. For such measurements to be meaningful, flow through the PRB should have stabilized, a point that may not be reached for several weeks or months, and by that point the construction equipment will have been demobilized. Therefore, preconstruction planning and careful implementation are the best way of avoiding/minimizing construction deficiencies. When PRBs include impermeable sections (funnels), the following construction-related factors need to be guarded against, tracked, and recorded:

- Discontinuities may occur at joints in the impermeable barrier. For example, unless careful inspection of each and every joint is conducted, the joints between sheet piles may turn out to be misaligned, especially at greater depths. Discontinuities may occur in a slurry wall if the backfill is not well mixed. Ensuring that there are no discontinuities may be particularly difficult when impermeable barriers are installed with innovative construction techniques, such as jet grouting or deep soil mixing, where considerable care has to be taken to ensure that adjoining injected/mixed sections intersect at all depths.

- Improper seals between the funnel-and-gate sections may occur, leading to leakage at points where the funnel meets the reactive cell. Special joints may have to be installed between the funnel-and-gate sections.

Minor leakage through impermeable sections may be difficult to detect, unless target contaminants start showing up on the downgradient side of the funnel. However, even this is not a firm indicator, as groundwater (and contaminants) flowing around the edge of the funnel may flow close to the funnel along the downgradient side. Measuring water levels immediately upgradient and downgradient of the funnel may be a possible way to verify funnel continuity after flow stabilizes.

7.6 Health and Safety Issues

The success of any construction application can be attributed to having prior knowledge of any foreseeable hazards and taking careful steps to avoid them through the implementation of safety practices under the guidelines outlined by the Occupational Safety and Health Administration (OSHA). A formal health and safety plan structured to address potential site-specific hazards will be required prior to commencement of construction activities. The following are several health and safety issues that must be considered:

- Confined space entry

- Knowledge of location of existing utilities, including overhead or buried power lines, sewer lines, phone lines, and water pipes

- Types and concentrations of contaminants involved, which will dictate the type and level of personal protective equipment (PPE) required

- Use of heavy excavating equipment, which will require the use of a hard hat, steel-toed boots, safety glasses, gloves, and hearing protection

- Trench entry, which may be necessary for visual inspection of important CQC issues (for example, it may be necessary to check that the excavation is keyed into a confining layer correctly). Trench entry also may be required if buried utilities hinder use of mechanical excavation equipment. Trench entry also may be required to clear out the spaces inside the corrugations of sheet piles that are not reachable by clamshell excavators.

7.7 Waste Minimization

Exposure to contaminated trench spoils is likely to occur during the construction of a subsurface barrier. The generation of hazardous or nonhazardous waste can be minimized through careful selection of a construction technique that involves either no generation of contaminated spoils or generation of only minimal amounts. Sometimes design factors will dictate that a barrier be constructed in uncontaminated soil located downgradient from a contaminant plume, thereby eliminating the problem of dealing with hazardous waste. The opposite scenario also could occur, requiring excavation of soils within a contaminant plume. In any event, the amount of trenching and disposal of spoils should be planned for when selecting an appropriate construction technique.

8.0 Monitoring the Performance of a PRB

Once the PRB has been designed and constructed, the system must be monitored as long as the plume exists. The primary objective of contaminant monitoring is to verify that the groundwater quality downgradient of the PRB is in compliance with the target cleanup objectives agreed to by site managers and regulators. In other words, monitoring seeks to establish that the plume is being adequately captured and treated. Monitoring is accomplished through groundwater sampling and analysis for target contaminants. The type and frequency of monitoring required to achieve this objective usually are decided during discussions between the site manager and the regulators. Most site managers conduct contaminant monitoring on a quarterly schedule in keeping with general sitewide monitoring.

A secondary objective of monitoring is to determine whether the operating performance of the PRB is consistent with the design objectives. Two types of monitoring usually are required: *contaminant* monitoring seeks to verify the current operating status of the PRB, and *performance* monitoring seeks to evaluate whether the desired hydraulic and geochemical conditions are being created by the PRB to enable good performance currently and in the future. Performance monitoring is conducted to some degree at most sites because it can forewarn site managers of any problems that may occur in the future, before the problems are identified by contaminant monitoring (that is, before plume breakthrough or bypass actually occurs). Potential performance problems that could be identified after PRB construction include the following:

- Hydraulic flow conditions in the PRB and its vicinity are different from those predicted by site characterization, modeling, and design. These conditions could lead to inadequate plume capture or inadequate residence time in the reactive cell.

- Geochemical conditions developing in the reactive cell are not suitable for current or continued good performance of the PRB.

Performance monitoring generally involves measurement of water levels, field parameters (ORP, pH, DO, and conductivity), and inorganic constituents in the groundwater monitoring wells in the PRB and its vicinity. Water levels and field parameters are simple measurements to perform and most site managers conduct these on a quarterly basis, along with groundwater sampling for contaminants. Quarterly monitoring also indicates any seasonal changes in contaminant distribution, groundwater flow, or geochemistry. Certain inorganic constituents can contribute to the formation of chemical or biological byproducts, which may take place over several years (or several pore volumes of flow). Therefore, groundwater sampling for inorganic parameters is generally conducted on an annual or biannual schedule.

Other specialized hydraulic and geochemical measurements, such as direct hydraulic measurements with in situ probes, tracer tests for flow and residence time verification, and collection and analysis of core samples from the field reactive cell, have been conducted at some sites during the development of the PRB technology. However, at most sites these specialized measurements may be needed only if routine or compliance monitoring indicates that the PRB is not performing as designed.

This section describes both contaminant monitoring and hydraulic and geochemical performance monitoring techniques. It is important to note that the successful use of post-construction monitoring data depends on the collection of detailed site characterization information in the vicinity of the PRB during the preconstruction (design) stage. Preconstruction contaminant, hydraulic, and geochemical characteristics of the site form the baseline for evaluation of PRB-induced changes in the affected aquifer.

8.1 Contaminant Monitoring Strategy

After installation of the PRB is complete, the site manager and regulators will need to know if the plume is being adequately captured and treated. From a compliance perspective, the monitoring is done to ensure that downgradient concentrations of the target contaminant (and any target byproduct) are below target cleanup levels. Contaminant monitoring involves watching for:

- Potential breakthrough of contaminants or environmentally deleterious byproducts through the reactive cell
- Potential contaminant bypass around, over, or beneath the barrier
- Potentially deleterious effects on groundwater quality due to the reactive medium itself.

A monitoring plan containing monitoring locations, frequencies, and parameters must be developed and agreed on by the site managers and regulators. Appropriate QA procedures should be followed in developing and implementing this plan to ensure that valid data are collected and analyzed.

8.1.1 Monitoring Locations and Frequencies

The monitoring locations and frequencies required for contaminant monitoring are likely to be very site-specific, although the ITRC's PRB Subgroup has recommended general guidelines for PRB monitoring (ITRC, 1997 and 1999). Figure 8-1 shows examples of monitoring well configurations that could be used, depending on site conditions, to monitor for breakthrough and/or bypass of contaminants.

In the Figure 8-1c and 8-1e configurations, monitoring is done in the downgradient aquifer using a row of long-screened wells. If the CVOC distribution in the aquifer is relatively homogeneous by depth or if the aquifer is relatively thin, long-screen wells are sufficient to monitor breakthrough and/or bypass. If the contaminant distribution in the plume is relatively heterogeneous with respect to depth, well clusters may be used instead of long-screen wells. Each well in a cluster is screened at a discrete depth interval of the aquifer and, together, the wells in the cluster provide a representative profile of the vertical distribution. However, the presence of elevated levels of target contaminants in the downgradient wells may make it difficult to differentiate between breakthrough and bypass. This is because modeling indicates that re-mixing of

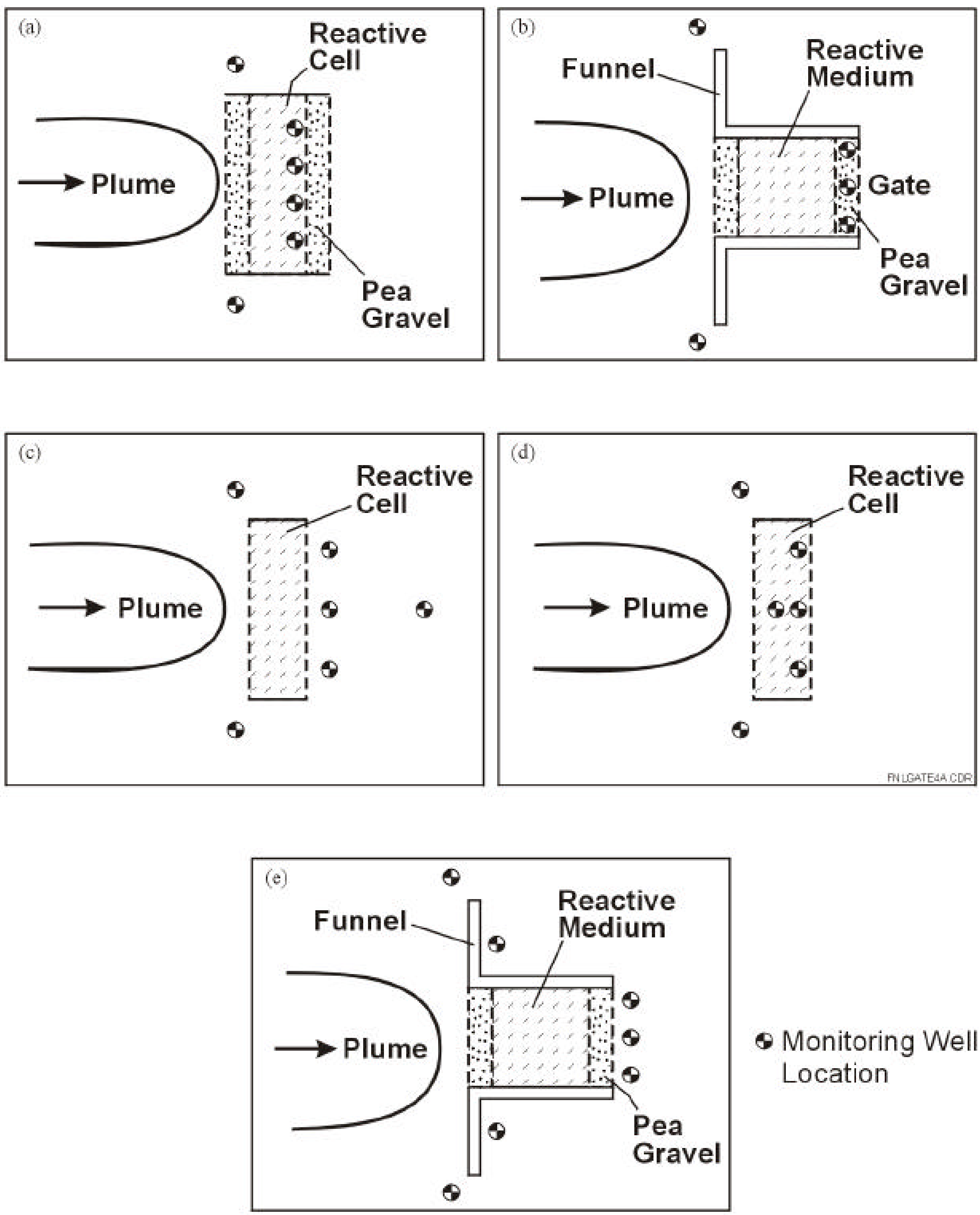


Figure 8-1. Various Monitoring Well Configurations for Contaminant Monitoring at a PRB

groundwater flowing through and around the PRB takes place very close to the downgradient edge of the PRB.

In the Figure 8-1a and 8-1d configurations, additional monitoring wells are placed a few inches inside the reactive medium to differentiate between potential breakthrough and bypass. If the PRB is located inside the plume instead of at the leading edge of the plume, monitoring wells in the downgradient aquifer may continue to show elevated contaminant concentrations for a long time after PRB construction, while the downgradient plume dissipates. Placing the monitoring wells within the reactive medium also provides a level of safety: if contaminant breakthrough is observed in these wells, there is still some reactive medium positioned beyond the well that can treat the contaminants further before the groundwater exits the reactive cell. Additional monitoring wells are placed at the two ends of the barrier to monitor for contaminant bypass that could result from inadequate flow capture. If there is potential for flow bypass beneath or around the barrier, this arrangement could provide more information. Flow bypass beneath the barrier would occur if the barrier is not properly keyed into the aquitard or if the aquitard itself has fractures. Flow bypass around the barrier could take place if the actual hydraulic capture zone becomes smaller than designed or if the plume shape changes over time.

The downgradient aquifer wells shown in Figure 8-1c also could be used to verify that the reactive medium itself is not releasing any environmentally deleterious products and that native geochemical parameters are being restored. Because mixing and rebound of geochemical parameters back to aquifer values may take place gradually, downgradient monitoring wells could be placed at increasing distances from the barrier.

It is essential to include one or multiple wells for monitoring CVOCs on the upgradient side of the PRB as well. Upgradient wells can provide an early warning of potential plume breakthrough if, over time, the plume develops in such a way that influent concentrations exceed those planned for in the design.

If there is any uncertainty regarding the imperviousness of the funnel, either because of geotechnical difficulties during installation or because innovative construction methods were used, additional wells could be installed immediately downgradient from the funnel (see Figure 8-1e) to monitor for breakthrough.

The required frequency of compliance monitoring is determined during discussions with the regulators. Quarterly monitoring usually is required for target contaminants at many sites. In general, the monitoring frequency for PRB installations need not be very high. As described in Section 1.0, the reactive medium is consumed slowly, over a time-scale of years. Quarterly monitoring would provide sufficient warning of any impending breakthrough of target contaminants. Quarterly intervals also are suitable for monitoring any seasonal changes in groundwater flow conditions.

Because monitoring costs constitute the only annual operating cost of the barrier for several years after construction, site managers will wish to optimize both the number of monitoring wells sampled and the information gained. Adequate site characterization in the vicinity of the proposed PRB location, as well as hydrologic modeling, can assist both site managers and regulators in determining the appropriate number and locations of monitoring wells to install at a given site.

Monitoring wells may be constructed using 1- or 2-inch-diameter PVC casing for most types of contaminants and most types of reactive media. The diameter of the monitoring wells is determined based on the space available in the reactive cell and on the size of the measuring instruments that will be inserted during monitoring. Monitoring wells in the reactive cell generally are installed prior to placing the granular medium in the excavation, and are supported by metal frames. Figure 8-2 shows monitoring wells being installed in two types of reactive cells. Figure 8-2a shows monitoring wells supported in a trench-type reactive cell in the PRB at former NAS Moffett Field. Figure 8-2b shows monitoring wells supported by a frame being installed in a caisson-based excavation for a PRB at Dover AFB. Monitoring wells in the aquifer are installed by routine well installation techniques.

8.1.2 Sampling and Analysis for Contaminants and Byproducts

The chemical parameters that are typically measured in the monitoring wells include concentrations of contaminants (e.g., TCE and PCE) and potential toxic byproducts (e.g., *cis*-1,2-DCE and VC). Sampling and analytical techniques for monitoring wells located in the aquifer are similar to those for site characterization described in Section 3.0. Groundwater sampling generally can be done with an appropriate length of Teflon™ tubing and a peristaltic pump. However, special precautions may be required while sampling monitoring wells located within the reactive cell or gate.

When collecting groundwater samples from the reactive cell or gate, traditional methods that involve purging several well-casing volumes of water prior to collection should be avoided, because such practices may capture water that represents a significantly lower residence time in the reactive cell. Rapid withdrawal of a water sample by any sampling method (e.g., bailer) may draw water quickly from the upgradient direction, and such water may have been incompletely treated by the reactive medium. Analyzing a mixture of water from locations partially outside of the monitoring well screen could suggest higher levels of the target analytes than actually exist.

The main precaution in obtaining a representative sample is to avoid creating a strong disturbance in the well, for example, by purging with a bailer or inserting a sampling tube repeatedly or too quickly. An alternative sampling method known as "micropurging" is expected to be more suitable for groundwater sampling in the PRB and its vicinity and yield representative water samples, and has been discussed by Kearl et al. (1994). This sampling method involves the removal of small volumes of groundwater from the well at low flowrates. Small volumes help ensure that water samples are representative of conditions near the well. Flowrates should be low so that sampling creates minimum disturbance to the groundwater within the reactive cell. In general, flowrates should be less than 1 L/min, and in some cases less than 100 mL/min, depending on the transmissivity of the medium (Powell and Puls, 1997). A conservative rule to follow is that drawdown of the water level in the well being sampled should not exceed 0.05 ft. Because annular sand packs are not typically employed in reactive media wells, purge volumes can be made quite low. For example, if discrete-level monitoring wells are used with 2-inch-inside-diameter casings and 1-ft screen sections, the volume in the screen section will be about 0.6 L. Standard practice calls for purging three times the volume of the screen section, which

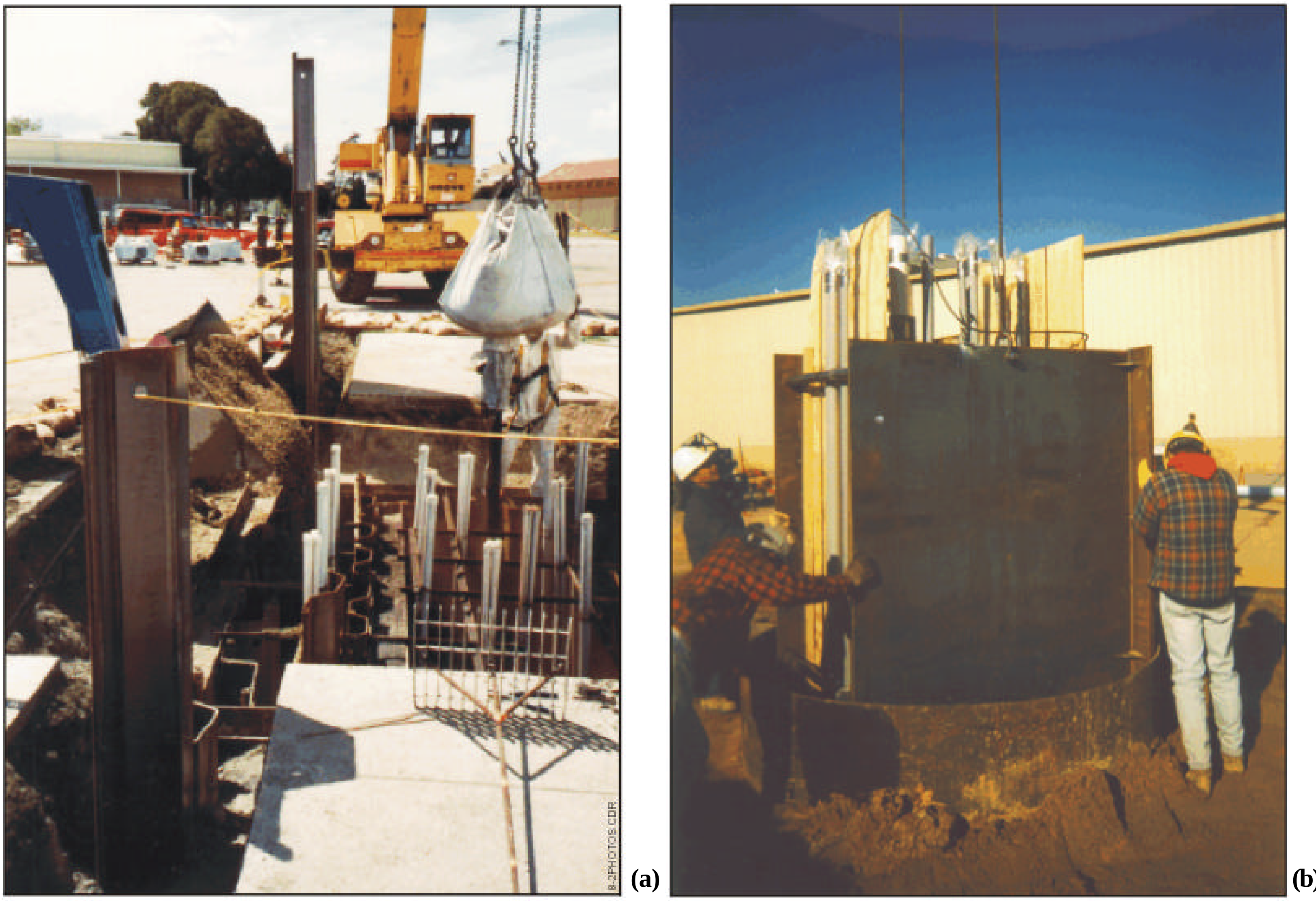


Figure 8-2. Monitoring Wells Being Installed in (a) Trench-Type and (b) Caisson-Type Reactive Cells

would require the removal of slightly less than 2 L of water. Monitoring the purge water for field parameters (pH, ORP, and conductivity) usually is desirable to confirm when they become stable and thus indicate that the water in the well has become representative of the water in the surrounding matrix.

8.2 Hydraulic Performance Monitoring Strategy

The goals of hydraulic performance monitoring are to evaluate the upgradient hydraulic capture zone induced by the PRB and to estimate the residence time available to the groundwater contaminants in the reactive cell.

8.2.1 Evaluating Hydraulic Capture Zone of the PRB

The capture zone evaluation strategy seeks to determine (a) whether or not the PRB is capturing groundwater and (b) the width and/or orientation of the capture zone.

Construction-related reasons why a PRB may not capture *any* water potentially include the smearing of fine-grained aquifer or construction materials around the face of the reactive cell and/or the densification of solids around the reactive cell. Site-related reasons why a PRB may not capture any water include transient flow reversal, as might occur at a site subject to tidal influences. The reasons why a PRB may be capturing water but not be achieving the designed width and/or orientation of the capture zone include unanticipated seasonal changes in groundwater flow velocity and direction.

Field techniques for determining the capture zones are similar to those for hydrogeologic site characterization; however, there may be some differences in their implementation. Capture zones can be evaluated using conventional techniques such as water-level measurements and tracer testing, or by emerging techniques such as in situ velocity probes, the HydroTechnics probe, or the colloidal borescope. These options are similar to those used for hydrogeologic site characterization and have previously been discussed in Section 3.0. Only the aspects pertinent to performance monitoring are discussed below. The main challenge in capture zone determination is that these investigations must be conducted over a small area at most PRB sites. Groundwater modeling may be used to determine the optimal placement of monitoring wells or velocity probes.

8.2.1.1 Evaluating Hydraulic Capture Zone with Hydraulic Gradient Measurements

The most common and effective approach for capture zone delineation is the determination of groundwater flow directions by measuring water levels in the PRB and its vicinity. The capture zone can be estimated by preparing a water-level map and plotting flow lines along the gradients indicated by the map. This strategy requires that a network of wells or piezometers be installed upgradient of the PRB. The number and configuration of the wells depends on the site-specific conditions and monitoring objectives. For example, if the only objective is to confirm that the groundwater is flowing into the PRB, then a few wells placed directly upgradient of the reactive cell may be sufficient. However, if the objective is to determine the width of the capture zone or to perform a detailed delineation of the part of the plume entering the reactive cell, then an extensive monitoring network is needed. The first objective (confirming flow into a PRB) generally can be met successfully in the field. The second objective (determining capture zone width or plume delineation) generally is very difficult to accomplish because the water-level differences (hydraulic gradients) between adjacent wells in the vicinity of the PRB are too small for statistically significant measurements. The simulated flow lines generated from PRB design modeling (see Figure 6-2) show that the flow lines start converging toward the reactive gate just a few feet upgradient of the PRB. Therefore, the monitoring efforts must be focused on this rather small transition zone if the flow divide and capture zone width need to be delineated. Over this small area, the measurement uncertainty is generally greater than the actual hydraulic gradient, which results in non-conclusive data. Determining capture zone width is further complicated at heterogeneous sites where the capture zone can be non-symmetrical. Precise surveying of the well elevations and careful and consistent water-level monitoring are of utmost importance in reducing uncertainties.

Despite the uncertainties, water-level monitoring is probably the most convenient and cost-effective method for demonstrating the capture zone of the PRBs, especially at sites with a sufficiently high hydraulic gradient. This is because the water levels can be monitored inexpensively and frequently in a large number of wells over a long period of time. The water-level maps and hydraulic gradients provide a more representative picture of the overall hydraulic conditions at the site than the in situ probes, which are more localized.

An example of using water-level measurements to estimate the capture zone for the PRB at Dover AFB is shown in Figure 8-3. This figure shows a network of 15 monitoring wells upgradient of one of the reactive gates and a water-level map for a single monitoring event. As shown here, a steep gradient toward the gate exists immediately upgradient of the gate. From this data, flow lines can be easily identified pointing toward the gate, which confirms that the groundwater is being captured by the PRB. However, upgradient of the funnel wall, the water levels in most wells are within 0.01 ft of each other and there is no clear flow divide. Therefore, it is almost impossible at this site to determine the location of the flow divide or the width of the capture zone, because the low aquifer hydraulic gradient at this site and the short distances between wells make the capture zone delineation difficult. Figure 8-4 shows the water levels and capture zones for the pilot-scale PRB at former NAS Moffett Field, a site with a higher hydraulic gradient than the Dover AFB PRB site. In this case, it was possible to show that the groundwater is flowing into the reactive gate and to determine the approximate location of the flow divide based on water-level measurements and flowpaths.

8.2.1.2 Evaluating Hydraulic Capture Zone with In Situ Groundwater Velocity Sensors

HydroTechnics probes (see Section 3.1) can be used for long-term continuous monitoring of groundwater flow velocity and direction. These probes are installed permanently in the aquifer media (see Figure 8-5). Therefore, one probe is needed for each location to be monitored. Compared to water-level maps, the probes provide an estimate of velocity only in the immediate vicinity of the probe. However, because the monitoring is continuous, the probes are ideal for evaluating short-term or seasonal variations in flow patterns. Again, if the only objective is to monitor for groundwater flow into the reactive gate, a single probe installed just upgradient of the gate may be sufficient. However, detailed delineation of the flow patterns in the vicinity of the PRB may require several probes. For observation of the flow divide upgradient of the funnel wall, two or more probes should be installed that straddle the expected zone of flow divide.

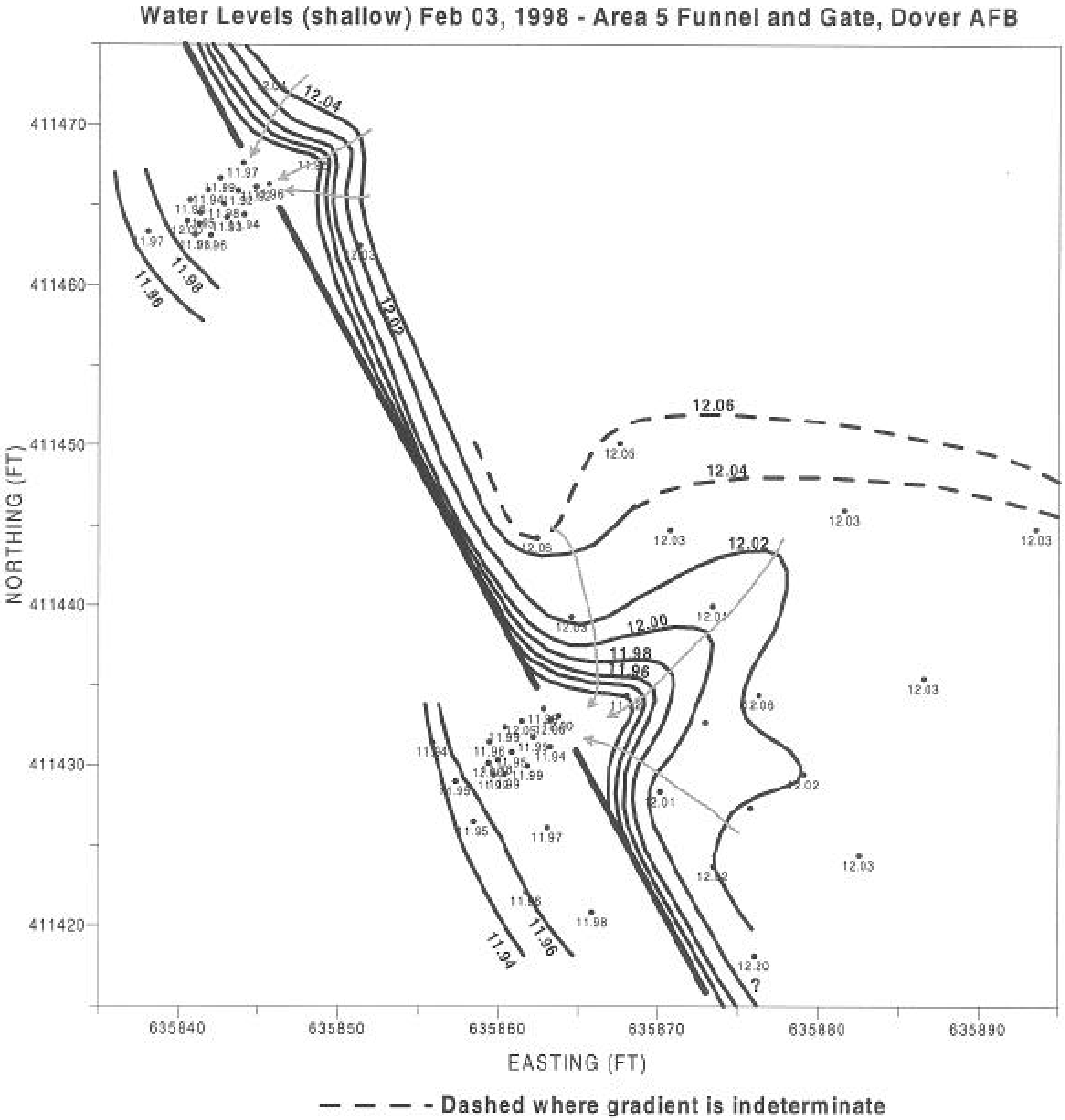


Figure 8-3. Water Levels and Capture Zone in Aquifer Near the PRB at Dover AFB (February 1998)

These probes should be placed as close as possible to the funnel walls because the modeling results show that the flow divide forms within only a few feet of the funnel walls. At PRB sites, the capture zones are expected to be wider than the width of the barrier. The placement of the probes at these sites for capture width monitoring should be based on the modeling results. Regional flow can be determined by installing the probes farther upgradient of the PRB. To date, these probes have been installed at several PRB sites for capture zone determination, including Dover AFB, Cape Canaveral Air Station Hangar 34, and former Lowry AFB.

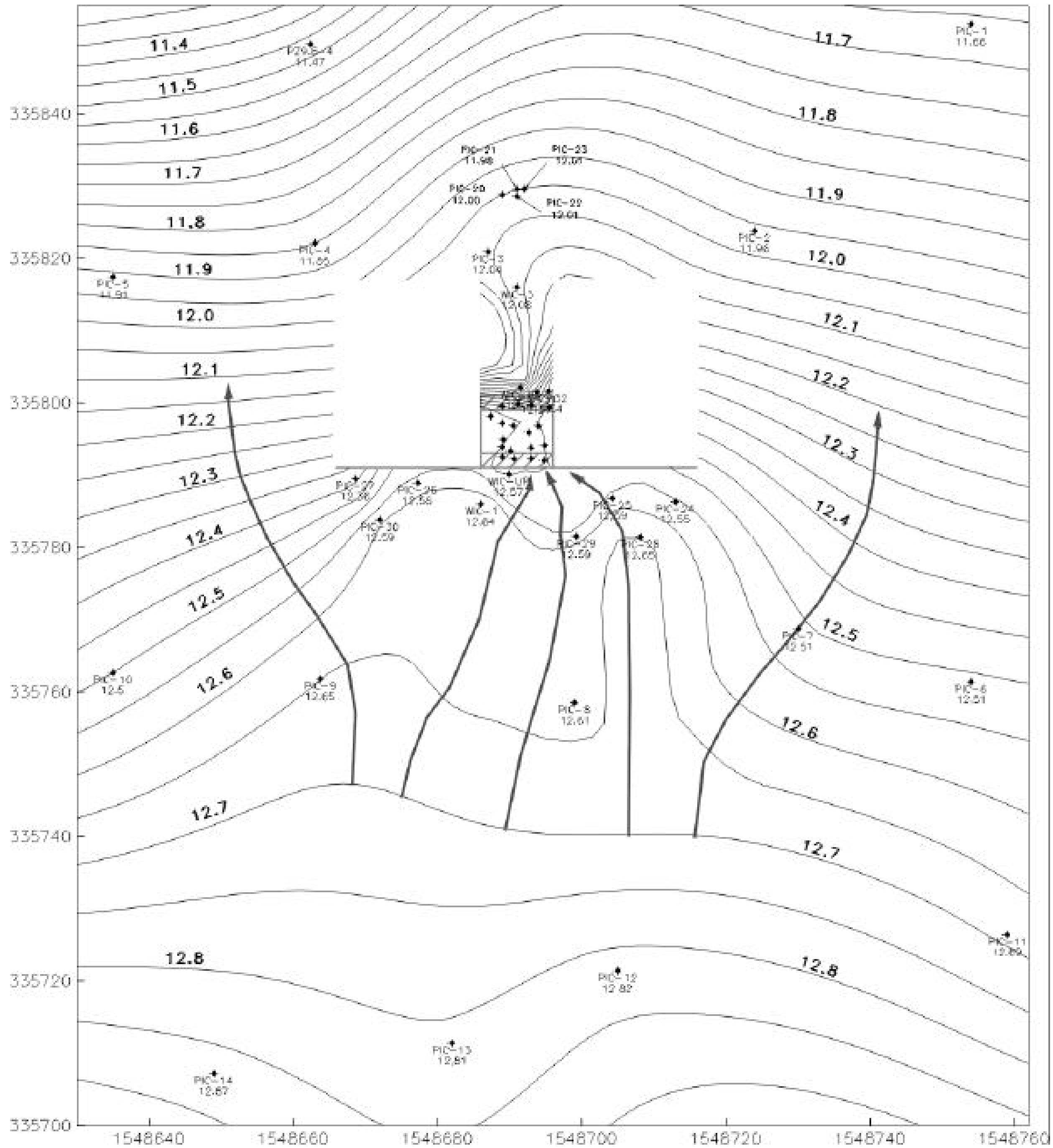


Figure 8-4. Water Levels and Capture Zone Near the Pilot-Scale PRB at Former NAS Moffett Field (May 1997)

(a) (b)

Figure 8-5. Pictures of (a) an In Situ Groundwater Velocity Sensor and (b) Its Installation

8.2.1.3 Evaluating Hydraulic Capture Zone with a Colloidal Borescope

Colloidal borescopes (see Section 3.1) are an emerging tool for direct observation of flow in monitoring wells. These can be used in 2-inch-diameter completed wells with sand packs to delineate the flow patterns across the monitoring network. An evaluation of these probes is underway at former Lowry AFB and Dover AFB (Battelle, 2000). Preliminary results show that the probes work only in wells that have a stable colloidal flow pattern. Generally, long screen wells screened across the entire depth of the aquifer are desired because the probe can be used to locate zones with stable colloidal flow. However, the probes may work accurately in only the high flow zones within the aquifer. Currently, these probes should be considered experimental, but they may be a relatively economical option for mapping groundwater flow patterns at a site if proved successful. Mapping may be repeated several times during the performance monitoring to evaluate seasonal variations.

8.2.1.4 Evaluating Hydraulic Capture Zone with Tracer Tests

Tracer tests may be used to evaluate flow patterns in the vicinity of the PRBs. This form of testing is generally an expensive and time-consuming option for capture zone delineation. However, when successful, tracer tests can provide direct evidence of flow into the reactive gate. Tracer testing involves injection of a known amount of tracer, such as bromide, into an upgradient aquifer well and monitoring for concentrations in observation wells. The observation wells are located in the upgradient aquifer surrounding the injection well, in the reactive gate, and around the edges of the PRB. It is preferable to use selective ion electrodes for continuous monitoring of tracer to prevent the possibility of missing a tracer arrival in the observation wells. Selective manual sampling can be used to supplement and verify continuous probes.

As with water-level measurements, the strategy for tracer testing depends on the monitoring objective. If the only objective is to determine the flowpath of the groundwater from a specific location upgradient of the PRB, simple tracer tests may be conducted with injection in one upgradient well and monitoring for tracer arrival in the reactive cell. However, if detailed delineation of the capture zone upgradient of the PRB is required, then multiple tracer tests using different tracers and an extensive monitoring network are needed. Even with a very detailed tracer test, it is generally very difficult to account for the mass balance of the tracer and determine precise capture zone width. Tracer tests may not be economical at most sites, unless other methods fail to resolve the uncertainty in capture. Tracer tests in the upgradient aquifer for capture assessment have been performed on PRBs at former NAS Moffett Field (Battelle, 1998) and at Fry Canyon, UT (Piana et al., 1999).

8.2.2 Estimating Residence Time Distribution in the Reactive Cell

Degradation of contaminants in a PRB generally is controlled by rate-dependent processes taking place in the PRB. Therefore, residence time (the amount of time that the water is in contact with the reactive medium) affects the degree to which susceptible groundwater contaminants are degraded. Groundwater flow velocity measurements within the reactive cell provide information pertaining to residence time. In general, the strategies for estimating groundwater flow velocity in the PRB are the same as those for hydrogeologic site characterization (discussed in Section 3.1). The main options include the use of Darcy's Law, tracer tests, and in-well or in situ flow probes. Flow velocity monitoring includes an assessment of both spatial and temporal trends.

Special considerations are needed for monitoring flow within the PRB, most of which result from the very small area of investigation and the presence of heterogeneities. Most reactive barriers are only a few feet thick, which makes it difficult to delineate flow patterns with certainty. Heterogeneous flow can be caused by several factors, such as differential compaction of the iron fines, development of corrosion products on reactive medium surfaces, and precipitation of secondary minerals in the interstitial pore space. Heterogeneous flow also is caused by sharp conductivity differences between the aquifer and reactive cell media. Heterogeneity can decrease the overall effectiveness of the reactive cell by accelerating flow at preferential locations within the cell and thus decrease contact time between the groundwater and reactive medium. Heterogeneity increases hydrodynamic dispersion, which can promote breakthrough of contaminants. Due to the spatial and temporal variations, the field-estimated residence time is actually a range, at best more than half an order of magnitude, rather than a single value. The resulting uncertainty in the design can be reduced by making more precise parameter estimates and by incorporating appropriate safety factors. At most sites the incorporation of the safety factors has not been a problem because influent contaminant concentrations are low and contaminants are degraded as soon as they enter the PRB. However, at sites with very high expected chemical concentrations, the incorporation of sufficient safety factors may lead to unacceptably high costs.

The most common approach for calculation of flow velocity through the PRB is by using Darcy's Law. For example, this approach has been used for velocity determination at Dover AFB (Battelle, 2000) and former NAS Moffett Field (Battelle, 1998). Darcy's Law requires measuring the water levels and estimating the porosity and permeability of the reactive cell media. When gathering the required hydraulic data for flow velocity calculation, the following concerns should be taken into consideration:

- It is generally not practical to conduct pumping tests in the PRB. Therefore, slug tests and laboratory permeability tests (falling head or constant head column tests) are the main options for K determination. In addition, the field permeability may be significantly different than the laboratory permeability. Therefore, slug tests usually are the preferred method for K determination. In the PRB setting, the slug tests need to be conducted very carefully, because the high K of the iron or sand/gravel particles results in very quick recovery. The larger diameter wells with largest possible slug should be used. To the extent possible, site-specific slug testing should be conducted. Significant differences have been observed between the K values reported in the literature and those measured in the field using slug tests (Battelle, 2000).

- Similarly, recent experience at field sites has shown that the actual porosity of the reactive media may be as high as 0.7, which is much higher than the previously expected values.

- Water levels can be monitored in the wells installed in different zones at the PRB. These zones include immediate upgradient aquifer, upgradient pretreatment zone, the reactive media, downgradient pretreatment zone, and the downgradient aquifer. It is been observed through modeling as well as field monitoring (Battelle, 1998 and 2000) that the gradient across different zones differs considerably due to conductivity contrasts. Thus, as the water enters from the lower-K aquifer to higher-K reactive cell, there is a drop in water-level gradient. At the downgradient end, there is generally some stagnation where water is moving from a very high K reactive cell to the lower-K aquifer. However, there is a steep gradient as soon as water leaves the exit zone. Overall, gradients generally are steep if water levels from upgradient to downgradient wells are used and are rather flat if only the wells within the PRB are used. The flatter gradients are generally balanced by the higher K in the reactive media. Therefore, theoretically, the overall flow balance is maintained. Continuous water-level monitoring may be performed in selected wells to supplement the periodic manual water-level measurements.

When using Darcy's Law with the above parameters, the geometric mean of K should be used. This calculated value for K can be further refined by weighting the thickness of the different media along the flowpath. Average and standard deviation of water levels from several monitoring events can be used to determine the range of possible flow velocities through the PRB.

8.2.2.1 Residence Time Estimation with In Situ Velocity Probes

In situ velocity probes from HydroTechnics, Inc. (see Section 3.1) can be installed in the PRBs during or after construction. The main advantage of these probes is that they provide continuous velocity data for about two years of operation. The limitations include the need to permanently install several probes in each PRB if an assessment of spatial variations is needed. This limitation is significant because velocity variations due to media heterogeneity and sharp contrasts in conductivity between reactive media and aquifer sediments have been observed at most sites. Another limitation is the potentially adverse effects of thermal and magnetic influences of the reactive media (such as iron) on the probe measurement; at a minimum, these influences result in the need for different calibration for the probes placed in the PRB, and should in any case be investigated further in future studies. An example of the velocity magnitude and direction monitoring data collected using a HydroTechnics probe installed in the PRB at Dover AFB (Battelle, 2000) is shown in Figure 8-6. At this site, the flow directions showed a good match with those determined from other methods. However, the velocity values were generally much lower than expected. It is not clear if the velocity values determined from the probe were correct or if they were affected by the thermal or magnetic influence of the reactive media.

A colloidal borescope (see Section 3.1) also may be used to measure groundwater flow velocity in the reactive cell. The borescope provides direct observations of flow in various zones within a monitoring well, and theoretically can be used to take several flow measurements in each monitoring well at different depths. Thus, borescopes can help determine vertical flow variations within each well. When repeated in several wells in the PRB, borescope measurements can be used to develop a 3-D understanding of flow velocity and directions. Furthermore, such measurements may be repeated over time to monitor for seasonal and long-term changes in flow patterns. As mentioned before, these probes are still experimental in nature. However, if they can provide accurate velocity estimates, then these probes may be the most useful option for evaluating flow patterns in the reactive cell.

8.2.2.2 Residence Time Estimation with Tracer Tests

Tracer tests involving a conservative tracer can be used to evaluate flow velocities and potential heterogeneities in the reactive cell. Many different tracers are available for this purpose, but they should be evaluated for potential retardation by the PRB reactive media. For example, sodium

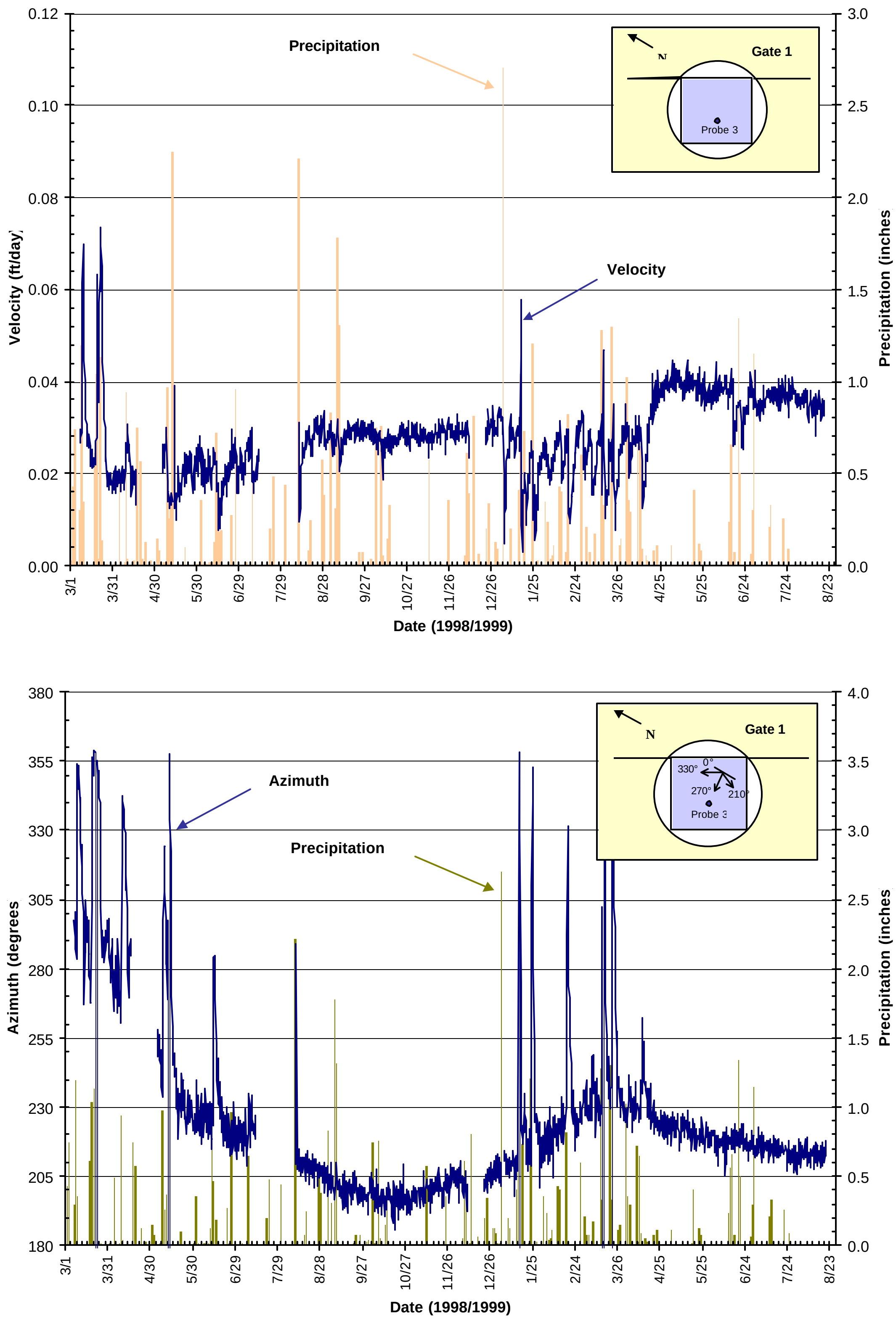


Figure 8-6. (a) Groundwater Velocity and (b) Direction Measured in the Reactive Cell of the PRB at Dover AFB Using an In Situ Velocity Probe