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Geotechnical techniques for the construction of reactive barriers

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Abstract

One of the newest and most promising remediation techniques for the treatment of contaminated groundwater and soil is the reactive barrier wall (commonly known as PRB for permeable reactive barrier or reactive barrier). Although a variety of treatment media and strategies are available, the most common technique is to bury granular iron in a trench so that contaminated groundwater passes through the reactive materials, the contaminants are removed and the water becomes 'clean'. The principal advantages of the technique are the elimination of pumping, mass excavation, off-site disposal, and a very significant reduction in costs. The use of this technology is now becoming better known and implemented. Special construction considerations need to be made when planning the installation of reactive barriers or PRBs to ensure the design life of the installation and to be cost-effective. Geotechnical techniques such as slurry trenching, deep soil mixing, and grouting can be used to simplify and improve the installation of reactive materials relative to conventional trench and fill methods. These techniques make it possible to reduce the hazards to workers during installation, reduce waste and reduce costs for most installations. To date, most PRBs have been installed to shallow depths using construction methods such as open trenching and/or shored excavations. While these methods are usable, they are limited to shallow depths and more disruptive to the site's normal use. Geotechnical techniques are more quickly installed and less disruptive to site activities and thus more effective. Recently, laboratory studies and pilot projects have demonstrated that geotechnical techniques can be used successfully to install reactive barriers. This paper describes the factors that are important in designing a reactive

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barrier or PRB installation and discusses some of the potential problems and pitfalls that can be avoided with careful planning and the use of geotechnical techniques.

Keywords: Permeable reactive barrier; Biopolymer; Guar gum; Slurry wall; Granular iron; Grouting; Deep soil mixing

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1. Introduction

Reactive barriers are a relatively new concept, which offer a simple, less costly solution to groundwater cleanup. A permeable reactive barrier (PRB), as shown in Fig. 1, is constructed underground, across the flow path of a contaminant plume and as the groundwater passes through the PRB, the contaminants are precipitated, adsorbed or degraded with treated groundwater emerging on the down-gradient side. This passive type of remediation results in reduced costs due to the semi-permanent installation, low energy input, focused cleanup on only the area of contamination, conservation of clean water, and continued productive use of the site almost immediately after installation.

The construction of PRBs requires installation below the groundwater table, and often on deep and difficult sites. For these sites, geotechnical construction methods can provide better, faster, cheaper, and safer installations. Geotechnical construction methods include slurry trenching, grouting, and deep soil mixing.

Currently, the scientific challenge of PRB technology is selection of reactive materials that will be most effective in removing the contaminants of concern that can be

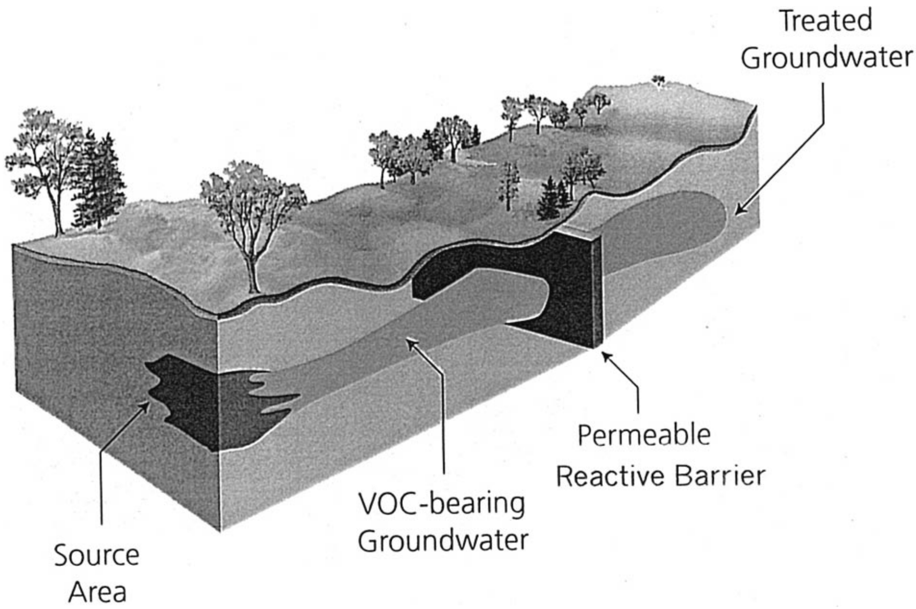

Fig. 1. Schematic illustrating reactive barrier concept (courtesy EnviroMetal Technologies).

placed in the subsurface and will persist over long periods of time. These reactive materials should be relatively inexpensive, readily available, compatible with the subsurface and should not produce toxic byproducts. Another important challenge is to provide cost effective installation methods for placing the reactive materials in the subsurface to the dimensions and depths required. Most of the construction methods used to date have used conventional excavation methods such as open excavation, sheet and shore, and trench boxes for shallow installations on relatively accessible sites. As the PRB technology matures, deeper and more difficult installations will be attempted and more advanced geotechnical construction methods will be needed to reduce waste, improve safety, and reduce cost.

2. Reactive Materials

Reactive barriers were developed to treat a range of dissolved organic and inorganic compounds including chlorinated solvents, petroleum hydrocarbons, selected pesticides, chromium and other toxic metals, nitrate, phosphate and sulfate-rich mine drainage [1]. Chemical, photochemical and biological processes that will degrade, remove or transform a range of groundwater contaminants are well known. However, selecting processes and reactive materials that will perform effectively in the subsurface remains a topic of active research. A variety of treatment materials are being tested at the bench scale and at the pilot demonstration stage to provide an array of cost-effective reactive materials [2].

Although other materials are under investigation, the material most often used in PRB installations is granular iron. The first granular iron-filled wall was constructed inside a sheeted excavation by the University of Waterloo in 1991. This installation was monitored for a period of 5 years, and performed successfully and consistently [3]. Granular iron has been effective in degrading a wide range of halogenated organic contaminants, such as trichloroethene, in groundwater [4,5] and has now been implemented at over 20 sites. Iron particles are shard-shaped, abrasive, and available in commercial quantities in sand size particles (2 to 0.3 mm). Because iron is relatively dense, it mixes readily with gravel or soil, sinks through water without difficulty, and yet can be suspended in viscous slurry.

Another treatment material that has limited use in PRB is granular carbon. At a site in California a funnel and gate was constructed by installing an impermeable soil–bentonite slurry wall to direct groundwater toward manholes filled with granular carbon [6]. The carbon adsorbs hydrocarbons and chlorinated compounds in the groundwater. Granular carbon is friable and light enough to float in water, creating a construction problem for trench installations below the groundwater. Geotechnical methods can inject carbon or mix the carbon with soil to facilitate installation.

An impermeable reactive barrier was installed in 1996 at a site in Michigan using carbon. This 100 000 m^2 industrial site utilized a 10-m deep slurry wall with a mixture of soil–bentonite and high carbon fly ash to both contain and treat groundwater contaminated with plating wastes and solvents. The fly ash was easily mixed with the soil–bentonite creating a simple, yet effective reactive barrier [7].

3. Installation configurations

The two most common types of configurations for PRB are (1) continuous walls, and (2) funnel and gates. A continuous permeable wall is generally the simplest to install and typically extends across the width and depth of the plume, and has the least impact on the existing groundwater flow patterns. The funnel and gate configuration, as shown in Fig. 2, allows the contaminated groundwater to be funneled or guided by impermeable sections or funnels to permeable gates, which contain the reactive materials. Slurry cutoff walls or sheet piling have typically been used to create the funnel sections [8,9]. The permeable gates hold the treatment material and can be placed within any suitable slot in the earth, or buried vessel containing reactive materials [6,10]. The length of these systems must be significantly longer than the plume width to assure complete capture of the contaminants. Typically, the ratio of the length of the funnel to length of the gate is less than six.

Groundwater modeling [11] indicates reactive barrier systems, like other groundwater barriers, should be in contact with a lower impermeable zone (aquitard) in order to assure that the groundwater flow will go through, not beneath, the treatment material. If the reactive barrier wall is not keyed into an aquitard, then it must be constructed much deeper than the contaminant plume to allow for capture [12]. By funneling the water, the groundwater velocity is increased about 2 to 5 times the natural velocity, depending on the funnel to gate ratio. However, in either a continuous wall or a funnel and gate configuration, the required volume of reactive material required is similar due to the similar mass flux of contamination through the system. The required thickness of the treatment zone (in the direction of flow) can vary from a few tens of centimeters to several meters, depending on contaminate loading and residence time.

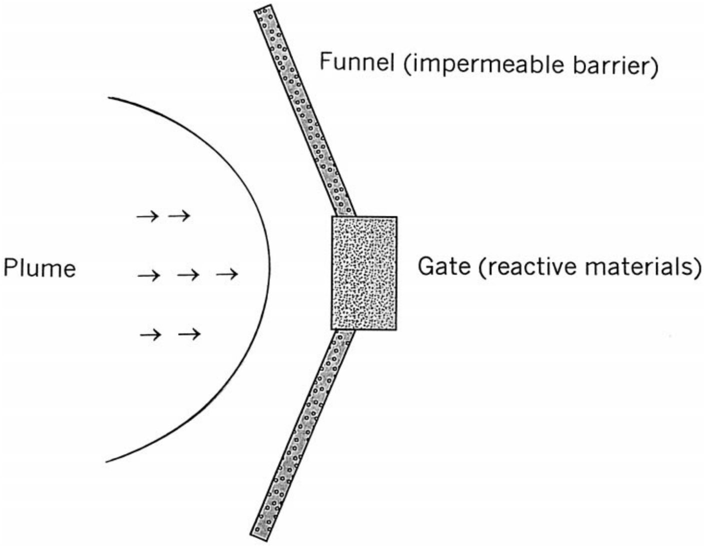

Fig. 2. Plan view illustrating funnel and gate concept.

A special type of funnel and gate uses a buried vessel to contain the reactive materials in removable/replaceable ‘cassettes’. The objective of the cassette systems is to permit the regular removal and replacement of reactive media and/or maintenance of the system without excavating and removing the vessel. Only a few experimental cassette systems have been constructed. Most of these systems provide for much greater control over groundwater flow by using valves, piping and plumbing. Since energy input from pumps are contrary to the objective of the passive system, all plumbing must operate by gravity and therefore is buried near the bottom of the system creating a much more difficult and costly installation. Therefore, systems that rely on buried plumbing should be avoided. Currently, the cost of most cassette systems is many times the cost of a simple barrier wall. Complex cassette systems may also involve continued maintenance and repair, further increasing costs. Still, the idea of cassette systems seems to hold promise, but needs more development. One of the cassette systems that may prove cost-effective is to combine containment with PRB treatment. This is accomplished by encircling the contaminated area with a slurry wall, thereby providing containment and then installing a factory built self-contained vessel in and through the slurry wall [10]. This type of system could be used to retrofit many sites (e.g. landfills, facility closures, etc.) that currently rely on pump and treat to handle the small volumes of infiltration and groundwater that builds up inside the slurry wall. Although potentially applicable in some situations, it is anticipated that for most plume remediations, the additional cost and risk involved in constructing removable cassette systems will not compare favorably with the maintenance cost of completely removing and replacing the reactive materials in a simpler gate or wall.

4. Construction considerations

A variety of methods can be used to install PRBs in the subsurface. The choice of method depends upon the depth and thickness of the treatment zone, safety considerations, the geologic site conditions and construction costs. In order to control costs, the construction method should (1) maintain the dimensions of the installation to avoid waste of costly reactive materials, (2) avoid dewatering and subsequent treatment of contaminated groundwater during construction, and (3) ensure a rapid, simple construction sequence. After technical factors are determined (i.e. barrier material, depth, thickness and length), the most important cost and construction factors are soil conditions and safety. The construction method of choice should result in the best combination of minimal risk to site workers, low cost and high quality. For shallow installations (less than about 4 m) in stable soils nearly any method may be usable, but for deeper installations, or in problem soils, the cost of construction can vary widely depending on the method, expertise of the contractor, type of soils, groundwater conditions, and the perceived risk of injury to site workers. In the United States, due to a history of accidental death and injury in excavations from poor safety practices, excavations in unstable soils and all open excavations deeper than 6 m require the on-site supervision of a responsible, professional engineer. Designers and engineers who ignore safety considerations can be found liable for unnecessary injuries. Therefore, the reasons for using geotechnical methods extend beyond technical considerations and should be the concern of all engineers including builders of PRBs.

Early installations of PRBs usually relied on conventional construction methods at shallow depths. Typical methods involved trench boxes or steel sheeting and shoring. While sheet piling maintains the dimensions of the treatment zone during excavation and backfilling, trench boxes are designed only to protect the workers in the box and have almost no effect on trench width. After backfilling inside sheeting or trench boxes, the steel is removed and groundwater allowed to flow through the treatment zone. Despite the relative simplicity of these installations, there have been cases where soil conditions have resulted in difficulties. One of the greatest problems with sheet pile installations is in penetrating hard layers, rock or boulders. Other potential difficulties with conventional sheeting and shoring methods include: densification of granular soils due to pile-driving vibrations thus limiting permeability; smearing of cohesive soils from pile-driving limiting permeability; the thinning of reactive media dimensions due to vibration; toxic fumes released while installing shoring; pumping and treatment of dewatering fluids; greater than required width of the excavation; limited effective depth; a relatively lengthy construction period; and the high cost of capital and labor.

5. Biopolymer slurry as an installation aid

Construction methods are already in common use in civil engineering for creating controlled, narrow, installations without area dewatering. These methods rely on injection (e.g. grouting, deep soil mixing) and/or ‘liquid shoring’ (slurry trenches) to avoid most of the usual construction limitations. Geotechnical construction methods require the reactive material be injected as slurry or submerged through slurry. To be effective, the slurry must not affect the long-term conductivity of the soil or diminish the reactivity of the media. Recent studies by the University of Texas [13] and the University of Waterloo [14] and completed pilot projects (described below) have shown that reactive barriers of granular iron can be installed using a biodegradable polymer (BP) slurry (guar gum) without significantly decreasing the reactivity or long term treatment characteristics of the granular iron. Research in this area will continue but, the safety, cost savings, and utility of the BP slurry as a construction aid can be expected to contribute to less costly PRB construction.

Biopolymer slurries can provide a number of characteristics for the enhancement of the excavation and material installation process. Polymers provide efficient viscosity production and low solids levels for use in grouting to suspend granular iron for injection or as liquid shoring for trenching. Suitable trenching polymers stabilize the soils, prevent fluid loss, suspend cuttings, and are easily broken down or reduced to simple compounds for disposal or for natural in situ degradation by native soil microorganisms.

The most common polymer for liquid shoring is guar gum. It is tolerant of salt solutions, low cost, requires simple maintenance and easy to breakdown [15]. Guar gum is a naturally occurring carbohydrate polymer (combination of mannose and galactose sugars in long linear chains) derived from guar beans. While the slurry formulation is much more complex than bentonite (up to seven additives may be needed), there are specialty contractors available in North America that are experienced with guar gum chemistry and use. The guar gum slurry does not form a cake that can plug soil pores. Guar gum slurry is broken down by naturally occurring microorganisms or by introducing enzyme compounds and bleach. Residual by-products (prior to consumption by soil microorganisms) are simple sugars and water. Guar gum is generally regarded as safe and a FDA-approved food additive.

The challenge when using BP slurry in construction is to keep the slurry active long enough to complete the required construction. Without additives, the slurry will only remain active for a few hours. With additives (biocides and/or pH controls) the active life of the slurry can be extended by about a week, while continually replenishing with new slurry. While BP slurry is resistant to most contaminants, hot weather and concentrated microorganisms (e.g. septic field, buried wood shavings, etc.) can create a situation in which stability is much more difficult to control.

6. Grouting installations

Grouting methods have been used on pilot projects to inject granular iron and create reactive walls. Grouting holds the promise of permitting the installation of deep barriers (deeper than 30 m) on small sites with congested access, because the equipment is usually relatively small and easily mobilized. Two methods of grouting seem to be most compatible with PRBs: jet grouting and hydraulic fracturing. Both methods use BP slurry to suspend the granular iron during construction. Jet grouting has been used experimentally (above the groundwater table) and verified by uncovering and examining the resulting treatment. Experimental PRBs have attempted to create a thin wall (about 4 cm thick) in intersecting panels by directing a very high pressure (35 MPa) grout stream bilaterally while withdrawing the drive stem vertically at a slow, controlled rate. The primarily limitations with jet grouting are difficulty to ensure continuity of the wall and the high cost. Experimental PRBs created by jet grouting have shown promising results, but again, most early tests have been in nearly ideal soil conditions at shallow depths.

Hydraulic fracturing is another grouting method that has potential advantages over other methods especially at significant depths. Vertical treatment zones can be installed using hydrofracturing. Vertical hydrofracturing uses a specialized tool to orient the vertical fracture and initiate the fracture process. The tool is placed into boreholes spaced at about 5 m intervals to the desired depth and the interval for fracturing isolated by packers. An iron-biopolymer slurry is then pumped under low pressure into the formation. The slurry is used as a fracturing fluid to separate the soil creating an iron treatment zone a few centimeters in width. Several fractures propagated from boreholes located along the line of installation coalesce to create a PRB (i.e., a thin vertical plane of granular iron). The dimensions of the wall created by this method are verified by hydraulic pulse interference testing. This technique has been used at a Superfund site in New Jersey to install two treatment walls from 5 to 15 m below ground surface [16]. The first wall was 46 m in length and a second wall placed downgradient of the first was

27 m in length. The second wall was intended allow higher VOC concentrations in the middle of the plume to degrade and to provide additional residence time. Preliminary results from this project indicate the method was successful. Concerns with the continuity and width of the installation resulting from this method must still be independently verified.

Another method similar to grouting which has recently been pilot-tested is the vibrating beam wall [17]. With this method, a hollow mandrel is driven into the ground with a vibratory pile-driving hammer to create a thin overlapping treatment zone. Once the maximum depth of the treatment zone is reached, iron is poured down through the mandrel. Granular iron fills the void as the mandrel is withdrawn. The process is then repeated with the second penetration being driven to overlap the previous. The PRB formed typically ranges from 5 to 15 cm thick. The vibrating beam method was demonstrated in October 1997 at a Cape Canaveral, FL site. Three walls were constructed to a depth of 14 m. Each wall was about 10 cm thick giving a total thickness for groundwater flow of 30 cm. Early results tend to indicate that this method was successful in sandy soils. Concerns over continuity, alignment, and densification of adjacent soils, due to vibration, and the creation of a less permeable zone that directs groundwater away from the PRB, still must be addressed.

7. Continuous trenching machine installations

Continuous trenching machines have been used for several years to install horizontal groundwater collection drains and impermeable barriers. These machines allow simultaneous excavation and backfilling without separate shoring. Excavation is performed by a cutting chain immediately in front of an attached trench-box (or ‘boot’) which extends the width and depth of the finished treatment zone. As the trencher moves forward removing the soil, iron is added to the boot, backfilling the trench and creating a continuous treatment zone. Trenchers are available to install treatment zones from 0.3 to 1 m in width and to depths of 7 m. Pre-excavating a bench on which to operate the trencher from lower elevation (groundwater conditions permitting) may extend the total depth. Continuous trenching was first used in 1996 to install a granular iron PRB at a site in North Carolina with nearly ideal soils. About 400 metric tons of iron was placed in a trench 46 m long and 7 m deep in 1 day [18]. At another site in Oregon, a funnel and gate system was constructed using a continuous trencher. However, the rocky soils at the site proved to be less than ideal. Although the planned thickness of the PRB and the installation equipment was 45 cm, only a 23-cm thick barrier could be installed. Boulders were also encountered which damaged the equipment, contributing to an extension of the schedule. After a redesign of the system, the project was completed using both a hydraulic excavator and the trencher, but at an increased cost [19]. At depths less than about 6 to 9 m the continuous trencher can be fast and cost-effective, but only when the soil conditions are suitable (i.e. sandy, limited clay and silt, no boulders). Local knowledge of site conditions is often as valuable as limited exploratory borings.

8. Slurry trench installations

Slurry trenching is a well-known technique, illustrated in Fig. 3, for creating impermeable barriers such as those required for the funnel walls of funnel and gate systems. During excavation a slurry of water and bentonite clay plugs the soil formation and provides liquid shoring. The excavation volume is replaced by a permanent backfill of soil–bentonite or cement–bentonite. With biopolymer slurry, guar gum (a BP) replaces the bentonite clay, permitting the construction of permeable zones such as the gate section of a funnel and gate system. The use of biopolymer slurry is a natural outgrowth of bentonite slurry trenching and oil field drilling fluids technology. Biopolymer liquid shoring has been used to construct trenches up to 25 m deep and typically from 0.5 to 1.5 m wide [20]. Slurry trenches have been installed up to 3 m wide and 120 m deep. In the USA, most BP trenches have been installed as lineal drains to collect contaminated groundwater. A picture of a typical BP trench under construction is shown in Fig. 4.

Trenches constructed with BP slurries have a controlled width and easily verified continuity. As the trench is excavated, biodegradable slurry provides liquid shoring and stabilizes the trench walls while the excavator removes the soil. Dewatering is not necessary with slurry trenching. Granular iron can be placed into the trench through the slurry by tremie methods, or by displacement using a gradual slope. After treatment and natural degradation i.e. the BP slurry degrades, allowing groundwater to pass through the reactive zone.

A granular iron PRB using biopolymer slurry was installed at the DOE Oak Ridge National Laboratories in late 1997 [21]. On this project, a conventional excavation failed, and therefore, the BP method was selected by necessity. A BP trench 6 to 9 m deep and 67 m long was constructed over a single weekend.

The BP trenching method has the potential to be one of the most economical and utilitarian installation methods for PRB installation. The continuity of slurry trenches is

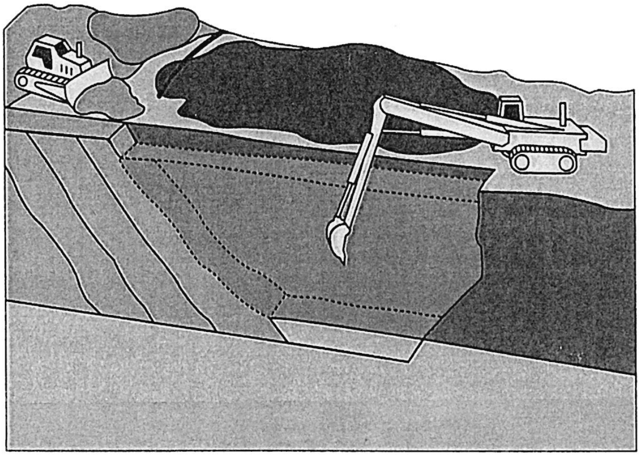

Fig. 3. Schematic of slurry trench construction.

Fig. 4. Biopolymer slurry trench construction.

superior to other methods, and the safety, speed and depth capability make these trenches cost-effective in nearly any soil type. Rocks and boulders that limit other methods can be removed from slurry trenches at much less cost than with any other method. Experienced slurry trench contractors are required to ensure proper control of the construction and slurry. Increased use of this method is expected.

9. Drilling and deep soil mixing methods

Drilling and deep soil mixing methods have been used to install circular columns of reactive materials. In certain cases, a pattern of overlapping columns or columns combined with impermeable walls can be an economical method to install funnel and gates. Truck-mounted caisson drills can be used to create columns with diameters in the range from 0.5 to 2.5 m. Drilling methods usually involve driving a large circular casing into the ground to the required depth and augering out the native material. The hole is then backfilled with iron and the casing removed. A less costly method is to use a biopolymer slurry, as liquid shoring, instead of the casing. Crane-mounted equipment is available for installing larger diameter columns. Overlapping or tangential columns can be used to create longer or larger treatment zones. The caisson installation method was used at pilot projects in New Hampshire to install a single 2.5 m diameter treatment gate to a depth of about 12 m [22], and at Dover AFB to install two 2.5-m diameter gates to a depth of about 15 m.

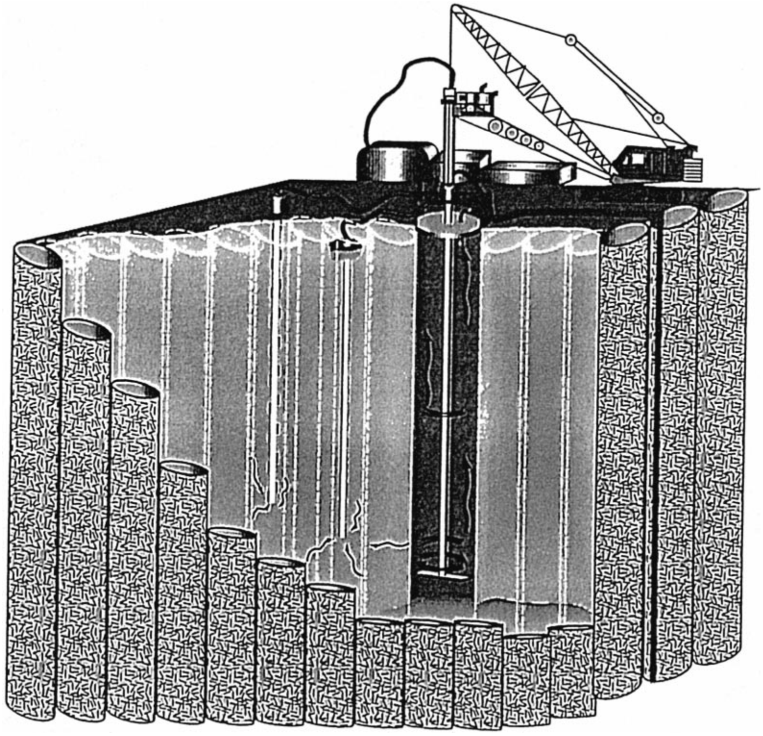

Fig. 5. Schematic of deep soil mixing.

Deep soil mixing is a modified caisson method which mixes the soils with a slurry, in situ and without excavation. The reactive material is injected through the hollow kelly bar as the mixing tool penetrates the soils (see Fig. 5). The reactive material must be in the form of slurry (e.g., granular iron, guar gum, and water). Pressurized air or steam may be used to aid penetration and mixing. Because the mixing is performed without an excavation, the amount of granular iron injected must be limited or more soil must be removed. Contaminated soil, as well as groundwater, can be treated in this manner. On a recent project in heavy, clayey soils in Illinois, granular iron was added at the rate of 5% by weight to treat tetrachloroethene and carbon tetrachloride contamination up to 10 m deep [23].

10. Installation methods and costs

The cost of PRB installation is a function of geology, design and construction factors. The overall costs of different installation methods can be compared by assuming material costs and access conditions are similar, as presented in Table 1 [24]. However, impact or additional costs from different methods will vary according to equipment and technique and will affect overall costs. For example, sheeting and shoring will necessi-

Table 1
Typical reactive barrier installation costs

Installation method	Mobilization costs	Minimum thickness (m)	Maximum depth (m)	Range in costs (US$/m^2)
Sheet and shore	Medium	1.3	12	150–400
Trench box	Low	1.3	6	50–125
Continuous trencher	High	0.3	7.5	50–300
Jet grouting (columns)	Low	0.6	30	200–1000
Deep soil mixing	Very High	0.75	30	90–200
Biopolymer trench	Medium	0.5	25	40–125

Costs do not include materials (sand and iron), mobilization, or site preparation including pre-excavation or benching.

tate a wider excavation and thus, excess soil for disposal. Continuous trenchers may be economical for one site, but on another site with boulders or harder soils, the impact costs from the difficult excavation may be excessive. BP trenches are generally economical, but the trench spoils will be saturated from the slurry excavation and may require additional handling prior to disposal. Impact costs are often related to site specific conditions as well and usually must be assessed separately on each project.

Construction costs are strongly related to time for the installation. For most shallow trench installations, the continuous trencher or the BP trenching method is the fastest and usually most economical due to their greater speed of installation. As the depth of the installation increases, deep soil mixing becomes more attractive and the continuous trencher becomes inadequate. Grouting installations are the most expensive method, but can be attractive for very deep installations, for very thin walls, or when the surface access is obstructed. Large gates can be installed economically by caisson drills, especially when the number of columns is limited and mobilization costs for other methods are excessive. The combination of BP trenches with slurry walls for funnel and gate construction can eliminate one mobilization cost (since the same equipment can be used for both) and provide a range of wall widths and depths for a wide variety of soil types.

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