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Alternative Methods for Fluid Delivery and Recovery

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Center for Environmental Research Information
Office of Research and Development
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Notice

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Chapter 1
Introduction

Controlling subsurface fluids is among the highest priorities in managing sites with in situ contamination. Some applications direct fluid movement continually inward towards the site, whereas others attempt to recover contaminants and, ultimately, close the site. Both these types of applications use physical methods of delivery and recovery, perhaps in conjunction with other methods, to meet their respective goals. Probably the most common physical system used to recover fluids at contaminated sites is a vertical well with a submersible water pump. However, this system is by no means the most effective in every situation. Therefore, this manual focuses on alternatives to conventional applications of vertical wells—alternatives that improve performance or reduce cost.

Developments in drilling technology over the past decade have resulted in considerable improvements. For example, technological advancements now allow wells to curve to a horizontal orientation, potentially placing great lengths of screen in a contaminated zone and offering several additional advantages over their vertical counterparts. Other developments involve methods of fracturing rock and soil to improve the performance of vertical and, in some cases, horizontal wells. This technique is particularly suited to increasing recovery from low permeability formations, but it also has some specialized applications. Trenches filled with gravel have long been used for dewatering, and they can still be a valuable option at a contaminated site.

This manual presents these three alternative methods of enhancing delivery and recovery. The scope of this document is confined to physical enhancement techniques. For this reason, detailed discussion of chemical methods (e.g., surfactant flushing) and thermal methods (e.g., steam stripping) has been omitted. These chemical methods are mentioned, however, because the alternative methods can be used in conjunction with a variety of other processes, including flushing and steam stripping. In fact, nearly any in situ method of remediation that involves subsurface fluid flow either has been or could be used with the methods described herein. Additional information on related technologies is available in the following U.S. Environmental Protection Agency (EPA) documents: *Handbook on In Situ Treatment of Hazardous Waste Contaminated Soils, Subsurface Contamination Reference Guide, Leachate Plume Management*, and *Evaluation of Ground-Water Extraction Remedies*, Volumes 1-3 (1-4). Additional information related to the existence, movement, and transport of ground water is described in Volumes 1 and 2 of the EPA document *Ground Water* (5, 6).

1.1 Role of Alternative Methods of Delivery and Recovery

Alternative methods of delivery and recovery are intended to improve the performance of remedies ranging from hydrodynamic containment, which arrests offsite migration, to restoration, which reduces contaminant concentrations. The methods are applicable during interim measures, in particular by improving the effectiveness of containment, and they also can augment the performance of a variety of remedial actions selected as possible long-term remedies.

1.1.1 Containment

Recent studies (4) have evaluated the performance of ground-water extraction systems. These studies have identified factors related to hydrogeology, contaminant properties, and system design that may impede the ability of those systems to reduce concentrations to targeted values over the entire area of contamination. Heterogeneities, such as natural fractures, karstic features, or variations in stratigraphy, result in preferential flow paths between wells, thus limiting recovery capabilities. Moreover, nonaqueous-phase liquid (NAPL) is present in the subsurface at many contaminated sites (7, 8) and, with components of the NAPL slowly dissolving in ground water, may act as a persistent source of contamination.

Those issues have led to a higher appreciation of the difficulty of remediation at some sites, and a recognition of the current technical impracticability of complete remediation at other sites (9). Nevertheless, the ability to halt migration and prevent the spread of contamination is well within the scope of current technology. Thus, emphasis grows on expeditiously implementing systems to halt dissolved phase migration by controlling hydraulic gradients early in the investigation of a site. Aggressively pursuing free-phase NAPL recovery also is recommended at the earliest possible time to reduce the potential for further contamination. Interim measures must be coordinated with final remedies so that they constitute the first phase of the overall remedial strategy. Accordingly, containment and source recovery during interim measures are a viable method of risk reduction at many contaminated sites.

The effectiveness of interim measures and the extent to which they reduce risks of exposure are based on their performance. In many cases, systems of alternative methods improve the ability to control hydraulic gradients beyond the capabilities of vertical wells. Central to improved performance is the geometry of flow fields that the systems produce. Whereas vertical wells are limited to producing radial flow (in the absence of regional flow), horizontal wells and trenches produce linear flows in a horizontal plane, and horizontal fractures produce vertical flows. This expands the versatility of containment systems, allowing them to be tailored more closely to the configuration of the site. An additional benefit of the alternative methods is the improvement in the amount of fluid recovered per unit of power. Increased values of specific capacities occur when using enhanced systems in productive aquifers. Moreover, in tight formations where recovery typically occurs at fixed drawdown, the enhanced systems are capable of increasing the discharges compared with conventional vertical wells. Where impenetrable surface structures cover NAPLs or aqueous plumes, horizontal wells offer the capability to recover contaminants close to their source.

1.1.2 Restoration

Fluid recovery by pumping vapor, aqueous, or nonaqueous phases may be sufficient to restore some sites, but heterogeneities, adsorption, low vapor pressure, and other factors conspire to limit the effectiveness of fluid recovery alone as a remedial tool. A wide range of other methods has been and are currently being developed to accelerate in situ remediation. Some methods involve injecting liquids or vapors that carry nutrients and electron acceptors to stimulate in situ organisms, thereby promoting contaminant degradation. Other methods involve degrading contaminants by injecting an oxidant or mobilizing the contaminant with a surfactant to enhance recovery. Another approach is to heat the subsurface by injecting steam or hot air to vaporize organic compounds.

This diverse range of technologies shares the common need to control the flow of subsurface fluids. Where the magnitude or uniformity of fluid flow is impaired, the performance of a conventional remedial method can be significantly reduced. Formations of low permeability or those marked by heterogeneities or other hydrologic complexities present particular difficulties. Stagnation zones in the flow field resulting from well placement and design further limit fluid flow. In view of these issues, the alternative methods described here can be a valuable asset when used in conjunction with other remedial methods involving fluid flow. In this application, the primary purpose of the delivery and recovery techniques is to improve the effectiveness of remedial methods involving fluid flow. Improved effectiveness reduces costs or may allow a technique to be successfully applied under conditions where it would otherwise be unsuccessful.

1.1.3 Technical Impracticability

Currently, it is technically impracticable to restore some sites to accepted standards due to the presence of immobile NAPL, strongly sorbed contaminants, formation heterogeneities, or other factors (9). As a result, the methods described herein may be no better than vertical wells in addressing limitations to restoration at some sites. Alternative methods of delivery or recovery should be implemented only when they provide a substantive benefit to technically achievable goals.

1.2 Overview of Contents

The handbook contains chapters describing:

- Horizontal wells
- Induced fractures
- Interceptor trenches

Each chapter contains a description of construction methods, with particular emphasis on factors to consider when selecting the method. The factors affecting design are summarized, with particular emphasis on the pattern of flow induced by the method, the geologic and hydrologic site conditions that affect performance, and access requirements for site implementation. In addition, an overview of applications suggests various possibilities, although by no means have all the potential applications been described. Each chapter closes with several case histories describing site conditions, system design, and results. Cost information is provided based on published or informally reported descriptions. The cost of a particular technique can vary greatly, however, and the reader should use the data given here as a preliminary guide to be supplemented by the cited references and site-specific vendor estimates.

1.3 Summary of Important Issues

Horizontal wells, induced fractures, and interceptor trenches present slightly different options for controlling subsurface fluids, and each has slightly different advantages and disadvantages among the issues facing applications at contaminated sites. Table 1-1 summarizes essential issues.

Table 1-1. Issues Affecting Application of Alternative Methods for Delivery or Recovery

Issue	Horizontal Well	Induced Fracture	Trench
Access			
Fragile structures over target	● Minimal surface disturbance	☐ Evaluate effects of surface displacement	☐ Excavation expected to be infeasible
Poor access over target	● Standoff required	○ Possible with horizontal well	☐ Excavation expected to be infeasible
Depth			
<6 m	● 1 m minimum depth	● 1–2 m minimum depth	● Installation with common equipment
6–20 m	● Cost of guidance system increases at >6 m	●	⊙ Excavation costs increase with depth
>20 m	● No depth limit within environmental applications	● No depth limit within environmental applications	○ Specialized excavation methods required
Recovered Phase			
Aqueous	●	●	●
LNAPL	○ Requires accurate drilling; best if water table fluctuations are minor	⊙ Best with access to individual fractures	● Widely used to ensure capture; accommodates water table fluctuations
DNAPL	⊙ Requires accurate drilling and site characterization	○ Caution; steeply dipping fractures may cause downward movement	● Assuming mobile phase present and accurately located
Vapor	● Consider omitting gravel pack to save costs	● Best with access to individual fractures	⊙ Requires tight seal on top of trench
Geology			
Normally consolidated clay	⊙ Smearing of bore wall may reduce performance	○ Induced fractures may be vertical and limited in size	● Large discharge expected relative to alternatives
Swelling clay	⊙ Smearing of bore wall may reduce performance	● Relatively large, gently dipping fractures expected	● Large discharge expected relative to alternatives
Silty clay till	⊙ Smearing of bore wall may reduce performance	● Relatively large, gently dipping fractures expected	● Large discharge expected relative to alternatives
Stratified sediment or rock	○ Anisotropy may limit vertical influence of well	⊙ Stratification may limit upward propagation and increase fracture size	● Good way to access many thin beds or horizontal partings
Vertically fractured sediment or rock	● Orient well normal to fractures when possible	⊙ Good where induced fractures cross-cut natural fractures (overconsolidated sediment and rock)	⊙ Orient trench perpendicular to natural fractures when possible
Coarse gravel	○ Possible problems with hole stability; penetrating cobbles	☐ Permeability enhancement may be unnecessary	● Stability a concern during excavation
Thick sand	⊙ May be difficult to access top and bottom of formation; hole stability problems	☐ Permeability enhancement may be unnecessary	● Stability a concern during excavation
Rock	○ Feasible, but drilling costs more in rock than in sediment	● Widely used in oil, gas, and water wells drilled in rock	☐ Excavation difficult but blasting possible to make trench-like feature
Availability	10 to 20 companies with capabilities; nationwide coverage but may require equipment mobilization	Several companies offer service; nationwide coverage with equipment mobilization	Shallow trench (<6 m) installation widely available from local contractors; deep trench will require mobilization
Current Experience (Approximate)	150 to 250 wells at 50 to 100 sites	200 to 400 fractures at 20 to 40 sites	1,000+ trenches at many hundreds of sites

Key
● Good application
⊙ Moderately good
○ Fair, with possible technical difficulties
☐ Poor; not recommended using available methods

1.3.1 Access

Access to the ground overlying the contaminated region is commonly restricted, or access may be obstructed by fragile structures such as product lines, tanks, and buildings. Horizontal wells are ideally suited to address access problems because the drill rig can be located at some distance from the obstructed area. Alternatively, induced fractures created from vertical wells are limited to areas where access allows creation of the well. Fractures have been induced in the vicinity of horizontal wells, although experience with this application for environmental purposes is currently limited. Because induced fractures displace the ground surface, this technique may be inappropriate where such displacement could damage overlying structures. Finally, the excavation required to create trenches precludes their application in many areas of limited access.

1.3.2 Depth

Depth is a minor factor for horizontal wells and induced fractures; both can be created at depths far greater than those that environmental applications require. Minimal depths of 1 to 2 meters (3.3 to 6.6 feet) are commonly required to contain induced fractures within the subsurface. Drilling horizontal wells requires similar minimum depths if high pressure jets are used to cut the bore. The current maximal limit of radio-beacon guidance systems, which are the most economical method of guiding horizontal wells, is 6 to 8 meters (19.7 to 26.2 feet). Therefore, creating a horizontal bore deeper than 6 to 8 meters (19.7 to 26.2 feet) requires a more sophisticated and expensive guidance system. Trench depth greatly influences cost, because deeper trenches increase both the volume of contaminated soil that must be handled (and possibly disposed of) and the cost of excavation. The maximal limit of conventional excavation equipment is approximately 4 to 6 meters (13.1 to 19.7 feet), so creating deeper trenches requires specialized equipment. Currently, trenchlike structures 100 meters (328 feet) or more in depth can be created using specialized excavators (Table 1-1).

1.3.3 Recovered Phase

All the alternative methods can recover aqueous phase contaminants, but they may differ in their ability to recover NAPL. It is feasible to recover free-phase light (LNAPL) and dense (DNAPL) nonaqueous-phase liquid using a horizontal well, but this application requires particularly accurate depth control during drilling, as well as a detailed understanding of each site's subsurface variability. Moreover, even with accurate placement of the well, rises and falls in the water table—and thus the LNAPL layer—can significantly hamper recovery of LNAPL. Induced fractures can improve the recovery of LNAPL from tight formations. In addition, creating several fractures over a range of depth can account for water table fluctuations. Trenches are widely used to recover shallow LNAPL because they can intercept lateral migration and accommodate changes in the water table.

Each of the three methods can be used to increase recovery of DNAPL. However, the benefits of recovering some DNAPL must be balanced against the risk of aggravating the recovery of liquid that remains in the ground. Addressing this issue entails locating the DNAPL, which is a formidable task unto itself, and using methods that limit the creation of vertical channels in the area containing DNAPL. Horizontal wells offer the possibility of accessing a DNAPL layer without creating a vertical conduit. Conversely, the location of induced fractures cannot be determined precisely, so it is possible that they will create pathways for downward migration. Moreover, methods of sealing induced fractures remain untested. Therefore, the feasibility of abandoning the fractures is currently unknown. Trenches also create vertical channels, but the trench location can be determined precisely, and methods of sealing and abandoning trenches are available. Feasibility tests, modeling, and pilot studies are recommended before conducting any DNAPL recovery project.

1.3.4 Geology

It is possible to use horizontal wells in fine-grained sediments, although smearing along the wall of the bore may require aggressive development. Anisotropy produced by stratigraphic layering limits the vertical influence of a horizontal well. In contrast, anisotropy produced by vertical fractures tends to enhance the performance of a well oriented perpendicular to the fractures. Although drilling through coarse gravel and rock is technically possible, these formations are relatively difficult to penetrate and thus increase the cost of the well. In thick sand, a horizontal well may present limited access to the upper or lower regions. Moreover, steering a directional bore is difficult in soft sand, so drilling accuracy may be compromised.

Induced fractures can increase the recovery of subsurface fluids from fine-grained sediments and particularly from overconsolidated deposits, such as glacial drift or swelling clay. However, induced fractures may tend to dip steeply in normally consolidated deposits, which can limit their size and effectiveness. Stratigraphic layering can inhibit upward propagation of an induced fracture and improve performance, even in normally consolidated formations. However, a horizontal fracture may offer little benefit in finely interbedded sands and clay. Where vertical fractures are the dominant flowpaths, induced fractures can be a benefit if they are flat-lying and cut across multiple natural fractures. In contrast, where induced fractures follow one vertical fracture, they may be of limited benefit. Both types of behavior have been noted. Highly permeable formations, such as sands and gravels, will benefit little from the permeability enhancement that induced fractures offer, although there may applications where treatment materials are injected into induced fractures in sand. Induced fractures are widely used to increase the discharge from wells in rock formations.

Trenches are suited to applications in a wide range of geologic formations. In fine-grained sediments, excavation is relatively easy, and trenches offer significantly greater discharge than vertical wells. In stratified sediments, they can cut across and access multiple thin permeable beds. Of course, excavating rock is generally infeasible, although trenchlike features can be created using explosives placed in a line of vertical boreholes.

1.3.5 Availability

Horizontal wells, induced fractures, and trenches are all methods available within the United States and Canada. As of the summer of 1993, approximately a dozen companies had installed a horizontal well, with more entering the market since that time. Most companies that create horizontal wells for environmental applications are specialists in that market, although some are capable of vertical drilling or directional drilling for utility installation. Depending on the location of the site, drilling equipment may need to travel several hundred miles or more.

At least two companies specialize in designing and creating induced fractures for environmental applications, and several others offer fracturing capabilities along with other environmental services; these companies are capable of mobilizing within the United States and Canada. Hydraulic fracturing of water wells is available from well drilling companies in many locations, although their experience with environmental applications typically is limited.

Widely available excavation equipment can create relatively shallow trenches and should require minimal mobilization. Deeper trenches require the more sophisticated equipment and engineering capabilities that specialist construction companies can offer.

1.3.6 Current Experience

Approximately 150 to 250 horizontal wells have been installed during the past 7 years for environmental applications at 50 to 100 sites. The drilling capabilities used to install horizontal wells draw upon the experience from directional boring of hundreds of kilometers to install utility conduits and oil wells. Specialized drilling and completion methods designed to meet the challenges of environmental applications continue to be developed.

From 200 to 400 fractures have been created at 20 to 40 sites. Fracturing capabilities draw upon the experience of thousands of applications in the petroleum and water well industries and on the methods and effects of injection grouting. Because creating induced fractures requires particular sensitivity to site conditions, the methods of creating fractures and anticipating their performance for environmental applications continues to develop. This is the newest of the three alternative techniques discussed in this manual.

Trenches are widely used to recover contaminated fluids from sites. Experience includes more than 1,000 applications at hundreds of sites, making this the most mature of the techniques discussed here.

1.3.7 Operating and Maintenance Costs

Methods other than a field of vertical wells may reduce operating and maintenance (O&M) costs in many ways, such as by decreasing the number of pumps that must be used, reducing the time for routine sampling and measurement of water levels, and decreasing power consumption. Some maintenance aspects, such as reconditioning, may be more expensive for a horizontal well or trench than for a vertical well, although the cost on a per-well basis may be offset if the horizontal well or trench is equivalent to several vertical wells. One comparative study (10) found that the capital cost of one horizontal well was similar to five vertical wells, but the O&M cost for the horizontal well was less than one third that of the five vertical wells. In general, however, costs are sensitive to site conditions and design quality, and the relative economic advantages of the alternative methods are difficult to generalize.

1.3.8 Monitoring

Induced fractures and horizontal wells in some circumstances can provide better monitoring capabilities than vertical wells. Small induced fractures can be used to increase the area sampled and the fluid recovered by a monitoring well. This application is particularly attractive in fractured clay or rock, where it can be difficult to obtain a water sample of adequate volume from the formation. Horizontal wells present the possibility of monitoring beneath potential sources, such as tanks or lagoons, that cannot be penetrated by a vertical well.

In situ monitoring of the distribution of head or pressure when using alternative methods of delivery or recovery can be accomplished using vertical piezometers in much the same manner as monitoring recovery by vertical wells. One exception is during the resolution of vertical head gradients; these gradients can be important in the vicinity of an induced fracture, horizontal well, or trench that partially penetrates an aquifer but are often ignored when vertical wells are used. Head distributions caused by vertical wells are commonly monitored using piezometers with long screens, whereas vertical gradients can only be measured with clusters of multiple piezometers with short screens at different depths or piezometers with multiple ports separated by packers (11).

Monitoring the rates and concentrations of recovered fluids or the concentrations of compounds in the subsurface is independent of the method of recovery; similar sampling and analytical techniques are used for alternative and conventional recovery methods.

1.4 References

1. U.S. EPA. 1990. Handbook of in situ treatment of hazardous waste-contaminated soils. EPA/540/2-90/002.

2. U.S. EPA. 1990. Subsurface contamination reference guide. EPA/540/2-90/011.

3. U.S. EPA. 1985. Leachate plume management. EPA/540/2-85/004.

4. U.S. EPA. 1989. Evaluation of ground-water extraction remedies, Vols. 1-3. EPA/540/2-89/054b,c.

5. U.S. EPA. 1990. Handbook: Ground water, Vol. 1. Ground water and contamination. EPA/625/6-90/016a (September).

6. U.S. EPA. 1991. Handbook: Ground water, Vol. 2. Methodology. EPA/625/6-90/016b (July).

7. U.S. EPA. 1993. Evaluation of the likelihood of DNAPL presence at NPL sites. EPA/540/R-93/073.

8. Cohen, R.M., J.W. Mercer, and J. Matthews. 1993. DNAPL site evaluation. U.S. Environmental Protection Agency. Ada, OK.

9. U.S. EPA. 1993. Guidance for evaluating the technical impracticability of ground-water restoration. EPA/540/R-93/080.

10. Losonsky, G., and M.S. Beljin. 1992. Horizontal wells in subsurface remediation. Hazardous Materials Control Conference, New Orleans, LA (February).

11. Rehtlane, E.A., and F.D. Patton. 1982. Multiple port piezometers vs. standpipe piezometers: An economic comparison. Second Aquifer Restoration and Ground Water Conference, Columbus, OH (May 26-28), pp. 287-295

Chapter 2
Horizontal and Inclined Wells

Recent advances in directional drilling have forever changed the well's image. No longer must a well be a vertical cylinder; directional drilling methods can create wellbores with almost any trajectory. Wells that curve to a horizontal orientation are particularly suited for environmental applications.

Horizontal wells are not technically an innovation; the water supply industry has used horizontal wells for many years to collect water from beneath rivers and other bodies of water (1). However, these wells are drilled radially from large caissons, making installation expensive and rarely practical for environmental applications.

Directional drilling methods use specialized bits to curve bores in a controlled arc; trajectory is monitored with electronic sensors. This enables bores to be initiated at a relatively shallow angle from the ground surface and gradually to curve to horizontal (Figure 2-1). *Blind* wellbores terminate in the subsurface. In some cases, however, the well is turned upward and returns to the ground surface, which makes it accessible from both ends. This is called a *continuous* wellbore. Most horizontal wellbores are drilled in roughly a straight line, but lateral curves are certainly possible and may be important in certain circumstances.

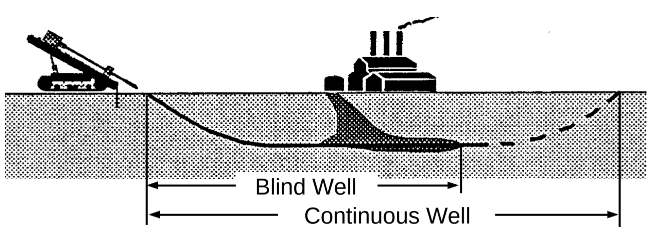


Figure 2-1. Horizontal well used to intercept a plume. The solid line represents a blind well; the solid line plus the dashed line represents a continuous well.

Directional drilling can create two basic types of bores:

- *Wellbores* preserve the permeability of the host formation.
- *Boreholes* penetrate the subsurface without particular regard to the permeability of the host.

Creating wellbores requires special methods to avoid or restore permeability damage, whereas methods used to create boreholes are less demanding.

Inclined, or slant, wells are installed in a straight wellbore typically created with conventional drilling equipment that is tilted. Inclined wells drilled with conventional drilling equipment cannot be horizontal if they originate from flat-lying ground.

In some cases, such as when drilling into a slope, an inclined well can be horizontal or even slant upward. Directional drilling equipment can create wells that duplicate the geometry of inclined wells.

The primary reason for including inclined wells in this chapter is that they have recently received renewed interest as a product of sonic drilling. This technique has the remarkable ability to create wellbores without drilling fluid and extraneous drill cuttings; all of the material in the path of the wellbore is collected as continuous core sample. These attributes make sonic drilling ideal for certain sampling and environmental drilling applications. Thus, the treatment of inclined wells in this chapter is limited to applications involving sonic drilling.

Because of its orientation, a horizontal well is particularly suited to recovering contaminants distributed as broad, flat layers (Figure 2-2a). Such a distribution may occur when LNAPL floats on a water table or when DNAPL accumulates on a low-permeability bed. Directional drilling can place 100 meters (328 feet) or more of well screen in the layer, whereas the screen of a vertical well may intersect less than a meter of an LNAPL layer. Often, when contaminants have moved with the regional flow, the compounds distribute as a long, narrow, roughly horizontal plume. A single horizontal well placed along the long axis of the plume (Figure 2-2b) offers an ideal geometry for recovering those contaminants.

In tight formations such as bedrock or till, where vertical fractures provide the primary flow paths, a horizontal well can intersect many vertical fractures (Figure 2-2c). This application facilitates access to the preferred flow paths, increases well discharge, and controls fluid flow in the formation (2, 3).

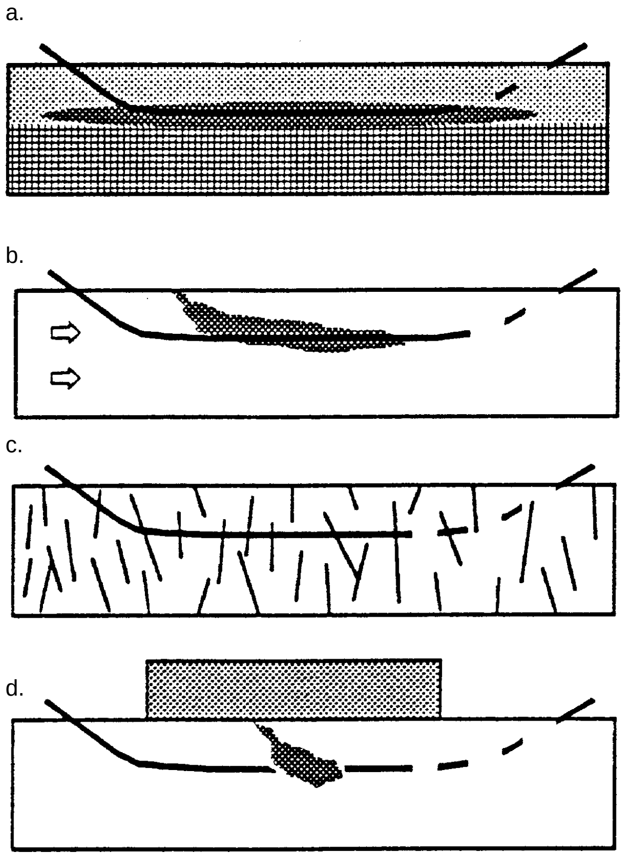


Figure 2-2. Some applications of horizontal wells: a) intersecting flat-lying layers, b) intercepting plume elongated by regional gradient, c) intersecting vertical fractures, and d) access beneath structures.

Some advantages of a horizontal well are unrelated to hydrologic performance. In many locations, such as beneath landfills, tanks, buildings, roads, lagoons, or bodies of water, access limitations prohibit entry by a drill rig, prevent penetration by a vertical hole, or restrict the aboveground facilities necessary for recovery operations. As a result, recovery, sampling, or monitoring with conventional drilling technology is difficult beneath many structures that may be sources of contaminants. Horizontal and inclined wells, however, overcome those difficulties by allowing the rig to be adjacent to the obstructing structure, and the wellbore to be created beneath it (Figure 2-2d).

This chapter contains four sections. The first section describes current methods of constructing wellbores and completing horizontal wells. The second section summarizes technical and economic factors that need consideration when planning to use horizontal wells at a contaminated site. Following this is a section that presents some possible environmental applications. The chapter closes with an extensive summary of environmental projects that have used horizontal wells and a detailed description of four case histories.

2.1 Well Construction

Constructing a horizontal well entails directionally drilling a wellbore and placing perforated tubing in the wellbore to hold it open and provide access to subsurface fluids. The well is developed to increase permeability in the vicinity of the bore, and a pump is installed to recover fluids. Details of this process follow.

2.1.1 Directional Drilling Components (or "Equipment")

Directional drilling uses three specialized components:

- A drilling rig to power the system
- A bit to create a curved hole
- A guidance system to locate and steer the bore

2.1.1.1 Directional Drilling

Directional drill rigs that currently create horizontal wells for environmental applications typically consist of a carriage that slides on a frame and holds the drill rods at an angle of 0 to 45 degrees (Figure 2-3). In most cases, hydraulic power energizes a motor on the carriage and rotates the drill rods. A chain drive, rack and pinion drive, or hydraulic cylinder may push or pull the carriage to advance or retract the drill string. A pump on the rig, capable of handling slurries at 1 to 30 megapascals (MPa) (145 to 4,351 pounds per square inch [psi]), is typically used to inject drilling fluid.

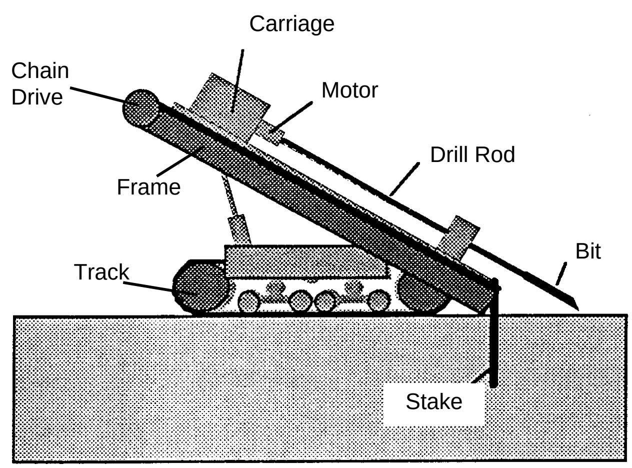


Figure 2-3. Directional drilling rig.

Drill rigs are available in a range of sizes and are distinguished chiefly by the torque and push/pull force they provide (Table 2-1). Despite the range in sizes and various details that manufacturers offer, the rigs share some common features. The drill rig provides thrust to the drilling tool and pull-back to the drill string. When drilling a vertical well, the weight of the drill motor and the drill string provide the downward force on the drill bit. In contrast, when drilling a directional wellbore, the drill

Table 2-1. Specifications of Directional Drilling Rigs (May 1994)

	Mini Rigs	Midi Rigs	Maxi Rigs
Thrust/Pullback	< 66.7 kN (15,000 lbs)	66.7-444 kN (15,000-100,000 lbs)	>444 kN (>100,000 lbs)
Maximum Torque	2.7 kN·m (2,000 ft·lb)	2.7 kN·m - 27 kN·m (2,000-20,000 ft·lb)	27 kN·m (20,000 ft·lb)
Drilling Speed	≥130 RPM	130-100 RPM	<100 RPM
Carriage Speed	>30 m/min	28-30 m/min	<28 m/min
Carriage Drive	Cable or chain	Chain or rack and pinion	Rack and pinion
Drill Pipe Length	1.5-3 m	3-9 m	9-12 m
Drilling Distance[a]	<200 m	200-600 m	>600 m
Power Source	<150 HP	150-250 HP	>250 HP

[a] Assumes nominal 12-inch wellbore, which is the effective maximum diameter wellbore for a mini-drill rig.

rig—typically a cable, chain, or rack and pinion system—must provide the forward force on the drill string. The rig must be anchored to provide a reaction against which the mechanical system on the rig can operate. Anchoring is typically accomplished by driving stakes through openings at the front of the rig (Figure 2-3) and attaching the drill rig to a buried weight ("dead man") or simply attaching it to a large, heavy piece of equipment on the surface. The drill rig must provide sufficient thrust to advance the drill string the full length of the proposed wellbore, and sufficient pulling force to retract casing into the completed wellbore. The relationship between thrust and drilling distance depends on the formation type and use of drilling fluids.

The drill rig must also provide torque to the drill string. Most drilling methods require that the drill string rotates while it advances into the wellbore in order to reduce friction on the drill string. The drill rig must have sufficient capacity to overcome wellbore friction and supply the necessary torque to the drill string throughout the proposed length of the wellbore.

In addition, some rigs use pneumatic or hydraulic hammers to help advance the drill string, a method rarely used for environmental applications. In most cases, the hammers are mounted on the drill rig, but several manufacturers also offer downhole hammers.

Some contractors have directional drill rigs of varying sizes, whereas others may only have one size of drill rig. In general, the midi-size rigs (Table 2-1) are the most versatile and can complete most projects.

The oil industry has used other methods of directional drilling, with perhaps the most notable technique using a high energy water jet to create the bore (4). This method employs a whipstock to bend continuous steel tubing in a tight arc (less than a 0.5-meter [1.6-foot] radius of curvature) at the bottom of a vertical hole. The result is a roughly straight horizontal hole extending radially from a vertical access bore. This geometry presents some advantages over the inclined entry rigs for applications where access is extremely limited. Although some have proposed environmental applications of this method (5), apparently no demonstrations have been conducted.

2.1.1.2 Creating and Steering the Wellbore

Directional drilling uses a downhole assembly that creates the wellbore and induces a curve in the trajectory. Wellbores are created by cutting the formation with a rotating bit, water jet, hammer, or combination of these. The trajectory is curved using a tool that is eccentric with respect to the axis of the drill rod. In some cases, there is a slight bend in the rod behind the bit, whereas in other cases the bit itself has a beveled surface. Most commonly, when creating directional wellbores, bits are driven by downhole motors, jetting tools, and compaction tools.

Downhole Motors. A downhole motor uses pressurized drilling fluid to rotate a cutting bit. The advantage of downhole mud motors is that they eliminate drill string rotation and make it possible to drill a wellbore with a short radius of curvature. Downhole motors are generally preferred when drilling rock or resistant sediments, where wellbore control is critical.

To curve the wellbore, a bent rod or "sub" is fixed behind the motor. Rotating the entire drill string slightly offsets the bent sub, causing the path of the wellbore to be approximately straight. Pushing the drill string without rotation, however, curves the wellbore by an amount dictated by the angle of the bent sub (Figure 2-4).

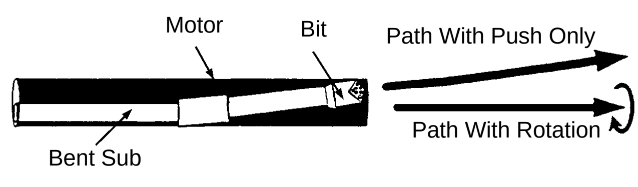


Figure 2-4. Directional drilling with a downhole motor.

Jetting Tools. Jetting tools use hydraulic pressure either to cut the geologic formation or to assist rotary drilling with bits. Water, mud, polymer, or other drilling fluid can be used to form the jet. The hydraulic jet is directed from either a bent housing or from a drilling fluid port on a drill bit that is attached to a bent subassembly. A pump on the drill rig controls the pressure of the hydraulic jet. To drill a curved section, the drill string follows the advancing bent subassembly along a curved path. To drill a straight segment of the wellbore, the drill string is rotated (in one direction or by alternating directions/every 180-degree turn); rotation prevents the hydraulic jet from having a preferred orientation, and the drill string will not deviate from the wellbore path.

Compaction Drilling Tools. A compaction drilling tool creates a wellbore by compacting sediments as it advances into the formation. The typical compaction bit resembles a wood chisel, with the beveled part of the chisel providing the eccentricity to curve the wellbore. Just as with the bent subassembly, rotation of a beveled bit results in a straight wellbore, whereas pushing the bit causes it to turn. Accordingly, compaction drilling requires significant torque and thrust by the rig at the ground surface. Compaction drilling is usually assisted by cutting the formation with a water jet or by advancing the drilling tool with a hammer. Water is used to help lubricate and cool the drilling tool, but neither drill cuttings nor drilling fluid return to the surface.

Steering during compaction drilling requires the resistance of the formation to be sufficient to bend the drill rods. In loosely consolidated sand, it may be difficult to steer using conventional beveled compaction bits, although some bits with enlarged cutting surfaces are available to make steering in soft formations easier.

2.1.1.3 Location and Guidance Systems

Typically, an electronics package placed behind the cutting head:

- Locates the end of the drill rod.
- Provides the azimuth and inclination of the bottomhole assembly.
- Provides the orientation of the drill face (bent subassembly).

This information, combined with the measured length of drill pipe, can be used to calculate the position of the bottomhole assembly. The most common guidance systems are magnetometer-accelerometer systems, gyroscopes systems, and electronic beacons.

Magnetometer-Accelerometer System. This system uses three magnetometers to measure the position (azimuth) of the tool in the earth's magnetic field and three accelerometers to measure the position (inclination) of the tool in the earth's gravitational field. The system sends information continuously to a surface computer that calculates and displays the tool azimuth, inclination, and drill-face orientation. An advantage of this system is that the location of the bottomhole assembly is available in real time.

If subsurface magnetic interference, for example from metal pipes or tanks, is suspected of influencing the azimuth readings, an electromagnetic secondary survey system may be used in conjunction with a magnetic guidance tool. The secondary system consists of a cable laid out on the ground in a rectangular configuration, with the well path running along the center of the long dimension of the rectangle. A direct current is applied to the cable, inducing an electromagnetic field of known intensity and size in the subsurface around the tool. The induced magnetic field generally is strong enough to overcome any indigenous magnetic interference, allowing the tool to display its location in the induced magnetic field. The cable is unobtrusive and can be used at most sites without fear that it will inhibit surface activities. The combination of a magnetometer-accelerometer tool and the secondary electromagnetic system provides the most accurate (plus or minus 2 percent of the vertical depth [VD]) guidance system for shallow directional drilling. The system loses accuracy at depths exceeding 35 meters (114.8 feet).

Gyroscope System. The gyroscope system is based on the same navigational principles used in guided missiles and airplanes. The system uses three gyroscopes to measure azimuth and three accelerometers to measure the inclination. Before the survey is made, the gyroscopes are aligned to true north at the ground surface. The gyroscopes detect any deviation from true north during the survey and relay the information to the surface, where a computer calculates the azimuth, inclination, and drilling tool orientation. This system is unaffected by magnetic interference and therefore may be used in areas that do not allow the use of a magnetic guidance system.

Electronic Beacon. The electronic beacon is a battery-operated sonde that sends a radio signal from the bottomhole assembly. A hand-held surface unit then locates the position of the beacon, calculates the depth to the beacon, and displays the drill-face orientation. This method is often called the "walkover" method because a technician carries the surface unit over the beacon. The system cannot be used in areas where surface obstructions prohibit access above the bottom assembly.

Electronic beacons were developed to use with directional drilling for utility installation. They are widely available and relatively easy to use, with satisfactory results. Widely available equipment can be used no deeper than approximately 8 meters (26.2 feet); however, recent advances in the technology provide walkover systems that can be used to approximately 17 meters (55.8 feet) in depth. Electronic beacons currently provide the least expensive method of locating and guiding directional wellbores. Vertical accuracy of current systems is at least within 5 percent of the VD.

2.1.2 Drilling Fluids

Drilling fluids have a variety of applications during directional drilling:

- Clean cuttings from the bit and the end of the wellbore, and transport the cuttings to the surface.
- Provide wellbore stability.
- Control subsurface pressures.
- Cool the drill bit and lubricate the drill string.
- Drive a downhole drill motor, if one is used.
- Ensure that formation information is obtained from cuttings, cores, or geophysical tools.
- Act as conduit for pressure pulses that communicate information from the guidance tool to the ground surface, if such a communication system is used.

Drilling fluids must provide these applications while minimizing both fluid loss to the formation and reduction in permeability around the wellbore. No single fluid readily meets these demands, requiring a tradeoff between drilling needs and treatment objectives.

Drilling needs may constitute a higher priority than well efficiency for many horizontal wells used for environmental applications. However, the drilling fluid should be compatible with well materials and formation soil and water. Drilling fluid that penetrates the formation can be difficult to remove and, thus, can have lasting negative consequences (6). For instance, the fluid may change the pH, redox potential, or ionic strength of the formation waters. These changes can cause minerals in the host formation to dissolve or precipitate. Clay-sized particles in some drilling fluids also increase the surface area available for precipitation of minerals. Depending on formation and drilling fluid chemistry, the minerals most likely to dissolve or precipitate are magnesium, aragonite, oxides, hydroxides of iron, and possibly dolomite (7). Drilling fluids that cause precipitation of minerals reduce pore space and permeability of the host formation (Figure 2-5). The worst place for reduced permeability is the vicinity of the wellbore because all the fluid that the well recovers must flow through this zone. Accordingly, it is critical to select drilling fluids and additives that minimize damage to the formation adjacent to the wellbore.

In addition to damaging the formation, it is possible for drilling fluids to contain contaminants that increase disposal costs and possibly contribute to migration or sorption of contaminants during drilling. Minimizing or eliminating liquid drilling fluids is the ideal. As mentioned above, compaction drilling techniques require a minimum amount of drilling fluid. Compaction drilling, however, is incompatible with some hydrogeologic conditions. Therefore, many horizontal environmental wells

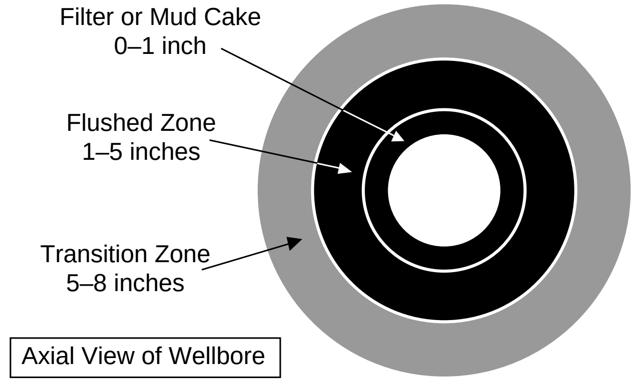


Figure 2-5. Potential damaged zones around a horizontal wellbore.

require fluids. Some experiments with air-based drilling fluids have been conducted in environmental directional drilling, and use of air to contain cuttings transported from the wellbore has recently been demonstrated (8). Investigation of cryogenic drilling fluids also is presently under way (9). Cryogenic drilling fluids have the advantage of freezing the wellbore wall to provide stability and improve sample recovery. In addition, they vaporize and minimize cross contamination after use.

Bentonite slurry and guar gum gel are the least expensive and most widely used drilling fluids. Many drillers are familiar with bentonite-based drilling fluid, which they can easily control to maintain a stable wellbore and efficiently remove cuttings. The major disadvantage is that this type of drilling fluid creates a mud cake that must be removed during well development to restore the original permeability of the formation. A selected drilling fluid should form an easily removed mud cake (less than a few millimeters thick).

Guar gum is a cellulose-like polymer derived from the guar bean and commonly used as a food additive. As a drilling fluid, guar gum is mixed with water to form a gel with the following strengths:

- It reduces friction on the drilling tool, thereby increasing drilling tool penetration rates.
- It lacks fine-grained clays that can clog formation pores.
- It either biodegrades naturally or it can be degraded with fluid additives.
- It is nontoxic.

Guar gum has several disadvantages, however:

- Biodegradation of guar gum can increase biomass in the vicinity of the wellbore; this can reduce permeability, which must be addressed during completion.
- Low gel strength can limit the ability to transport cuttings.

- Crosslinking to create a stiff fluid improves ability to transport cuttings but increases problems with circulation.
- Elevated temperatures accelerate bioactivity, which could cause premature degradation in the mud pit.

Guar gum is also used with the other alternative methods discussed in this manual. Those applications are described in detail in following chapters.

2.1.3 *Inclined Wellbores Created With Sonic Drilling*

This section describes two sonic drilling methods with respect to inclined wellbores: rotosonic and resonant sonic. Both methods use the same type of sonic drill head and dual drill pipe or casing advance method, but they differ in the capabilities to rotate the casing during drilling. These methods entail advancing a casing into the formation and removing drill cuttings from the inside of the casing via an inner drill pipe/core pipe. In some cases, the inner drill pipe advances first into the formation, and the outer casing follows. The major difference between the two sonic drilling methods is the rotosonic method relies on rotary power and water as a drilling fluid to aid in drilling, whereas the resonant sonic method uses rotary power and drilling fluid only when drilling rock. Following is a discussion of the principles of sonic drilling and sonic drilling equipment, and a description of sampling methods used in sonic drilling.

2.1.3.1 Sonic Drilling Principles

The axial oscillations that the sonic drill head produces induce a sinusoidal energy wave in the drill pipe (10). Maximum energy transfers from the drill head, through the drill pipe, and to the formation when the sinusoidal wave is in resonance with the drill string and a standing wave is created in the pipe (Figure 2-6). More than one frequency of axial oscillations can produce resonance and a standing wave. The fundamental resonance frequency, R_f, relates to the length of the pipe by the equation

$$R_f = v/(2L), \quad (2\text{-}1)$$

where v is the speed of sound through steel and L is the length of the drill pipe. For instance, for a steel drill pipe 30 meters (97.8 feet) long,

$$R_{f30} = (5{,}000 \text{ m/sec})/(2 \times 30 \text{ m}) = 83 \text{ Hz}. \quad (2\text{-}2)$$

Additional resonance frequencies are whole number multiples (overtones) of the fundamental resonance frequency. Higher resonance frequencies are used when greater energy is required to advance the drill string through more resistant formations or at greater depths. The maximum sonic drilling depths depend on the host formation. For example, for unconsolidated sand (sediments most compatible with sonic drilling), the maximum drilling depth is approximately 200 meters (656 feet).

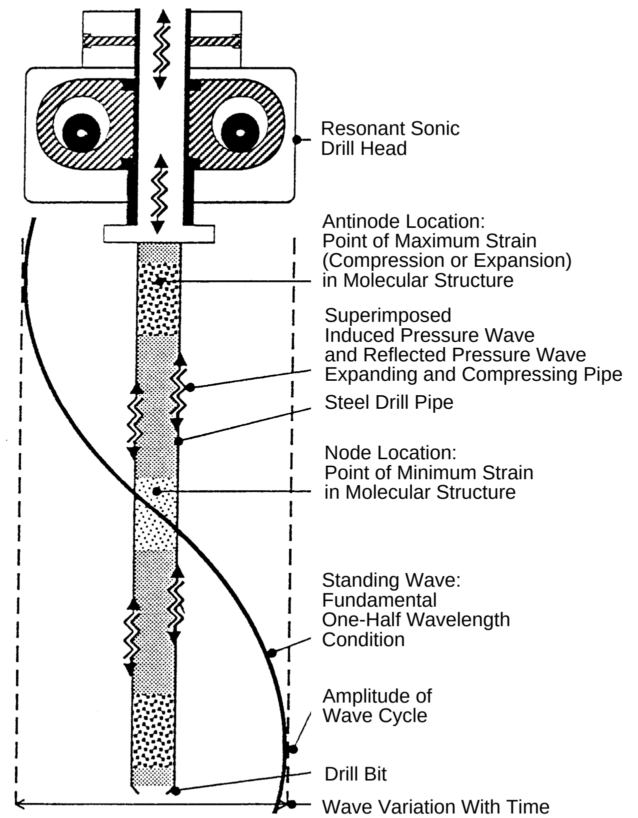


Figure 2-6. Resonant stress wave providing energy to the drill bit (10).

The drill pipe's penetration rate can be optimized by controlling its frequency of oscillations between resonance overtones. As a result, the soil particles adjacent to the drill pipe cannot vibrate in unison with the drill pipe, and they begin to vibrate in random directions. This random movement fluidizes the soil within approximately 0.6 centimeters (1/4 inch) of the drill pipe, thereby reducing the friction on the drill pipe.

2.1.3.2 Sonic Drilling Equipment

The sonic drilling method uses a combination of techniques to penetrate the subsurface:

- Thrust or pull-down
- Mechanically induced vibrations
- Rotary power

A hydraulic chain driven winch on the drill tower provides the pull-down (and hoist). The sonic drill head provides the vibrations (axial oscillations) and rotary power.

2.1.3.3 Sonic Drill Head

The sonic drill head contains three main components within its housing (Figure 2-7): an oscillator that consists of two out-of-balance counter rotating rollers, an air spring isolator, and a rotational drive (10).

The out-of-balance counter rotating rollers are hydraulically driven. The rotation of the rollers is timed and synchronized to provide a sinusoidal oscillation in the drill string (Figure 2-7). The energy from the rollers transfers through the drill string to the cutting head and, thus, to the formation. The oscillation can have a frequency as high as 150 Hz.

The air spring isolator is a large-diameter piston set within a closed cylinder. The piston connects to the portion of the drill head that contains the counter-rotating rollers, and the cylinder is attached to the drill tower. An air compressor supplies the volume of air on each side of the piston; this air acts as a soft spring that isolates the compression waves from the drill rig.

A hydraulically driven motor superimposes rotary movement on the axial vibration of the drill string. The pipe rotation is used to attach and remove pipe from the drill string and to aid in drilling. The rotation of the pipe also helps remove cuttings from the drill bit and keeps the cutting edge of the bit against the formation.

2.1.3.4 Drill Pipe

The sonic method causes the drill pipe to, in part, behave like a spring (10). The axial oscillations that the drill head creates cause the pipe to expand and contract (to the extent allowed by its natural elasticity and inertial properties). The alternating expansion and contraction causes the pipe to dilate over its length, and the outside diameter of the pipe to decrease cyclically and increase with each expansion and contraction. This movement decreases the friction on the outside of the pipe but also induces stresses that common drill pipe does not normally experience. The stresses, which are concentrated on surfaces found at the drill pipe joints, can cause occasional failure of the drill pipe. The rate of failure of the drill pipe, however, can be minimized by:

- Using threaded drill pipe with hardened steel joints
- Avoiding use of welded drill pipe connections
- Periodically replacing drill pipe

2.1.3.5 Drilling Tool

Sonic drilling penetrates a formation by displacement, shearing, or fracture by impact (11). Displacement drilling tools are used to drill through sands and light gravels. Displacement occurs by fluidizing the soil particles and causing them to move either into the formation or into the center of the drill pipe. The displacement drill tool has no special shape or hardening requirements,

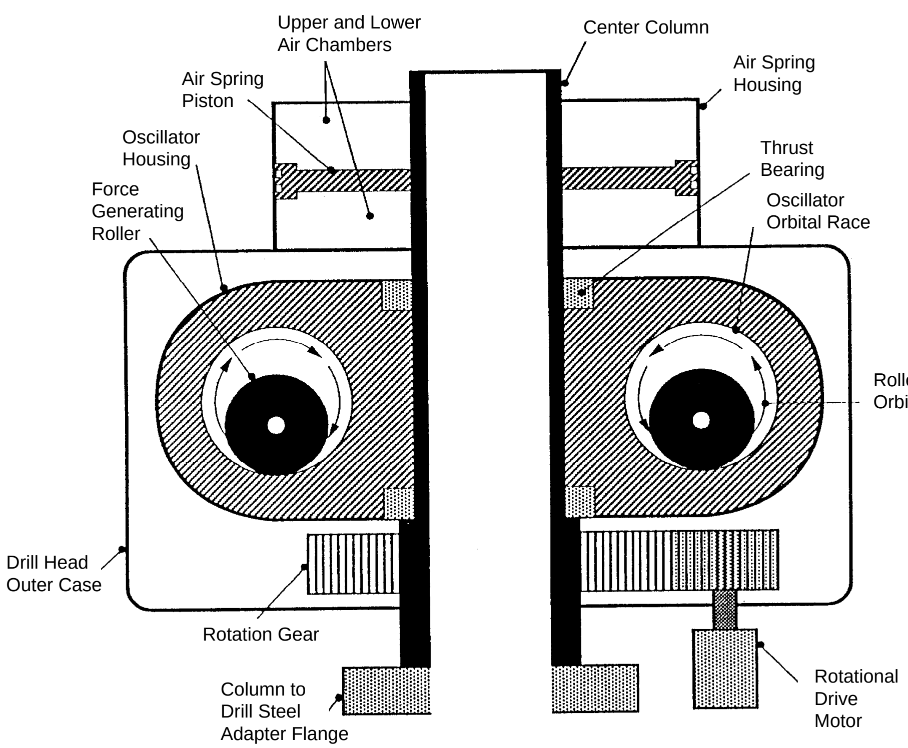


Figure 2-7. Sonic drill head (10).

but a hard welded facing generally is used to prevent surface erosion.

The shearing drilling tool is used to drill clayey soils. The clayey soils can only be sheared if the axial oscillations of the drill pipe overcome the elastic nature of the material. Because clayey soils have a high dampening effect on the drill pipe, the tool is designed with an increased wall thickness at the cutting face. This provides clearance for the external and internal pipe surfaces that follow.

The fragmentation tool is used to penetrate lithified sediments and rock. The axial oscillation of the drill pipe causes the drilling tool to impact and fracture the rock. The continuous rotation of the drill pipe clears away rock fragments from the cutting surface. A flushing medium often is used to remove rock fragments from the wellbore. A fragmentation tool generally has a hemispherical array of tungsten carbide buttons on a reinforced tool surface. The tool is built with passages to allow the flushing medium to remove cuttings from the drill face.

2.1.3.6 Sampling Equipment and Methods

Traditionally, sonic drilling has used three types of sampling methods: a core tray or plastic sleeve, a split tube, and a core barrel liner (12). These methods can collect core samples at any angle. The core tray or plastic sleeve is a commonly used core retrieval method. The core sample is taken with the inner drill pipe either inside the outer casing or below the outer casing. The inner drill pipe is removed from the wellbore. Then, the final length of drill pipe that contains the core sample (still attached to the drill head) is swiveled to about 55 degrees from vertical, and the drill head vibrates the drill pipe. This causes the core sample to slide out of the pipe and into either a plastic sleeve or onto a core tray placed at the open end of the pipe. The core tray or plastic sleeve method works well for lithologic characterization and/or soil sampling. Because the samples are disturbed when they slide out of the drill pipe, however, they cannot be used to identify fine sedimentary structures or to characterize hydraulic properties.

The split tube sampler is constructed of split carbon steel tubing, which has tapered threads and open caps on each end. The tube attaches to the end of the inner drill pipe and is driven into the formation. Then, the outer casing is drilled over the split tube, and the inner drill pipe and tube are removed. After removing both the split tube from the drill pipe and the open end caps, the tube is split open. This sample method provides an undisturbed core sample that can be used for lithologic characterization (including fine sediment structure analysis), hydraulic properties characterization, and soil sampling.

A core barrel liner method was investigated at the Department of Energy's (DOE's) Hanford, Washington, site. The method uses a polycarbonate liner installed inside the lowest piece of the inner drill pipe. The drill pipe and liner are drilled into the formation and then removed. The liner and core sample are removed by vibrating the drill pipe. The core sample this technique provides is equal in quality to a split tube core sample.

The temperatures of the core samples collected using all three methods described are generally higher than the ambient subsurface temperatures. The sample temperatures can be kept near ambient temperature (less than 27°C [80.6°F]) by decreasing the drilling rate and cooling the core sampler before it is inserted in the formation (12).

2.1.4 Well Installation and Completion

Horizontal well construction can create two types of wellbores: continuous wellbores and blind wellbores.

2.1.4.1 Continuous Wellbores

Many drilling contractors are familiar with methods of completing continuous wellbores. These methods are based on techniques developed in the trenchless technology industry for installing cable and pipe below roads and rivers. The continuous wellbore is an advantage for treatment systems that require access at both ends of the horizontal screen.

Some disadvantages of continuous wellbores are that they require twice the surface access (exit and entrance access) as a blind wellbore. In addition, the continuous wellbore path is longer and possibly more expensive to drill. Also, well installation in a continuous wellbore is more stressful on the well materials because of two wellbore curves. Therefore, the strength requirements of the well materials are greater than those in a blind wellbore.

The continuous wellbore generally has a 7- to 25-degree approach angle and a medium to long radius of curvature (greater than 45 meters [147.6 feet]). To construct a continuous wellbore, a pilot hole first is drilled from the surface, through the curved section to the target depth. The pilot hole then is drilled along the horizontal section, through another curved section, and back to the ground surface. The well materials, such as casing, screen, and filter packs, are assembled at the exit hole and attached to the drill string in the wellbore. Generally a hole opener or reamer is placed at the end of the drill string, just before the well materials, to facilitate their installation. The drill string, with the hole opener and well materials in tow, is pulled back through the wellbore. The hole opener removes any excess cuttings or formation materials that may have sloughed into the wellbore and enlarges the pilot hole to the desired diameter. When all the drill string has been removed from the wellbore, the well materials are in place. Figure 2-8 illustrates this

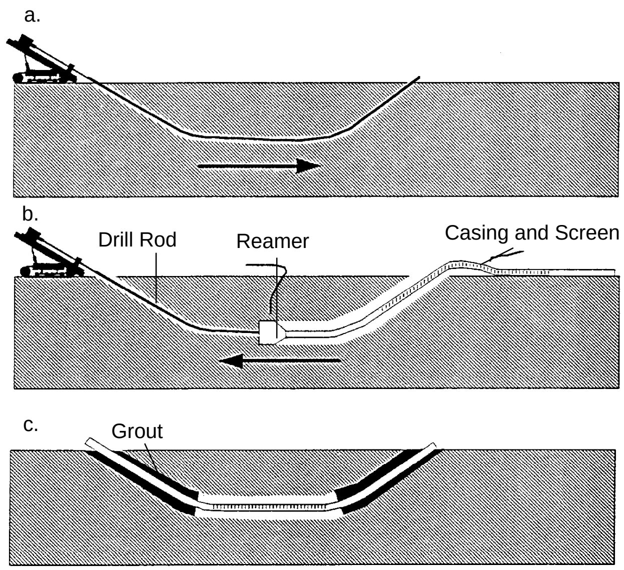


Figure 2-8. Creating a horizontal well with the pull-back method: a) drilling a continuous wellbore, b) reaming and pulling in casing, c) the finished well.

technique of installing casing, which is often referred to as the pull-back method; the name is sometimes used to refer to the entire task of installing a continuous well.

2.1.4.2 Blind Wellbores

Blind horizontal wellbores have an entrance hole and terminate at the vertical depth of the target zone (Figure 2-8). This type of horizontal wellbore was first developed in the petroleum industry. The radius of curvature for a blind wellbore can be short, medium, or long. An advantage of a blind wellbore is that only one wellbore curve needs to be negotiated during well installation. In addition, there is no need for site-access at an exit hole, and, because a blind wellbore is shorter than a continuous wellbore, it may be less expensive to create. However, these cost savings generally are offset because the drilling and well installation methods are more complex than for continuous wellbores. Drilling methods usually require multiple trips in and out of the hole, as opposed to a single round trip for continuous wells.

Blind wellbores can be drilled using three techniques: washover pipe, open wellbore, and pulling casing while drilling. Washover pipe drilling entails initially drilling a prior hole (Figure 2-9). Then, the washover pipe is drilled over the pilot drill rods to enlarge the wellbore and provide a conduit for well installation. The washover pipe installation is difficult because it requires drilling two pipes into the ground, thereby doubling the chances of experiencing drilling problems. However, well installation is much easier in a washover pipe than in an open wellbore.

Open wellbore installations have the advantage of being the simplest and easiest to complete but are limited to sites where wellbore stability is not a problem. In this method, the wellbore is drilled and cased to the end of the curve. Then, a pilot hole is drilled in the horizontal section, and a hole opener is used to make the horizontal section the desired diameter. Finally, the well casing is installed in the open wellbore. The obvious risk in this method is that the wellbore may collapse before the well casing is completely installed.

The most complicated technique for completing a blind wellbore involves pulling a casing as drilling proceeds. A problem associated with this technique is that casing materials stick because the hole cannot be properly cleaned as it is drilled (13). A modified method involves drilling a pilot hole and installing the casing as the pilot hole is reamed to a larger diameter.

Either a washover casing or an open hole can be used to install well materials into blind wellbores. The well materials are assembled at the surface and pushed into the wellbore. When well materials are in place, the washover casing, if used, is withdrawn the desired distance.

2.1.4.2 Stresses on the Casing During Installation

Friction against the wellbore is the primary cause of stress on the casing during installation. Pushing or pulling casing or well materials into a well requires force greater than the friction generated along the surface of contact between the hole and the casing or screen.

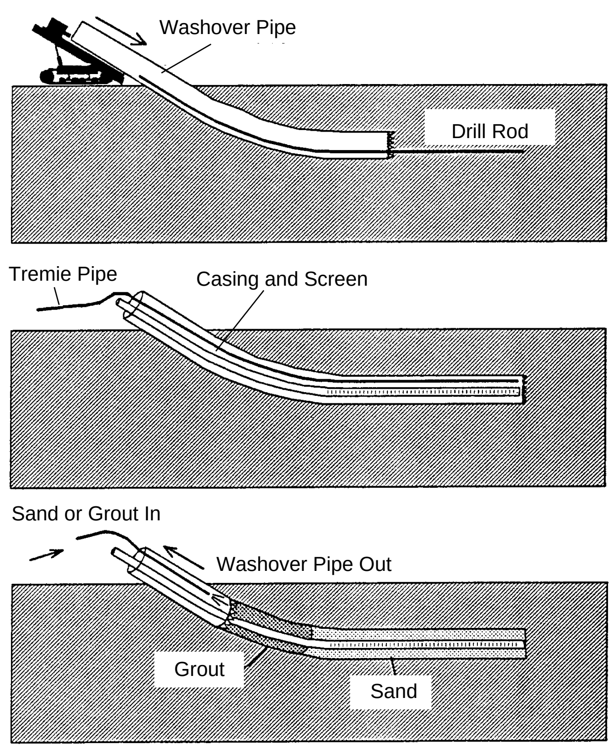


Figure 2-9. Completing a blind well using the washover pipe method.

Friction force is characterized as the product of a friction coefficient and force normal to the surface between moving objects. Although neither of these two parameters can be precisely characterized, identifying and considering several influential factors should assist in minimizing the force required to complete a horizontal well.

Friction coefficients between solid objects at rest range from 0.1 to 4. The exact value depends significantly on the smoothness of the surface and nature of the materials, and especially on surface properties such as interfacial energy. Thus, steel and plastic casings will have different coefficients of friction. Likewise, coarse sand will differ from clay. If solid surfaces are separated by small amounts of a third material, such as a liquid, effective friction coefficients can be markedly less than dry surface friction coefficients. Small particles can also lubricate surfaces by acting as ball bearings, thus yielding lower effective friction coefficients. Consequently, friction coefficients during drilling operations can vary, although Ta Inglis (14) recommends values of 0.2 to 0.4.

Several types of forces perpendicular to casing or well screen can exist simultaneously. Figure 2-10 illustrates the origin of some of these forces, all of which can occur in blind and continuous wells. The long arc of the curve section between the entrance angle and the horizontal section bends casing and well screen. The stiffness of these materials requires that a force normal to the axes be realized to affect the shape. This force should be inversely proportional to the radius of curvature of the hole. In the horizontal section, the normal force can be as small as the weight of the casing or screen. This lower limit requires that the hole be open and straight, so that it bears no other force. If the surrounding formation contacts the well materials, then the in situ stresses transmit as a normal force. Formation materials also can exert normal forces through capillary action; for instance, the stickiness of clay is, in large part, a manifestation of the strong capillary action exhibited by clays.

Perfectly straight horizontal holes are difficult to drill. The highs and lows of the trajectory deflect the pipe from a straight path. Even though the deflection may not be sufficient to cause flexural reaction force in the pipe, an additional normal force is generated when the force along the trajectory is resolved into components parallel and perpendicular to the general direction of the well. In a mechanistic sense, the normal force components try to straighten the serpentine wellbore. This force varies inversely with radius of curvature. The force is proportional to the tension force that is placed on the casing or well materials. This has the consequence of compounding the friction force along the length of the well.

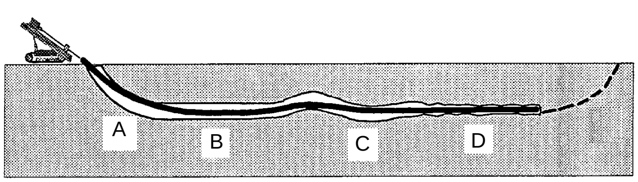


Figure 2-10. Types of force normal to axes during installation of casing or well materials: A) flexural stress in long arcs, B) casing weight in straight open sections, C) lateral stress created by tension through serpentines, D) pressure by surrounding formation.

Friction is generated at all the points along the well, and the required force for placement can be represented by the integral of friction force per unit length along the well. Considering the types of normal forces described, an expression of tractive force is

$$F_p = \int \eta \, F_\perp \, dx = \int \eta \, (F_{flex} + W + 2\pi \, r \, N + \alpha \, F_p) \, dx, \qquad (2\text{-}3)$$

where F_p is the force required for placement, η is an effective coefficient of friction, and $F_\perp$ is the sum of normal forces per unit length of casing or well materials. The normal force components are the reaction force F_{flex} of flexing the pipe normalized by length, the weight *W* of pipe per unit length, stresses and pressure *N* exerted by the formation, and the perpendicular component of the overall tractive force. In this equation, *r* is the radius of casing or well materials and α is a constant that accounts for the geometry of serpentine sections.

For the pull-back method of installing well materials in a continuous well, the pulling force is transmitted as a tensile stress in the casing material. It follows that the tensile stress, σ, in the casing is

$$\sigma = \frac{\beta \, F_p}{\pi \, (2 \, r \, w - w^2)} = \frac{F_{flex} + W + 2\pi \, r \, N}{\alpha \, \pi \, (2 \, r \, w - w^2)} \, \beta \, (e^{\eta \alpha x} - 1), \qquad (2\text{-}4)$$

where *x* is the length of casing in the ground, *w* is the wall thickness, and β is a factor that accounts for the loss of material due to the slots. (A simple approximation of β is the ratio of the total to the intact cross-sectional area of the casing, while more complex analysis might include the stress intensity imposed by the sharp comers of the slots.) The origin of coordinates is where the casing enters the ground. The casing breaks in tension when σ exceeds the tensile strength of the material. According to Equation 2-3, stress increases as more casing is pulled into the ground, and the increase in stress is exponential if the well is serpentine. The maximum stress occurs where the combination of *x* and β is the greatest. (The other terms are constant.) This means that the casing will break either near the end that is being pulled or at the first piece of screen; this prediction is consistent with observations of broken casing in the field.

Simple calculations using Equation 2-3 show that some screens break if they are pulled into the ground unsupported. As a result, a cable or rod is sometimes threaded from the reamer through the casing and used as an interior support. The interior support fastens to the end of the casing so that much of the load during pull-back is supported by the pipe or cable rather than the casing. This allows materials that are relatively weak in tension, such as plastic casing with threaded or barbed joints, to be pulled into a continuous wellbore. The elasticity of a cable, however, must be sufficiently small for the cable not to stretch enough to allow the well materials to part.

Equation 2-3 can be similarly extended to assess the compressive forces that occur while pushing casing and well materials into a washover pipe or open hole. Wu and Juvkan-Wold (15) present an analysis of compression stress that includes buckling of the well material.

2.1.4.4 Well Completion

Two methods of installing a gravel pack are available for horizontal wells. One method places a tremie pipe along the casing and injects the filter material into the annulus between the casing and the wellbore. Placement of the tremie pipe to the end of the well screen must be accomplished either during well material placement or as part of a washover casing system. If the tremie pipe clogs, however, it can be difficult to replace. Placing continuous sandpack around the well screen can be particularly difficult because the rate required to flush the sand through a tremie pipe over a long horizontal distance (greater than 90 meters [295.3 feet]) tends to wash out the wellbore during backfilling.

An alternative method is to install a prepacked screen, which consists of an inner and outer screen with sand in the annulus between them. Thus, the filter pack is contained within the prepacked screen. Installation of a prepacked screen requires a larger radius of curvature for installation than standard wire wrapped screens. Another alternative is to wrap the well screen with a geotextile filter membrane.

Another option is to use tremie pipe to install a bentonite seal and grout in the annulus around the riser casing. A grout basket placed on the riser casing before installation keeps bentonite and grout from flowing into the well screen. It is advisable to first install sand in the grout basket to ensure that the bentonite and grout do not seep around the edge of the basket.

A gravel pack may be unnecessary for some applications. Where horizontal wells are placed in sands, removing the fine-grained sediments from the vicinity of the well may not be possible during development. This results in a natural sand pack that resembles similar applications used for vertical wells (16). Moreover, a gravel pack often is unnecessary for applications involving vapor extraction or bioventing. Eliminating a gravel pack can significantly reduce the costs of a horizontal well.

2.1.5 Well Development

Well development concerns and techniques for horizontal wells are similar to those for conventional vertical wells; they depend on the hydrogeologic setting and remediation objective of the well. The drilling techniques for installing a horizontal well in the vadose zone for the purpose of vapor extraction or injection ideally will not use a drilling mud because of concerns of reducing the gas permeability of the formation. However, if a drilling mud is required, the well development technique would be similar to that used for a well installed in the saturated zone.

When drilling a well installed in the saturated zone and using a bentonite- or polymer-based drilling fluid, well development should begin as soon as possible after well installation and/or well completion. The drilling fluid and mud cake need to be removed to restore formation permeability around the well screen and/or filter pack. Well development may include volume flushing the annular space with water, jetting water into the well screen to remove drilling fluid, treatment with an acid or base chemicals to dissolve the drill fluid or mud cake, or treatment with a disinfectant to prohibit bacterial growth in the case of a biodegradable drilling fluid. The development fluid should be chemically compatible with the formation water to avoid detrimental effects on the formation.

2.1.6 Pumps

The pump used in an inclined or a horizontal groundwater extraction well must be able to function continuously in an inclined or a horizontal position. Currently available well pumps are designed to operate vertically, but no studies have been published to date on the long-term performance of well pumps in nonvertical environmental wells.

Electrical centrifugal pumps can function in the horizontal position, but the life of the motor and impeller bearings, which were designed to operate vertically, may limit their endurance. Of the pumps that are currently available, electrical centrifugal pumps are the most commonly used in horizontal wells because of their versatility and ability to be used at any depth.

Pneumatic pumps can be either diaphragm or bladder actuated and typically make use of two check valves. Usually the valves must be vertical to seat properly. Apparently some diaphragm pumps function horizontally, because Wilson and Kaback (17) used diaphragm pumps to recover NAPLs in shallow, low-volume horizontal wells.

2.2 Design Considerations

In horizontal well applications, it is important to consider many factors that can affect the performance of a well and the ability to drill and complete the wellbore. The pattern of flow in the vicinity of a well is a major factor affecting performance. In addition, geologic and hydrologic conditions and contaminant distribution affect decisions regarding:

- Drilling methods
- Horizontal wellbore specifications
- Length and elevation of the well
- Composition and design of well materials

2.2.1 Pattern of Flow

The pattern of flow created by a horizontal well is a fundamental aspect of performance (18). Under ideal conditions—a thin, confined aquifer of infinite extent with no regional flow—radial flow adjacent to the well is confined to a small area and streamlines in the vicinity of the well run roughly parallel and perpendicular to the long axis of the well (Figure 2-11). At great distances from the well, streamlines run approximately radially, so that in a thin aquifer the pattern of flow to a horizontal well resembles flow to a trench (19). At steady state in a thin aquifer, the specific discharge from a horizontal well with no head loss along the casing approaches that of a vertical well with a radius equivalent to one-fourth the total length of a horizontal well. Clearly, this can represent a very large vertical well.

The pattern of flow changes as the formation becomes thicker and the zone of radial flow around the well

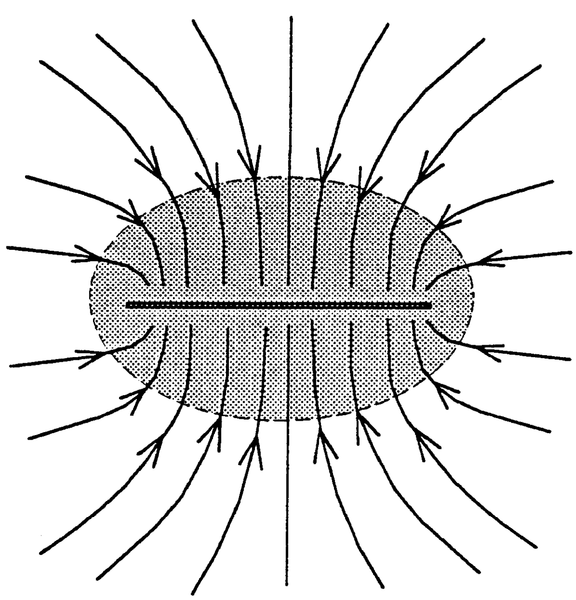


Figure 2-11. Flow paths to a horizontal well in a thin aquifer with no regional flow. Lines are nearly straight and parallel within the patterned area.

becomes larger (18). In this case, the pattern is similar to Figure 2-11 in plan but develops components of flow in the third dimension (depth). Head losses associated with the vertical component of radial flow adjacent to the well (Figure 2-12) limit the advantages that a horizontal well may offer over a fully penetrating vertical well, which causes no vertical flow. The effect is exacerbated by anisotropic conditions, in which the ratio of vertical to horizontal hydraulic conductivity is less than one (3), such as in interbedded fine- and coarse-grained sediments. Nevertheless, for many commonly encountered geologic conditions, effects of formation thickness and anisotropy are small relative to improvements in specific capacity resulting from a horizontal well's longer screen length (2).

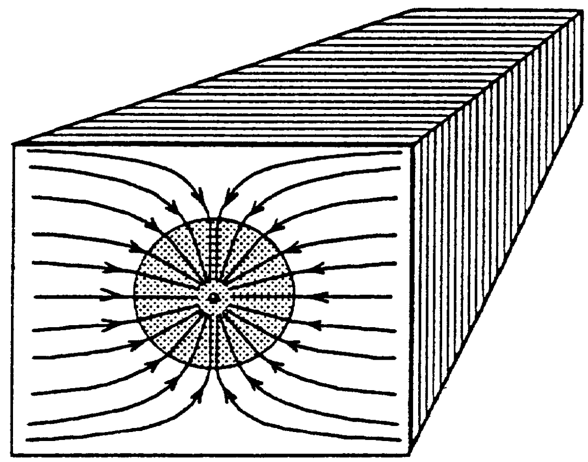


Figure 2-12. Radial flow in a vertical plane in the vicinity of a horizontal well.

A secondary benefit of a long screen is reduced velocity of fluid in the vicinity of the well. This effect reduces the possibility of inducing turbulence and associated nonlinear head losses (2, 20). Decreasing fluid velocities in horizontal wells also should reduce damage to well screens and filter packs due to migration and entrapment of fine-grained sediment (2).

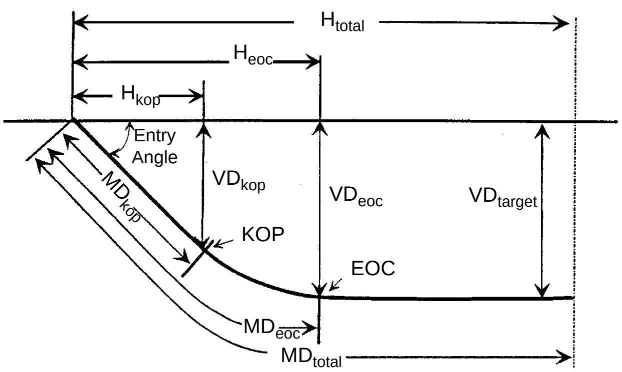
2.2.2 Wellbore Specifications

The well trajectory and materials of construction are the principal wellbore specifications. To some extent, these specifications are interdependent. Installation and residence in the subsurface put stress on the wellbore tubing. The magnitude of the stresses depends on the method of installation, curvature and depth of the bore, and other factors. To ensure subsurface access, the wellbore tubing selected must withstand these stresses.

2.2.2.1 Specification of Trajectory

Horizontal wells currently used for environmental applications typically enter the ground at a shallow angle, gradually curve until they are horizontal, proceed through the contaminated interval, and then either terminate or curve upward to the ground surface. Accordingly, this trajectory is specified by the following parameters (Figure 2-13):

- Well head location
- Entry angle
- Vertical depth to target
- Measured depth to target
- Wellbore curve
- Step-off distance
- Plan path



KOP	Kickoff Point
EOC	End-of-Curve
VD_{kop}	Vertical Depth to KOP: Equation 2-5
VD_{eoc}	Vertical Depth to EOC: Equation 2-6
VD_{target}	Vertical Depth to Target: Given
MD_{eoc}	Measured Depth to EOC: Equation 2-7
MD_{kop}	Measured Depth to KOP: Equation 2-8
MD_{total}	Total Measured Depth: MD_{eoc} + Horizontal Length
H_{eoc}	Horizontal Distance to EOC: Equation 2-9
H_{kop}	Horizontal Distance to KOP: Equation 2-10
H_{total}	Total Horizontal Length: H_{eoc} + Length of Horizontal Section

Figure 2-13. Nomenclature describing a horizontal well (14).

Well Head Location. Generally the well head is in line with the horizontal well at a practical distance from the target zone. It is possible, however, to curve laterally before reaching the target zone to offset the well head from the major line of the well. Lateral curves stress the drill rods, reduce the distance capabilities of the rig, and increase stresses on the well materials. The following points should be considered when selecting the well head location:

- Surface obstructions may inhibit the selection of a well head location. There must be sufficient room at the well head location for the safe operation of the drilling equipment.
- The length of surface piping to a treatment facility should be minimized.
- Multiple horizontal wells may radiate from the same well head location. This enables well heads to be located in a single well vault and one treatment system to be used for an extensive area.

Entry Angle. The entry angle (I_i), sometimes referred to as the approach angle, is the angle between the drill stem and the ground surface at the entry hole. The entry angle may be between 7 to 90 degrees from horizontal (10 to 35 degrees is most common), depending on the type of drill rig being used. Shallow horizontal well installations (less than 8 meters [26.2 feet] VD) generally have a 10- to 15-degree entry angle, whereas deeper horizontal well installations (greater than 8 meters [26.2 feet] VD) have a 15- to 35-degree entry angle.

Vertical Depth to Target. The VD to target is the difference in elevation between the wellbore entry location and the target zone.

Measured Depth to Target. The measured depth (MD) to the target is the distance along the wellbore path from the wellbore entry to the target zone. The MD is equal to the length of drill rod in the ground.

Wellbore Curve. A radius of curvature defines the curved portion. By industry convention, the radius of curvature is measured in feet, and a well is drilled with a buildup rate (BUR) measured in degrees of angle per 30.5 meters (100 feet) of wellbore drilled. The curve begins at the kickoff point (KOP) and ends at the end-of-curve (EOC). The curve BUR that provides the desired radius of curvature is given in Table 2-2.

Selection of a radius of curvature depends on the target zone location, well materials, and drilling equipment.

Table 2-2. Wellbore Curve Measurements

Radius of Curvature (RoC) (feet)	Buildup Rate (BUR) (degrees/100 feet) RoC x BUR = 5,730
50	114.6
100	57.3
150	38.2
200	28.7
250	22.9
300	19.1
400	14.3
500	11.5
750	7.6
1,000	5.7

Wellbore curves have been classified based on their radii of curvature as short-, medium-, or long-radius wells: a short radius of curvature is less than 45 meters (147.6 feet); a medium radius of curvature is 45 to 250 meters (141.6 to 820 feet); and a long radius of curvature is greater than 250 meters (820 feet).

As the radius of curvature tightens, both the bending stresses on the drill rods and the frictional resistance between the rods and the formation increase. These stresses conspire to effectively reduce the total length that can be achieved by a particular combination of drill rods and boring machine. Horizontal sections are limited to approximately 100 meters (328 feet) in short radius of curvature boreholes (13, 14). The diameter and material of the casing also affect the wellbore radius. A rule of thumb in the river crossing industry is that the radius of curvature, measured in feet, should be 100 times the diameter of the installed pipe measured in inches. For example, if diameter of the well casing is 4 inches, then the radius of curvature should be approximately 120 meters (394 feet).

The radius of curvature of a borehole should be as long as practical within the constraints of the other borehole criteria. A shallow entry angle and large radius of curvature increase the borehole length and reduce the possible locations for the well head. The increase in drilling cost associated with drilling a longer borehole must be weighed against the benefit of reduced stress on well materials.

Step-Off Distance. The step-off distance (H_{eoc}) is the horizontal distance between the entry hole and the beginning of the horizontal section or the EOC of the wellbore. The step-off distance may be determined by site-specific conditions, such as the available surface area for the drilling equipment, well head(s), and associated treatment systems.

Plan Path. Normally a horizontal well is planned to be straight from entry point to wellbore termination or exit. The size and shape of the plume and subsurface obstructions, however, may require the well path design to include lateral curves. A horizontal wellbore can be drilled with a lateral curve, but the radius of curvature should be large to reduce stress on well materials.

2.2.2.2 Estimating Wellbore Specifications

A detailed determination of the wellbore trajectory is required during drilling. This allows the expected location to be compared with information from the electronic systems that locate the bore in the subsurface. Typically, designs of wellbore trajectories are developed and revised graphically in conjunction with site conditions. After establishing the trajectory, either graphical or geometric methods should quantify it. A few equations that may be helpful follow.

For the VD of the KOP (VD_{kop}),

$$VD_{kop} = VD_t - [k_1(\cos I_f - \cos I_i)]/BUR, \qquad (2\text{-}5)$$

where VD_t is the VD to the target zone, k_1 is a constant that equals 5,730 when BUR is in degrees per 30.5 meters (100 feet), I_f is the final wellbore angle (0 degrees for a horizontal well), and I_i is the entry angle. The VD to the EOC is equal to the VD to the target zone if the surface elevation at the entry point is equal to the elevation of the point above the target zone. If those elevations are unequal, then the VD to the EOC relative to the entry point is given by

$$VD_{eoc} = VD_{kop} - [k_1(\cos I_f - \cos I_i)]/BUR. \qquad (2\text{-}6)$$

The MD to the EOC (MD_{eoc}) is given by

$$MD_{eoc} = MD_{kop} + [(\pi k_1)/180]\,[(I_f - I_1)/BUR], \qquad (2\text{-}7)$$

where MD_{kop} is the MD to the KOP and is given by

$$MD_{kop} = VD_{kop}/\sin(I_i). \qquad (2\text{-}8)$$

If the step-off distance is not fixed, then it can be determined by the entry angle (I_i) and the radius of curvature of the borehole (or BUR) as follows:

$$H_{eoc} = H_{kop} + (k_1 \sin(I_i)/BUR), \qquad (2\text{-}9)$$

where the horizontal distance to the kickoff point (H_{kop}) is given by

$$H_{kop} = VD_{kop}/\tan(I_i). \qquad (2\text{-}10)$$

2.2.2.3 Casing and Screen

Casing and screen in a horizontal well must be stronger than in vertical applications. Horizontal wells require the extra strength to withstand tensile or compressive stresses along the axis of the casing that result from pulling or pushing the casing into the bore. Furthermore, the weight of the overburden produces stresses that may collapse a horizontal casing.

Strength of casing depends on the casing material, diameter, and wall thickness. In general, stainless and carbon steel casings are stronger than plastic casing. However, plastic casing, particularly high-density polyethylene (HDPE), can bend in a tighter radius than steel casing. The collapse strength, which is the maximum allowable force applied perpendicular to the casing, decreases with increasing diameter (Table 2-3). Conversely, the tensile strength, which is the maximum allowable axial force, increases with increasing diameter. A typical formation exerts approximately 0.02 MPa per meter depth (0.8 psi/foot), so the collapse strength is related to the allowable depth at which the casing can

Table 2-3. Strengths of Prepacked Screens (According to Johnson Filtration Systems, Minneapolis, Minnesota)

Nominal Size	Collapse Strength (MPa)	Tensile Strength (kN)
Prepacked 304 Stainless Steel		
2 inch	10.3	24
4 inch	4.14	58
6 inch	1.38	170
Prepack Schedule 40 PVC		
2 inch	1.72	4.9
4 inch	1.03	7.1

be used. Tensile strength is important when pulling casing into a horizontal bore, so the allowable stress has been converted to allowable pulling force in Table 2-3.

To estimate allowable pulling force for casings of other sizes and materials, multiply the effective pulling area times the strength of the tubing (Table 2-4). The effective pulling area is the continuous cross-sectional area, which for solid casing is $\pi dw/2$ (with d the outer casing diameter and w the wall thickness). Most casings that fail in tension crack at either the slots in the screen or the joints between individual pieces of casing. To estimate the upper limit of the strength of a screen made from plastic pipe with slots cut in it, use the approach outlined above, but reduce the effective pulling area to account only for the solid material in between the slots. The strength of joints between casing sections can range widely, from essentially the same as the casing itself for welded joints to small values for threaded joints designed for vertical wells.

Table 2-4. Tensile Strengths of Pipe

Pipe	Tensile Strength (MPa)
PVC	9.4
HDPE	6.5
Fiberglass	1.3–6.9

Casing and screen in a horizontal well used for environmental applications must also be resistant to whatever chemicals exist at a particular site. In this respect, the requirements for horizontal wells are the same as those for vertical wells.

New materials and joining capabilities are being developed for casing and screen for environmental wells. Distributors of well supplies should be able to supply information about the capabilities of these new products.

2.2.2.4 Filter Pack

Filter packing around a well screen is recommended for horizontal wells that produce liquids from formations containing fine-grained sediments, just as it is for vertical wells in similar sediments. To select a size gradation for a granular filter pack, use the same approach as for a vertical well (16), although keep in mind that entrance velocities into horizontal wells can be considerably less than those into vertical wells.

Several methods exist to place filter packing into the annulus around a casing or screen, most of which involve injecting the particles of the filter pack in a liquid or air stream (21). Moving fluid more readily transports HDPE particles, but these methods are more expensive than sand. Quality assurance is problematic in the injection of filter pack materials; it is difficult to ensure that the packing is continuous around the entire casing.

An alternative to injecting filter pack materials is to use a prepacked screen, which consists of an inner screen, an annulus filled with sand, and an outer screen. The prepacked screen currently is the most popular method of installing a gravel pack in horizontal wells because it ensures that the pack is continuous and uniform. Prepacked screens are available in most sizes and casing materials.

Unlike most vertical wells, filter packing in a horizontal well can be a significant component of the cost of the well. Therefore, careful examination of each application should establish the need for a filter pack and determine whether the cost of the pack will result in a valuable increase in the performance of the well. Many wells used for vapor extraction, for example, may require only a well screen. Likewise, liquid-phase recovery wells completed in clean sands formations may have naturally developed filter packs (16), thereby avoiding the cost of the filter pack.

2.2.3 Geologic Site Conditions

Geologic conditions, ranging from composition of the formation to the heterogeneities caused by depositional environment, affect details related to drilling and completion and the use of horizontal wells.

2.2.3.1 Formation Composition

The composition of the formation affects the methods used to drill a directional wellbore. Highly resistant formations, such as siliceous sandstones and metamorphic or igneous rocks, are difficult to cut. Loosely consolidated formations that are cobble-rich can be difficult to penetrate because the cobbles rotate with the drill bit. Generally, loosely consolidated granular sediments present steering problems because the bit cannot exert enough lateral force on the formation to deflect the drill rods. Specialized technology can address all these issues, although it also may increase the cost of creating the wellbore.

2.2.3.2 Stratification

Drilling in a stratified formation may present problems in some cases, particularly when intersecting a resistant unit at a shallow angle. In this case, the wellbore tends to ride along the top of the resistant formation. If recognized, however, this problem can be addressed.

Formation stratification largely affects the application of horizontal wells, particularly when the distribution of contaminants follows a sequence of alternating fine- and coarse-grained sediments (impermeable and permeable layers). In this case, recovery would be primarily from thick, high permeability strata in the vicinity of the well, with recovery from strata overlying or underlying the well less than anticipated. The degree to which this occurs depends on the thickness and permeability of the stratigraphic layers.

In general, contaminants flow in a horizontal plain unless hydraulic, chemical, or gravitational forces provide an impetus for flow in the vertical direction. A horizontal well should be placed as near the contaminant as possible to decrease the likelihood of an impermeable layer impeding the flow between the well and the contaminant.

2.2.3.3 Heterogeneities in the Horizontal Plane

Horizontal wells are suited to accessing formations that are heterogeneous in a horizontal plane. Formations whose major component of permeability comes from vertical fractures are excellent candidates. In addition, horizontal wells can access braided stream deposits with laterally discontinuous sand bodies. Many glacial sediments contain both vertical fractures and laterally discontinuous sand bodies, and many near-surface rock formations contain vertical fractures.

2.2.3.4 Aquifer Thickness

Horizontal wells can be effective in aquifers of any thickness. However, the efficiency of a horizontal well relative to a fully penetrating vertical well increases as the aquifer becomes thinner (2). This is because flow must converge from increasing distances both above and below the well as the aquifer thickens (Figure 2-12). A vertical well that fully penetrates an aquifer, however, induces primarily horizontal flow and does not suffer from the effects of vertical flow (assuming that drawdown is modest). The specific capacity of both horizontal and vertical wells increases as the aquifer thickens. Therefore, the performance (measured by specific capacity) of a horizontal well in a thick aquifer is better than the same well in a thin aquifer. This occurs because less interaction with the upper and lower no-flow boundaries occurs in a thick aquifer than in a thin layer.

2.2.3.5 Anisotropy

The permeability of most formations is anisotropic, although the principal directions depend on the geologic conditions. Interbedded sediments, for example, typically are more permeable in a horizontal than in a vertical plane, and even in the horizontal plane permeability is greater along one direction than other directions. Accordingly, the directions of greatest, intermediate, and least permeability are mutually perpendicular in an orthogonal set. In other geologic formations, the principal directions of permeability may differ significantly. In any case, these directions should be considered when locating horizontal wells.

For situations with distinction only between vertical and lateral permeability, the effects of anisotropy resemble the effects of aquifer thickness; an anisotropic aquifer of a certain thickness behaves the same as an isotropic aquifer of different thickness (20, 22). The effective thickness h_e of an anisotropic aquifer of actual thickness h is given by $h_e = h\ k_h/k_v$, where k_h and k_v are the horizontal and vertical permeabilities, respectively. Accordingly, an anisotropic aquifer, for which $k_h/k_v = 100$, that is 5 meters (16.4 feet) thick behaves like a homogeneous aquifer 50 meters (164 feet) thick with $k = k_h$. Similarly, if k_v is greater than k_h, as is possible where vertical fractures are common, then the effective thickness of the aquifer is less than the actual thickness.

In general, a horizontal well drains the largest volume if placed normal to the plane that contains the axes of maximum and intermediate permeability (Figure 2-14a). This only can be possible if the direction of greatest permeability is vertical. Where the greatest permeability is horizontal, a horizontal well placed perpendicular to the direction of intermediate permeability drains the largest volume (Figure 2-14b).

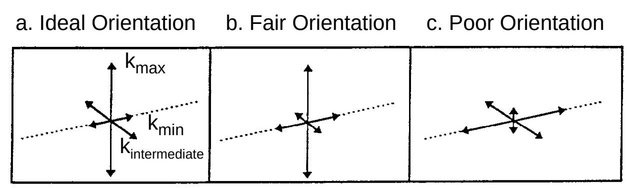


Figure 2-14. Orientations of horizontal well (dashed line) relative to principal directions of permeability.

When locating the well, other factors to consider along with the direction of anisotropy include surface obstructions, direction of regional flow, and location of contaminants.

Well tests are available to estimate formation anisotropy (23).

2.2.3.6 Drawdown and Discharge

The drawdown and discharge of a horizontal well depends on aquifer and well characteristics. Aquifer characteristics include permeability, storage coefficient, and thickness and boundary conditions. Relevant well characteristics are length, height in the aquifer, and details of the hydraulics resulting from flow through the slots in the screen and along the axis of the wellbore. Most of these factors also are common to analyses of vertical wells, with the exception of wellbore hydraulics, which are commonly ignored for vertical wells that have fairly short screens. The next section includes a discussion on wellbore hydraulics; therefore, this section examines the effects of the other factors.

Horizontal wells placed in productive aquifers commonly use a pump operating at constant discharge. The pump produces a drawdown that increases with time, just as with a vertical well, and the magnitude of the drawdown depends on the factors listed above. As an example, consider a horizontal well of length L at midheight in a confined aquifer of thickness h and infinite lateral extent. The dimensionless drawdown P_d as a function of time depends on the ratio of well length to aquifer thickness, and on the ratio of vertical to horizontal permeability (Figure 2-15). This is consistent with the conclusions presented in the qualitative discussion above. At any given time, the drawdown increases as the well becomes shorter, the aquifer becomes thicker, or the ratio of vertical to horizontal hydraulic conductivity becomes smaller—all of which contribute to decreasing L_d (Figure 2-15). It is noteworthy, however, that these variables cause the most severe differences early on, but the differences diminish and approach the results for $L_d = \infty$. The interpretation of $L_d = \infty$ is that the well cuts the full thickness of the aquifer, which is impractical for most horizontal wells but is fairly typical of many installations of trenches. Thus, based on Figure 2-15, the drawdown in a horizontal well apparently approaches that of a trench with increasing time. The abscissa of Figure 2-15 is dimensionless time, which must be translated to real time using the aquifer properties and well length (18).

The results for a well operating at constant discharge in a confined aquifer are by no means applicable to all horizontal wells. For example, results from cases in which horizontal wells extract vapor from areas where the ground surface is open to the atmosphere differ significantly from results when the ground surface is sealed. Moreover, it would be inappropriate to use Figure 2-15 to analyze cases in which horizontal wells are used in confined aquifers of relatively low permeability; the difficulty in this case results from the requirement of constant discharge. In many applications in low permeability formations, horizontal wells operate at constant drawdown using a water level sensor to control the pump. This results in a well with a roughly constant drawdown but with a discharge that decreases with time.

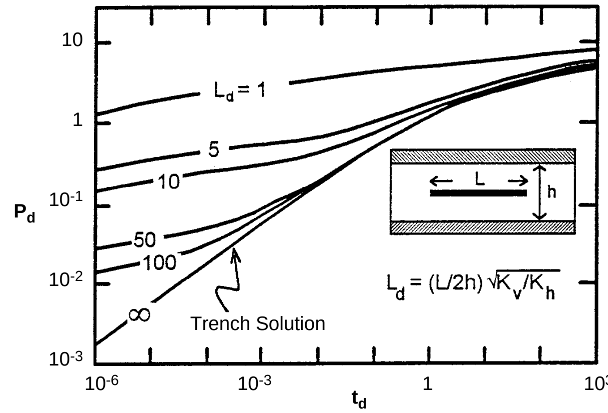


Figure 2-15. Drawdown resulting from a horizontal well as a function of time and dimensionless length. Drawdown and time are dimensionless.

For example, consider a well at the top of a confined aquifer, where the aquifer thickness is $h = 20$ (variables are defined in Table 2-5). The dimensionless discharge decreases as a function of time and also as a function of well length (Figure 2-16). The effect of well length on dimensionless discharge occurs because the discharge per unit length of the well (Q/L), not the total discharge, decreases with increasing well length. For example, at $t_d = 10{,}000$, the dimensionless discharge is 0.078 when $L = 10$, whereas it is 0.055 for $L = 20$. As a result, the actual discharge, obtained using the expression in Figure 2-16, is proportional to 10 x 0.078 = 0.78 for $L = 10$, whereas it is proportional to 20 x 0.055 = 1.1 for $L = 20$. Therefore, as the well length increases from 10 to 20, the actual discharge increases 40 percent. By presenting the results in dimensionless form, estimates can be obtained of the actual discharge for any combination of aquifer conditions. Details of this analysis are presented in Murdoch and Franco (24).

2.2.3.7 Vertical Fractures

The presence of naturally occurring vertical fractures enhances the performance of a horizontal well according to the principals outlined above, but such fractures

Table 2-5. Summary of Variables

K_v	Vertical Hydraulic Conductivity
K_h	Horizontal Hydraulic Conductivity
K	Average Hydraulic Conductivity
h	Aquifer Thickness
S	Storage Coefficient
L	Well Length
t	Time
r_w	Well Radius
ΔP_w	Drawdown at the Well

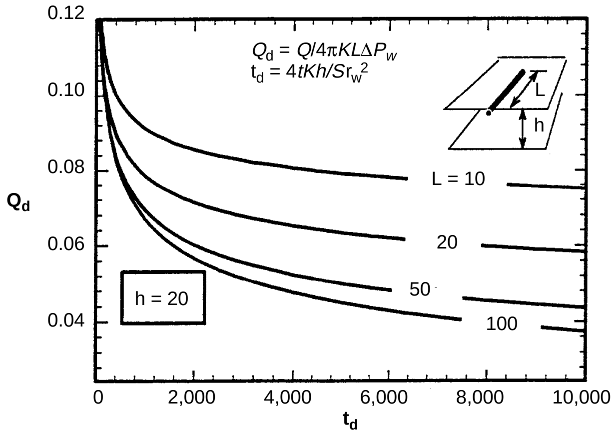


Figure 2-16. Discharge from horizontal wells of different lengths operated at constant drawdown (24).

are absent in many formations. Vertical fractures can be induced from horizontal wells using methods developed for vertical wells, described in Chapter 3. Such induced fractures can significantly reduce limitations related to formation thickness, anisotropy, and layering. The petroleum industry routinely induces hydraulic fracturing of horizontal wells. In addition, techniques developed for soil (25) have been used to create fractures from horizontal wells used for environmental applications.

2.2.3.8 Regional Gradient

Horizontal wells can provide hydrodynamic control in aquifers with a regional gradient. Special considerations are necessary, however, if the wells are intended to intercept contaminated plumes. In some cases, horizontal wells can be placed in the direction of the regional gradient, particularly to intercept an elongated plume that is moving relatively slowly.

In other cases, horizontal wells can be placed perpendicular to a regional gradient to intercept ground water. This application is best suited to relatively thin aquifers and relatively minor regional flow rates. This is because the certainty of all the water being intercepted decreases as the aquifer becomes thicker or the regional flow rate increases. Other aquifers above or below the well also may affect interception. Monitoring piezometric heads with multilevel vertical piezometers and estimating gradients at various depths in the vicinity of the horizontal well are recommended to ensure that all water is being intercepted.

2.2.4 Distribution of Contaminants

Once the distribution of contaminants is known, or as it becomes resolved in more detail, locating horizontal wells ensures hydrodynamic containment before recovery begins. Details of the plume geometry also may affect the design of a horizontal well.

2.2.4.1 Elongated Plume

Elongated plumes can resemble the shape of the capture zone of a horizontal well, which also is elongated (2). Therefore, elongated plumes are ideally suited to this application. A regional gradient, however, affects the capture zone of a horizontal well with travel time contours forming teardrop shapes. The narrow end of these teardrops is on the downgradient side of the well. Inasmuch as many plumes are elongated in the direction of regional flow, regional effects must be considered when designing the horizontal well. Using a few vertical wells downgradient from the horizontal well may be advisable to ensure complete capture.

An elongated plume may be wide enough to warrant placing a horizontal well perpendicular to its long axis to intercept migration with the regional flow.

Some elongated plumes result from elongated sources and can be independent of regional flows (e.g., contaminants beneath a leaking pipe). Horizontal wells are ideally suited to this application.

2.2.4.2 Equidimensional Plume

Horizontal wells that access equidimensional plumes provide the best performance when located perpendicular to the direction of maximum permeability.

2.2.5 Wellbore Hydraulics

A notion carried over from experience with vertical wells is that a horizontal well recovers water uniformly along its length. This is true with wells that have a large screen diameter (greater than 15 centimeters [6 inches]) and are installed in low-permeability formations. Head loss in large diameter screens is negligible when compared with the head loss in the formation next to the screen. However, when small diameter wells are installed in highly permeable formations, the head loss along the screen can cause the rate of inflow into the well to vary with distance from the pump (Figure 2-17).

Although a detailed analysis of wellbore hydraulics is beyond the scope of this manual, the effects of various parameters can be anticipated. Consider a very long, small-diameter well with a small pump operating at one

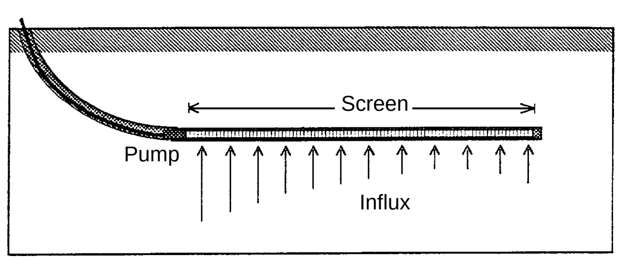


Figure 2-17. Schematic of distribution of influx into a horizontal well.

end. Fluid flows into the well adjacent to the pump at some rate per unit length of well screen. That rate of influx must decrease with increasing distance along the wellbore due to head losses associated with flow through the casing. It follows that the inflow rate, and thus the effect of the well, may be negligible beyond some critical distance where the sum of all the influx is equal to the discharge of the pump (26). This effect would be most severe where long, narrow wellbores are installed in highly permeable formations (as mentioned above). In some applications, however, the influx would decrease along the wellbore but then increase as it approaches the far end of the well (27). This occurs because water converges from beyond the end of the well (as in Figure 2-17). This effect from the flow pattern in the aquifer offsets the effects of wellbore hydraulics.

Hydraulics cause variations in inflow along the length of the wellbore, although the magnitude of this effect during field applications has yet to be quantified. Formation heterogeneities (e.g., vertical fracture) that are intersected by the wellbore also cause variations in the rate of inflow and may dominate the effects of wellbore hydraulics. Logging techniques that use a borehole flowmeter (16) to determine the inflow into a vertical well are available, and similar methods could be applied where the distribution of inflow into a horizontal well is critical.

2.2.6 Site Conditions

The major site conditions that affect well design are related to access and obstructions of the well trajectory. A horizontal or inclined well typically is selected when surface structures restrict subsurface access. In some cases, such as at refineries or other large industrial complexes, surface structures exist a considerable distance from the contaminated zone and restrict access to even a directional wellbore. In other cases, sites are simply too small to permit sufficient step-off distance. The entry location for a horizontal well must provide sufficient space to set up the drill rig and related equipment. The required area for this activity currently is at least 5 by 10 meters (16.4 by 32.8 feet), and can be considerably more depending on the type of drill rig.

The following are additional considerations related to site conditions:

- Elevation differences in excess of 16 meters (52.5 feet) between the entrance hole and the exit hole should be avoided because they may cause problems with the drilling fluid system.
- The wellbore path should avoid existing piles, monitoring wells, metal footings and pipelines. Subsurface metallic objects decrease the accuracy of a primary magnetometer-type steering tool. Drilling projects that use a magnetometer-type steering tool and require wellbore accuracy in an area that has subsurface magnetic interference need a secondary subsurface survey system.
- Drilling should not occur in areas where overhead structures or wires may limit the use of construction equipment.
- A continuous wellbore design should provide at least a 12-meter (39.4-foot) wide area for the exit hole and an available area for laying out the well string during pull-back installation.

2.3 Applications

Horizontal or inclined wells have been used for most of the same purposes as vertical wells (28): air sparging, soil vapor extraction, ground-water extraction, and injection. The following sections discuss only the effects of horizontal and inclined wells on the efficacy of these methods.

2.3.1 Pump and Treat

Recovery and treatment of ground water, “pump and treat,” is perhaps the most common method of addressing ground-water contamination, accounting for approximately one-quarter of horizontal well applications (28). Horizontal wells can recover aqueous-phase compounds at reduced energy costs by using fewer pumps. It is important to recognize that processes such as sorption, diffusion, and dissolution from NAPL sources are unaffected by well geometry. Accordingly, limitations of pump and treat systems now widely recognized for vertical wells (29) also apply to horizontal wells.

Horizontal well design approaches depend on specific site conditions, but the following general approaches are applicable to many field cases:

- Use horizontal wells to increase the rate of recovery from low-permeability formations. This is particularly applicable to relatively massive formations with vertical fractures. The well should be placed in the area of greatest contamination, and perpendicular to vertical fractures. To pump, maintain constant drawdown to maximize discharge.
- Place a horizontal well along the axis of an elongated plume to recover contaminated water and arrest migration (Figure 2-18a). Because the shape of many plumes resembles the elongated capture zone of a horizontal well, an excellent opportunity exists to recover a majority of the plume with one well. Keep in mind, however, that an elongated plume probably is moving, and that regional gradients can skew the capture zone of the well. Well placement should anticipate the effect of the regional gradient. For instance, it may be appropriate to extend the well further downgradient than the current extent of contamination. Pumping should begin immediately after

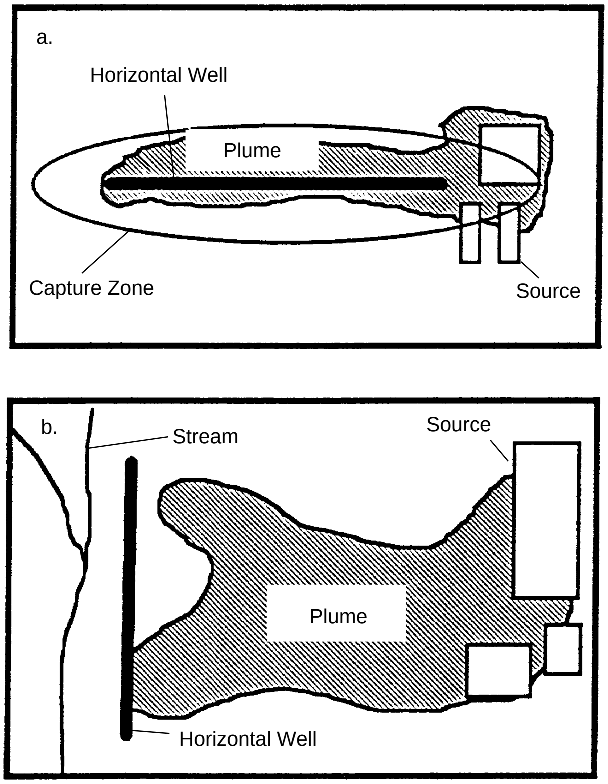


Figure 2-18. Two approaches using horizontal wells to intercept contaminant plumes.

creating such a well because, if neglected, the well offers a path along which contaminants can migrate under the natural gradient. Horizontal wells also may combine with vertical wells to contain downgradient migration.

- Place a horizontal well perpendicular to the direction of migration of a plume (Figure 2-18b). This approach, which resembles that of an interceptor trench, is most applicable when a relatively thin stratigraphic unit contains a broad plume. Because some of the plume may travel above or below the horizontal well, this approach may be appropriate when trenching is not an option because of access, depth, or other factors.

All of the applications described above would benefit from modeling studies to improve the chances of plume capture. This effort requires that site hydrogeology and distribution of contaminants are well known. Moreover, the pattern of flow that a long horizontal well induces may take some time to become steady, so transient analyses are recommended during the design process to avoid using the overly optimistic conditions seen at steady state.

2.3.2 Vapor Extraction

Vapor extraction projects account for approximately one-quarter of the applications of horizontal wells. This is because of the relatively large area covered by the well and the ability to access beneath structures and place recovery wells close to the source of volatile organic compounds (VOC). The source of air is a key factor during the design of vapor extraction systems that use horizontal wells. One horizontal well beneath an open surface causes flow that is vertically downward and converges toward the screen (Figure 2-19a). This focuses the extraction on the ground overlying the well, although the lateral extent may be limited. It is possible to increase the lateral extent affected by the well by placing a layer, or cap, with low pneumatic conductivity over the well (Figure 2-19b). In this case, air flows into the subsurface beyond the covering layer and expands the size of the area affected by the well (30). This increased area, however, comes at the expense of reducing the magnitude of air flux through the ground directly above the well. In some cases, the region above the well may become stagnant and receive little remedial effect. Installation of air inlets in the cap may be advisable so that the benefits of both covered and uncovered sites may be realized. Other horizontal wells or vertical wells may also be used to provide air inlets in the subsurface.

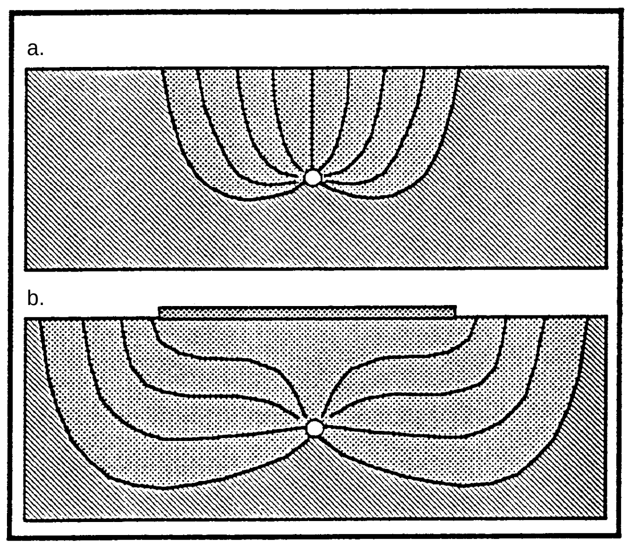


Figure 2-19. Schematic of flow patterns with horizontal wells: a) without cap and b) with cap.

2.3.3 Free-Product Recovery

A horizontal well can present an ideal geometry to recover layers of free-phase LNAPL or DNAPL, although complicating factors can make this application difficult to execute effectively. Free-phase LNAPL, and in some cases DNAPL, commonly occurs as broad, flat-lying layers and can be recovered by a horizontal well placed within or slightly below the layers. This, of course, requires that the NAPL location is known and well placement is accurate. However, accurate determination of LNAPL location can be difficult, and even approximate determination of DNAPL location can be difficult (31). Assuming that the NAPL can be identified, to optimize recovery, well placement must have a relatively narrow window of depth. For example, consider a LNAPL layer 0.3 meters (1 foot) thick. The best placement of the recovery well would be at or slightly below the NAPL/water interface. If the well is a few decimeters too shallow, it would overlay the NAPL, and recovery would be minimal. (Suction would have to be used to recover any liquid.) If it is a few decimeters too deep, water recovery must precede NAPL recovery. Lowering the water table significantly may cause the newly created vadose zone to trap some of the NAPL (32). For depths within 10 meters (32.8 feet) of the ground surface, current methods can drill accurately to within a few vertical decimeters (less than a foot) (accuracy is better than 5 percent of the depth).

Natural fluctuations in the water table may change the depth of the interface between NAPL and water. This can be particularly problematic if fluctuations cause the NAPL to move significantly above or below the horizontal well. The severity of this problem can be assessed by monitoring water levels for at least 1 year and, preferably, by accessing historical records. Using an interceptor trench may be preferable at NAPL sites with large seasonal fluctuations in water level.

NAPL recovery deflects the interface with water so that it may be advantageous to simultaneously recover water using another pump either below (for LNAPL) or above (for DNAPL) the interval of contaminant recovery. Using two pumps is a common method of recovering LNAPL with vertical wells (32), and this method has been used to improve the recovery of DNAPL (33). A similar geometry is feasible with a horizontal well, except an additional well must be created either above or below the contaminant recovery well (Figure 2-20). Alternatively, it may be cost effective to control water levels with vertical wells while a horizontal well recovers free product.

At least eight horizontal wells have been installed to recover free product. One of those wells was designed to recover machining oil beneath a building and, although specific data are unavailable, it is reportedly producing more oil than expected (17). At least seven wells were installed for free-product recovery and hydrodynamic control to halt the migration of petroleum-contaminated ground water into a residential area (34).

2.3.4 Sparging and Vapor Extraction

A technique that couples sparging with vapor extraction has been used with horizontal wells at a minimum of five locations since the DOE Savannah River site in Aiken, South Carolina, first demonstrated this approach (35). During an initial 139-day demonstration, air was injected into one well below the water table, and air and VOCs were recovered from another well above the water table. This approach recovered 7,200 kilograms (15,873 pounds) of trichloroethylene (TCE), which was five times more than was estimated for recovery using vertical wells (35).

This application consists of two horizontal wells, one located over the other as shown in Figure 2-20. The primary advantage of using horizontal wells in this application is that they encourage the injection of air along the length of the well, thus lengthening the area covered compared with sparging using vertical wells. This can represent a significant improvement because in the absence of confining layers, air channels from a vertical well may rise rapidly, remain close to the well, and cover a small portion of the aquifer. A horizontal well used for the upper well in this application is less critical and can be replaced with several vertical wells to recover injected air and stripped VOCs. As of 1993, at least 19 horizontal wells have been installed in integrated sparging and vapor recovery systems at five sites.

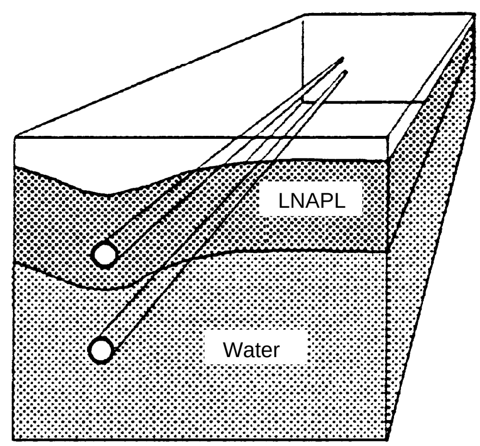


Figure 2-20. Recovery of LNAPL with one horizontal well, and water control with another well below.

2.3.5 Bioremediation

Horizontal wells can be used to enhance bioremediation, either by injecting liquids, such as nutrients and hydrogen peroxide, or by injecting gases, such as air or oxygen. The design considerations and approaches are similar to applications for pump and treat or vapor extraction.

2.3.6 Flushing

Uniform infiltration from a horizontal well can be tapped to enhance soil washing or flushing. Twenty-six horizontal wells have been installed as surfactant infiltration galleries, and two wells as recovery wells. Information on their performance is unavailable, but Wilson and Kaback (27) provide some information resources.

2.3.7 Soil Monitoring and Sampling

Another potentially beneficial application of horizontal wells involves collecting samples and/or monitoring beneath structures. Two known cases of horizontal wells used for monitoring or sampling exist. A slotted pipe was installed beneath a mixed-waste landfill at Sandia, New Mexico, to obtain soil vapor samples (36). At another site, soil samples were taken while drilling a horizontal well. The sampler was a hydraulically powered coring tool with an inner barrel actuated by the drilling fluid pump pressure (37). The inner barrel was hydraulically pushed into the formation, forcing the sample into an enclosed plastic cylinder. After withdrawing the cylinder into an outer housing, a valve closed to protect it from contamination while the drill string and core sample were withdrawn from the wellbore. This method allowed access to high-quality samples during drilling, but it required removal of the drill bit, insertion and removal of the core barrel, and reinsertion of the drill bit. Each drill rod required handling four times during this operation, which illustrates the excessive labor involved in recovering one sample from a long wellbore. Moreover, this sampling method requires that the wellbore remain open while the drill rods are removed, which either requires specialized drilling techniques or a stable formation.

Methods of obtaining soil samples without removing drill rods are currently unavailable. Such a method would markedly increase the value of horizontal drilling and thus, is currently being investigated. Lower drilling costs and improved methods should increase horizontal well applications for sampling and monitoring.

Inclined wells created by sonic drilling greatly complement horizontal wells because they promise to markedly improve sampling capabilities. Sonic drilling uses high-energy vibrations to resonate a drill string of heavy casing. The vibrations enhance penetration and force formation material into the casing. A sample retrieval system clears the casing and brings the sample to the surface. Thus, sample recovery is integrated with the drilling process. The quality of the samples that this technique obtains can be excellent because no fluids are required during drilling.

Sonic drilling has created approximately 12 inclined wellbores and slant wells. The Sandia National Laboratory in 1993 obtained soil samples beneath a mixed-waste landfill using two wellbores inclined at 15 degrees from horizontal and 43 meters (141.1 feet) long (Figure 2-21) (38). Soil samples were taken ahead of the drill bit to reduce sample temperature and analyzed in the field for metals. (Chromium was the primary contaminant.) A pipe 15 centimeters (6 inches) in diameter was driven to create the wellbore. Then, a 10-centimeter (4-inch) polyvinyl chloride (PVC) casing and screen was inserted as the pipe was jacked out. An inverted plastic sleeve was inflated in the screen to obtain vapor samples.

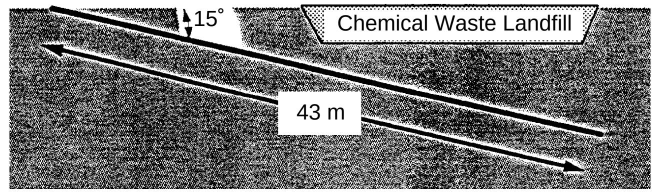


Figure 2-21. Inclined wellbore created with resonant sonic drilling, Sandia National Laboratories (38).

Similar studies have been conducted at the DOE Hanford site, where approximately five wellbores were created for sampling and one inclined wellbore was completed for soil vapor extraction by 1993 (12). The "Case Histories" section that follows describes the soil vapor extraction well. Cobble-rich sediments at Hanford present extremely challenging conditions for drilling and sampling, and the success of sonic drilling at this location is a powerful testament to the capabilities of this application.

Using sonic techniques to drill three inclined wellbores, continuous cores were recovered at Newark Air Force Base (AFB), Newark, Ohio (39). The wellbores were drilled under a building at 45 degrees to a VD of approximately 5.5 meters (18 feet). The wellbores readily penetrated a reinforced concrete beam.

2.4 Case Histories

This section overviews known applications, discusses average costs of previous projects, and describes four selected applications of horizontal or inclined wells.

2.4.1 Overview

As of the summer of 1993, there were more than 100 applications of horizontal wells at 30 contaminated sites (17). Approximately one-quarter of the wells strictly extracted ground water, one-quarter extracted vapor, and the remaining half was used for a variety of techniques including free-product recovery, sparging, sampling, or combinations of two recovery techniques (Table 2-6). The majority of the wells were created at depths of less than 8 meters (26.2 feet). This partially reflects the tendency to find more contaminants at shallow depths than at great depths. The depths of the majority of these

Table 2-6. Summary of Applications of Horizontal Wells (28)

Vertical Depths	Ground-Water Extraction Wells	Soil Vapor Extraction Wells	Other Wells	Totals
≤8 m	13	18	52	83
8-30 m	9	4	1	14
≥30 m	4	3	2	9
Totals	26	25	55	106

wells also reflect the lower limit of electronic beacon locating systems. The electronic beacon, or "walkover," method currently is significantly less expensive than any alternative. Therefore, the cost of creating wells increases abruptly if they are deeper than 8 meters (26.2 feet).

The measured depth, or total length, of horizontal wells created for environmental purposes generally ranges from 10 to 670 meters (32.8 to 2,197 feet), but the majority of the wells are in the range of 30 to 150 meters (98.4 to 492 feet) (Figure 2-22). Like the range of depths, the range of well lengths probably also results from both technical and economic factors. Wellbores 150 meters (492 feet) long can be drilled with relatively small, compaction-type rigs and can be completed with pull-back techniques. Accordingly, this type of well is typically less expensive than those created with more sophisticated rigs and completion methods.

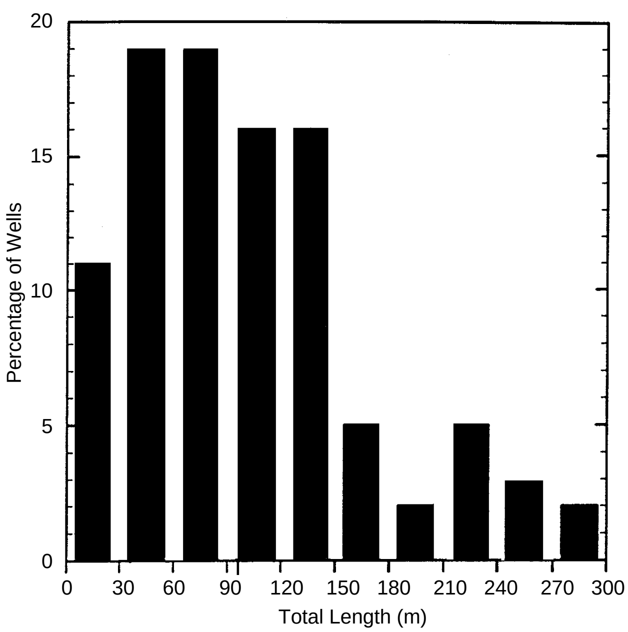


Figure 2-22. Distribution of total lengths of horizontal wells drilled by summer 1993 (17).

Details of the specifications and applications of horizontal wells are summarized in Table 2-7 through Table 2-10.

2.4.2 Typical Costs of Completed Projects

Cost is a critical factor when considering the application of a horizontal well. Examining results of completed projects can offer some guidance toward anticipated costs. Those results (17) indicate the costs of horizontal wells range widely depending on:

- Drilling method and size of rig
- Vertical depth and total well length
- Site geology
- Well materials (screen length and composition)
- Type of drilling fluid

Other factors, too, can affect project costs. For example, cost considerations should include risk factors related to the probability of losing equipment downhole. Drilling accuracy also affects costs by dictating the sophistication of the guidance system and the time required to finish a bore. In addition, costs of designing the horizontal well and managing the field effort must be considered.

Records of previous projects indicate that wells created with a small- to medium-size utility-type drilling rig, a radio beacon/receiver guidance system, a simple drilling fluid system, and a compaction drilling tool cost approximately $164 per meter ($50 per foot). This cost is based on using a guidance system limited to depths of less than 7.6 meters (24.9 feet) and assumes the drilling fluid system and the drilling tool limit use of the method to appropriate geologic conditions. In addition, the average cost is for wells using PVC or HDPE as the well casing.

A more sophisticated directional drilling method uses a larger drilling rig, a magnetometer-accelerometer guidance system, and a more advanced drilling fluid system and drilling tool or mud motor. Depth or geologic conditions do not limit this method. With this method, the average cost for horizontal wells constructed from PVC or HDPE materials and installed at less than 7.6 meters (24.9 feet) VD is $1,036 per meter ($316 per foot); for VDs between 7.6 and 30 meters (24.9 to 98.4 feet), the average cost is $602 per meter ($183 per foot); for VDs greater than 30 meters, the average cost is $744 per meter ($227 per foot). VDs less than 7.6 meters (24.9 feet) cost more due to the short drilled length of the shallow boreholes and the fixed mobilization and daily costs for the equipment this method uses. Therefore, the cost per unit length is less for longer boreholes.

Horizontal well materials may be constructed from any combination of PVC, HDPE, and stainless steel. The well screen may be a simple slotted pipe or may have prepacked filter packs. The average cost per unit length of horizontal wells with casing and screens of PVC or HDPE is approximately half the average cost of wells with stainless steel casing and screen and/or a prepacked filter on the screen (17).

2.4.3 Selected Examples

This section focuses on two sites with horizontal well applications and two sites with sonic drilled inclined wells. These case studies represent rather large, high-profile projects, or applications of new technology. Case studies of modestly sized projects, which can be

Table 2-7. Sites Where Horizontal Wells Have Been Used for Ground-Water Recovery

Reported Contaminant Type/Phase	Site	Date	Number and Type of Wells	Site Geology	Type of Wellbore	Measured Depth/ Horizontal Length (Feet)	Vertical Depth (Feet)	Well Materials	Drilling Contractor
TCE/APL and DNAPL	Taylor, MI	1987	2 GWE	Unconsolidated sediments	Blind	550/—	<25	7 in. ID SS	Drilex
TCE/APL and DNAPL	Savannah River Site, Aiken, SC	June 1991	1 GWE	Fine silty sand, silt, and clay	Blind	488/258	152	6 in. ID HDPE	Eastman Cherrington
Halogenated hydrocarbons/ APL and DNAPL	Geismar, LA	August 1992	2 GWE	Sand and clay	Blind	435/363 469/400	14 16	6 in. ID, 20-slot HDPE; 4 in. ID, 12-slot SS filter pack	Eastman Cherrington
TCE/APL and DNAPL	Union City, CA	July 1992	1 GWE	Fine silty sand and clay	Blind	100/70	15	3 in. ID, 10-slot PVC	Eastman Cherrington
TCE/APL and DNAPL	San Francisco Bay area, CA	1992	1 GWE	Sand, sand and gravel, intermittent clay	Blind	200/80	25	3 in. ID, 10-slot SS	Eastman Cherrington
TCE/APL and DNAPL	Tinker AFB, OK	November 1992 to February 1993	5 GWE	Fine sand, silt, and clay with shale and sandstone units	Blind	920/200	110 150 3 x 35	6 in. ID, 20-slot HDPE 4 in. ID, 12-slot SS filter pack	Eastman Cherrington
Petroleum hydrocarbons/ APL and LNAPL	Sacramento, CA	December 1991	1 GWE	Sandy clay	Blind	362/100	50	3 in. ID, 20-slot PVC	Eastman Cherrington
Petroleum hydrocarbons/ APL and LNAPL	Carson City, NV	April 1992	1 GWE	Unconsolidated channel sands	Blind	250/100	25	3 in. ID, 20-slot PVC	Eastman Cherrington
Petroleum hydrocarbons/NR	Fullerton, CA	April 1992	1 GWE	Silt, clay, and intermittent fine sand	Blind	460/325	110	6 in. ID, 20-slot HDPE	Eastman Cherrington
Petroleum hydrocarbons/NR	Beaumont, TX	July 1992	2 GWE	Silty sand with clay stringers	Blind	—/300	25	6 in. ID 20-slot HDPE; 4 in. ID HDPE filter pack	Eastman Cherrington
JP-4 jet fuel/APL and LNAPL	Williams AFB, AZ	July 1992	2 GWE	Fine sand and silt clay with gravel and cobbles	Continuous	2,200/500	235	6 in. ID prepack SS	Michels Environmental
Leaking underground storage tank/APL and LNAPL	Houston, TX	September 1992	1 GWE	Clayey soil	Blind	320/—	35	4 in. ID, 10-slot PVC	Eastman Cherrington
Petroleum hydrocarbons/NR	Geismar, LA	November 1992	1 GWE	Sand and clay	Blind	185/—	18	6 in. ID, 20-slot HDPE	Eastman Cherrington
Petroleum hydrocarbons/NR	Geismar, LA	February 1993	2 GWE	Clay and sand	Blind	295/— 320/—	36 20	6 in. ID Enviroscreen	Eastman Cherrington
Lime Lake leachate/APL	Barberton, OH	February 1993	9 GWE	Clay and sand-size tailings	Blind	750/—	40	4 in. ID, 20-slot HDPE	Eastman Cherrington
TCE/NR	Savannah River Site, Aiken, SC	May 1991	1 SVE	Fine silty sand, silt, and clay	Blind	300/152	105	6 in. ID HDPE	Eastman Cherrington
TCE/NR	Savannah River Site, Aiken, SC	November 1992	2 SVE	Fine sand, silt, and clay	Blind	725/420 720/420	110	3 in. ID, 10-slot PVC	Eastman Cherrington
Petroleum hydrocarbons/NR	Los Angeles, CA	February to March 1992	2 SVE	Unconsolidated silty sand	Blind	600/400	45 85	3 in. ID, 10-slot PVC	Eastman Cherrington
Petroleum hydrocarbons/NR	Norwalk, CA	August to September 1992	2 SVE	Silty sand and sandy silt	Blind	360/— 320/—	25	4 in. ID, 20-slot HDPE	Eastman Cherrington

Table 2-7. Sites Where Horizontal Wells Have Been Used for Ground-Water Recovery (continued)

Reported Contaminant Type/Phase	Site	Date	Number and Type of Wells	Site Geology	Type of Wellbore	Measured Depth/ Horizontal Length (Feet)	Vertical Depth (Feet)	Well Materials	Drilling Contractor
Petroleum hydrocarbons/NR	Orcutt, CA	October 1992	4 SVE	Sandy soil	Continuous	1 x 120/— 3 x 70/—	1 x 4 3 x 5	2 in. ID, 10-slot PVC	UTILX
Petroleum hydrocarbons/NR	Charlotte, NC	June 1993	2 SVE	Sandy silt and sandy clay	Continuous	150/100 120/110	8 7	2 in. ID, 10-slot PVC	UTILX
Hydrocarbons/NR	Las Vegas, NV	1993	1 SVE	NR	Continuous	426/—	<5	4 in. ID HDPE	UTILX
Hydrocarbons/NR	Las Vegas, NV	1993	1 SVE	NR	Continuous	840/—	<5	4 in. ID HDPE	UTILX
Hydrocarbons/NR	Cherry Hill, NJ	1993	2 SVE	NR	Continuous	—/140	<5	2 in. ID HDPE	UTILX

APL = aqueous phase liquid; DNAPL = dense nonaqueous phase liquid; GWE = ground-water extraction;
LNAPL = light nonaqueous phase liquid; NR = not reported; SS = stainless steel; SVE = soil vapor extraction; TCE = trichloroethylene

Table 2-8. Sites Where Horizontal Wells Have Been Used for Vapor Extraction

Reported Contaminant Type	Site	Date	Number and Type of Wells	Site Geology	Type of Wellbore	Measured Depth/ Horizontal Length (Feet)	Vertical Depth (Feet)	Well Materials	Drilling Contractor
TCE	Savannah River Site, Aiken, SC	May 1991	1 SVE	Fine silty sand, silt, and clay	Blind	300/152	105	6 in. ID HDPE	Eastman Cherrington
TCE	Savannah River Site, Aiken, SC	November 1992	2 SVE	Fine sand, silt, and clay	Blind	725/420 720/420	110	3 in. ID, 10-slot PVC	Eastman Cherrington
Petroleum hydrocarbons	Los Angeles, CA	February to March 1992	2 SVE	Unconsolidated silty sand	Blind	600/400	45 85	3 in. ID, 10-slot PVC	Eastman Cherrington
Petroleum hydrocarbons	Norwalk, CA	August to September 1992	2 SVE	Silty sand, and sandy silt	Blind	360/— 320/—	25	4 in. ID, 20-slot HDPE	Eastman Cherrington
Petroleum hydrocarbons	Orcutt, CA	October 1992	4 SVE	Sandy soil	Continuous	1 x 120/— 3 x 70/—	1 x 4 3 x 5	2 in. ID, 10-slot PVC	UTILX
Petroleum hydrocarbons	Charlotte, NC	June 1993	2 SVE	Sandy silt and sandy clay	Continuous	150/100 120/110	8 7	2 in. ID, 10-slot PVC	UTILX
Hydrocarbons	Las Vegas, NV	1993	1 SVE	NR	Continuous	426/—	<5	4 in. ID HDPE	UTILX
Hydrocarbons	Las Vegas, NV	1993	1 SVE	NR	Continuous	840/—	<5	4 in. ID HDPE	UTILX
Hydrocarbons	Cherry Hill, NJ	1993	2 SVE	NR	Continuous	—/140	<5	2 in. ID HDPE	UTILX

APL = aqueous phase liquid; DNAPL = dense nonaqueous phase liquid; GWE = ground-water extraction;
LNAPL = light nonaqueous phase liquid; NR = not reported; SVE = soil vapor extraction; TCE = trichloroethylene

Table 2-9. Sites Where Horizontal Wells Have Been Used for Assorted Environmental Applications

Purpose	Site	Date	Number of Wells	Site Geology	Type of Wellbore	Measured Depth/ Horizontal Length (Feet)	Vertical Depth (Feet)	Well Materials	Drilling Contractor
Characterization, monitoring at landfill	Kirtland AFB, NM	May 1993	1	Sand, gravel, and cobbles	Continuous	400/—	40	None	Charles Machine Works—Ditch Witch
Bioventing-diesel	Cincinnati, OH	July 1993	2	Fluvial sediments	Continuous	190/140	10	2 in. ID, 20-slot PVC	University of Cincinnati
Ground water and petroleum recovery-LNAPL	Seattle, WA	June 1993	1	Medium to coarse sand	Continuous	320/180	13	4 in. ID, 20-slot prepack PVC	UTILX
Product recovery-petro-hydro	Ponca City, OK	1988	7	Fine sand, silt, and clay	Continuous	980/—	17	4 in. ID slotted PVC	UTILX

APL = aqueous phase liquid; DNAPL = dense nonaqueous phase liquid; GWE = ground-water extraction; LNAPL = light nonaqueous phase liquid; SVE = soil vapor extraction; TCE = trichloroethylene

Table 2-10. Sites Where Horizontal Wells Have Been Used for Several Purposes

Purposes	Site	Date	Number and Type of Wells	Site Geology	Type of Wellbore	Measured Depth/ Horizontal Length (Feet)	Vertical Depth (Feet)	Well Materials	Drilling Contractor
In situ stripping of TCE-contaminated soil and ground water	Savannah River Site, Aiken, SC	October 1988 September 1988	1 SVE 1 injection	Fine silty sand, silt, and clay	Blind Blind	290/200 485/300	75 155	4 in. ID, 10-slot SS screen; 2 in. ID steel perforated pipe	Eastman Cherrington
Air injection, SVE, bioactive barrier hydrocarbon	Ponca City, OK		3 SVE/ bioinjection	Unsaturated fine silty sand, silt, and clay	Continuous	—/400	20	2-4 in. ID, 20-slot PVC	S&S Harris
Dual well system for SVE and GWE with TCE in soil and ground water	Tinker AFB, OK	November 1991	1 SVE 1 GWE and control	Fine silty sand, silt, and clay	Blind Blind	270/70 270/70	15 25	6 in. ID prepack SS 6 in. ID prepack SS	Michels Environmental
Radio frequency heating/SVE of TCE in soil	Savannah River Site, Aiken, SC	September 1992	1 SVE	Fine silty sand, silt, and clay	Continuous	570/230	40	4 in. ID, 10-slot fiberglass	Charles Machine Works
Dual well system for SVE and GWE of TCE-contaminated soil and ground water	South San Francisco Bay Area, CA	October 1992	1 SVE 1 GWE	Sand, gravel, and intermittent clay	Blind Blind	210/110 210/110	18 20	3 in. ID, 20-slot HDPE; 3 in. ID, 20-slot SS	Eastman Cherrington
Washing soils contaminated with gasoline	Minden, NV	October 1992	22 infiltration galleries 2 recovery 4 recovery	Sandy clay with gravel	Blind Blind Blind	20/— 35 and 65/— 135/—	3 3 3	2 in. ID PVC 4 in. ID PVC 2 in. ID PVC	UTILX
Air injection, SVE, and gasoline remediation system for underground storage tank	Del City, OK	October 1992	3 GWE/ SVE/ injection	Fine silty sand, silt, and clay	Continuous	300/—	12	2 in. ID, 20-slot PVC	S&S Harris

Table 2-10. Sites Where Horizontal Wells Have Been Used for Several Purposes (continued)

Purposes	Site	Date	Number and Type of Wells	Site Geology	Type of Wellbore	Measured Depth/ Horizontal Length (Feet)	Vertical Depth (Feet)	Well Materials	Drilling Contractor
Dual well system for diesel recovery and GWE and ground-water control	Cincinnati, OH	December 1992	1 product recovery 1 GWE and control	Fluvial sediments	Continuous Continuous	297/— 325/—	19 21	4 in. ID PVC 4 in. ID PVC	Underground Research, Inc.
In situ stripping of soil and ground water contaminated by underground storage tank	Fallon, NV	December 1992	3 SVE 4 air injection	Silty sand	Continuous Continuous	170/— 170/— 280/— 150/— 180/— 240/— 280/—	4 5 4 14	2 in. ID, 10-slot PVC 2 in. ID, 10-slot PVC	UTILX
Air injection, SVE, and gasoline remediation system for underground storage tank	Moore, OK	March 1993	4 GWE/ SVE/ injection	Fine silty sand, silt, and clay	Continuous	500/—	12	4 in. ID, 20-slot PVC	S&S Harris
Dual wall system for SVE and GWE of contaminated soil and ground water by underground storage tank	Portland, OR	April 1993	1 SVE 1 GWE and control	Silt	Continuous Continuous	475/300 475/300	6.5 23	4 in. ID, 20-slot PVC 4 in. ID, 20-slot PVC prepack screen	UTILX

APL = aqueous phase liquid; DNAPL = dense nonaqueous phase liquid; GWE = ground-water extraction; LNAPL = light nonaqueous phase liquid; SS = stainless steel; SVE = soil vapor extraction; TCE = trichloroethylene

significantly less costly than the ones detailed here, were unavailable at the time of writing. Each discussion includes the following information:

- Location of site, date of study, contact for the contracting agency, and contact for the drilling contractor.
- Remediation objective.
- Geology of site as related to drilling operations.
- Design, description of well trajectory, completion technique, intended purpose, and well performance (if available).
- Results, discharge, contaminant concentration with time, area where drawdown is affected, comparison to model, and cost of project (if available).

2.4.3.1 Ground-Water Recovery, Geismar, Louisiana

Location. Two ground-water extraction wells were installed in Geismar during August 1992 at an abandoned herbicide manufacturing plant (37).

Objectives. The wells were installed as components of a pump and treat ground-water extraction system. The system was designed to remediate ground water contaminated with ethylene dichloride (EDC) and monochlorobenzene (MCB) beneath the plant. There were two ground-water contaminant plumes: the south plume had an area of approximately 1,486 square meters (16,000 square feet), with MCB concentrations of 100 to 200 ppm and EDC concentrations of 10 to 100 ppm; the north plume had an area of approximately 557 square meters (6,000 square feet), with MCB concentrations of 100 to 370 ppm and EDC concentrations of 10 to 70 ppm. The conceptual plan was to install two horizontal wells with screens 122 meters (400 feet) long. The goal was to install each horizontal well on top of a clay layer along the base of the affected zone, parallel and through the longitudinal axis of each plume.

Site Conditions. The two wells, H-50 and H-51, were installed beneath an abandoned wastewater pipeline (south plume) and a product loading area (north plume), respectively. The contaminated portion of the aquifer consisted of Holocene silty clay.

The wellbore path for H-50 was designed to run west to east through the principal area of contamination. The wellbore path had to run through a narrow corridor of vertical subsurface drill shafts and pilings that supported an overhead steel superstructure. The corridor was

6.1 meters (20 feet) wide, allowing a maximum of 2.4 meters (8 feet) clearance to the south and 3.7 meters (12 feet) clearance to the north. The abandoned wastewater pipe ran about 1.5 meters (5 feet) above the proposed well path.

The wellbore path for H-51 was adjacent to an active railcar loading area and beneath a concrete road. The H-51 wellbore was allowed a 0.6-meter (2-foot) vertical and a 2-degree horizontal deviation.

Well Geometry. The well geometry for the two horizontal wells is presented in Table 2-11.

Table 2-11. Specifications of Horizontal Wells, Geismar, Louisiana

	H-50	H-51
Entry Angle	15° to Horizontal	15° to Horizontal
Kickoff Point	19 ft MD/5 ft VD	19 ft MD/5 ft VD
End-of-Curve	59 ft MD/12 ft VD	67 ft MD/14 ft VD
Horizontal Length	459 ft	467 ft

Drilling Method. The drill rig used for this job was rated to 610 meters (2,000 feet) for vertical drilling, with a hydraulic drill stem hoist that had a 311-kilonewton (kN) (70,000-pound) hoist and a 133-kN (30,000-pound) pullback capacity. The drill rig mast could incline from vertical to 15 degrees to horizontal.

This application used two different downhole assemblies. In the curved section of the wellbore, the downhole assembly consisted of a 30.5-meter (100-foot) radius, and a 17.1-centimeter (6.75-inch) diameter PDM mud motor with a 31.1-centimeter (12.25-inch) expandable bit. Wellbore surveying was done with a tool face indicator, which provided inclination and tool face orientation but did not provide wellbore azimuth. Data from the surveying system were communicated to the ground surface by creating pressure pulses in the drilling mud. When drilling neared the end of the curve, a film-based multishot magnetic survey tool confirmed the tool face indicator readings and the wellbore location. (The tool face indicator and the multishot magnetic survey tools are not commonly used in environmental directional drilling.) In the horizontal section of the wellbore, the downhole assembly consisted of a 91.4-meter (300-foot) radius and a 12.1-centimeter (4.75-inch) diameter PDM mud motor with a 22.2-centimeter (8.75-inch) expandable bit. Here, wellbore surveying was accomplished with a wireline magnetometer-accelerometer locator and an electromagnetic secondary survey system.

The wellbores were drilled and the curved section of the wellbore was cased with a 10-inch HDPE casing. The horizontal section of the wellbore was left open for the well installation. The open hole method was possible because the formation had a high clay content. In addition, a mixed metal hydroxide (MMH) additive was used with bentonite in the water-based drilling fluid. MMH is an insoluble crystalline inorganic compound containing two or more metals in a unique hydroxide lattice. The bentonite/MMH mixture extended the gel strength of the drilling fluid and allowed suspension of soil cuttings indefinitely when the drilling fluid circulation was halted.

Well Materials. The wells were constructed of 6-inch internal diameter (ID), 0.5-millimeter (0.02-inch) slotted HDPE with a 4-inch ID stainless steel prepack inside.

Well Installation. The well materials were pushed into the open wellbore. The horizontal section of the wellbore was relatively clear of cuttings, so the well materials did not experience extra friction during well installation. Each well was wash developed before the drill rig was removed from the drill site. Drilling fluids were displaced with potable water and pumped into tanks for treatment and disposal. The drill crew washed the HDPE liner with a wash tool to remove the filter cake and the fine-grained sediments. Water discharging from the wells became relatively free of sediments after 6 to 8 hours of flushing with water.

Field Effort. Well H-50 required 17 days of construction, 11 days longer than anticipated. A mechanical problem with the steering mechanism on the downhole mud motor resulted in two aborted curved section attempts before the problem was recognized and corrected. There also was one aborted attempt to drill the horizontal section due to overcompensating while controlling the elevation of the wellbore. The well was completed with a 110-meter (363-foot) horizontal well screen (as opposed to the 122-meter (400-foot) planned length). Most of the wellbore was steered along the specified trajectory, except a 12.5 meter (41-foot) section that fell 0.3 meters (1 foot) below the specified trajectory. The wellbore was successfully steered through the narrow corridor and away from the vertical pilings and monitor well. Soil cores were also retrieved successfully.

H-51 was constructed in 6 days. The completed well had 122 meters (400 feet) of well screen, as planned. Most of the wellbore was placed as specified, although a 21.6-meter (71-foot) section lay 0.3 meters (1 foot) below the maximum specified depth of 4.9 meters (16 feet), according to the surveys performed after completion.

Results of Tests Performed on Wells. Three steps were required to determine the pumping performance of each well:

1. The well was pumped for 8 hours to evaluate pump size and flow rates.

2. The well pump control was manually operated to obtain the optimum settings for the continuous automatic pumping operation.
3. The well was placed in continuous automatic operation.

Each well elicited different pumping results because of the heterogeneity of the sediments' hydraulic properties.

The results for H-50 were:

- A long-term pumping rate of 4.9 liters (1.3 gallons) per minute.
- An area of influence that spanned 48.8 meters (160 feet) on either side of the well.
- An estimated one pore volume of the well capture zone that pumped once every 149 days.

The results for H-51 were:

1. A long-term pumping rate of 22.3 liters (5.9 gallons) per minute.
2. An area of influence that spanned 21.3 meters (70 feet) on either side of the well.
3. An estimated one pore volume of the well capture zone that was pumped once every 15 days.

Current Status. The wells are pumping as part of a full-scale remediation system.

*Cost.*The wells cost approximately $400,000 each.

2.4.3.2 Ground-Water Recovery, Barberton, Ohio

The horizontal well project in Barberton exemplifies a multiple-well installation. A pilot well was installed to characterize drilling conditions, determine sediment hydraulic properties, and test the well screen and filter pack design. The pilot well installation provided important information that was used to optimize the design of the remaining eight horizontal wells (40).

Location. One pilot and eight production ground-water extraction wells were installed in Barberton during 1993.

Objectives. The wells were installed to collect leachate seeping from the base of two Solvay Process waste impoundments (lime lakes) into adjacent streams. The leachate had a pH of 12 to 13 and contained various hazardous constituents, including chlorinated hydrocarbons, asbestos, and lead (40).

Site Conditions. The lime lakes, Lime Lake 1 and 2, are located within a large chemical manufacturing facility that includes several portions of major waterways. There are two streams that flow along the north, east, and south boundaries of Lime Lake 1 and the north and northeast boundaries of Lime Lake 2. The lakes are about 12.2 meters (40 feet) above local grade and contain clay- to sand-sized lime spoils that are 12.2 to 15.2 meters (40 to 50 feet) thick and rest upon a hard, chemically altered layer of native soils. The hard layer acts as an aquitard and causes the leachate to form a mound within the lime lakes. A thick slaker sand and cinder cover was spread across the surface of the lakes to prevent surface erosion (40).

Well Geometry. The pilot well was constructed in a blind wellbore with a 17-degree to horizontal entry angle, drilled with a 183-meter (600-foot) radius of curvature, 231-meter (757-foot) MD, 152-meter (500-foot) horizontal length, and 11.6-meter (38-foot) VD. The geometry of the eight horizontal wells resembled that of the pilot well. Two wells had the horizontal section shortened to 91.4 meters (300 feet) due to a rapid change in the elevation of the hard layer (40).

Drilling Method. The pilot well was drilled with a medium-sized utility-type drilling rig equipped with a hydraulic spud jet drilling tool, a mud motor to drill through hard layers, and a magnetometer-accelerometer steering tool. A washover pipe enlarged the wellbore. A guar gum, water-based drilling fluid was used during drilling. The eight production wells were drilled in a similar manner, except for modifications based on the experience gained from drilling the pilot well. The modifications included additives mixed to the guar gum drilling fluid to improve its ability to clean the wellbore and maintain wellbore integrity and a reduced rate of penetration during drilling.

Well Materials. The pilot well was constructed of 10-centimeter (4-inch) ID, 0.5-millimeter (0.02-inch) slotted HDPE casing, and a 20/40 sand filter pack. The other eight wells were constructed of 15-centimeter (6-inch) ID HDPE, 0.5-millimeter (0.02-inch) slotted HDPE casing, and no filter pack. The decision not to include a filter pack in the eight production wells was based on the assumption that it would become encrusted and clogged with carbonate minerals. The fine materials that did enter the pilot well were attributed to over-pumping and not the well design. The decision to omit the filter pack in the production wells proved correct because fine-grained materials did not enter the wells during well development and testing. An electrical centrifugal pump was used in each well.

Well Installation Method. The well materials for the pilot well were pushed into the washover pipe. The filter pack was installed around the well screen with a "sand shoe" as the washover pipe was withdrawn from the wellbore. Installation of the remaining wells was similar except that they did not have a filter pack.

Field Effort. The pilot well installation required two attempts. Some problems occurred while constructing the pilot well:

- Drilling fluid and lime spoils fractured to the surface.

- The hydraulic spud jet met refusal at several thin, hard layers.
- The washover pipe became stuck twice and was retrieved by pulling on it with bulldozers.

These problems were overcome by changing the drilling fluid rheology, slowing the rate of penetration of the drill stem, and using a downhole mud motor to drill through the hard layers.

Results of Tests Performed on Well. The pilot well produced 6.1 liters (1.6 gallons) per minute after 45 days of pumping. The eight production wells produced 15.1 liters (4 gallons) per minute on an intermittent pumping schedule that was determined for each well. The rate of 15.1 liters (4 gallons) per minute was selected to provide a flow velocity that would keep the pump discharge line clear of solids and minimize the infiltration of fine materials into the wells.

Current Status. The wells currently are being used to collect the lime lake leachate.

Cost. The total cost of the nine-well system has not been released.

2.4.3.3 High-Angle Inclined Boreholes, Newark AFB, Ohio

Location. Three high-angle boreholes were drilled at Newark AFB in Newark during 1993.

Objectives. The purpose of the boreholes was to obtain continuous core samples beneath Building 4. The soil beneath the building was believed to be contaminated with chlorofluorocarbons.

Site Conditions. The soil was silty clay with some sand and gravel.

Well Geometry. Three boreholes were drilled, each at a 45-degree angle. The boreholes reached vertical depths of 5.2 to 5.5 meters (17 to 18 feet).

Drilling Method. The wellbores were drilled using the rotosonic technique described earlier with the drill rig mast at a 45-degree angle.

Field Effort. The wellbores successfully penetrated a reinforced concrete beam.

Cost. The three boreholes were drilled at a total cost of $7,530.

2.4.3.4 Inclined Well for Soil Vapor Extraction Well, Hanford Site, Washington

Location. The DOE (through the Westinghouse Hanford Company and Pacific Northwest Laboratory) and Water Development Corporation formed a Cooperative Research and Development Agreement (CRADA) for the purpose of developing a resonant sonic drilling method that can meet the rigorous drilling conditions found at the DOE's Hanford site in southeast Washington. Phase I of the research program included installing a 45-degree angle soil vapor extraction well at the 200 West Area Carbon Tetrachloride Expedited Response Reaction site (200 West area) at the Hanford site (12).

Objectives. The purpose of the inclined well was to demonstrate the ability of the resonant sonic drill rig to create an angled wellbore, and to install a soil vapor extraction well at the 200 West area.

Site Conditions. The upper geologic unit of the Hanford formation beneath the 200 West area consists of two facies: coarse-grained sand and granule-to-boulder gravel from which matrix is commonly lacking; and fine- to coarse-grained sand and silt that commonly display normally graded rhythmites from an inch to several inches. In general, the coarse facies is 5-percent boulder and ranges in thickness from 6.1 meters (20 feet) to greater than 61 meters (200 feet). The underlying fine facies consists of 1.5 to 18.3 meters (5 to 60 feet) of silts and fine sands, which in turn overlay sediments of Plio-Pleistocene Ringold formation (12).

Well Geometry. The wellbore was drilled at a 45-degree angle to a 36.3-meter (119-foot) VD and a 51.2-meter (168-foot) MD.

Drilling Method. The wellbore was drilled using the resonant sonic technique with a 300-horsepower drill head and the drill rig mast at a 45-degree angle.

Well Installation Method. The well materials were pushed into the wellbore.

Well Materials. The well materials consisted of a 7.6-centimeter (3-inch) ID stainless steel screen and riser.

Field Effort. The wellbore was drilled and the well was installed in 9 days.

Results of Tests Performed on Well. The inclined well yielded satisfactory flow rates compared to an adjacent soil vapor extraction well drilled with a cable tool drill rig.

Current Status. The well will be used to remediate the vadose zone at the 200 West area.

Cost. No cost analysis was performed on this well. Phase II of the CRADA will include cost analysis of the resonant sonic drilling method.

2.5 References

When an NTIS number is cited in a reference, that document is available from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-487-4650

1. Hantush, M.S., and I.S. Papadapulous. 1962. Flow of ground water to collector wells. Proceedings of the American Society of Civil Engineers. 88(HY5):221-244.

2. Losonsky, G., and M.S. Beljin. 1992. Horizontal wells in subsurface remediation. Hazardous Materials Control Conference, New Orleans, LA (February).

3. Mukherjee, H., and M.J. Economides. 1991. A parametric comparison of horizontal and vertical well performance. Society of Petroleum Engineers (June). pp. 209-216.

4. Dickinson, W.W., R.W. Dickinson, J. Nees, and E. Dickinson. 1991. Field production results with the ultrashort radius radial system in unconsolidated sandstone formations. Presented at the 5th UNITARJUNDP International Conference on Heavy Crude and Tar Sands, Caracas, Venezuela (August).

5. Dickinson, W.W., R.W. Dickinson, P.A. Mote, and J.S. Nelson. 1987. Horizontal radials for geophysics and hazardous waste remediation. In: Superfund '87. Silver Spring, MD. Hazardous Waste Control Research Institute. pp. 371-375.

6. Howsam, P., and R. Hollamby. 1990. Drilling fluid invasion and permeability impairment in granular formations. Quarterly J. Engin. Geol. (London) 23: 161-168.

7. Hayatdavoudi, A.Z. 1994. Personal communication from drilling fluid specialist, Eastman Cherrington Environmental Corporation, to D. Wilson, Independent Environmental Consultants, LLC (February).

8. Westmoreland, J. 1994. Evaluation of an air drilling cutting containment system. Sandia Report SAND94-0214 UC-721 (April). Albuquerque, NM: Sandia National Laboratories.

9. Simon, R., and G. Cooper. 1994. Use of cryogenic fluids for environmental drilling in unconsolidated formations. In: Vozniak, J.P., ed. Drilling technology. New York, NY: American Society of Mechanical Engineers. PD-Vol. 56: pp. 199-207.

10. Barrow, J.C. 1994. The resonant sonic drilling method: An innovative technology for environmental restoration programs. Ground Water Monitor. Rev. 14(2):153-161.

11. Dance, D.R., and N.W. Beattie. 1981. Sonic drilling. Northwest Mining Association Fall Short Course (no address available).

12. Westinghouse Hanford Co. 1994. Phase I: Resonant sonic CRADA report. WHC-SD-EN-TRP-007. Richland, WA: Westinghouse Hanford Company.

13. Westinghouse Savannah River Co. 1993. Summary report of the drilling technologies tested at the integrated demonstration site. WSRC-TR-93-565. Aiken, SC: Westinghouse Savannah River Co.

14. Ta Inglis, T.A. 1987. Directional drilling, petroleum engineering, and development studies, Vol. 2. Boston, MA: Graham and Trotman.

15. Wu, J., and H. Juvkan-Wold. 1994. The effect of wellbore curvature on tubular buckling and lockup, drilling technology. In: Vozniak, J.P., ed. New York, NY: American Society of Mechanical Engineers. PD-Vol. 56. pp. 17-25.

16. Driscoll, F.G. 1986. Ground water and wells, 2nd ed. St. Paul, MN: Johnson Division Publisher.

17. Wilson, D.D., and D.S. Kaback. 1993. Industry survey for horizontal wells. Final report. WSRC-TR-93-511. Aiken, SC: Westinghouse Savannah River Company.

18. Joshi, S.A. 1991. Horizontal well technology. Tulsa, OK: PennWell Books.

19. Murdoch, L.C. 1994. Transient analysis of an idealized interceptor trench. Water Resour. Res. (in press).

20. Bear, J. 1979. Hydraulics of ground water. New York, NY: McGraw-Hill.

21. Karlsson, H., G. Losonsky, and G.E. Jacques. 1992. Horizontal wellbore completions for aquifer restoration and their economics. Proceedings of the 10th Annual Hazardous Materials and Environmental Management Conference, Atlantic City, NJ (June). pp. 154-181.

22. Muskat, M. 1937. The flow of homogenous fluids through porous media. Ann Arbor, MI: J.W. Edwards, Inc.

23. Streltsova, T.D. 1988. Well testing in heterogeneous formations. New York, NY: John Wiley and Sons.

24. Murdoch, L.C., and J. Franco. 1994. The analysis of constant drawdown wells using instantaneous source functions. Water Resour. Res. 30(1):117-124.

25. U.S. EPA. 1991. The feasibility of hydraulic fracturing of soil to improve remedial actions. Final report. EPA/600/2-91/012 (NTIS PB91-181818).

26. Dikken, B.J. 1990. Pressure drop in horizontal wells and its effect on production performance. JPT Nov:1,426-1,433.

27. Tarshish, M. 1992. Combined mathematical model of flow in an aquifer-horizontal well system. Ground Water 30(6):931-935.

28. Wilson, D.D., and D.S. Kaback. 1993. Results of a survey of horizontal environmental well installations. In: Vozniak, J.P., ed. Drilling technology 1994. New York, NY: American Society of Mechanical Engineers. PD-Vol. 56. pp. 193-199.

29. U.S. EPA. 1993. Guidance for evaluating the technical impracticability of ground-water restoration. EPA/540/R-93/080.

30. U.S. EPA. 1991. Soil vapor extraction technology handbook. EPA/540/2-92/003.

31. Cohen, R.M., J.W. Mercer, and J. Matthews. 1993. DNAPL site evaluation. Ada, OK: U.S. Environmental Protection Agency

32. American Petroleum Institute. 1989. A guide to the assessment and remediation of underground petroleum releases. API Publication 1628. Washington, DC: American Petroleum Institute.

33. Sale, T.C., and D. Applegate. 1994. Oil recovery at a former wood treating facility. Proceedings of the Innovative Solutions for Contaminated Site Management, Water Environment Federation, Miami, FL.

34. Downs, C. 1993. Personal communication from Conoco Corporation to D. Wilson, Independent Environmental Consultants, LLC (June).

35. Looney, B.B., T. Hazen, D. Kaback, and C. Eddy. 1991. Full-scale field test of the in situ air stripping process at the Savannah River Integrated Demonstration Test Site. WSRC-RD-91-22. Aiken, SC: Westinghouse Savannah River Co.

36. Wemple, R. 1994. Personal communication from drilling specialist, Sandia National Laboratories, to D. Wilson, Independent Environmental Consultants, LLC (April).

37. Conger, R.M., and K. Trichel. 1993. A ground-water pumping application for remediation of a chlorinated hydrocarbon plume with horizontal well technology. In: Proceedings of the Seventh National Outdoor Action Conference and Exposition, Las Vegas, NV. Dublin, OH: National Ground Water Association. pp. 47-61.

38. Sandia National Laboratories. 1993. Sonic drilling rig hits heavy metal at closed landfill. Lab News 45(10). Albuquerque, NM: Sandia National Laboratories.

39. Clough, R. 1994. Personal communication from Alliance Environmental, Inc., to D. Wilson, Independent Environmental Consultants, LLC (March).

40. Gaillot, G. 1994. Design and installation of an in situ leachate collection system utilizing horizontal wells within two former waste impoundments. Proceedings of the Eighth National Outdoor Action Conference and Exposition, Minneapolis, MN (May 23-25). Dublin, OH: National Ground Water Association (in press)

Chapter 3
Induced Fractures

More than 50 years ago, petroleum engineers recognized that induced fractures could increase the productivity of oil wells. Within the past 5 years, EPA research has shown that similar techniques can improve the performance of environmental wells (1, 2). This chapter focuses on the methods currently used for environmental applications that primarily involve injection of fluids to drive fracture.

Several fluid injection methods induce fractures using fluid pressure to dilate a wellbore and open nearby cracks. Once fluid pressure exceeds a critical value, a fracture begins to propagate and continues to grow until injection ceases, the fracture intersects a barrier (or the ground surface), or the injected fluid leaks out through the fracture walls. After injection is complete, fractures are held open either by asperities on the fracture walls *(naturally propped* fractures) or by permeable material, or *proppant,* injected during propagation. The result is a layer designed to be more permeable than the adjacent formation.

The maximum dimension of fractures created by injecting fluids is limited by either a tendency for the fracture to climb and intersect the ground surface or by the loss of fluid through the fracture walls. Therefore, all else being equal, the maximum dimension increases with increasing depth and decreasing permeability of formation. At a depth range of 1.5 to 5 meters (4.9 to 16.4 feet) in overconsolidated silty clay, the typical maximum dimension of a fracture is approximately three times its depth.

The primary application of induced fractures is to increase the discharge of and the area affected by a well. Field demonstrations conducted in rock or silty clay have shown that, compared with a conventional well, induced fractures can increase well discharge 10 to 50 times and increase the distance for detecting pressure effects 10 times. According to theoretical modeling studies, these results are consistent with the expected change in performance when adding a permeable layer to the vicinity of a well.

Even though the improvement in performance is striking, induced fractures do not solve all the problems of remediation in tight formations. The relative increase in performance is greatest in the tightest formations, where the performance of conventional wells is poorest. Accordingly, it may be possible to improve the rate of recovery of a contaminant by an order of magnitude or more and still have a rate that is less than desired for timely closure. In tight formations, induced fractures may improve the performance of hydraulic control and containment at the site, or they can be combined with other enhancement technologies, such as hot air injection (3), to accelerate recovery.

A secondary application of fracturing techniques is to deliver solid compounds to the subsurface. This application fills fractures with granular compounds that improve the remedial process in various ways. For example, injecting solid nutrients or slowly dissolving oxygen sources can improve bioremediation, or injecting electrically conductive compounds (e.g., graphite) can improve electrokinetics.

Hydraulic (injecting air) and pneumatic (injecting liquid) fracturing both are recognized methods of inducing fractures for environmental applications. Both the mechanisms and the results of the methods share some striking similarities (3, 4), yet they each have distinctions. Capabilities are evolving so rapidly, however, that a direct comparison of hydraulic and pneumatic fracturing methods is unnecessary. For this reason, this chapter focuses on the characteristics and factors affecting performance of induced fractures, and avoids direct reference to hydraulic or pneumatic fracturing except in the description of techniques.

Most induced fractures that have been used for environmental applications to date are shaped like gently dipping disks, or in some cases they are slightly bowl shaped. Vertical fractures have been used infrequently. Therefore, this chapter focuses on gently dipping fractures. Applications of induced vertical fractures hold promise, however, particularly to improve the performance of horizontal wells.

3.1 Methods of Inducing Fractures

Methods used to induce fractures and improve the performance of wells range from injecting fluid to detonating explosives. Many of the environmental applications involve fluid injection, although a few cases have involved use of explosives to enhance permeability of bedrock and improve contaminant recovery (5, 6). The following section focuses on methods that use fluid injection.

3.1.1 General Considerations

The fundamental process of inducing fractures by injecting a fluid is straightforward: the fluid is injected into a borehole until the pressure exceeds some critical value and a fracture nucleates. This method can create fractures in most naturally occurring materials, from rock to unlithified sediment or soil. Once the fracture nucleates, fluid continues to be injected, driving propagation away from the borehole.

3.1.1.1 Injection Fluids

Three fluids have been used to create fractures for most environmental applications: gas, water, and gelled water. The major issues affecting choice of injection fluid are:

- The equipment required for injection.
- Safety concerns.
- The potential to mobilize contaminants or other injection restrictions.
- The ability to transport solid grains into the fracture.

Air is the primary gas used to create fractures, although other gases may have applications in specialized conditions, such as when anaerobic conditions are required. Air injection requires relatively simple equipment. Large injection rates, however, demand special safety precautions. There is relatively little possibility of mobilizing liquid phases, although there is a strong possibility of mobilizing vapor phases. Local regulations may govern injection of air into the subsurface.

Fine-grained particles or powders can readily be transported into fractures by injecting air (7). The ability to transport particles decreases with increasing grain size and density, however, limiting capabilities of injecting significant volumes of coarse-grained sand. This is a topic of current research, and the development of specialized equipment and proppants promises to markedly improve the transport of proppant during air injection.

Injecting water can create fractures in low-permeability rock formations. Relatively simple pumps and packers are used, although pressures in excess of 5 MPa may be required to initiate the fracture. Safety precautions relate to potentially high pressures. Injection of water is restricted by regulations in some locations. Injecting water will have limited effect on mobilization of vapors, although it may mobilize liquids. In most cases, the injected water and any fluids mobilized as a result of injection should be readily recovered through the resulting fracture. Water can transport solid grains into a fracture, although the best results are achieved using plastic particles that have a density similar to water (8).

Guar gum gel is a viscous fluid commonly used to create fractures. Guar gum is a food additive derived from the guar bean. Mixed with water, guar gum forms a short-chain polymer with the consistency of mineral oil. Adding a crosslinker causes the polymer chains to link and form a thick gel capable of suspending high concentrations of coarse-grain sand. This property makes guar gum gel ideal for filling fractures with solid material. An enzyme added to the gel breaks the polymer chains, allowing recovery of the thinned fluid from the fracture.

Fracturing with guar gum gel requires several specialized pieces of equipment. A mixer is required to blend the gel, crosslinker, and enzyme, as well as sand or other solids. This method also requires a pump capable of handling a slurry containing a high concentration of sand grains. The safety precautions are similar to those for pressurized water. Injecting guar gum gel negligibly effects mobilization of vapors, although it may slightly mobilize liquids after the gel breaks down. The fracture confines the gel during injection, however, and prompt recovery of the gel should eliminate interaction with pore fluids. Areas that regulate subsurface injection may restrict injection of guar gum gel. Because in situ organisms metabolize the organic components of guar gum gel, its use is commonly avoided when fractures are created to enhance discharge from a drinking water well. The major benefit to using guar gum gel is the ability to suspend a high concentration of coarse-grained sand (1.2 to 1.8 kilograms of sand per liter of gel [10 to 15 pounds of sand per gallon of gel]) as a slurry in the gel.

3.1.1.2 Injection Pressure and Rate

The pressure required to initiate a fracture in a borehole depends on several factors, including confining stress, toughness of the enveloping formation, initial rate of injection, size of incipient fractures, and pores or defects in the borehole wall. In general, the injection pressure increases with increasing depth, injection rate, and fluid viscosity. For instance, propagating a fracture by injecting liquid into soil at 75 liters (19.8 gallons) per minute and at a 2-meter (6.6-foot) depth requires 60 to 85 kPa (8.7 to 12.3 psi) of pressure, which increases approximately 20 kPa per meter (0.9 psi per foot) of depth. In contrast, the pressure required to create a fracture by injecting air, with injection rates of 20,000 to 30,000 liters (706 to 1,059 cubic feet) per minute, is in the range of 500 to 1,000 kPa (73 to 145 psi).

The pressure during propagation decreases in most operations, but the details of the pressure history depend on a variety of factors. For example, slight increases in pressure occur when sand concentration in slurry increases (Figure 3-1).

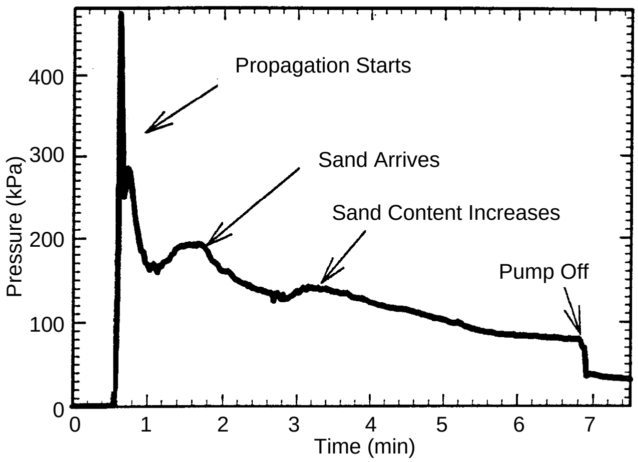


Figure 3-1. Injection pressure during creation of a fracture by injecting a sand-laden slurry.

3.1.1.3 Leakoff

Propagation could continue indefinitely if the fracture is created in infinitely impermeable material, but in real materials several factors limit the size of the fracture. Some of the injected fluid flows out through the walls of the fracture and into the pores of enveloping soil or rock (Figure 3-2). Workers in the oil industry dubbed this process "leakoff." The rate of leakoff increases as the fracture grows and offers more surface area through which the injected fluid can flow. Other factors that affect the leakoff rate include the relative permeability of the fractured formation and the viscosity and pressure of the fluid. Accordingly, the rate of fracture propagation decreases as the rate of leakoff increases, and propagation ceases entirely when the leakoff rate equals the rate of injection.

In most environmental applications, leakoff generally controls the size of the gas-driven fractures. For example, injecting gas at 25 to 50 cubic meters (883 to 1,766 cubic feet) per minute into sandstone for approximately 20 seconds typically results in a fracture roughly 10 to 20 meters (32.8 to 65.6 feet) in maximum dimension. A longer injection period negligibly affects fracture dimension (3). Thus, the rate of injection is a critical design variable affecting fracture size during air injection (9). The fast rates of leakoff during air injection also may yield the secondary benefit of dilating fractures or pores adjacent to the main fracture.

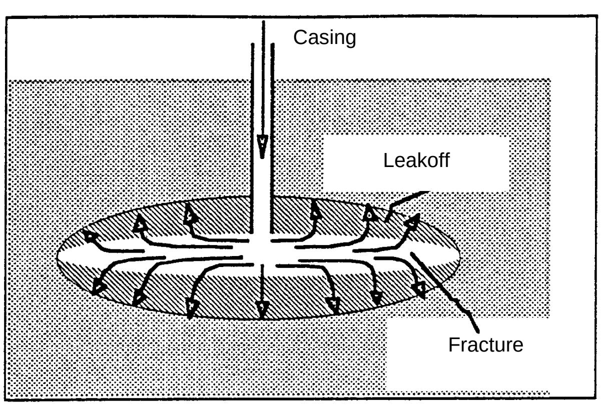


Figure 3-2. Injected fluids leaking out of fracture during propagation.

Leakoff tends to be more significant when creating fractures by injecting slurries into sand or gravel. This is because in other situations (e.g., when creating fractures at shallow depths in silty clay by injecting water or viscous gel), other effects (e.g., intersecting the ground surface) become important before the fractures become large enough to be affected by leakoff.

3.1.1.4 Other Fracturing Methods

Although effective, injection of fluid is by no means the only method of inducing useful fractures in the vicinity of wells. Propagating at high rates can create multiple fractures in the vicinity of a bore. This process involves detonating explosives (10) or igniting rapidly burning propellants to drive fractures at high rates (11, 12). Early practitioners of this technique lowered glass bottles filled with nitroglycerin into wells and detonated the explosive with a sudden shock. This procedure probably helped to clear the zone adjacent to the well that was plugged during drilling. A variety of modern propellants, which rapidly produce gas without an explosive shock, have been used to fracture wells. In some cases propellants lowered into a well perforate the wall of a bore, whereas in other cases the propellant rapidly drives a gas-filled fracture into the adjacent formation (11).

Another method involves applying an electric field to the vicinity of a bore to induce fractures. This method has been used to a limited extent to affect the productivity of wells (13). Myriad microfractures in low permeability formations accompany the application of radio-frequency heating, presumably resulting from the rapid boiling of pore water.

3.1.2 Monitoring Fracture Location

The most widely used method of monitoring fracture location is measuring the displacement of the ground surface (3, 4, 9). The displacement over a gently dipping fracture at shallow depths appears as an asymmetric dome (Figure 3-3). Net displacements can be determined by surveying a field of staffs with finely graduated scales before and after fracturing. Alternatively, tiltmeters can measure extremely gentle slopes of the ground surface in real time while the fracture is being created. The former method is inexpensive and provides reliable data on the final displacements, whereas the latter method supplies information on the growth of the fracture, which may be necessary when creating fractures in the vicinity of sensitive structures.

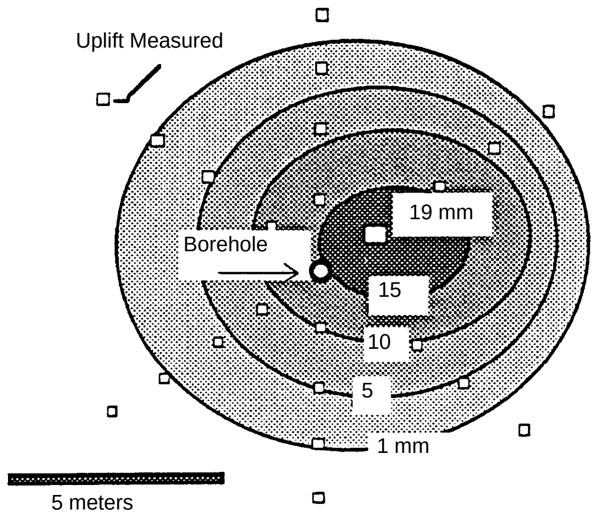


Figure 3-3. Typical pattern of uplift over a shallow, gently dipping hydraulic or pneumatic fracture.

The pattern of uplift indicates characteristics of the fracture at depth. A broad, symmetric dome indicates that the fracture gently dips and is roughly symmetric. Many fractures propagate in a preferred direction, which is reflected by displacements that are asymmetric with respect to the borehole. At shallow depths (where the ratio of fracture length to depth is roughly 3), the magnitude of uplift appears roughly equivalent to the aperture of the fracture. Thus, in these cases, fracture aperture and extent can be estimated directly from the uplift. Lesser ratios of length to depth (deeper fractures) generally require mathematical inversion of appropriate analyses (14-16) to estimate geometry of the fracture.

Borehole extensiometers fitted to open bores also can detect the location of induced fractures. This application directly detects the opening of the fracture tip as an increase in the length of the bore. This provides a direct determination of the aperture of the fracture that is more reliable than measurements of uplift. In one application, borehole extensiometers placed in the vicinity of a retaining wall ensured that induced fractures were terminated before they reached the wall (17).

Monitoring induced fractures through their displacement field is not without its limitations. Accurately determining the dip and aperture of deep fractures is difficult, even when using numerical inversion methods (14, 18). Moreover, details such as fracture bifurcation or intersection of adjacent fractures generally cannot be detected. Heterogeneities in the subsurface may produce results that are difficult to interpret.

3.1.3 Equipment

The equipment used to induce fractures consists of an aboveground system, which must be capable of injecting the desired fluid at the required pressures and rates, and a belowground system, which must be capable of isolating the zone where injection will take place.

3.1.3.1 Aboveground Equipment

The type of fluid to be injected largely determines the aboveground equipment. *Pneumatic fracturing*, which entails injecting air to create fractures, requires equipment that rapidly delivers air to the subsurface. The most versatile equipment developed for pneumatic fracturing employs a series of high-pressure gas cylinders with a pressure regulator to control injection (Figure 3-4) (9). This equipment injects air at rates of 25 to 50 cubic meters (883 to 1,766 cubic feet) per minute and at pressures of 0.5 to 2 MPa (72.5 to 290 psi). The process can be tailored to site conditions and is particularly suited to delivering air at high rates. Moreover, this method can create fractures with compressed gases other than air, which may have applications during bioremediation, in situ oxidization, or other remedial processes.

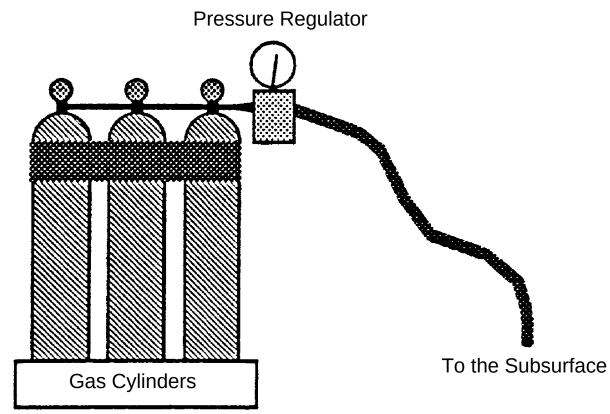


Figure 3-4. Aboveground equipment used for pneumatic fracturing (9).

Injecting air directly from a compressor may induce fractures under some circumstances. Filters or specialized compressors are required to eliminate traces of oil in the air stream. Typically, compressors are unable to supply the pressure or the rate available from pressurized cylinders; therefore, this approach may be limited in relatively permeable formations where leakoff limits the size of fractures that are created by injecting at modest rates.

Injecting liquid to induce fractures, *hydraulic fracturing*, requires equipment to prepare and inject the liquid. Hydraulic fractures created by injecting water alone require equipment that consists primarily of a high-pressure positive displacement pump with associated pressure relief devices (19). Hydraulic fractures that are filled with sand or other granular proppant require a mixer to create the slurry. A batch mixer consisting of one or two open tanks fitted with agitators can be used to create the slurry, a labor-intensive approach that can limit field productivity when desired fracture volumes are larger than the tanks. An alternative is to use a continuous mixer, which blends metered streams of gel, crosslinker, breaker, and sand to form slurry. This type of device represents a larger capital investment than a batch mixer, although it reduces the time, labor, and thus the cost required to create fractures. In most cases, positive displacement pumps inject slurry to create hydraulic fractures. Duplex and triplex piston pumps, as well as progressive cavity pumps, are widely used for this purpose.

3.1.3.2 Belowground Equipment

Belowground equipment for inducing fractures consists of a device for isolating the zone of injection. Both pneumatic and hydraulic fracturing use straddle packers in open holes (Figure 3-5) (19). A specialized nozzle assembly (3, 20) fits between straddle packers and improves gas delivery during pneumatic fracturing. This technique allows fractures to be spaced approximately every 0.5 meters (1.6 feet) along an open borehole. In some cases, the seal that straddle packers provide in open holes in saturated silts and clays may be insufficient.

When fractures are created in unlithified sediments, driven casing (4) offers an alternative to straddle packers. One example of this approach is to drive a casing with an inner-pointed rod to depth (Figure 3-6). After removing the rod, a high-pressure pump injects a water jet to cut a notch in the sediments at the bottom of the borehole. The notch reduces the pressure required to start propagation, much as the notch in plastic packaging reduces the effort required to open the package. The notch also ensures that the fracture starts in a horizontal plane at the bottom of the casing. A fracture can be created at the bottom of the casing by injecting either gas, liquid, or slurry. After creating the fracture, the rod can be reinserted and driven to greater depth to create another fracture, or the casing can be left in place to access the fracture during recovery.

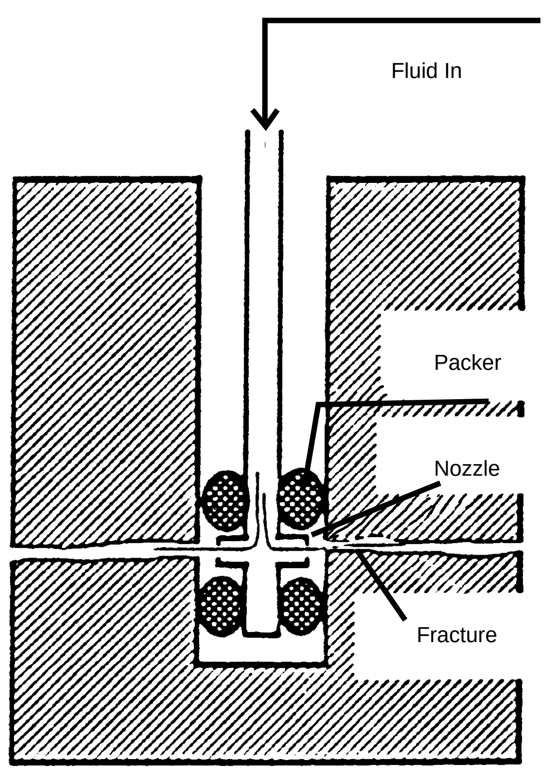


Figure 3-5. Fracture created by isolating a zone with a straddle packer.

Using this approach in unlithified sediments allows casing to be advanced by either hammering (using a dropweight, pneumatic, or hydraulic hammer) or direct push (using the weight of a drill rig or cone penetrometer). Packers or related methods are appropriate in rock and in some unlithified sediments.

3.1.4 Well Completion

The method used to complete a well that has been hydraulically fractured affects the versatility and cost of the well. Completions that allow access to individual fractures provide the most versatility, but they can consume more time and money than completions that offer access to all fractures by one casing. Access to individual fractures can improve performance during vapor extraction. For example, this method can allow alternating between air inlet and suction on adjacent fractures, or can provide dewatering capabilities from lower fractures and vapor recovery from upper fractures. It also can improve recovery of NAPL by directing aqueous and nonaqueous phases to separate pumps. Other applications, such as water recovery from a confined aquifer, may benefit little from access to each fracture.

Completion techniques that access all fractures simultaneously (Figure 3-7a) resemble standard well completion methods (10). To provide individual access, a grouted zone along the bore can isolate each fracture (Figure 3-7b). Alternatively, casing driven to create fractures in unlithified sediments can be left in place to access the fracture during recovery (Figure 3-7c).

3.2 Design Considerations

Several factors affect the form and permeability of induced fractures. These factors should be evaluated when considering using induced fractures to increase the performance of wells at a site. Geologic conditions play a major role in affecting fracture form and dictate the need for using a sand proppant. Site conditions, particularly structures that may interfere with propagation, also are important considerations. Table 3-1 summarizes the important factors and their favorable or

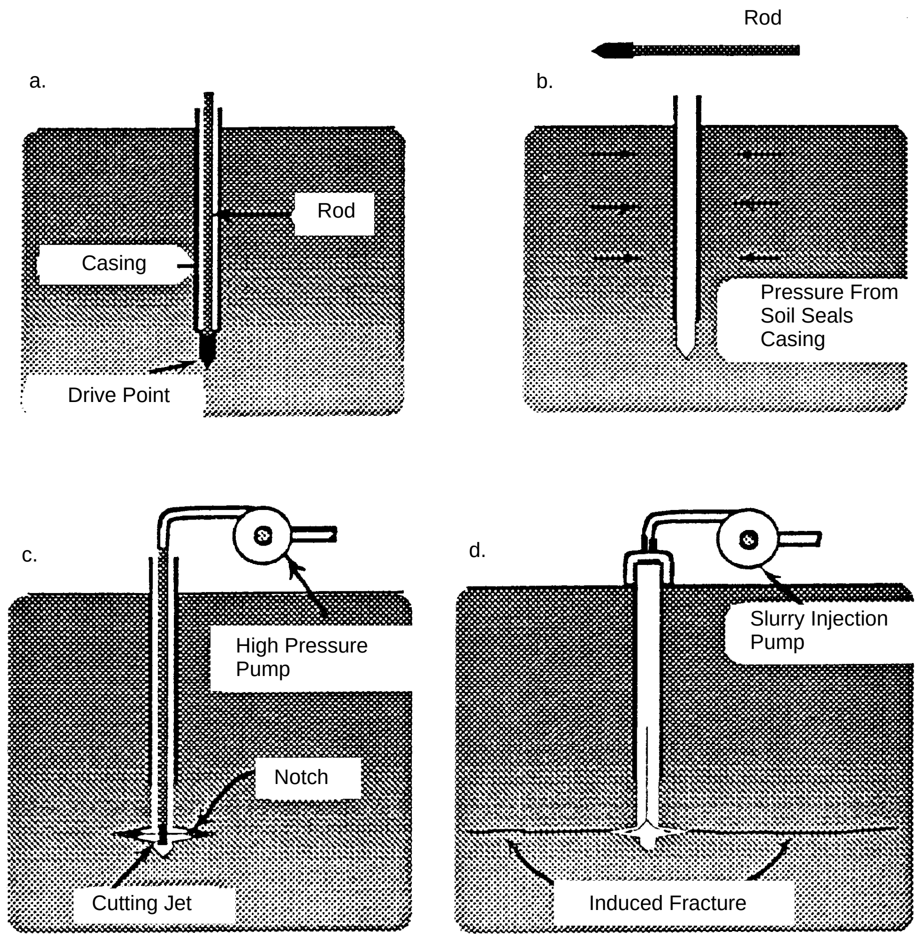


Figure. 3-6. Fractures created at the bottom of driven casing.

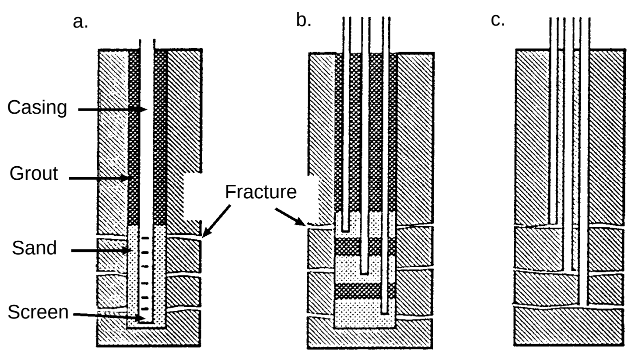


Figure 3-7. Methods of completing wells with induced fractures: a) screen across all fractures b) casing to each fracture, and c) driven casing to each fracture.

Table 3-1. Design Considerations for Induced Fractures

Factor	Favorable	Unfavorable
Fracture form	Gently dipping for vertical wells	Vertical (fracture may reach ground surface)
Formation permeability	Moderate to low ($k < 10^{-8}$ cm^2)	Unnecessary in high permeability formations (clean sand)
Fracture permeability	>1,000 times formation k	<100 times formation k
Formation type	Rock or fine-grained sediment	Coarse-grained sediment
Sand proppant	Unlithified, saturated sediments	May be unnecessary in rock formations
No proppant	Rock formations	Soft formations where fracture may close
State of stress	Horizontal stress > vertical stress (overconsolidated)	Horizontal stress < vertical stress (normally consolidated)
Well completion	Access to each fracture most versatile	Screen to several fractures less versatile but less costly than individual access
Site conditions	Open ground over fracture	Structures sensitive to displacement over fracture

unfavorable results. These factors specifically target relatively shallow applications typical of many contaminated sites. The table is based on current findings and is subject to change as fracturing techniques are modified.

3.2.1 Flow to a Gently Dipping Fracture

To better understand the impact of some of the factors listed in Table 3-1, consider the effects of creating a fracture in the vicinity of a well. One perspective ignores the geometry of the fracture and views the improvement in well performance as an increase in the effective permeability of the material enveloping the well (21). From another view, the fracture is a discrete layer that affects the pattern of flow in the subsurface. The former provides a simple method of assessing the improvement resulting from the fractures, whereas the latter provides more detailed insight into effects in the subsurface.

For example, consider the effect of a sand-filled fracture on subsurface air flow during a field test (22). The fracture in this case was 1.5 meters (4.9 feet) deep and 3 meters (9.8 feet) in radius and had an average thickness of 6 millimeters (0.2 inches). The fracture was accessed via a well 5 centimeters (2 inches) in radius and screened from 1.4 to 1.7 meters (4.6 to 5.6 feet). An identical well with no fracture was used for control. Silty clay, of permeability 10^{-9} square centimeters (10^{-12} square feet), underlays the site. The surface of the site was exposed to the atmosphere (no cap), and an impermeable boundary was assumed at 7 meters (23 feet) (bedrock was at this depth). Air was pulled from the wells using a suction head of 2.5 meters (8.3 feet) of water (absolute pressure head of 7.9 meters [25.75 feet] of water). To evaluate subsurface flow, field observations allowed calibration of a numerical analysis of these conditions.

Assuming the conditions cited above, the discharges from a vapor well were calculated for fractures with permeabilities ranging from 10^{-9} to 10^{-3} square centimeters (10^{-12} to 10^{-6} square feet). The results (Figure 3-8) indicate that discharge increases only slightly if the fracture permeability is less than 10^{-7} square centimeters (10^{-10} square feet), or not even 100 times greater than the formation permeability. The discharge increases significantly, however, if the fracture permeability is greater than 1,000 times that of the formation. Using Figure 3-8, field measurements of well discharge, and other analyses, the permeability of the fracture used for this test was estimated at 5 x 10^{-6} square centimeters (5 x 10^{-9} square feet), approximately the permeability of coarse-grained sand injected into the fracture.

The fracture influences each of the essential measures of subsurface flow—pressure, flux, and travel times. Pressure contours form concentric shells around the conventional well screen, whereas they elongate around

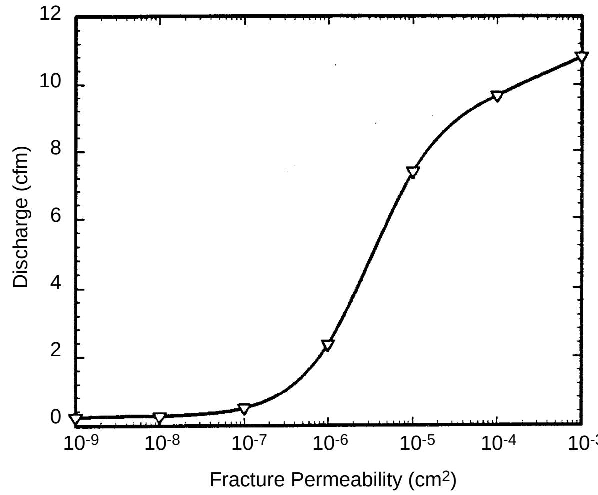


Figure 3-8. Air discharge from a well intersecting a flat-lying circular fracture as a function of the permeability of the fracture. (Formation permeability is 10^{-9} cm^2.)

the fracture. The pattern of flow paths also elongates by the fracture (Figure 3-9). The suction felt by the formation less than 0.5 meters (1.6 feet) from the control well is equal to the suction in a broad area 3 meters (9.8 feet) from the well, and more than 1 meter (3.3 feet) above and 2 meters (6.6 feet) below the fracture. Remember that equal suction was applied to both wells; thus, most of the applied suction was lost within a few tenths of a meter of the conventional well, whereas significant suction occurred several meters from the well along the fracture.

The most easily measured formation parameter in the field is pressure, or suction. Flux (volumetric flow/unit area) and travel time, however, are more important than pressure for environmental applications. The flux pattern resembles the pressure pattern in that it forms concentric shells around the conventional well and elongated shapes around the fracture. Fluxes in the vicinity of the fracture are at least two orders of magnitude more than fluxes roughly a half meter from the conventional well. The flux 2 meters (6.6 feet) from the conventional well is roughly the same as the flux 6 meters (19.7 feet) from the fractured well.

Travel times, which were determined by tracking a particle from its starting location to the well, are shorter in the vicinity of the fracture. Travel time is particularly short in the region over the fracture, and the travel time roughly 5 meters (16 feet) from the well with a fracture is less than travel time 2 meters (6.5 feet) from the conventional well. This is significant because some estimates of remediation are based on the number of pore volumes, and the travel time is a measure of the time required to exchange one pore volume within that contour. Note that travel times in Figure 3-9 are given in units of time/effective porosity, so that the actual time of travel is obtained by multiplying the number on the plot

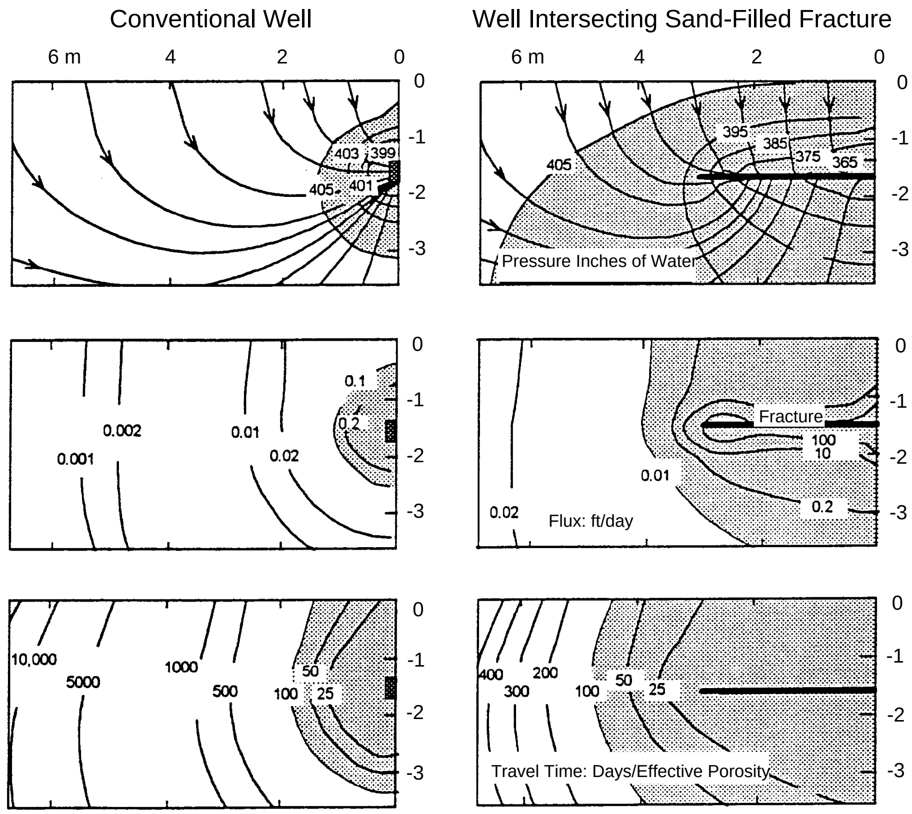


Figure 3-9. Pressure, flux, and travel time to a conventional well and a well intersecting a sand-filled fracture. Shaded areas are for comparison (based on the results of a numerical simulation using field data [22]).

by the effective porosity of the site. The results are presented this way because estimates of effective porosity were unavailable from this site. Estimates of effective porosity are 0.001 or less (23) at a similar site underlain by fractured silty clay till, so that air in the pores that are available for flow, shown in the shaded areas in Figure 3-9, would be exchanged in 2.4 hours.

The essential conclusions of this study are:

- The fracture increased the discharge by a factor of 20 and increased the radial distance where pressure is affected by a factor of 10 compared with the control well.
- The fracture changed the flow paths and patterns of pressure, flux, and travel time in the subsurface. Values of those parameters in the vicinity of the fracture were typically more than 10 times greater than in the vicinity of the control well.
- A theoretical model that treated the fracture as a thin layer of coarse-grained sand aided in predicting field observations.
- The fracture permeability was critical to well performance. Well discharge was nearly unaffected when the fracture permeability was less than 100 times that of the formation, whereas it increased abruptly as the fracture permeability increased from 100 to 10,000 times that of the formation.

3.2.2 Forms of Fractures

The effectiveness of an induced fracture depends primarily on its form, that is, its shape, aperture, orientation, length, width, and location with respect to the borehole. In most cases, fractures created by injecting fluids consist of one to several fracture surfaces. The general forms of fractures range from a steeply dipping, elongated feature to a flat-lying circular disk or bowl-shaped feature. The flat-lying fractures are useful to many applications because they can grow to significant sizes without intersecting the ground surface. Conversely, steeply dipping fractures tend to climb upward and intersect the ground surface.

The form of an induced fracture results from both fracturing technique and site conditions. Critical factors related to fracturing technique include type of fluid, rate or pressure of injection, and configuration of the borehole. Critical site conditions affecting form include loading at the ground surface, permeability, formation heterogeneities, and subsurface borings. Fractures created by injecting sand-laden slurry are easy to identify; their form is better known than the form of naturally propped fractures, which lack a proppant and can be difficult to identify in split-spoon samples. Most sand-filled fractures used for environmental applications have been created in glacial sediments or vertisols. Therefore, the impression of fracture form is biased toward fractures created under those conditions.

A database containing characteristics of approximately 140 fractures was analyzed to estimate the characteristics of a typical fracture created using methods described in Murdoch et al. (4). According to the analysis, the "typical" fracture induced by injecting liquid at shallow depths in overconsolidated silty clay is slightly elongated in plan and dips gently toward its parent borehole. The major axis of the fracture is approximately three times greater than the depth of initiation and 1.2 times greater than the minor axis (Figure 3-10).

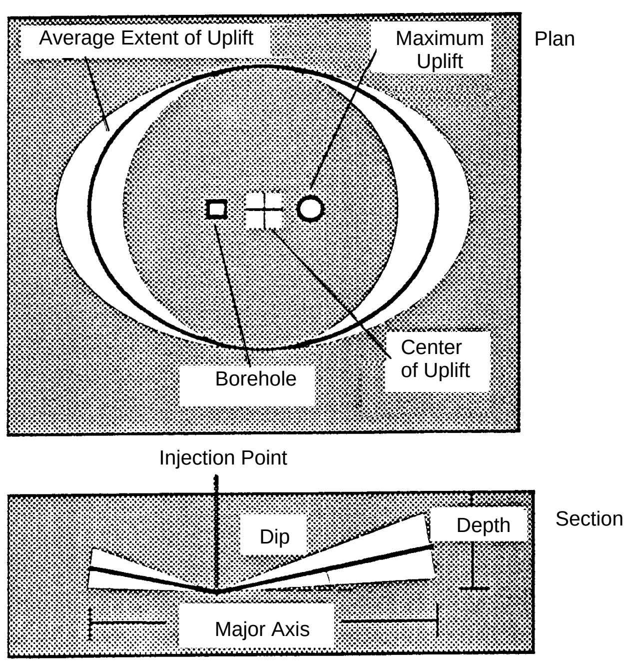


Figure 3-10. Plan and section of a typical hydraulic fracture created in overconsolidated silty clay.

Ground overlying the fracture displaces upward to create a gentle dome, and the amplitude of the dome resembles the aperture of the fracture at depth. The fracture closes and the dome subsides after injection, but the injected sand prevents the fracture walls from closing completely. The amount of closure depends on the concentration of sand in the slurry. Here, the ratio of maximum aperture when the fracture is pressurized to thickness of sand is similar to the ratio of the total slurry volume to the bulk volume of sand in the slurry. The major axis of the extent of uplift ranges from 5 meters (16.4 feet) to more than 12 meters (39.4 feet), with an average of 8.5 meters (27.9 feet). The maximum uplift ranges from a few millimeters to more than 30 millimeters (1.2 inches), with an average of 19 millimeters (0.75 inches).

The typical extent of uplift is roughly elliptical, with an aspect ratio of 1.2:1. The borehole used to create the fracture and the point of maximum uplift rarely coincide with the center of the extent of uplift. Interestingly, both the borehole eccentricity (ratio of distance between the center of uplift and the borehole to the major axis) and the displacement eccentricity (ratio of distance between the center of uplift and the point of maximum uplift to the major axis) are 0.14. Those two points, however, typically are on opposite sides of the center of uplift (Figure 3-10).

The average dips of fractures at seven different sites in the Midwest and Gulf Coast range from 5 to 25 degrees. At each site, however, the dips were fairly consistent, with the standard deviations of dips approximately 5 degrees. The dips at some sites were statistically different from dips at other sites, so that dip angle appears to depend strongly on site conditions.

3.2.3 Geologic Conditions

Geologic conditions significantly affect the forms of induced fractures. Details of all the effects are still being evaluated, but a discussion of some of the major geologic factors follows.

3.2.3.1 Permeability

A fracture must be significantly more permeable than the enveloping formation to have a major impact on well discharge (Figure 3-8). Therefore, the relative improvement resulting from induced fractures increases as the permeability of the formation decreases. In most cases, rock or formations of silt or clay are best suited to induced fracturing because they have the lowest initial permeabilities.

One exception involves using induced fractures to deliver solid compounds to the subsurface. This application can address processes independent of formation permeability and may require creating fractures and filling them with permeable sand, gravel, or rock.

3.2.3.2 State of Stress

The state of stress in the formation affects the orientation of an induced fracture once it has propagated away from the borehole. Induced fractures are usually flat-lying where horizontal formation stresses are greater than vertical stresses, whereas they tend to be steeply dipping where vertical stresses are greatest. In rock formations that erosion has buried or exposed, the lateral stresses are typically greater than the vertical stresses near the ground surface, effecting flat-lying induced fractures. Most shallow rock formations, with the possible exception of recent lava flows, have relatively high lateral stresses.

The state of stress of soils and unlithified sediments depends on several factors, including consolidation history (24) and wetting and drying history. Soils that were consolidated under a load greater than the present load are overconsolidated, and many such soils contain horizontal stresses that exceed vertical stresses. For example, loading by a glacier results in overconsolidation, so sediments deposited subglacially are good candidates for high lateral stresses. Soils containing clay minerals that undergo a large volume reduction upon drying become overconsolidated with repeated cycles of wetting and drying. For instance, vertisols (soils rich in swelling clays) are particularly susceptible to relatively large lateral stresses.

Glacial sediments are common in the northern Midwest and Canada, and vertisols are common along the Gulf Coast of Texas (Figure 3-11). The states of stress found in these areas favor the creation of gently dipping fractures.

Other conditions also result in favorable states of stress. Local geotechnical engineers can evaluate the state of stress at a particular site.

3.2.3.3 Bedding

Induced fractures may follow contacts in interbedded sediments, or they may follow partings between rock beds. The effect of bedding can be capricious, with fractures following beds in some cases and crosscutting beds in others. In some cases, it appears that flat-lying fractures are created in interbedded sediments with a state of stress that would favor vertical fractures. Generally, field tests need to establish the effects of bedding at a particular site.

3.2.3.4 Formation Strength

The strength of the formation plays an important role in determining whether fractures can be naturally propped or if they should be propped with sand. The section on fracture permeability includes a more detailed discussion of this issue.

3.2.3.5 Water Content

Water content of a formation appears to have negligible effect on creating fractures by injecting fluid.

3.2.4 Fracture Permeability

Because the permeability of the induced fracture is half the ratio between fracture and formation permeability, it critically affects the performance of wells. To compare the permeabilities of real fractures induced around boreholes, it is helpful to express their performance in terms of a smooth-walled slot with an aperture w_e that has the

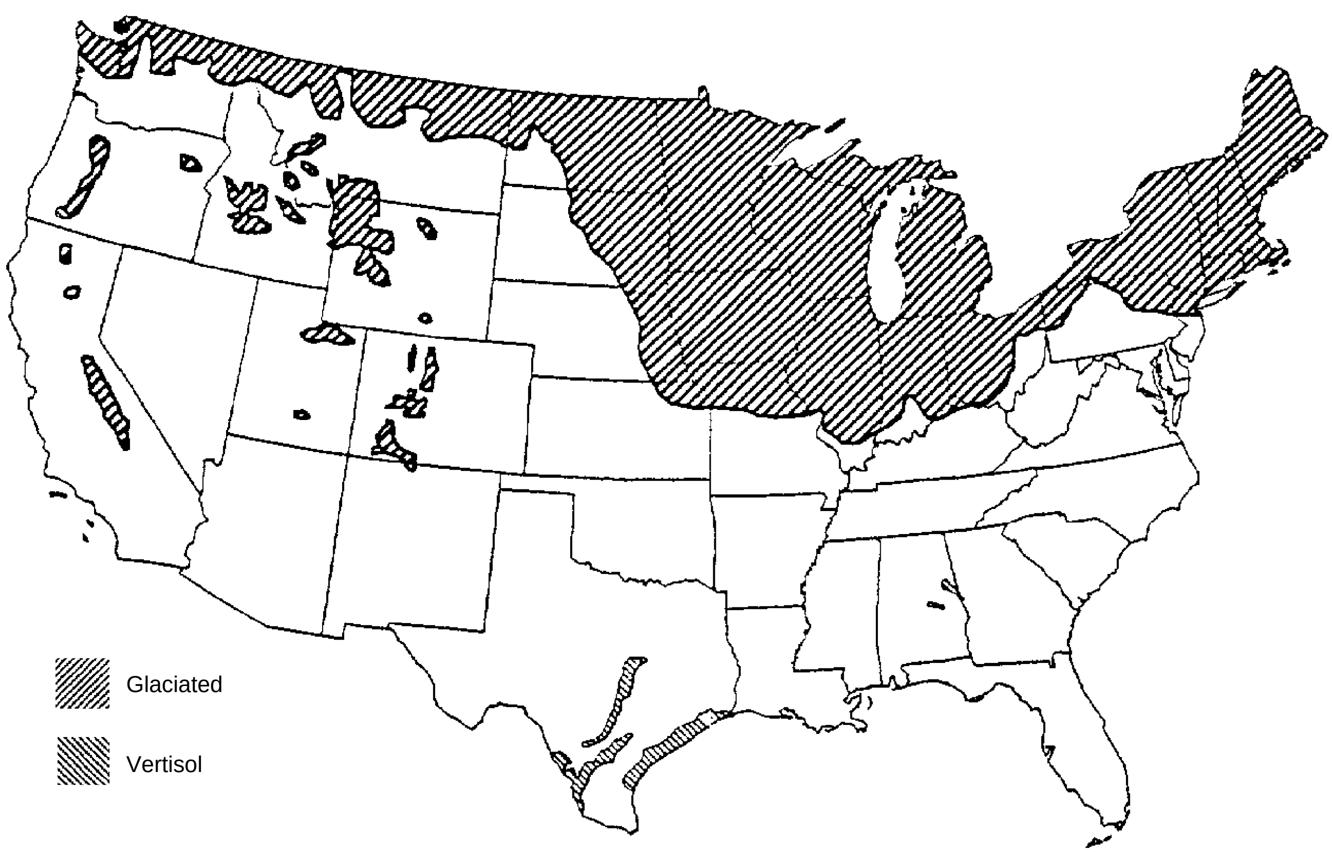


Figure 3-11. Locations of major areas of soils related to glaciers and vertisols (25, 26).

same effective permeability as the real fracture. Several methods relate effective permeability k_e and effective aperture (27), but one of the most commonly used (28) is

$$w_e = \sqrt{12 k_e}. \quad (3\text{-}1)$$

The aperture of a real fracture varies greatly along its length. Thus, the effective aperture is an average that accounts for how some locations with wide gaps and other locations that may be closed completely affect flow through the fracture. Accordingly, only hydraulic or tracer tests in the field can measure the effective permeability of natural fractures. The effective apertures of induced fractures adjacent to boreholes are incompletely known but have been estimated for several natural fractures. In one example, several flat-lying fractures in dolomite had an effective aperture of 0.022 to 0.023 centimeters, (0.0087 to 0.0091 inches), according to constant head tests (29).

The effectiveness of a fracture propped open with sand is expressed in terms of the product of proppant permeability k_p and aperture w. Using this basis, it follows that the equivalent aperture of a proppant-filled fracture is

$$w_p = (12\, k_p\, w)^{1/3}. \quad (3\text{-}2)$$

According to field tests and tabulated values (30), the permeability of medium- to coarse-grained sand used as a proppant is approximately 10^{-5} to 10^{-6} square centimeters (1.6 x 10^{-6} to 1.6 x 10^{-7} square inches). The actual aperture of sand-filled fractures typically ranges 0.5 to 1.0 centimeters (0.2 to 0.4 inches), so that the equivalent aperture is 0.02 to 0.05 centimeters (0.008 to 0.02 inches) (Figure 3-12). This overlaps with the effective apertures observed for fractures in rock.

The discussion above suggests that the effective aperture of naturally propped fractures may be similar to that of sand-filled fractures in rock. In soils, however, the strength of fracture asperities are less than those in rock, so naturally propped fractures may close. The rate of closure increases with decreasing strength of the soil or increasing driving stress on the fracture. In general, the strength of fine-grained soil decreases with increasing water content or decreasing consolidation. Thus, fractures may stay open in dry soils but may close when the soil becomes saturated. The stress driving closure is the stress the formation applies (for a horizontal fracture, the unit weight of the formation times the depth) plus the amount of suction applied to the fracture. Accordingly, fractures probably can be naturally propped when soil or rock is strong relative to the closure stress (9). If strength decreases, depth increases, or suction increases past a critical value, however, fractures should be propped with granular materials. Figure 3-13 schematically depicts this concept. Data are currently

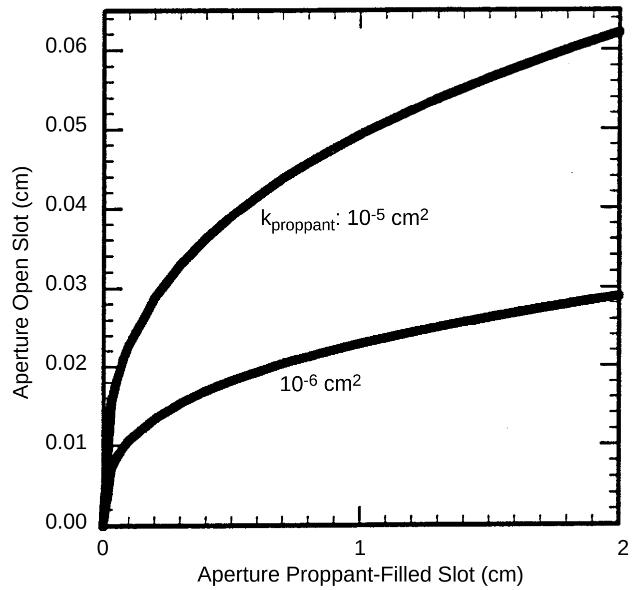


Figure 3-12. Effective aperture of an open slot that is equivalent to that of a fracture filled with proppant.

unavailable to determine the critical values, so the axes of Figure 3-13 are qualitative.

3.2.5 Fracture Size

Fracture size is an important design consideration because performance generally increases with increasing size. The rate and volume of injected fluids are the primary variables affecting size. Where significant leakoff may occur, such as when injecting air to create fractures, increasing the rate of injection increases the size of the fracture. In other cases, the volume of injected fluid determines the size of the resulting fracture. The major exception is when a fracture climbs and

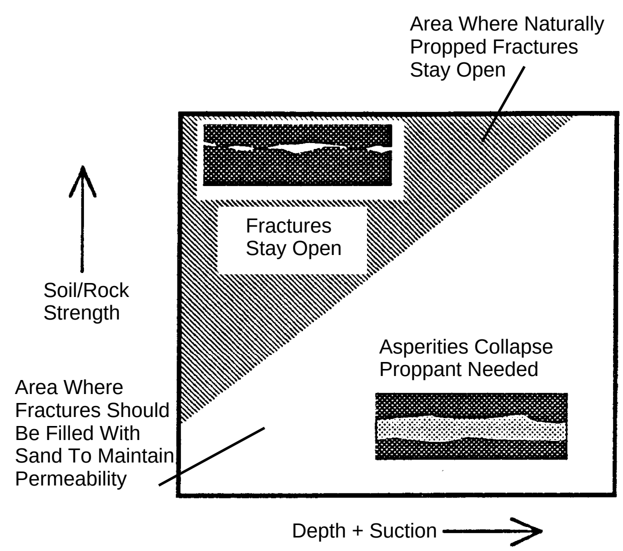


Figure 3-13. Factors that affect how fractures should be propped.

reaches the ground surface, in which case it may be smaller than anticipated.

The thickness of sand in a fracture can be manipulated to some extent by controlling the concentration of sand in the injected slurry or by changing other process variables. Sand in the fracture should be thick enough to provide a large contrast with the permeability of the formation. Once the contrast is sufficient, however, creating a thicker sand pack to obtain additional contrast provides only minor improvement. Once sand in the fracture is several millimeters thick, a decision must be made as to whether the cost of additional sand is worth the incremental benefit achieved by a thicker fracture.

Typical applications (in the depth range of 2 to 5 meters [6.6 to 16.4 feet]) have created fractures that are 6 to 10 meters (19.7 to 32.8 feet) in maximum dimension and 1 to 2 centimeters (0.4 to 0.8 inches) in maximum thickness. The size of the fracture increases with depth, and ratios of maximum length to depth of 3:1 to 4:1 are typical.

3.2.6 Well Completion

The type of well completion affects the flexibility of subsurface control, versatility in creating additional fractures, and cost. Some methods of completion provide access to each fracture or group of fractures, whereas others simultaneously access all the fractures in a well. Individual completions provide versatility by allowing each fracture to be used for either injection or recovery of fluids. This is particularly beneficial during vapor extraction or the simultaneous recovery of two separate phases, particularly NAPL and water. Individual completions are also more costly than continuous screening across all fractures.

In some cases, it may be necessary to return to a well and create additional fractures. Additional fractures can be created in wells that consist of open bores, and fracture size can be increased where completions consist of driven casing. Using currently available methods, it is difficult to create fractures using wells that have already been completed with a screen and gravel pack.

3.2.7 Site Conditions

Both surface and subsurface structures (e.g., buildings, pavement, buried utilities, wells, piezometers, or backfilled excavations) may affect, or be affected by, the creation of subsurface fractures. Creating fractures beneath structures may displace them. A structural engineer should be involved to estimate displacement tolerances for particular structures. In cases where surface displacements are critical, it is advisable to use real time monitoring of the displacements so that the procedure can be terminated before structures reach displacement tolerances.

Surface structures also may affect the propagation of fractures by loading the ground surface. In one case where injecting air created a fracture adjacent to a building, propagation was away from the building apparently in response to the surface loading by the structure. Fractures filled with liquid behave in a similar manner.

A fracture also may displace shallow subsurface utilities, pipe, or related features that lie above the fracture. A propagating fracture actually may intersect deeper features, such as wells, piezometers, or grouted sampling holes. There is limited evidence regarding the effects of this type of interaction.

Fracture propagation may terminate or alter markedly if the fracture intersects a backfilled excavation. The severity of this effect depends on site details and can only be evaluated case by case.

3.3 Applications

The typical application for induced fractures is to improve the performance of wells. Induced fractures can improve most in situ remedial actions involving fluid flow. Other applications include placing solid compounds in the subsurface and enhancing electrical conductivity. The sections that follow outline the principal applications that have been either demonstrated or proposed.

3.3.1 Vapor Extraction

Vapor extraction is one of the most widespread and effective methods of remediation, and induced fractures can improve vapor extraction in a variety of low-permeability formations. In most cases, applications include creation of multiple fractures at various locations along the length of vertical wellbores.

The primary purpose of inducing fractures for vapor extraction is to improve the discharge and areas affected by wells. Typically, results increase discharge by factors ranging from 10 to 100, and increase the distance affected by a well 10 times or more compared to control wells (1, 2). In addition, coupling individual completion methods with induced fractures allows air flux in the subsurface to concentrate in different areas.

Design variables to consider when inducing fractures for vapor extraction remediation include selection of proppants and details of completion. Some applications use fractures that are naturally propped, whereas others prop fractures with sand. Both methods can increase vapor discharge and contaminant recovery rate by an order of magnitude or more. In general, the duration of improvements of vapor discharges by naturally propped fractures are greatest in competent formations, such as sandstone and siltstone. Naturally propped fractures stay open in competent formations, whereas in soft sediments they may close due to the weight of the overburden and applied suction. However, naturally propped fractures in relatively stiff sediments, such as glacial drift, can stay open for many months. Propping fractures with sand offers an alternative that may increase the duration of the discharge in unlithified formations.

Completion methods range from installing screen over the entire interval of fractures to installing individual casings and screen to service each fracture. Screening the entire interval containing fractures reduces completion costs, but also reduces versatility and may limit the effectiveness of the application. The limitation results from how suction is applied to a stack of fractures. For instance, suction is applied equally when a screen is placed across all the fractures. As a result, air flux is particularly great in the region overlying the upper fracture, and it is significant at the ends of the lower fractures (Figure 3-4). Flux can be limited, however, in the region below the upper fracture, even close to the well. Air from either a neighboring inlet well or from the ground surface converges toward the ends of the lower fractures and avoids the area close to the well (Figure 3-14). As a result, screening a well across multiple fractures may result in incomplete remediation in the vicinity of the well.

An approach to avoiding this problem is to use one or more fractures as air inlet sources. This results in air flowing from one fracture to another and flux concentrating in the area between the fractures (Figure 3-14b). To use this process, it must be possible to access fractures individually. Several methods of well completion can accomplish individual access. One method includes boring through the interval containing fractures and placing sand or gravel at the depth of each fracture and grout in the intervals between fractures.

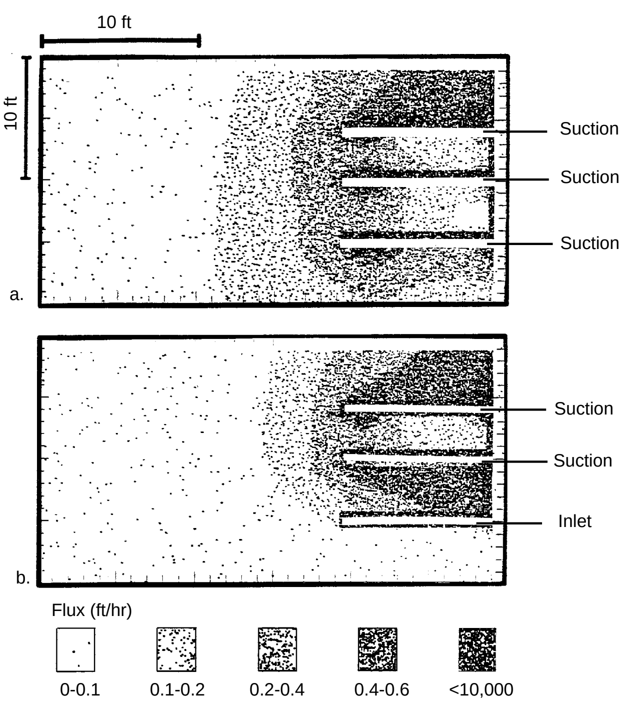


Figure 3-14. Flux of air to three flat-lying fractures (white band) shown in cross section: a) suction of 100 inches of water on all three fractures, and b) air inlet (atmosheric pressure) at the bottom and suction on the other two fractures.

Five sites have used fractures filled with coarse-grained sand for the purpose of vapor extraction, and naturally propped fractures have been created at one to several dozen sites.

3.3.2 LNAPL Recovery

Induced fractures can increase the recovery of free-phase LNAPL by increasing the discharge of recovery wells. This application can use either naturally propped fractures in rock or sand-propped fractures in unlithified sediments. LNAPL recovery from an aquifer closely resembles oil recovery from a reservoir.

This application requires creating fractures in or slightly below the contaminated zone. Recovering contaminants using fractures significantly below the LNAPL should be avoided because of the potential for trapping NAPL as a residual phase during drawdown (31).

One strategy for recovering a thick layer of LNAPL is to create one or several fractures in the contaminated interval and to complete the well to access all the fractures simultaneously. This approach can increase the recovery of the NAPL phase by an order of magnitude compared with a conventional well in a low-permeability formation.

In many cases, however, the contaminated zone is relatively thin, and recovery of LNAPL causes the upward displacement of the underlying NAPL/water interface. When the interface reaches the well, the ratio of NAPL to water diminishes, even though a significant amount of LNAPL may exist in the vicinity of the well.

In addressing the problem of water recovery from a LNAPL well, one approach is to create and separately access a fracture below the LNAPL/water interface. Water is recovered from the lower fracture, thereby preventing upward migration of water. This, in turn, prevents the reduction of the ratio of LNAPL to water recovered from the overlying fracture. A test in swelling clays near Beaumont, Texas, demonstrated this principle. At this site, several sand-filled fractures were installed to recover gasoline. At one location, the interface between gasoline and water was at a depth of approximately 3.3 meters (10.8 feet). Fractures were created at depths of 3.0 and 3.6 meters (9.8 and 11.8 feet), and individual pumps accessed each fracture. While both pumps were operating, the ratio of gasoline to water was between 5 and 6 from the upper fracture, whereas it was 0.01 from the lower fracture. The pump in the lower fracture was turned off while the upper pump continued to operate. Four hours later, the total rate from the upper fracture had increased markedly to slightly less than the rate produced when both pumps were operating. The rate of recovery of gasoline from the upper fracture, however, actually diminished, and the gasoline-to-water ratio decreased from 5 to 0.3. The case history section provides more details of this project.

3.3.3 Dual-Phase Recovery

Simultaneous recovery of vapor and liquid is inevitable when extracting vapor near saturated zones, and it may occur when accelerating liquid recovery by placing vacuum on a well. This process, called dual-phase recovery, uses a well with an inner tube attached to a vacuum pump (Figure 2-1) (31, 32). The system induces vapor flow during normal operation but also aspirates and removes liquid should it enter the well (Figure 3-15).

Wells containing induced fractures in the vadose zone of low-permeability formations tend to produce more water than conventional wells (22). Vapor discharge diminishes during water recovery, so the dual-phase recovery approach accelerates dewatering and enhances vapor recovery. Most applications that have extracted vapor using sand-filled fractures have used the dual-phase recovery approach.

3.3.4 NAPL Recovery

Dual-phase recovery from wells with induced fractures is similar to applications from conventional wells. The design uses a conventional well with a tube that passes through a seal at the well head and extends to the bottom of the screened section (31). Suction is applied either to the inner tube or to the annulus between the tube and the well casing. Vapor is recovered during normal operation. In addition, water that enters the well is aspirated in the vapor stream and also recovered.

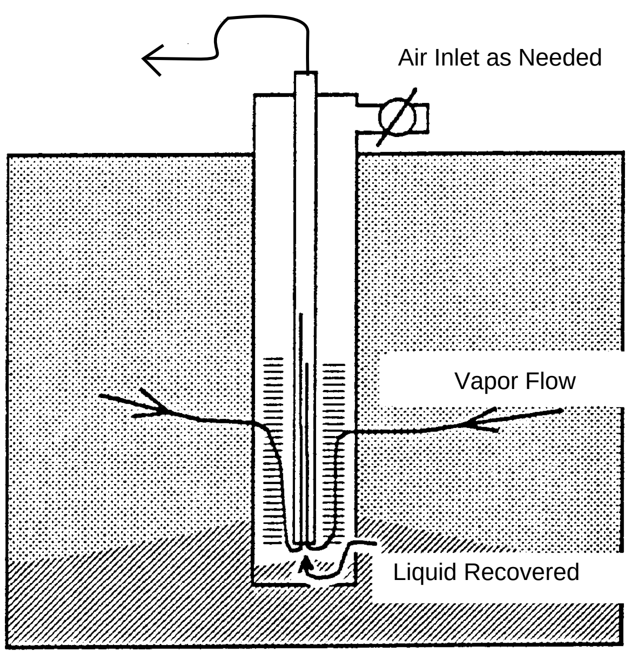


Figure 3-15. Well configuration to recover liquid and vapor phases using suction at the ground surface.

3.3.5 DNAPL Recovery

Using induced fractures can increase the recovery of DNAPL, particularly from low permeability formations. However, the benefits of increased recovery must be balanced against the possible risks. Creating vertical fractures or intersecting natural vertical fractures may result in downward migration of DNAPL that cannot be captured by the well. As a result, induced fractures may increase the recovery of some DNAPL while making the remaining liquid more difficult to recover because it has migrated to greater depth.

In view of this possibility, only sites where gently dipping fractures can be created should be considered for DNAPL applications. The orientation of an induced fracture depends on a variety of conditions, including the state of stress, density of injected fluid, rate of fracture propagation, depth, and the nature of bedding, fabric, and preexisting fractures in the soil or rock. These factors make the orientation of induced fractures difficult to predict with confidence prior to site activity. In most cases, and particularly at DNAPL sites, feasibility testing is recommended to determine fracture orientation.

A pilot test (21), described in the "Case Histories" section, demonstrated that induced fractures increase the recovery of free-phase DNAPL.

3.3.6 Bioremediation Applications

Using induced fractures can enhance bioremediation in a low-permeability formation by either of two methods:

- Increasing the rate of injection of nutrients and oxygen-bearing fluids (33).
- Filling fractures with solid compounds that provide the essential ingredients for bioremediation (34).

Induced fractures have been used to accelerate bioremediation of fine-grained soils by increasing the rate of injection of nutrients and oxygen, typically in the form of hydrogen peroxide. In one application where fractures were created in silty clay glacial drift, the rate of injection increased by nearly two orders of magnitude (33). In this example, one location contained sand-filled fractures at depths of 1.2, 1.8, 2.4, and 3 meters (3.9, 5.9, 7.9, and 9.8 feet). The fractures were gently dipping and reached maximum dimensions of 5 to 7.5 meters (16.4 to 24.6 feet). The well was screened from 1.2 to 3 meters (3.9 to 9.8 feet) depth, accessing all the fractures simultaneously. Another well, which lacked induced fractures, was created as a control. A solution of nutrients and hydrogen peroxide was injected into both wells at constant head. The rate of injection into the well containing induced fractures ranged from 2.5 to 4.6 liters (0.7 to 1.2 gallons) per minute, whereas the rate into the control well ranged from 0.02 to 0.08 liters (0.005 to 0.02 gallons) per minute. This example demonstrated one of the largest differences of injection rates between wells with and without induced fractures, with a ratio between 50 and 125.

Pilot-scale field tests have been conducted in which solid compounds designed to slowly release oxygen were injected into a fracture (33). A bioventing application to promote bioremediation of solvents, in which sand-filled fractures will be used to enhance air injection, is currently in progress.

3.3.7 Air Injection

The rate of air injection also can be increased by inducing fractures in the vicinity of an injection bore (35, 36). Injecting ambient air can stimulate the activity of aerobic organisms, or heated air can heat the formation and increase the vaporization of VOCs. During one test, air heated to between 100°C and 130°C (212°F to 266°F) was injected for 90 hours at 70 standard cubic feet per minute (scfm) into a fractured well. Temperatures increased from 14°C (57.2°F) to between 21°C and 25°C (69.8°F to 77°F), according to measurements 1.5 and 3.0 meters (4.9 to 9.8 feet) from the point of injection (36).

3.3.8 Steam Injection

Induced fractures can enable steam injection to heat low-permeability formations. This application has been evaluated during a pilot-scale test. In addition, a program designed to lead to a field demonstration at a contaminated site is currently under way.

The well design for steam injection resembles other applications except that steel, rather than plastic casing, is recommended because of steam temperature. Moreover, wells should be able both to inject steam and to recover condensate. One possible design involves injecting steam into the middle one of three fractures while applying suction to the other two (Figure 3-16). This approach would induce upward and downward migration of steam and a condensate front accelerated by the applied suction.

The lower fracture plays another important role in this approach. Active suction on the lower fracture should intercept DNAPL mobilized in the condensate front, thereby enhancing the reliability of the system. Several fractures could serve this function, depending on the requirements at the site.

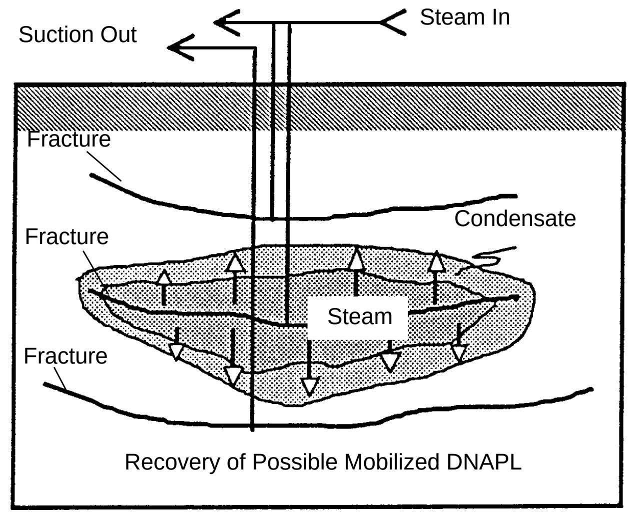


Figure 3-16. Schematic application of steam injection into induced fractures.

A pilot-scale test of a simplified version of this approach has been conducted. It involved injecting steam into a well that accessed a sand-filled fracture at a 2.4-meter (7.9-foot) depth. The test compared the rate of injection and the temperature field with results from a control well. An upper and lower fracture were present, but they received no suction during this preliminary test. The test site was underlain by silty clay glacial drift with hydraulic conductivity of 10^{-6} centimeters per second. Steam was injected for 17 days at approximately 34 kPa (4.9 psi). The rate of injection of steam into the fracture was 0.19 to 0.23 kilograms (0.4 to 0.5 pounds) per minute, whereas the rate of injection into the control well was less than 0.006 kilograms (0.013 pounds) per minute. Thus, the rate of injection into the fracture was more than 30 times greater than that into the control well. Moreover, the rate of steam injection was enough to result in significant heating of the silty clay (Figure 3-17). A monitoring point 1.2 meters (3.9 feet) from the point of injection of the fractured well showed that temperatures reached 80°C (176°F) in 4 days, but the temperature was roughly 25°C (77°F) after 6 days of injection into the control well. Temperature continued to increase around the fractured well, and the temperature profile formed a 0.6-meter (2-foot) thick zone of 95°C (203°F) after 17 days of injection. This was interpreted as a zone of live steam that propagated outward into the silty clay. (A 5°C temperature loss is associated with the method of temperature measurement.)

3.3.9 Electrokinetics

Graphite can be used as a proppant to create fractures that are electrically conductive. This application, currently being evaluated, may enhance migration of water and contaminants via electrokinetics. The approach is to create two graphite-filled fractures, one over the other and separated by several meters. To drive vertical

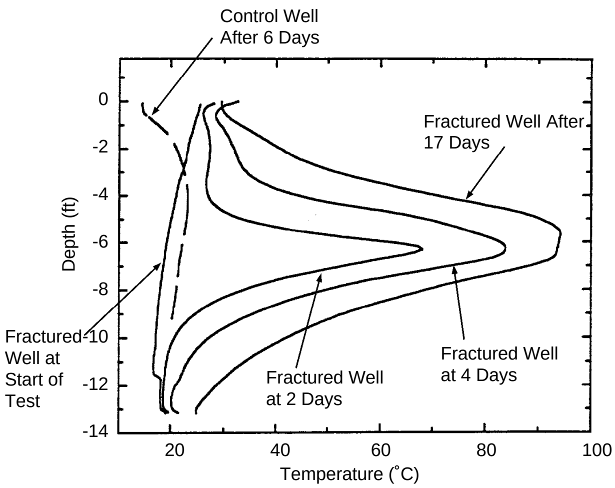


Figure 3-17. Temperature as a function of depth and time.

migration by electrokinetics, a voltage difference is maintained between the two fractures. This process is analogous to maintaining a pressure difference between two fractures to drive flow, except that migration by electrokinetics can be faster than migration by hydraulic flow in fine-grained soils.

3.3.10 In Situ Treatment Zones

Chemically or biologically active compounds injected into fractures can act as broad sheets in the subsurface. Examples of these types of compounds include fine-grained 0-valence iron, which degrades chlorinated solvents on contact (37), or encapsulated sodium percarbonate, which releases oxygen to stimulate aerobic bacteria for several months (33). Fractures filled with these compounds could be designed to create in situ treatment zones.

One approach of this application creates flat-lying treatment zones in the vadose zone through which contaminants migrate as they flow downward by gravity. Alternatively, electrokinetics can induce contaminants to migrate through the treatment zones. The development of in situ treatment zones is in its infancy, but it can potentially be a low-maintenance system that offers major cost reductions compared to current methods.

3.3.11 Barriers

For years, induced fractures have been recognized as a possible consequence of grouting (38, 39). Techniques that purposefully fill fractures with grout are also available (40). Most of these grouting techniques call for creating many cross-cutting fractures to reduce the permeability of a zone. In one application, however, grout-filled fractures from neighboring boreholes linked together to form a continuous horizontal sheet (41). The technique, termed the block displacement method (42), probably was the first horizontal barrier successfully created beneath a site. However, this test involved spacing the boreholes a few meters apart and creating a slot, which was nearly equal to the distance between the boreholes, with a water jet. Accordingly, the fractures propagated relatively short distances before they intersected adjacent fractures. With wider spacing between the wells, which many practical applications would probably require, it would be difficult to ensure that the fractures form a continuous sheet.

The use of grout-filled fractures as barriers to flow has received limited attention since the initial demonstration. Bifurcation of a fracture into several lobes commonly occurs. Moreover, current methods cannot detect this phenomenon. Accordingly, ensuring that multiple fractures connect to serve ultimately as a flow barrier would be difficult.

3.3.12 Monitoring

Conventional wells in low-permeability formations are associated with slow rates of sample recovery. Therefore, monitoring the chemical composition of fluids in these formations can be difficult. Inducing fractures in the vicinity of a monitoring point would increase the rate of sample recovery as well as broaden the area represented by the sample. This application is currently under investigation, although results were unavailable as of this writing.

3.4 Case Histories

Induced fractures have been used to improve environmental applications since the late 1980s. Most of the applications to date have been pilot-scale tests that evaluate the technology and provide data for progressing to full-scale. The petroleum industry, however, has used the general technique for more than 50 years, and it is a common means for improving the discharges of water wells, particularly in granitic or metamorphic terrains. All the applications strive to improve the performance of wells, and the petroleum and water applications provide important insights into possible environmental applications.

3.4.1 Overview

Records of oil production establish the benefits of hydraulic fracturing; ratios of production rates before and after fracturing suitably measure those benefits. According to data collected from several dozen oil wells (43), recovery ratios (production rate after fracture : initial rate) range from 1.4 to 100 or more. In general, the ratio ranges from 1.5 to roughly 10 for wells that were producing before fracturing (Table 3-2). The ratios are large, however, for wells that showed negligible production prior to fracturing.

Table 3-2. Summary of the Effects of Induced Fractures Used To Improve the Recovery of Wells

Location	Purpose	Injection Fluid	Fracs/ Well	Formation Type	Performance Without Fractures[a]	Performance With Fractures	Ratio
Environmental Applications							
Dayton, OH (33)	Bioremediation	Gel + sand	4	Silty clay glacial	0.14-0.57 L/min m	18-33 L/min m	50-100
Beaumont, TX	Liquid recovery	Gel + sand	2	Swelling clay	0.0027 L/min m	0.13 L/min m	50
Beaumont, TX	LNAPL recovery	Gel + sand	2	Swelling clay	0.0024 L/min m	0.046 L/min m	19
Cincinnati, OH (22)	Air recovery	Gel + sand	1	Silty clay glacial	3.34 L/min m_{H_2O}	67 L/min m_{H_2O}	20
Chicago, IL (1)	Vapor extraction	Gel + sand	3	Silty clay glacial	4.4 L/min m_{H_2O}	56-136 L/min m_{H_2O}	22
Cincinnati, OH	Steam injection	Gel + sand	1	Silty clay glacial	<0.0019 kg/min m_{H_2O}	0.055-0.066 kg/min m_{H_2O}	30+
Frelinghuysen, NJ (9)	Air recovery	Air	2	Silty clay glacial	6.6-11 L/min m_{H_2O}	87-204 L/min m_{H_2O}	13-19
Newark, NJ (9)	Air recovery	Air	2	Sandstone	27-113 L/min m_{H_2O}	397-580 L/min m_{H_2O}	5-14
Bristol, TN (21)	DNAPL + water	Water	2	Sedimentary rock	0.32-0.98 L/min m	1.6-2.7 L/min m	2.8-6.2
Petroleum Applications							
California (43)	Oil recovery	Gel	1	Reservoir rock	20 bopd	120 bopd	6
California (43)	Oil recovery	Gel	1	Reservoir rock	10 bopd	70 bopd	7
Alaska	Oil recovery	Gel	1	Reservoir rock	1,128 bopd	1,584 bopd	1.4
Texas (43)	Oil recovery	Gel	1	Reservoir rock	6 bopd	65 bopd	10.8
Texas (43)	Oil recovery	Gel	1	Reservoir rock	50 bopd	130 bopd	2.6
Texas (43)	Natural gas	Gel	1	Reservoir rock	15 mcfd	1,100 mcfd	73
West Virginia (43)	Natural gas	Gel	1	Reservoir rock	3.5 mcfd	66.1 mcfd	19
Water Supply Applications							
New Hampshire (45)	Water	water	1	Rock	18 L/min	109.2 L/min	6
New Hampshire (45)	Water	water	1	Rock	15.6 L/min	68.4 L/min	4.4
Massachusetts (47)	Water	water	1	Rock	0.46 L/min	11.4 L/min	22-25
Australia (48)	Water	water	1	Rock	1.8 L/min	13.2 L/min	6.9

[a] Performance measured as rate or rate/drawdown
bopd: barrels of oil per day
mcfd: millions of cubic feet of gas per day
1 m_{H_2O} head = 1.42 psi

Hydraulic fracturing also increases discharge of water wells, and the relative increases resemble results from the petroleum industry. Thirty years ago, Koenig (44) examined data from wells used for waterflooding or waste disposal and reported that 78 percent of those wells increased discharge following hydraulic fracturing. The recovery ratios ranged up to 100, with a median of 5.0 (44). More recent tests in the United States (19, 45-47) support these results (Table 3-2).

Recovery rates typically decrease as a function of time due to depleting target fluid (oil, gas, water, or NAPL) or reduced fracture permeability from closure or clogging. Sediment or mineral precipitate are known to close or clog fractures induced for petroleum recovery. In many cases, however, creating another fracture can restore oil recovery. Although environmental applications would be expected to experience similar problems, several projects demonstrated that shallow fractures retain their permeability for more than a year (9, 22, 49).

The recovery ratios for environmental applications resemble some of the more successful applications from the petroleum and water well industries, with typical values between 10 and 50. Many of the environmental applications involve silty clay or rock of quite low permeability. Therefore, the initial specific discharges (ratio of discharge to head differential at the well) are exceptionally small, leaving a large margin for improvement. Similar ratios are observed for both naturally propped fractures in rock (created by injecting air or water) and sand-filled fractures in silty clay. Interestingly, the ratios seem to be relatively independent of the type of fluid recovered and the remedial method used; applications for vapor extraction, liquid injection, steam injection, and NAPL recovery report similar values (Table 3-2).

3.4.2 Selected Examples

Documents published through the Superfund Innovative Technology Evaluation (SITE) program describe case histories of hydraulic and pneumatic fracturing (36, 49). These projects chiefly involve vapor extraction in tight soils and rock. The following sections present two applications of NAPL recovery.

3.4.2.1 DNAPL Recovery From Bedrock, Bristol, Tennessee

At a site near Bristol, naturally propped fractures were created in July 1991 in rock at depths of 30.5 to 61 meters (100 to 200 feet) to enhance the recovery of free-phase TCE and other DNAPLs. Injecting water into intervals of the well isolated by straddle packers created the fractures. Pumping tests and vapor extraction tests were conducted to evaluate the effects of the fractures.

Site Conditions. Sandstone, shale, and limestone underlie the vicinity of the site and form a broad fold and dip approximately 45 degrees beneath the site itself. The site lies in a local recharge area of a bedrock aquifer characterized by downward vertical hydraulic gradients of approximately 0.5 units (21). The hydraulic conductivity of the water-bearing formation is approximately 10^{-6} centimeters per second, based on constant rate tests.

Contaminants. The site contains a free-phase plume of TCE, other solvents, and cutting oil that extends to a depth of 100 meters (328 feet). A dissolved-phase plume of primarily TCE extends to greater depths—at least 130 meters (426 feet)—and has migrated at least 300 meters (984 feet) from the suspected source. The specific gravity of the free-phase liquid is 1.3 (21).

Design. Recovery using a pump and treat system yielded approximately 3.7 liters (1 gallon) per minute of water per well and fewer than 1.4 kilograms (3.1 pounds) per day of DNAPL. These low rates of recovery provided impetus for using hydraulic fracturing techniques to stimulate the wells. The intent was to increase formation permeability that, in turn, would promote liquid flow and possibly permit sufficient air flow into wells for recovery though vapor transport.

Three new wells were drilled to 60 meters (197 feet) with open hole completion, and the performance of these wells was characterized before and after hydraulic fracturing. Each well was fractured by setting open hole packers 15 meters (49.2 feet) apart and injecting 4,500 to 9,000 liters (1,188 to 2,376 gallons) of clean water; no proppants were injected. Injection pressures ranged between 0.5 and 5 MPa (73 and 725 psi), and the injection rate was approximately 280 liters (73.9 gallons) per minute. This approach resembles methods used to increase the discharge of water wells (19). Injection was terminated when water flowed around the upper packer and began to spill to the surface. In one case, an observation well 2.5 meters (8.2 feet) away responded with discharge of injected water. The initial discharge was muddy but cleared with continued injection, suggesting that fine-grained particles had been removed from fractures in the formation (21).

Results. The specific discharge of the three wells increased by factors ranging from 2.8 to 6.2. These effects are typical of naturally propped fractures created by hydraulic fracturing of water wells (Table 3-3). Pumping tests helped determine the effective hydraulic conductivity after fracturing. In general, the results indicated that the effective hydraulic conductivity increased by factors of 20 or more. (Actual values depend on the method of solution used to analyze the test data.)

Table 3-3. Specific Capacities Before and After Hydraulic Fracturing

	Before L/min m	After L/min m	Ratio
TW-1	0.32	1.6	5.0
TW-2	0.45	2.8	6.2
TW-3	0.98	2.7	2.8

Inducing fractures appeared to make vapor extraction a feasible remedial technique. After fracturing, vapor discharges were on the order of 285 to 700 L/min, and suction was detectable 10 meters (32.8 feet) from the recovery well. In contrast, both discharge and suction in the formation were negligible prior to fracturing.

During a 2-day test of vapor extraction, DNAPL was recovered at a rate of approximately 82 kg/day (180 lbs/day). Concentrations diminished during this test, probably representing an upper limit of the recovery rate. Nevertheless, the combination of hydraulic fracturing to increase conductivity and suction to induce dewatering and DNAPL recovery appeared to be a viable method of increasing contaminant recovery at this site.

Cost. Reportedly, the cost to create the fractures used during this project was $1,500 per well.

3.4.2.2 LNAPL Recovery From Swelling Clay, Beaumont, Texas

In July 1993, sand-filled hydraulic fractures were created in swelling clay to enhance the recovery of free-phase

LNAPL at a site in Beaumont. A pilot test followed in late February 1994.

Site Conditions. Silty clay of the Beaumont formation underlies the site to a depth of 6 to 8 meters (19.7 to 26.2 feet), with fine-grained sand below it. In general, the Beaumont formation consists of kaolinite, illite, calcium smectite, and fine-grained quartz (50). Wetting and drying cycles have resulted in overconsolidation in the upper 8 to 10 meters (26.2 to 32.8 feet). Drying near the ground surface largely decreased clay volume there, commonly resulting in dessicated areas. Moreover, in the interval containing hydraulic fractures, lateral stress is two to three times greater than vertical stress in the upper few meters (50).

The upper meter of the site is fill, composed of silty clay, gravel, and shells. From 1 meter (3.3 feet) to approximately 3.6 meters (11.8 feet), the formation is a firm to stiff, dark gray, silty clay with reddish to olive yellow mottling. Slickensided partings, which indicate preexisting fractures, are common. A light gray, clayey silt occurs at approximately 3.6 meters (11.8 feet).

Fractures were created between 2 and 3.6 meters (6.6 to 11.8 feet) deep so most of them were initiated in the dark gray, silty clay. The deepest fractures, however, were initiated in the light gray, clayey silt. The water table was between 1 and 1.5 meters (3.3 to 4.9 feet) deep, so all the fractures were created in saturated conditions.

Contaminants. The area of the test contained gasoline and cyclohexane, which infiltrated from surface spillage. The contaminant appeared as free-phase NAPL from approximately 1.5 to 3 meters (4.9 to 9.8 feet) in depth in the vicinity of Wells I, C, and PW-1, and it thinned to the east toward Well G (Figure 3-18).

Design. The pilot test was designed to compare the performance of two designs of fractured wells with a control well. One of the fractured wells in the test consisted of two casings that accessed fractures at different depths, one in the LNAPL and the other in the water bearing zone below. The other well only contained one fracture near the bottom of the NAPL zone (Figure 3-19). The goal of the two-fracture design was to recover NAPL from the upper fracture and water from the lower one. This approach, if successful, would limit upward coning of water, which would both increase the rate of recovery of NAPL and improve the NAPL-to-water ratio (to reduce costs of phase separation) compared with recovering from one fracture. Both fractured wells were expected to produce at greater rates than the conventional well.

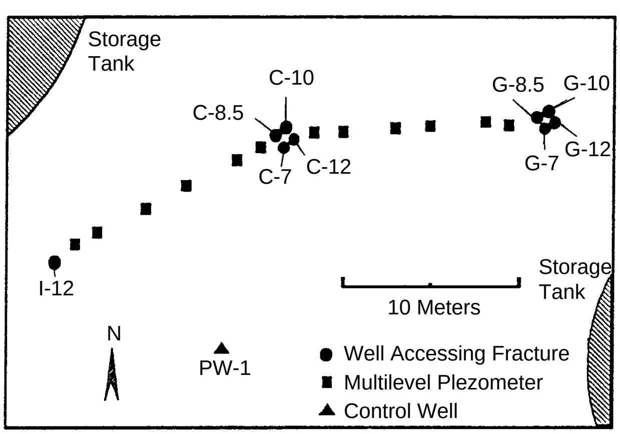


Figure 3-18. Area of LNAPL recovery using fractured and conventional wells.

Sand-filled fractures were created at six locations at the site, but only two of them, I and C, were used during the pilot test. At I-12 (Figure 3-18), a single sand-filled fracture was created at a depth of 3.6 meters (11.8 feet). At Well C, four fractures were stacked one above the other, but the test used only the deepest two, C-10 and C-12. The fracture at C-10 was initiated at a 3-meter (9.8-foot) depth, and it curved upward and cut through much of the zone containing NAPL. Fracture C-12, which was initiated at 3.6 meters (11.8 feet), extended mostly beneath the NAPL zone (Figure 3-19). The fractures were planned to be approximately circular, with diameters of 7 to 8 meters (23 to 26.2 feet) and average thicknesses of 5 to 6 millimeters (0.20 to 0.24 inches) (Table 3-4). A conventional well, PW-1, was screened from 2 to 4 meters (6.6 to 13.1 feet) in depth and used as control. Clusters of multilevel piezometers (depths of 1.2, 2.4, and 3.6 meters [3.9, 7.9, 11.8 feet]) with short screens were installed along a line from Well I through Well C (Figure 3-18).

Table 3-4. Specifications of Fractures Used During the Pilot Test

	Depth m	Maximum Uplift mm	Average Sand Thickness mm	Average Diameter m	Sand Volume m^3 (ft^3)
C-10	3	16	6	7	0.23 (8)
C-12	3.6	24	5.5	8	0.28 (10)
I-12	3.6	22	5.5	8	0.28 (10)

A constant head was maintained approximately 10 centimeters (4 inches) above each fracture, producing a drawdown of 1.5 to 2 meters (4.9 to 6.6 feet). Fluid was pumped from the wells to storage drums and periodically diverted to a graduated cylinder to determine discharge rate. The proportion of NAPL and water in the beaker was measured to estimate the discharge of each phase.

Results. Both wells containing fractures produced LNAPL at rates an order of magnitude greater than the conventional well (Table 3-5). The C location was particularly noteworthy, producing both the greatest NAPL

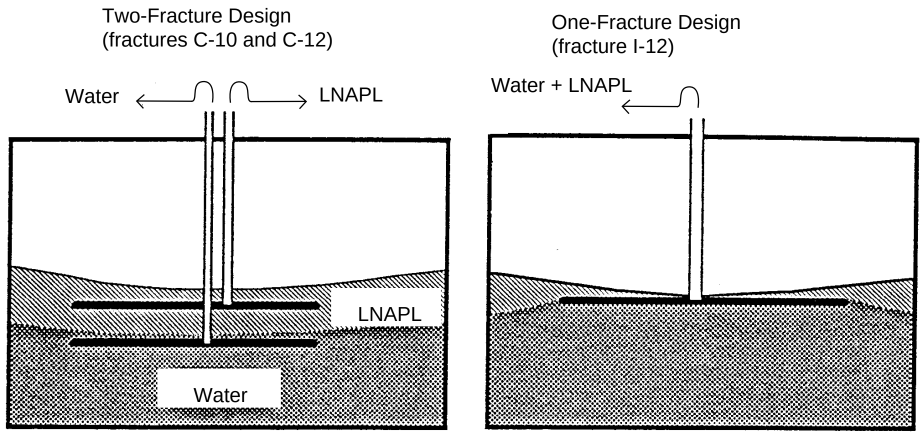


Figure 3-19. Methods of completing a well containing hydraulic fractures to recover LNAPL.

Table 3-5. Average Discharges and Ratios of Discharge

	NAPL L/hr	Water L/hr	Total L/hr	NAPL/ Water	NAPL/ PW-1	Total/P W-1
C-10	4.33	0.34	4.7	13	19	18
C-12	0.07	8.24	8.3	0.008	0.3	32
C (combined)	4.40	8.58	13.0	0.5	19	50
I-12	1.85	5.61	7.5	0.3	8	29
PW-1	0.23	0.03	0.26	7		

rate and the greatest NAPL-to-water ratio. Fracture C-10 produced a high concentration of LNAPL at a rate that was 19 times greater than the control, whereas C-12 produced almost completely water. The combined rate of liquid recovery from the C location was 50 times greater than from the control.

As an additional test, the rates were evaluated as a function of time, then the pump in the C-12 fracture was turned off. These results show that Well C initially rapidly recovered water, presumably as it drained out water used to created the fractures. Then C-12 recovered water at a constant rate while C-10 primarily recovered NAPL (Figure 3-20). After the pump was turned off at 116 hours, the discharge from C-10 changed abruptly; the total discharge from C-10 increased, but the recovery of NAPL actually decreased. Apparently, turning off the pump in C-12 caused water to flow upwards, effectively reducing the area at C-10 available to recover NAPL.

The distribution of head was consistent with the relatively large NAPL recovery by wells intersecting sand-filled fractures. Bowl-shaped zones of relatively large drawdown occurred in the vicinity of the fractures (Figure 3-20). In addition, significant drawdown occurred throughout the area between Wells I and C, and drawdown of 7 centimeters (2.8 inches) occurred over a band 25 meters (82 feet) long in the vicinity of the two wells.

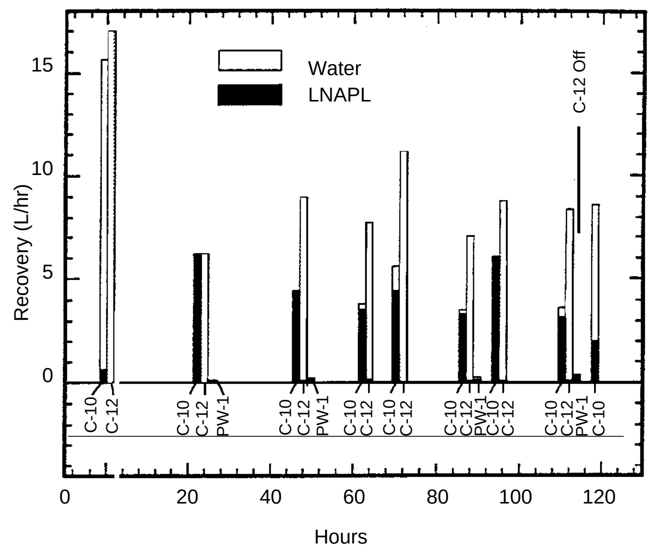


Figure 3-20. Discharges from C-10, C-12, and PW-1 as functions of time.

Drawdown in the vicinity of PW-1 was unavailable, but similar tests in the area have shown that drawdown is negligible within 1 to 2 meters (3.3 to 6.6 feet) of conventional wells.

It is noteworthy that the fractures caused large vertical head gradients (Figure 3-21). Multilevel piezometers with short screens (25 centimeters [9.8 inches]) were required to characterize the head distribution. Conventional piezometers screened over a large interval would have missed the vertical gradients, resulting in a misleading estimate of the effects of the fractures in the subsurface.

Cost. The fractures cost approximately $800 to $1,000 each to create and complete as wells. This cost includes mobilization, materials, labor, and equipment. The pilot test itself cost approximately $40,000.

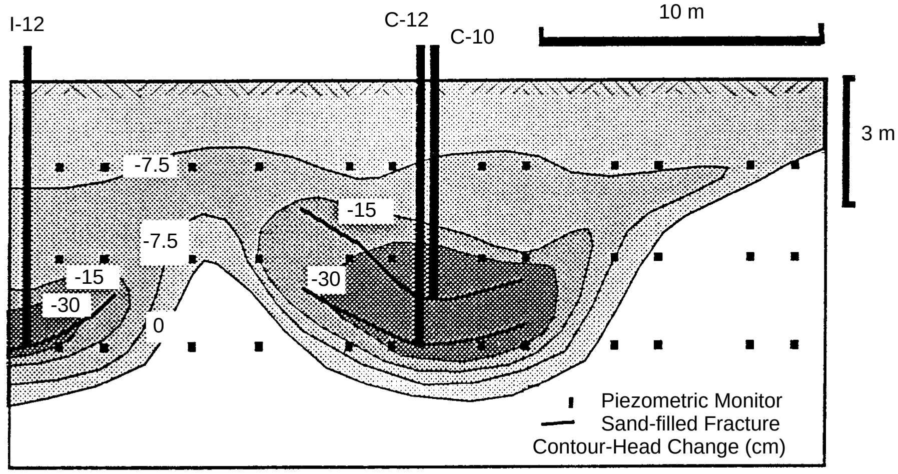


Figure 3-21. Cross section along line of piezometers showing change in head after 5 days of pumping.

3.5 References

When an NTIS number is cited in a reference, that document is available from:

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703-487-4650

1. U.S. EPA. 1993. Hydraulic fracturing technology: Applications analysis and technology evaluation report. EPA/540/R-93/505.

2. U.S. EPA. 1993. Accutech pneumatic fracturing and hot gas injection, Phase I. Technology demonstration summary. EPA/540/SR-93/509.

3. Schuring, J.R., V. Jurka, and P.C. Chan. 1991. Pneumatic fracturing to remove VOCs. Remediation Winter:51-67.

4. Murdoch, L.C., G. Losonsky, P. Cluxton, B. Patterson, I. Klich, and B. Braswell. 1991. The feasibility of hydraulic fracturing of soil to improve remedial actions. Final report. EPA/600/2-91/012 (NTIS PB91-181818).

5. Frappa, R.H., and T.H. Forbes. 1994. Innovative ground water remediation solutions for the Mercury aircraft site. Presented at NYS WEA Spring Conference, Corning, NY (June).

6. Begor, K.F., M.A. Miller, and R.W. Sutch. 1989. Creation of an artificially produced fractured zone to prevent contaminated ground water migration. Ground Water 27(1):57-65.

7. Zinck, E. 1984. Method of and device for loosening agriculturally used soil. U.S. Patent 4,429,647.

8. Waltz, J.P., and T.L. Decker. 1981. Hydro-fracturing offers many benefits. Johnson Drillers J. 53:4-9.

9. Schuring, J.R., and P.C. Chan. 1992. Removal of contaminants from the vadose zone by pneumatic fracturing. NTIS PB92-161207. Reston, VA: U.S. Geological Survey, Water Resources Division (January).

10. Driscoll, F.G. 1986. Ground water and wells, 2nd ed. St. Paul, MN: Johnson Division Publisher.

11. Passamaneck, R.S. 1993. Controlled propellant fracturing for vertical wells. SPE Paper 26271.

12. Chu, T.Y., N. Warpinski, R.D. Jacobson. 1988. In situ experiments of geothermal well stimulation using gas fracturing technology. Sandia Report SAND87-2241. Albuquerque, NM: Sandia National Laboratories.

13. Sarapu, E. 1985. Electrofrac rock-breaking systems. Skillings Mining Rev. January:2-8.

14. Du, Y., A. Aydinm, and L. Murdoch. 1993. Incremental growth of shallow hydraulic fracture at a waste remediation site. 34th Symposium on Rock Mechanics, Madison, WI (June).

15. Davis, P.M. 1983. Surface deformation associated with a dipping hydrofracture. J. Geoph. Resour. 88:5,826-5,834.

16. Sun, R.J. 1969. Theoretical size of hydraulically induced fractures and corresponding surface uplift in an idealized medium. J. Geophys. Resour. 74:5,995-6,011.

17. Warpinski, N.R. 1985. Measurement of width and pressure in a propagating hydraulic fracture. Soc. Petrol. Eng. J. February:46-54.

18. Holzhausen, G.R., C.S. Haase, S.H. Stow, and G. Gazonas. 1985. Hydraulic-fracture growth in dipping anisotropic strata as viewed through the surface deformation field. Proceedings of the 26th U.S. Symposium on Rock Mechanics, Rapid City, SD.

19. Smith, S.A. 1989. Manual of hydraulic fracturing for well stimulation and geologic studies. Dublin, OH: National Water Well Association.

20. Schuring, J.R., P.C. Chan, J.W. Liskowitz, P. Papanicolaou, and C.T. Bruening. 1991. Method and apparatus for eliminating non-naturally occurring subsurface, liquid toxic contaminants from soil. U.S. Patent 5,032,042 (July 16).

21. Lundy, D.A., C.J. Carleo, M.M. Westerhiem. 1994. Hydrofracturing bedrock to enhance DNAPL recovery. Proceedings of 8th Annual NGWA National Outdoor Action Conference (May).

22. Wolf, A., and L. Murdoch. 1993. A field test of the effect of sand-filled hydraulic fractures on air flow in silty clay till. Proceedings of the Seventh National Outdoor Action Conference, Las Vegas, NV (May).

23. McKay, L.D., J.A. Cherry, and R.W. Gilham. 1993. Field experiments in a fractured clay till, 1. Hydraulic conductivity and fracture aperture. Water Resour. Res. 29(4):1,149-1,162.

24. Brooker, E.W., and H.O. Ireland. 1965. Earth pressures at rest related to stress history. Can. Geotech. J. 11(1):1-15.

25. U.S. Geological Survey. 1967. Distribution of principal kinds of soils: Orders, suborders, and great groups. Sheet 86.

26. Flint, R.F. 1971. Glacial and quaternary geology. New York, NY: John Wiley and Sons.

27. Tsang, Y.W. 1992. Usage of “equivalent apertures” for rock fractures as derived from hydraulic and tracer tests. Water Resour. Res. 28(5):1,451-1,455.

28. Muskat, M. 1949. Physical principles of oil production. Boston, MA: McGraw-Hill.

29. Novakowski, K.S. 1988. Comparison of fracture aperture widths determined from hydraulic measurements and tracer experiments. In: Hitchon, B., and S. Bachu, eds. Proceedings of the Fourth Canadian/American Conference on Hydrogeology. Dublin, OH: National Water Well Association. pp. 68-80.

30. Bear, J. 1979. Hydraulics of ground water. New York, NY: McGraw-Hill.

31. American Petroleum Institute. 1989. A guide to the assessment and remediation of underground petroleum releases. API Publication 1628. Washington, DC.

32. Blake., S.B, and M.N. Gates. 1986. Vacuum enhanced hydrocarbon recovery. Proceedings of the Second Hazazardous Materials Management Conference, Long Beach, California (December). pp. 17-25.

33. Vesper, S. J., L.C. Murdoch, S. Hayes, and W.J. Davis-Hoover. 1994. Solid oxygen source for bioremediation in subsurface soils. J. Haz. Mat. 36:265-274.

34. Davis-Hoover, W.J., L.C. Murdoch, S.J. Vesper, H.R. Pahren, O.L. Sprockel, C. L. Chang, A. Hussain, and W. A. Ritschel. 1991. Hydraulic fracturing to improve nutrient and oxygen delivery for in situ bioreclamation. In situ bioreclamation. Boston, MA: Butterworth-Heinemann. pp. 67-82.

35. Mack, J.P., and H.N. Apsan. 1993. Using pneumatic fracturing extraction to achieve regulatory compliance and enhance VOC removal from low-permeability formations. Remediation Summer:309-326.

36. U.S. EPA. 1993. Accutech pneumatic fracturing and hot gas injection, Phase I. Applications analysis. EPA/540/AR-93/509.

37. Gillham, R.W., and D.R. Burris. 1992. In situ treatment wells: Chemical dehalogenation, denitrification, and bioaugmentation. Proceedings of the Subsurface Restoration Conference, Dallas, TX (June). pp. 66-68.

38. Morgenstern, N.R., and P.R. Vaughan. 1963. Some observations on allowable grouting pressures. Proceedings of the Conference on Grouts and Drilling Muds. London, England: Institute of Civil Engineering. pp. 36-42.

39. Wong, H.Y., and I.W. Farmer. 1973. Hydrofracture mechanisms in rock during pressure grouting. Rock Mechanics 5:21-41.

40. Zuomei, Z., and H. Pinshou. 1982. Grouting of the karstic caves with clay fillings. In: Baker, W.H., ed. Proceedings of the Conference on Grouting in Geotechnical Engineering, New Orleans, LA (February). pp. 92-104.

41. Brunsing, T.P., and R.B. Henderson. 1984. A laboratory technique for assessing the in-situ constructability of a bottom barrier for waste isolation. Proceedings of the National Conference on Managing Uncontrolled Hazardous Waste Sites, Washington, DC. pp. 135-140.

42. Brunsing, T.P. 1987. The block displacement method field demonstration and specifications. U.S. Environmental Protection Agency Project Summary 600-S2-87-023. pp. 1-6.

43. Howard, G.C., and C.R. Fast. 1970. Hydraulic fracturing. New York, NY: Society of Petroleum Engineers, AIME.

44. Koenig, L. 1960. Survey and analysis of well stimulation performance. J. Am. Water Works Assoc. 52:333-350.

45. Stewart, G.W. 1974. Hydraulic fracturing of crystalline rock stimulates yield of two test wells drilled in New Hampshire. Ground Water 12:46-47.

46. Stewart, G.W. 1978. Hydraulic fracturing of drilled water wells in crystalline rocks of New Hampshire. New Hampshire Department of Resources and Economic Development and Water Resources Research Center.

47. Mony, P.M. 1989. Hydro-frac: One man's opinion. Water Well J. Feb:48-50.

48. Williamson, W.H., and D.R. Woolley. 1980. Hydraulic fracturing to improve the yield of bores in fractured rock. Australian Water Resources Council Technical Paper 55:1-76.

49. U.S. EPA. 1993. Hydraulic fracturing technology: Applications analysis and technology evaluation. EPA/540/SR-93/505.

50. Mahar, L.J., and M.W. O'Neill. 1983. Geotechnical characterization of desiccated clay. J. Geotech. Engin. 109(1):56-71.

Chapter 4
Interceptor Trenches

Other than vertical wells, trenches are the most widely used method of controlling subsurface fluids and recovering contaminants; trenches are remarkably effective, and widely available construction equipment can be used to install them. The construction and agricultural industries have long used trenches or drains for dewatering, and many environmental practices are based on dewatering methods. However, new methods of installing and completing trenches for environmental purposes have recently been developed. For instance, techniques for analyzing a trench's ability to control ground-water flow directions and travel times differ from the dewatering techniques.

A trench provides a long zone with which to collect fluids. Perhaps the most common applications of this linear feature are to increase the rate of recovery from low-permeability formations or to intercept the migration of a plume. The former uses the large surface area available for drainage, whereas the latter places the trench normal to the regional gradient to enhance plume capture. Trenches also can have a significant vertical component, which cuts across and can allow access to the permeable layers in interbedded sediments. Alternatively, the vertical component can facilitate LNAPL recovery from areas with considerable seasonal fluctuations in the water table. Although trenches primarily recover liquids, vapor extraction also benefits from the large area exposed by a trench.

Although trenches have various applications, most of this chapter discusses the trenches used to recover and deliver fluids: interceptor trenches. In their simplest form, interceptor trenches are slots excavated in the earth and filled with highly permeable material. More sophisticated designs involve placing perforated pipe or casing at the bottom of the excavation (Figure 4-1); the casing commonly slopes downward from the ends of the trench towards a sump, which collects and removes water or contaminant through a vertical access casing (1). Commonly, low-permeability material caps trenches to prevent surface water or air (for vapor extraction applications) from diluting the fluids recovered from the formation.

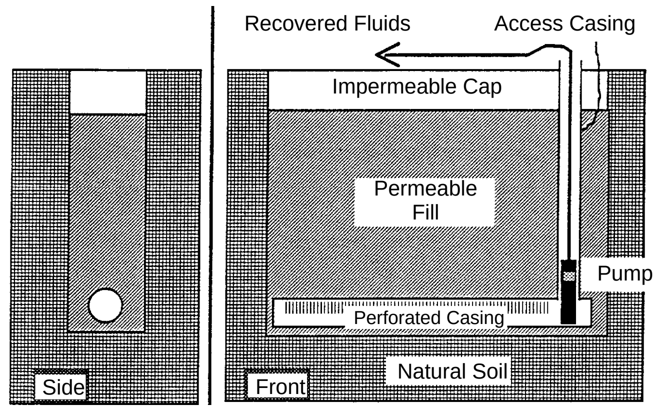


Figure 4-1. Cross sections of a basic interceptor trench configuration showing permeable backfill and perforated casing.

This chapter presents methods of constructing trenches and discusses some of the factors that affect their design and the decision to use trenches at a site. It also presents an overview of some of the applications of trenches and several case histories of sites where trenches have been used.

4.1 Trench Construction

Most interceptor trenches are created with construction methods adapted to environmental applications. Some specialized techniques are available for particularly deep installations, streamlining the installation and completion process, or for forming trenches in rock.

4.1.1 Conventional Methods

Creating an interceptor trench typically involves:

- Excavating material
- Supporting the trench walls
- Backfilling with permeable material
- Installing casing and pumps
- Sealing the surface over the trench

Standard construction equipment, either a backhoe or a trenching tool, commonly is used to perform the excavation. Backhoes capable of digging a trench up to 5.5 meters (18 feet) deep are readily available in most locations. Extended-reach hydraulic excavators (2) may reach depths approaching 15.2 meters (50 feet), with widths of 0.9 to 1.5 meters (3 to 5 feet). Trenches of intermediate depth (6.1 to 9.1 meters [20 to 30 feet]) may require an excavation wide enough to accommodate the backhoe or trencher if the equipment is to reach the desired depth.

Trenching tools are available to construct trenches of various depths and widths. Small vibratory plow/trencher units create slots a few inches in width and up to 0.6 meters (2 feet) deep. Many of these small units were designed for utility installation (gas line, electric, telephone) and can install the pipe or cable while creating the slot.

Medium-sized, tractor-mounted trenching units may reach depths of 2.4 to 3 meters (8 to 10 feet), with widths of up to 0.6 meters (2 feet). Attachments for these units permit trench excavation through concrete and asphalt pavement. Large trenching systems are discussed in detail in the next section.

Vertical walls on the side of a trench may stay open if the trench is relatively shallow and cuts through cohesive soil. In many cases, however, the walls of the trench collapse if they are unsupported. Traditional methods of support include a sliding trench box, sheet pilings, or timber beam bracing (shoring). Bentonite slurry also sometimes supports trenches, although the bentonite may significantly reduce the permeability of the formation adjacent to the trench; therefore, this technique should be avoided for interceptor trenches.

Recently, a slurry formed from guar gum, a cellulose-based polymer, has been used to support deep trench excavations in an effort to avoid the problems associated with bentonite (2, 3). Guar-based slurries have high gel strength and viscosity (greater than 40 centipoises) and low water loss (filtrate less than 25 milliliters); these properties permit efficient transfer of hydrostatic head from the slurry to the trench walls. Slurry head of 0.9 meters (3 feet) or more over ground-water head should stabilize most soil types. Guar gum used to support a trench is treated so that it degrades when construction is completed; the guar decomposes to water and biodegradable sugars and is pumped from the trench. Usually three trench pore volumes circulate to remove residual slurry, in a process similar to well development. Small amounts of degraded slurry may remain as excess fluid in the trench and must evaporate, solidify, or be disposed of through a wastewater treatment facility (2-4).

Permeable backfill material (coarse sand or gravel) and injection/extraction structures (perforated casing, sumps, access pipes, and wells) are placed in the trench through the slurry. The fill material typically consists of clean washed gravel (e.g., crushed stone, pea gravel). When anticipating fine sediment clogging, engineered gradation or a geotextile filter fabric may be included. Engineered gradation involves placing the fill material into the trench by sliding it down the slope of previously deposited fill or by tremie tube. (Sand and finer material must be pre-wetted; gravels may be tremied dry.) Tremie tube emplacement is preferable around wells and perforated casing. Using woven geotextile fabrics can inhibit siltation. Geotextile filters generally must be weighted to sink through the slurry. Overlapping sheets of geotextile is usually sufficient to ensure filter continuity.

The backfill should extend near the ground surface and always above ground-water level. Excavated soil can usually fill the remainder of the trench, although regulations may prevent backfilling with contaminated material at some sites. Backfill or clay usually seals the top of the trench to prevent infiltration of surface runoff or air.

Vertical access pipes installed in the fill material are the most common injection/extraction structures. Perforated pipe, which is commonly laid along the bottom of the trench, connects to the vertical access pipes. This technique is particularly prevalent in relatively shallow trenches created in cohesive soil with free-standing walls. Slurry in the trench may buoy the perforated pipe and make installation cumbersome in deep excavations. Practitioners disagree on the need for perforated pipe in trenches; some argue that permeable backfill is sufficient. A variety of casing types exist, including PVC, polyethylene, and galvanized and stainless steel. Submersible ejector and progressive cavity pumps have been successfully implemented.

4.1.2 Specialized Methods

Most interceptor trenches are installed using methods similar to the ones outlined above. Some cases, however, require specialized methods to increase the efficiency of the installation procedure or to create trenches that are particularly deep or in rock.

4.1.2.1 Continuous Excavation and Completion

A recently developed technology combines trench excavation, well installation, and barrier installation processes in a single step (5). The equipment digs a trench up to 6.1 meters (20 feet) deep, lays in a flexible horizontal well screen, and backfills the trench with the original soil. Typically, a vertical excavation 35.6 centimeters (14 inches) wide is completed to the desired depth. Then, a vertical casing is installed through the trenching head. The well is coupled to the flexible well screen. The trenching machine then moves along the trench line (Figure 4-2), installing the horizontal well screen at an average rate of 0.9 to 1.5 meters (3 to 5 feet) per minute (7). Sections of screen can be coupled to create continuous well screens in excess of 610

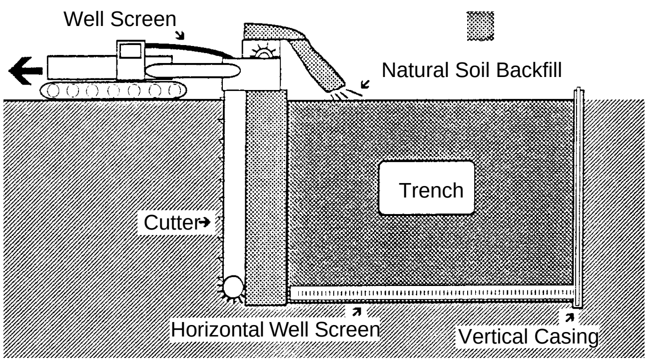


Figure 4-2. Schematic of continuous excavation and completion technique (6).

meters (2,000 feet). A permeable polyester and glass filter system encases the flexible well screen to reduce or eliminate clogging by fine sediments. Moreover, the well screen/filter system may be installed within a sand or gravel filter pack in the trench. (The sand or gravel is placed at the same time as the well screen.)

Reportedly, continuous excavation and completion systems are about half the cost of bored (drilled) horizontal well systems, and as much as 70 percent less expensive than vertical well systems (5). At a site in North Carolina, initial remediation plans called for 100 vertical wells to recover a hydrocarbon plume at an estimated cost of $1 million. Instead, a continuous excavation and completion system was installed at a cost of under $350,000. A second benefit under some settings is faster remediation. A fuel storage facility in Florida opted for a continuous excavation and completion system with nine wells over a conventional vertical well system requiring 41 wells. Actual time for successful remediation was just 8 weeks, compared with an estimated 30 months for the vertical well system (5). Finally, this technology reduces worker exposure to contaminants.

This technique has some limitations:

- The trenching head cannot penetrate bedrock.
- The equipment cannot access beneath buildings or landfills.
- The equipment is currently limited to a depth of less than 6 meters (19.7 feet).

4.1.2.2 Deep Applications

Traditional excavation of deep trenches requires the use of chisels or grabs suspended on cables or guided by kelly bars. Recent developments have elicited new technologies for deep excavation for trench and slurry wall construction. An example is “trench cutting.” Large-toothed cutting wheels loosen the soil material and mix it with a bentonite slurry (Figure 4-3). The equipment then pumps the soil-slurry suspension to the surface, where oil particles are removed and the slurry is returned to the trench for reuse. This technique may be used to construct trenches 0.5 to 1.5 meters (1.6 to 4.9 feet) wide and up to 120 meters (394 feet) deep. Excavation rates in unconsolidated sediments and soft rock of 25.2 to 39.8 cubic meters (33 to 52 cubic yards) per hour have been reported (8); excavation rates in rock with high compressive strength 145 to 179 MPa (21,000 to 26,000 psi) are reported to be 1.1 to 1.9 cubic meters (1.5 to 2.5 cubic yards) per hour. This technique is effective in all types of unconsolidated sediments and in medium to hard bedrock formations (e.g., limestone, sandstone). To create cutoff walls, the trench may be filled with low- permeability materials (e.g., bentonite, concrete). Alternatively, to create an interceptor trench, fill may consist of high permeability materials. Additionally, a crane can be used to install precast/preconstructed panels. Benefits of the trench cutting technique include:

- Higher rates of productivity than traditional deep excavation methods.
- Greater control on verticality of the trench because of the rigid excavation platform.
- Reduced shock and vibration (commonly associated with grab and chisel excavation), resulting in decreased risk of damage to adjacent structures and of trench wall collapse.

4.1.2.3 Trenches in Rock

Economic reasons generally preclude excavating trenches in rock. Trenchlike structures can be created in

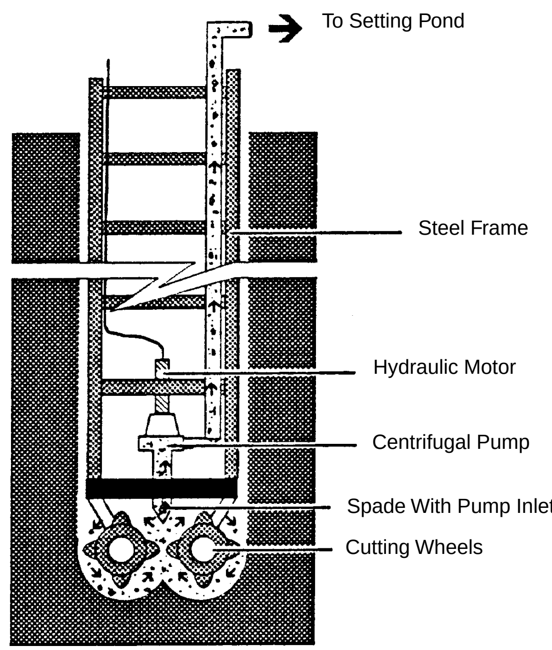


Figure 4-3. Schematic of deep trench excavation equipment (redrawn from material provided by Coastal Caisson Corp., Clearwater, FL).

rock, however, by detonating explosives in closely spaced boreholes. One case in New York (9) created an elongated fracture zone resembling a trench by placing approximately 900 kilograms (1,984 pounds) of explosive in 60 boreholes on a line 100 meters (328 feet) long and perpendicular to ground-water flow. The bores were 7 meters (23 feet) deep and penetrated a sandstone aquifer with a hydraulic conductivity of 2.8 x 10^{-4} centimeters per second. After detonation, fractures extended between boreholes, from 7 meters (23 feet) deep to the ground surface, and 3 to 4 meters (9.8 to 13.1 feet) into adjacent rock. A conventional well placed in the zone recovered water. Other instances of blasting to create a permeable wall in rock exist, although published accounts are scarce.

4.2 Design Considerations

The design of an interceptor trench system requires information related to geology, hydrology, trench hydraulics, and nature of contaminants. These factors influence the length, depth, and location of a trench, as well as the method of operation and type of completion.

4.2.1 Pattern of Flow to a Trench

The advantage a trench offers over other physical methods of recovery mostly results from the pattern of flow that the trench induces in the contaminated formation. Unlike a vertical well, which causes flow along radial paths, the pattern of flow to a trench changes with time. Under ideal conditions, the flow pattern to a trench progresses through three basic periods: linear flow, transition, and radial flow. These periods are best recognized when the trench penetrates a laterally extensive, confined aquifer with minimal recharge and regional gradient. In the presence of boundaries, recharge, or a regional gradient, the flow pattern differs from the idealized case; however, the pattern still changes with time, and this change still affects the trench performance.

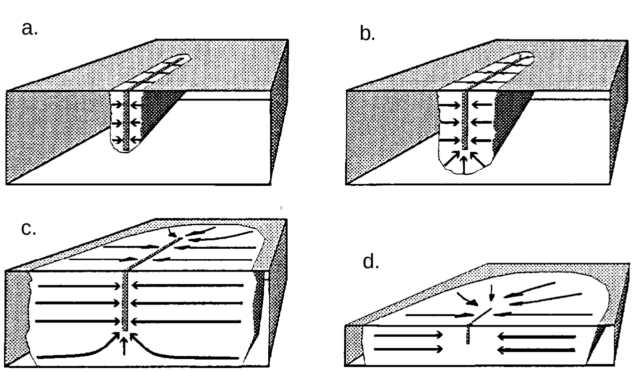


Figure 4-4. The pattern of flow to a trench with no regional gradient: a) linear flow, b and c) transition, and d) radial flow (11).

The period of linear flow occurs early on, shortly after the onset of pumping, when ground water flow is nearly perpendicular to the plane of the trench (Figure 4-4a). During the linear flow period, flow vectors are essentially parallel, and the region affected is small when compared with the entire length of the trench.

In contrast, the period of radial flow occurs after the trench has been operating for a relatively long time. During this period, flow converges from great distances toward the trench (Figure 4-4d), much as flow converges toward a well. Except in the vicinity of the trench, flow vectors are essentially radial during this period, causing the trench to behave like a well of large diameter.

Details of the flow pattern during the transition period, as the flow changes from linear to radial, depend on details of the trench geometry. For example, if the trench partially penetrates the aquifer, the linear period is followed by a period when the flow is linear and adjacent to the trench, radial and converging upward beneath the bottom of the trench, or radial and converging horizontally toward the ends of the trench (Figure 4-4b). With increasing time, the lower radial zone expands downward and affects the bottom of the aquifer, and the area influenced by the trench increases (Figure 4-4c). Eventually, the area of horizontal radial flow grows until it is dominant and the period of radial flow begins. The transition period is somewhat simpler when the trench fully penetrates the aquifer because it lacks the early period of upward flow toward the bottom of the trench.

The pattern of flow underlies much of the hydrodynamic performance of an interceptor trench. For example, analyses that consider an interceptor trench in section view only include flow normal to the trench and omit flow from areas beyond the ends of the trench (published analyses of trenches are summarized in Beljin and Murdoch [10]). The consequences of this assumption are relatively minor early on, but amplify as time increases. Neglecting the effects of the ends of the trench may significantly underestimate the discharge (11).

One approach to estimating the discharge of a trench at late times represents it as a well of large diameter. It is possible to represent a trench of infinite hydraulic conductivity (1,000 or more times the conductivity of the aquifer) by considering a well whose radius is one-quarter the total length of the trench (11).

The actual times when the flow pattern changes depend on the length of the trench, the hydraulic conductivity of the aquifer K, aquifer thickness h, aquifer storage S, trench length $2x_t$, and perhaps other quantities. Rather than examining all the different possibilities of trench length and aquifer properties, it is convenient to combine those quantities with time t to give dimensionless time:

$$t_d = 4tKh/Sx_t2. \quad (4\text{-}1)$$

The periods of flow to a fully penetrating trench follow (11):

Linear flow (early time): $t_d < 0.25$
Transition: $0.25 < t_d < 25$
Radial flow (late time): $t_d > 25$

This framework shows that the duration of the different flow periods in real time t can vary widely, depending in particular on the hydraulic conductivity of the aquifer and the length of the trench. Consider, for example, a trench 200 meters (656 feet) long (x_t = 100 meters [328 feet]), in a layer of silty sand that is 5 meters (16.4 feet) thick, with $K = 10^{-4}$ centimeters per second and $S = 0.1$. The linear flow period would last approximately 0.4 year, and the radial flow period would not begin before 40 years. However, if the trench were half that long (x_t = 50 meters [164 feet]) and installed in a clean sand ($K = 10^{-2}$ centimeters per second), the linear flow period would be only 8.7 hours, and the radial flow period would begin after 36 days. Note that when the trench is very long, the linear flow period lasts an extremely long time and the cross-sectional analyses are appropriate.

4.2.2 Site Geology

Site geology affects the design process in two areas: performance efficiency and trench construction. Several geologic factors affect the performance of the trench system, including heterogeneity of the aquifer, formation composition, and degree of saturation (12).

4.2.2.1 Heterogeneities

Formation heterogeneity is one of the most notorious obstacles to contaminant recovery, and trenches probably present the best physical method of addressing this obstacle. This is particularly true when the heterogeneity involves horizontal stratification because the trench can cut across the strata and access all the permeable units simultaneously.

Vertical heterogeneities, such as fractures, may be drained effectively if the trench is roughly perpendicular to the fracture strike. Pumping tests or geological mapping may help delineate the orientation of vertical fractures when locating the trench.

Vertical fractures or other heterogeneities may cause preferential flow of fluids in the subsurface. Therefore, even though a trench can access many fractures and produce fluids at an impressive rate, vertical fractures may cause the flow to channel and avoid unfractured areas. In this case, diffusion from the unfractured areas can control recovery of contaminants. Accordingly, trenches are an excellent method of controlling fluid flow in fractured or heterogeneous formations, although even the advantage of accessing many of the fractures (compared with a vertical well) may be insufficient to recover contaminants from unfractured areas.

4.2.2.2 Formation Composition

The composition of the formation primarily affects how the trench is constructed. Most excavation methods are capable of removing formations from unlithified sediments to weathered rock. However, they are unable to effectively penetrate well-cemented sediments or metamorphic or igneous rocks. In the latter case, it is still possible to use a trenchlike approach for recovery, although the approach requires specialized trench-cutting methods (8) or blasting to create the permeable zone (9).

To prevent collapse of the trench walls during excavation, many sediments must be supported, typically by filling the trench with a dense fluid. The need for support of the trench walls increases as the depth and the degree of saturation increase. Moreover, granular sediments, such as sand, are more prone to collapse than cohesive sediments, such as clay. Should a fluid be necessary to hold open the trench, the type of fluid selected should minimize potential reductions in permeability adjacent to the trench. Accordingly, bentonite slurry, which supports trenches in standard construction practice, should be avoided. Proper support of the trench is critical when installing perforated pipe and access casing for pumps, which require that the trench remain open for several days.

4.2.2.3 Degree of Saturation

The degree of saturation affects both the construction and application of trenches. The stability of trench walls increases as the soils become drier, so it may be possible to create and complete trenches in relatively dry soils without holding them open using fluids. When fluids are used to hold open trenches in unsaturated soil, some of the fluids may leak out of the trench during construction. In many cases, the fluids are designed to form filter cakes, or they have sufficient gel strength to minimize penetration into even relatively dry soils.

The degree of saturation also affects the method of remediation, although the extent to which this is applicable is similar to other methods of recovery.

Vibratory plow trenching units are used where the percentage of large rocks near the ground surface are low. Earth saws are commonly used when the trench excavation must cross pavement, such as a sidewalk, roadway, or parking lot. Earth saws have also allowed trenching through shallow, “soft” bedrock, such as limestone. Using chain-type trench cutters is possible with most unconsolidated sediments; the use of tungsten-carbide tipped bits allows chain-type cutters to be used in hard, rocky soils, and even to trench through asphalt paving.

4.2.3 Hydrologic Conditions

Hydrologic conditions affect the location, depth, and sizing of a trench. Of particular importance are the effects of hydraulic conductivity, regional flow, and aquifer extent.

4.2.3.1 Hydraulic Conductivity

A trench is an effective method of enhancing the recovery of subsurface fluids if it is more permeable than the enveloping formation. Based on field experience, a trench requires a contrast of at least 100 between the permeability of trench filling and that of the aquifer, although extremely long trenches may require either a greater contrast or several pumps. Accordingly, it may be difficult to obtain sufficient permeability contrast when the trench is in a very permeable sand or gravel. Consequently, a trench oriented perpendicular to regional gradient may fail to capture the regional flow, with water flowing in one side and out the other. One option in this situation is to install a low permeability liner on the downgradient side (or the side containing the least amount of contamination) of the trench.

The permeability and thickness of the aquifer also play central roles in determining the operating parameters of the recovery system. For example, trenches installed in relatively permeable material typically operate at constant discharge, and the drawdown decreases with time. The drawdown decreases rapidly in trenches installed in low-permeability formations, so a float switch is commonly used to hold the drawdown constant above the intake of the pump. In the latter case, the drawdown is held constant, and the discharge decreases with time. Similar behavior occurs with wells. When a well operates at constant discharge, the Theis solution is commonly used to estimate the drawdown as a function of time.

A solution similar to the Theis solution for a well can help predict the drawdown at a trench operating at constant discharge (11). Following the assumption of Theis, the trench is analyzed as a sink over which the inflow is uniform. This is an idealization, but it results in head gradients along the trench that approximate field conditions where the permeability of material in the trench is approximately 100 times greater than the aquifer. A similar analytical solution can predict drawdowns if material of infinite permeability fills the trench. (A permeability contrast between the trench filling and the aquifer that is greater than 1,000 is essentially an infinite contrast.)

As in a well, the drawdown increases with time (Figure 4-5). The major difference, however, is that drawdown increases at a much slower rate than it does for a well of reasonable size. Table 4-1 lists the variables used to analyze trenches, including the ones represented in

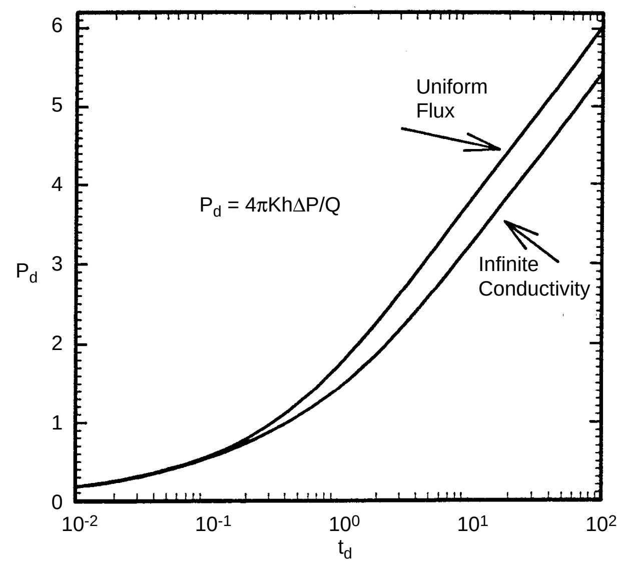


Figure 4-5. Drawdown at the midpoint of a trench where discharge is constant (11).

Table 4-1. Variables Used in Trench Analysis

Q	Pumping Rate
S	Storage Coefficient
K	Hydraulic Conductivity
R	Retardation Factor
n	Effective Porosity
h	Aquifer Thickness
α	Regional Gradient

Figure 4-5. The results in Figure 4-5 allow forecasting of the drawdown so that the pump can be sized and located properly. Forecasting drawdown can also help in estimating aquifer parameters from a pumping test, just as aquifer parameters are estimated from pumping tests using wells. The uniform flux case in Figure 4-5 resembles a trench with a permeability contrast of roughly 100. Keep in mind, however, that the results assume that the trench does not interact with lateral boundaries, nor is it affected by recharge. A more comprehensive analysis should consider both conditions because they affect drawdown.

The performance of a trench held at constant drawdown is markedly different from one operating at constant discharge. The discharge from a trench held at constant drawdown is greatest at the onset of pumping. Discharge then decreases with time (Figure 4-6) as head gradients in the vicinity of the trench flatten. Note that this effect may decrease the discharge by an order of magnitude or more. The real time of this decrease

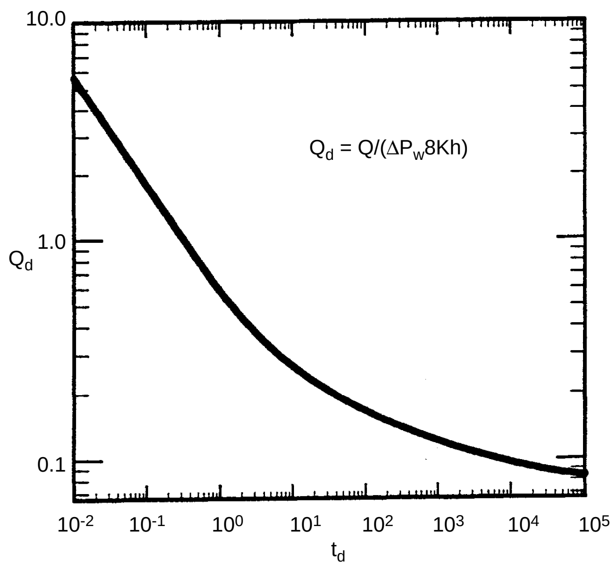


Figure 4-6. Discharge from a trench held at constant drawdown (11).

depends on the aquifer properties, just as the real time separating the different flow periods depends on the properties described earlier. As a result, an appreciable decrease in discharge may take place over several minutes or several years, depending on the aquifer properties. Over long periods, fluctuations in natural hydrologic conditions may mask this effect.

Nevertheless, the discharge from a trench held at constant drawdown may decrease with time as an inevitable consequence of the dynamics it creates in the aquifer. Therefore, this effect should be considered along with others when trying to diagnose diminishing discharge. Other factors that may contribute to diminishing discharge include biofouling or siltation of the material filling the trench.

4.2.3.2 Aquifer Extent

The lateral extent of the aquifer affects the performance of a trench, causing it to differ from the theoretical results based on the infinite aquifer given above. In general, aquifer boundaries that are within several trench lengths, or perhaps longer, probably have a major effect. Constant head boundaries, provided by a lake or river, reduce the drawdown or increase the recovery rate in Figure 4-6. No-flow boundaries, such as where the aquifer terminates, have the opposite effect, increasing drawdown or decreasing rate.

In addition to the operational considerations, lateral boundaries of an aquifer should affect the decision of where to locate a trench. For example, the boundary between a contaminated aquifer and a surface water body may be a critical point of exposure that a trench could protect when installed parallel to the boundary.

The vertical extent of the aquifer is an important consideration when designing a trench system to establish control of the site. If the vertical extent of the aquifer is shallow, then the trench should fully penetrate the aquifer thickness. In circumstances where it is impractical to penetrate the full extent of the aquifer, however, contaminated fluids escaping beneath the trench may be a concern (13). The severity of this concern depends on the location and nature of the contaminants, which must be determined prior to designing the recovery system.

The path of the dividing streamline (Figure 4-7), which separates the area where the trench captures water from the region where water escapes capture, depends at least on the depth of the trench, pumping rate, hydraulic conductivity, regional gradient, and recharge. Methods of estimating the position of the dividing streamline are available in Zheng and others (13) and have been validated with field tracer studies by Chambers and Bahr (14).

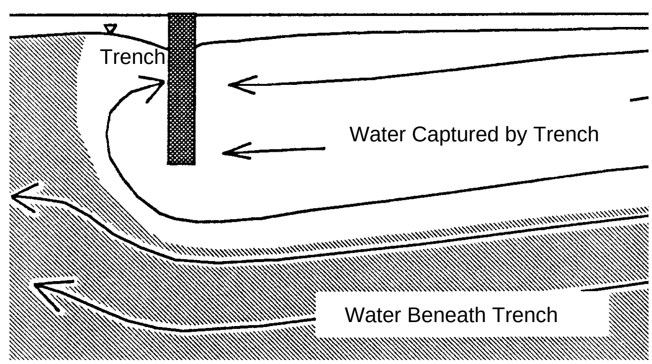


Figure 4-7. Cross section of a trench partially penetrating an aquifer in a regional flow, showing the vertical extent of aquifer captured by the trench.

4.2.3.3 Regional Flow

Many applications of trenches involve installations normal to the regional gradient in an effort to cut off migration of a plume (12, 15) or to flush fluids through a zone to enhance recovery (16). In these cases, the areas the trench influences and the time required to reach the trench are of interest. It is possible to estimate those areas and times for various regional gradients and trench orientations using relatively simple methods (11). The most useful presentation of the results involves combining the various parameters in dimensionless groups. Because it is independent of actual aquifer parameters, this presentation allows analysis of many field scenarios using just a few graphs. The following example illustrates how it works.

Assume that the trench cuts completely through a confined aquifer of thickness h and infinite lateral extent. A regional gradient is present and flows either north to south, northeast to southwest, or east to west

(Figure 4-8). The dimensionless strength of the regional gradient is

$$\beta = x_t \alpha S/4hRn. \quad (4\text{-}2)$$

The variables of the equation are presented in Table 4-1. A discussion earlier in this chapter pointed out that the pattern of flow to a trench changes with time, so this problem requires a transient analysis. Therefore, the analysis must specify the strength of the trench relative to aquifer properties, whereas a steady-state analysis incorporates strength in the travel time. The dimensionless strength is

$$\Psi = QS/16Kh^2\pi Rn. \quad (4\text{-}3)$$

Figure 4-8 presents a series of maps where the strength of the trench is fixed at 0.01 and both the orientation and magnitude of the regional gradient vary. Regional flow sweeps away some particles. The areas where particles are captured form U-shaped zones, with the principal axis in the direction of regional flow. The shape of the capture zone changes with increasing β by shortening in the downgradient dimension and lengthening in the upgradient dimension. Shortening of the capture zone also occurs normal to the regional flow, but to a lesser extent than shortening in the downgradient. The contours of equal arrival time can change shape but not area as a result of the changing direction of a uniform and constant regional flow. This is because contours of equal arrival time must circumscribe the same volume

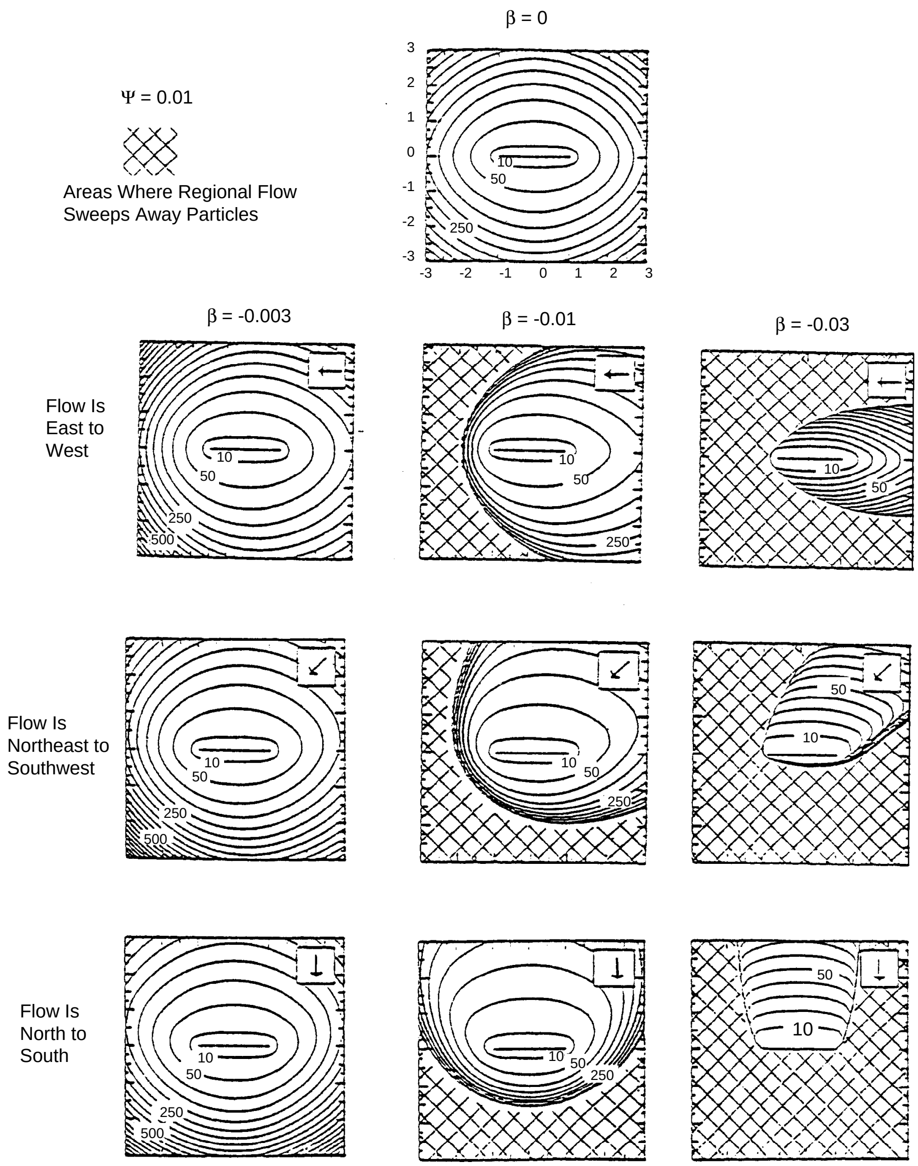


Figure 4-8. Dimensionless arrival times as a function of location for various strengths and directions of regional flow (11).

of water in a system operated at constant discharge (17). It follows that the arrival time contours for a well would be the same area as those for a trench, except the zones for a well would be longer and narrower than those for a trench.

To apply the maps of arrival times, assume a hypothetical situation in which a trench is installed in an aquifer with the following parameters:

$K = 10^{-4}$ meters per second
$S = 0.1$
$n = 0.1$
$h = 5$ meters
$x_t = 50$ meters

For $\Psi = 0.01$, it follows that $Q = 0.16\pi nKh^2/S = 0.07539$ cubic meters (20 gallons) per minute . Assuming the regional gradient is 0.004, then $\beta = -0.01$, and the map at the bottom of the middle column in Figure 4-8 represents the site conditions. The arrival times for specific points can be estimated by obtaining t_{da} from Figure 4-8. For example, a point $x = 50$ meters, $y = 50$ meters, where y is up the regional gradient ($x_d = 1.0$, $y_d = 1.0$), yields $t_{da} = 38$. According to the equation $t_d = 4tKh/Sx_t2$, this corresponds to 55 days in real time. The effect of the regional gradient is illustrated by taking a point of equal distance down the regional gradient ($x_d = 1.0$, $y_d = -1.0$), where $t_{da} = 164$, or 237 days. Alternatively, the area affected after 6 months is circumscribed by the contour of $t_{da} = 126$.

The maps in Figure 4-8 can be applied to most aquifer settings with valid limitations set by assuming confined conditions and an absence of nearby boundaries. The effect of regional gradient is negligible and probably can be ignored for $|\beta| < 0.001$. At large values of regional gradient ($|\beta| > 0.05$), a trench operating at a strength of $\Psi = 0.01$ is unable to generate a sink strong enough to effectively capture particles. The maps in Figure 4-8 are limited to $\Psi = 0.01$, so other strengths require calculating other maps.

The versatility and value that interceptor trenches may offer is noteworthy. Interceptor trenches oriented at acute angles to the regional flow may be valuable for contaminant recovery. An interceptor trench oriented parallel to the regional gradient is an effective sink for areas upgradient of the trench. Moreover, in areas where access or other factors prevent installing a trench normal to the regional flow, it may be possible to achieve the desired performance by installing the trench oblique to the flow. Where the regional gradient is inclined 45 degrees to the axis of the trench, the arrival times in the region upgradient of the trench are similar to those where $\beta = 90$ degrees (Figure 4-8).

4.2.4 Trench Hydraulics

The hydraulics of the trench itself are relatively unimportant for dewatering applications but become increasingly important when the trench must maintain control over long periods. Because the objective of dewatering applications is to remove water as quickly as possible, the trench is operated at maximum drawdown. Alternatively, the objective during long-term control is to affect hydraulic gradients at the site while removing as little water as possible and still maintaining some factor of safety. As a result, the traditional methods of designing trenches for dewatering applications typically ignore trench hydraulics. Therefore, much of the detail of this process has yet to be analyzed.

The hydraulics of a trench involve coupling flow in the trench with flow in the aquifer. There is a point of lowest potential, either head or air pressure, at the pump, and then potentials increase along the trench until reaching maximum values at the end. The flow per unit area, or flux, into the trench is relatively large adjacent to the pump, and then decreases towards the end. If the trench terminates in an aquifer boundary the influx will be lowest at the end of the trench (Figure 4-9). In the absence of a boundary, however, the influx may increase as it approaches the end of the trench. This is because flow converges from distant points toward the end of the trench. In this respect, the flow paths resemble Figure 2-17.

In general, flowrate along the trench increases as flow approaches the pump from the end of the trench. This occurs unless fluid flows out of the trench at some point. For example, isolated perched water that may flow into a trench locally may be lost from the trench as it passes an unsaturated interval. Another possibility is to lose DNAPL out the bottom of a trench.

The magnitude of the variation of influx depends on the permeability of the trench filling (including perforated casing if it is used), permeability of the aquifer, amount of drawdown, trench length, and location of pump. The variation increases as:

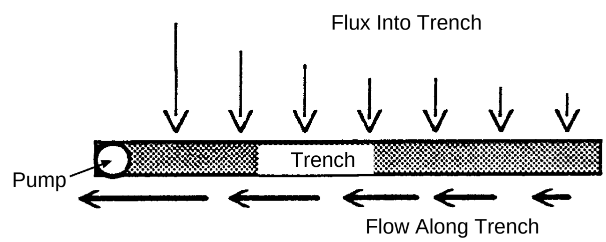


Figure 4-9. Map of the distribution of influx and flow along an idealized trench.

- The permeability of the trench filling is reduced compared with that of the aquifer.
- The drawdown increases.
- The trench becomes longer.

Heterogeneities in the aquifer result in local fluctuations of influx that differ from the effects described above. In highly heterogeneous aquifers, the heterogeneities, rather than trench hydraulics, may dominate the variation of influx.

The distribution of influx becomes a concern when trying to operate the trench to maintain control while recovering a minimal amount of water. These efforts minimize power as well as, possibly, treatment or disposal costs. Currently, analytical methods of designing the hydraulics of the trench are unavailable. Consequently, monitoring the heads within and adjacent to the trench is recommended to ensure maintenance of the head gradients toward the trench.

4.2.5 Contaminants

The type of contaminant mostly affects the method of completing a trench. Trenches completed with methods developed for dewatering can recover aqueous phase contaminants (18), whereas specialized completions can most effectively recover NAPLs.

NAPL completions may involve one pump and resemble dewatering applications. This approach is commonly used to recover LNAPL. Another possibility for completion involves the use of two pumps: one to recover water and the other to recover the nonaqueous phase. Two perforated pipes can also be effective, with each pipe installed at the approximate depth of water and NAPL. Recovery of water and NAPL simultaneously inhibits the upward or downward migration of the NAPL/water interface. This effect tends to pinch off the NAPL layer and reduce the effectiveness of recovery.

Sealing the upper portion of the trench is a key consideration when recovering vapors. Details of the vapor-recovery design may also include components to recover water, depending on site conditions.

The depth of the trench is another factor that partially depends on contaminant type. Trenches designed to recover LNAPL must extend at least as deep as the lowest seasonal depth of the water table; it may be unnecessary for this trench to be much deeper. A design for DNAPL recovery, however, must key trenches into the formation on which the DNAPL has pooled. The trench must not be cut too deeply and penetrate the lower formation, because this could lead to loss of the DNAPL from the trench. In cases where this could occur, it may be advisable to place a liner along the bottom of the trench.

Flammability of the contaminants is a consideration when designing trench components, particularly the pump and controller. Flammable vapors can accumulate in the trench or access casing, then be ignited by a spark from the pump. Design of the casing and pipe, as well as the pump itself, must ensure they can withstand contaminants that are corrosive compounds or vigorous solvents.

4.2.6 Site Conditions

Site conditions need consideration before the start of trench construction. Access for excavation equipment along the path of the trench is important. Buildings can pose a major obstacle, although trenches can be placed inside some buildings. Prior to excavation, underground structures (e.g., utility lines, sewers, or tanks) must be located and marked. Space must be sufficient to accommodate storage of excavated material during construction, or provisions must be made to haul the material as it is excavated.

In some locations, regulations prevent using contaminated material removed during excavation as backfill for the trench. Regulations may require disposing of the excavated material as contaminated waste, which can significantly increase the cost of installation.

Some sites are covered with concrete, pavement, or a building, which may act as a cover to confine air flow. The presence of such structures and how they affect the sources of air should be considered when trenches are used for vapor extraction. Many older paved surfaces are cracked and underlain by gravel, so they may provide a poor seal.

4.2.7 Trenches and Horizontal Wells

The geometry of a trench can resemble that of a horizontal well. In fact, both trenches and horizontal wells can be used for similar applications. In many applications, the decision between using a trench or horizontal well hinges on economic rather than technical issues. Depth can increase the cost of trench installation significantly, and there is a maximum depth below which trench installation is impossible. In contrast, depth has less effect on the cost of a horizontal well (although exceeding the 8-meter [26.2-feet] depth limit for electronic beacon locators may increase the cost). Rock can present problems to both technologies, although blasting can create trenchlike structures at shallow depths in rock, and it is certainly possible to bore horizontal wells in rock. In both cases, however, rock can increase installation cost substantially. Access problems, too, can increase the cost of a trench or make installation impossible, whereas access requirements for a horizontal well are restricted to entry and possible exit points.

Trenches present significantly more vertical exposure of the contaminated area than horizontal wells. This is particularly important in stratified formations, where a trench can cut across many thin permeable layers while a horizontal well directly intersects only a few layers. Moreover, where contaminants are present over a large vertical extent, trenches may be preferable, although the increase in trench cost with depth should be considered. For example, the vertical extent of trenches would make them perform better than a horizontal well when recovering LNAPL where large fluctuations in the water table occur seasonally. Interception of a contaminated plume migrating with regional flow is an application for which a trench has no equal, particularly when excavation equipment can reach the bottom of the aquifer.

Methods of creating both horizontal wells and trenches for environmental applications are evolving rapidly, with both improvements in capabilities and lower costs.

4.3 Applications

Interceptor trenches have a wide variety of environmental applications, including hydrodynamic control and dewatering, plume capture, NAPL recovery, and vapor extraction. Trenches also have been central to an innovative remedial application that decontaminates ground water in situ as it flows through reactive material.

4.3.1 Hydrodynamic Control

Interceptor trenches have been used extensively to control local, site-scale, hydraulic gradients (3, 19, 20). One site-scale application involves reducing the flow through a contaminated area by pumping water from the upgradient side of the contaminated area and injecting the water on the downgradient side (Figure 4-10). This essentially produces a stagnant area in the region between the trenches, which inhibits movement of contaminants.

Interceptor trenches can also be used in conjunction with barriers around a site to control offsite migration (19, 20). In this case, barriers placed around the site and the interceptor trenches reduce piezometric levels within the barriers. Vertical wells can supplement this application, which is similar to traditional dewatering applications for trenches. The barriers should be keyed into underlying an aquitard, if possible.

In some cases, using barriers can restrict flow into one side of the trench (21), or can divert ground water moving under a regional gradient away from a contaminant source (3). This configuration (Figure 4-11) is used when clean surface water (e.g., lake or river) provides significant ground-water recharge within the area influenced by the trench. This application is most effective when the barrier is keyed into a low permeability formation so that ground water does not travel underneath the barrier.

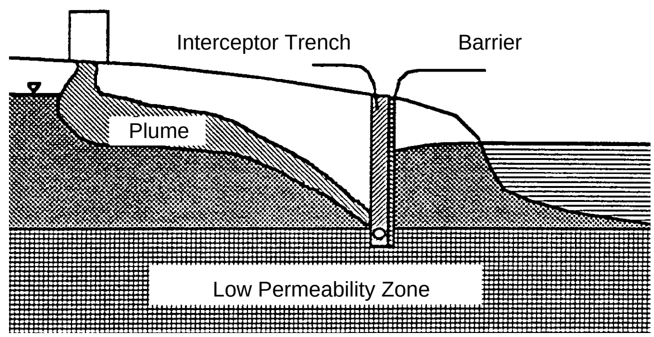


Figure 4-11. Interceptor trench coupled with a hydraulic barrier to minimize recharge from an adjacent surface waterbody.

4.3.2 Plume Interception

The classic, common application of a trench involves placing a trench perpendicular to the regional gradient on the downgradient side of a plume to intercept contaminated water (3, 6, 12, 15). Figure 4-12 illustrates the concept. The application serves the same function as a line of wells but is more reliable, because water may escape between the wells in the presence of permeable zones unaccounted for during design or as a result of other factors. This application, therefore, is useful when high reliability is required, such as when protecting a

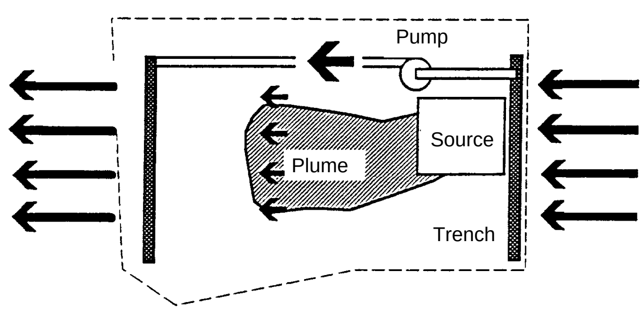


Figure 4-10. Controlling the flow through a contaminated area by pumping from an upgradient trench and injecting into a downgradient trench.

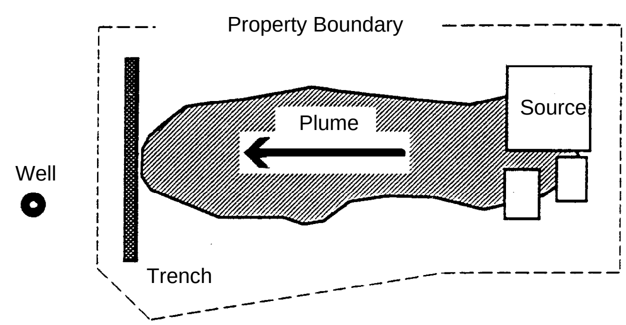


Figure 4-12. Trench used to capture plume and prevent migration to an offsite well.

downgradient well. Installing the trench, however, by no means guarantees that it will totally intercept the plume. Monitoring enough locations of hydraulic heads in the vicinity of the trench should ensure that the flow is inward toward the trench. A barrier on the downgradient side of the trench helps to ensure the reliability of plume capture.

The idealized trench is a single straight feature, such as in Figure 4-12, but in practice many applications involve creating networks of trenches oriented to best achieve remedial objectives and avoid obstacles to excavation. Networks may have several segments oriented normal to regional flow to arrest migration, or an irregular pattern of contamination may dictate their location. In cases where the ideal path for the trench is obstructed, a trench network is used instead.

4.3.3 NAPL Recovery

The recovery of NAPL is one of the most widely used applications of interceptor trenches, because trenches offer an effective method of ensuring capture and arresting possible offsite migration of NAPL. In cases where NAPL is relatively shallow (LNAPL in particular), commonly available excavation equipment can be used to install the trench. Moreover, trenches can cut across a significant depth range, making them well suited to NAPL recovery at sites where seasonal hydrological factors cause wide variations in piezometric levels.

The simplest trench design to recover DNAPL calls for constructing a trench on top of an underlying impermeable unit. The product collects in drain lines within the trench, then flows laterally to sumps, where it is pumped to the surface (Figure 4-13a). Using two recovery (drain) lines may enhance DNAPL recovery (22): one drain in the DNAPL itself and the second drain in ground water above the DNAPL drain (20). Pumping ground water from the upper drain produces drawdown of the water and upwelling or mounding of the product (Figure 4-13b). Pumping both drains results in drawdown in both ground water and DNAPL (Figure 4-13c).

To enhance DNAPL recovery, water removed from the upper drain of the two-drain system can be reintroduced to the system through a nearby trench or drain (Figure 4-14). The reintroduction of the water to the aquifer system enhances the hydraulic gradient, further driving the mobile DNAPL (20).

Caution is required when pumping DNAPL recovery systems; excessively high pumping rates can cause the drawdown of the overlying ground water to "pinch-off" the DNAPL plume (Figure 4-15). This results in a marked decrease in the ratio of NAPL to water in the recovery fluid, even though large volumes of NAPL remain relatively close to the trench.

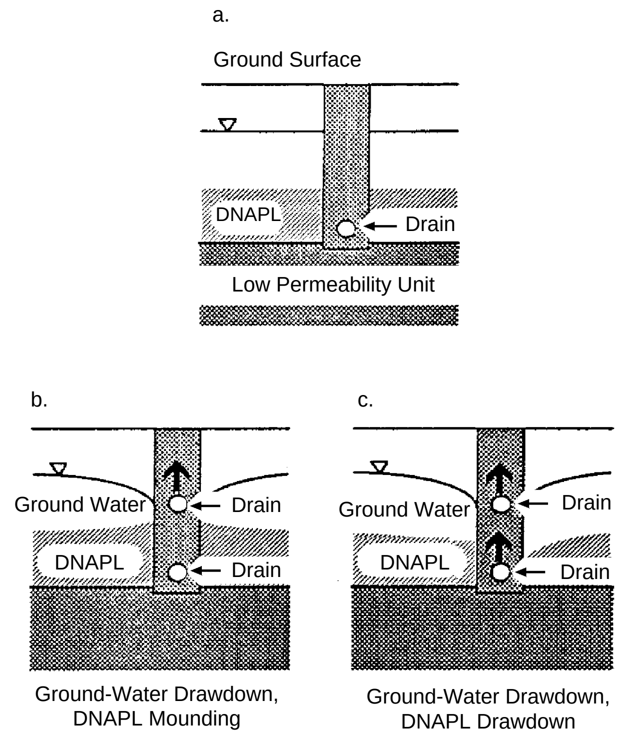


Figure 4-13. Trench systems for DNAPL recovery: a) one-drain system, b) two-drain system with upper drain pumping, and c) two-drain system with both drains pumping (22).

Trenches are also widely used to recover LNAPLs (2, 3). This application may make use of a single pump, or it can use a two pump system to reduce the upward migration of the LNAPL/water interface. In this sense, the LNAPL application resembles the approach described above for DNAPLs.

4.3.4 Vapor Extraction

Interceptor trenches have been used successfully to recover VOC, including petroleum hydrocarbons and halogenated compounds (e.g., tetrachloroethane, 1,1,1-trichloroethane, TCE). Vapor extraction with an interceptor trench requires an impermeable trench cap. In practice, low-permeability soils from trench excavation have capped the trench. This requires compaction to maximize the integrity of the seal. The combination of

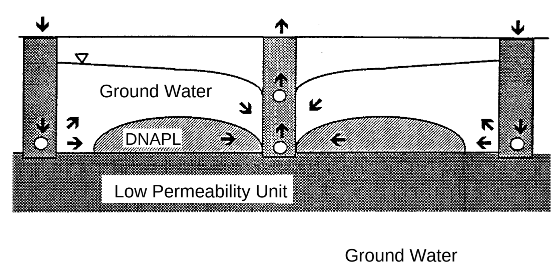
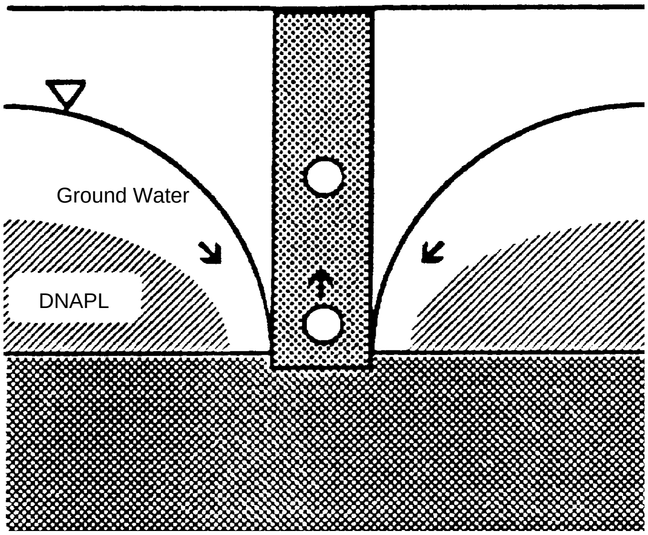


Figure 4-14. Enhanced recovery of DNAPL by reintroducing water to increase the hydraulic gradient (20).



Ground Water Drawdown,
DNAPL “Pinch Off”

Figure 4-15. Excessive pumping rates from the ground-water and DNAPL drains causing “pinch off” of the DNAPL plume.

using an extremely low-permeability liner material (e.g., HDPE) along with the natural soils can result in a cap with a sufficiently low permeability. Multiple soil-liner layers also may be sufficient. Another technique involves using a bentonite slurry in the upper few feet of the trench. Liner material, such as HDPE, may also supplement the bentonite slurry method.

To initiate vapor extraction, suction applied to perforated casing within the permeable trench material induces air flow from the adjacent soil into the trench. This results in vaporization of the VOCs. Air and contaminant vapors are collected and delivered to secondary treatment systems, just as in applications using conventional wells.

The path of air flow through the soil is critical to this application. To estimate the path, it is best to evaluate the location of a source of air as well as possible heterogeneities in the site. If the air flows in from the ground surface, then much of the flow would follow a steeply dipping path close to the trench. This effect is particularly acute if the formation is homogeneous or contains vertical fractures. Alternatively, if a naturally occurring low-permeability unit overlies the contaminated area, the effect is less serious. In the absence of such a unit, it may be possible to add a cap to induce air through more of the subsurface. A similar situation exists with flow patterns of horizontal wells (e.g., Figure 2-19).

Using wells or another trench to provide a source of air below the subsurface may augment flow through the contaminated region. Perhaps the most effective implementation involves two parallel trenches, with suction applied to one trench and atmospheric or positive pressure applied to the other. Keep in mind, however, that even with two trenches and a cap, heterogeneities between the trenches (such as fractures or sand lenses) may cause an uneven distribution of flow.

One effect of vapor extraction may be the production of water or other liquid phases, either by draining perched zones or lifting the water table. The presence of water reduces pneumatic conductivity, and thus performance, during vapor extraction. Therefore, if the site may produce water, the trench design should aim to recover the water as well as the vapor. Using a sump pump to recover water while applying suction with a blower should accomplish this goal. Alternatively, a dual-phase extraction system (23) can recover both water and other liquid phases using suction from the blower.

Adding air sparging can enhance a vapor extraction system (24). Injecting air into VOC-contaminated ground water enhances remediation by:

- Stripping the dissolved-phase VOCs.
- Increasing dissolved oxygen levels to promote biodegradation.

Design guidelines for installation of a coupled sparge/vapor extraction system are similar to those for standard vapor extraction and ground-water pump and treat systems. The lateral and vertical extent of contamination as well as the nature of the soil affect the sparging radius of influence, which controls the overall scale of the system. Individual design parameters that these factors affect include depth and length of the screen, well construction, and air pressure. All these variables are necessary to predict rates of VOC removal and project duration. For a coupled sparge/vapor extraction system, a recommended vacuum-to-injection ratio is 10:1 (24). This should meet the objective of adequate airflow into the contaminated ground water without increasing the potential for offsite migration of the contaminant.

Operation of a combined sparge/vapor extraction system should include monitoring of the following parameters (24):

- Injection: Air temperature, pressure, and air flow.
- Extraction: Temperature, vacuum, air flow, and contaminant concentration.

4.3.5 Other Applications

Trenches have a variety of other environmental applications that are beyond the scope of this document because they are not directly related to delivery and recovery. In many cases, trenches filled with low-permeability materials form vertical barriers to flow (3, 19, 20). Such barriers can enhance the control of fluids within a site, in many cases in conjunction with recovery systems.

Recently, trenches have been filled with reactive compounds capable of degrading or adsorbing contaminants in situ (25, 26). This application involves placing a trench filled with permeable material perpendicular to a regional gradient so that natural flow sweeps contaminants through the trench. Ideally, compounds in the trench remove the contaminants from the flow, and the ground water is "clean" after it passes through the trench. Several variations of this concept have been proposed or are currently under development (16, 27-30).

4.4 Case Histories

This section provides an overview of several dozen applications and describes five case histories in which trenches have been used for various environmental purposes.

4.4.1 Overview

Tables 4-2 through 4-4 summarize information on representative applications of interceptor trenches from published descriptions and case histories provided by consultants. Table 4-2 lists the general site character, including contaminant, site geology, and hydrologic characteristics. Table 4-3 details the installed trenches, including dimensions and fill material. Table 4-4 highlights operational parameters of the trenches and product recovery.

4.4.2 Selected Examples

Following is a more detailed discussion of site implementations of interceptor trench technologies.

4.4.2.1 LNAPL and Dissolved-Phase Recovery, Texas

At a former petroleum refinery located in southeastern Texas (12), the predominant soil type was a massive, laterally extensive marine clay with very thin silt and sand interbeds. Slug tests from the site indicated hydraulic conductivity from 9.3×10^{-6} to 2.5×10^{-4} centimeters per second (0.0266 to 0.720 feet per day). The saturated clay zone varied in thickness from 15.2 to 30.5 meters (50 to 100 feet). Depth to ground water typically was no more than 3 meters (10 feet). Average annual precipitation was 88.9 centimeters (35 inches), and the regional ground-water gradient was 1.7×10^{-3}. Contamination consisted of petroleum hydrocarbons, which existed both in the dissolved phase and as free-product phase on ground water. The total free-product plume was estimated to contain more than 1,514 cubic meters (400,000 gallons) and to cover approximately 8,094 square meters (87,120 square feet).

The trench was oriented normal to the regional ground-water gradient and located near the downgradient end of the free-product plume. It was constructed using a backhoe and was backfilled with pea gravel. The trench was 0.9 to 1.2 meters (3 to 4 feet) wide, 3.7 to 4.3 meters (12 to 14 feet) deep, and 4.7 meters (16 feet) long. A 30.5-centimeter (12-inch) diameter recovery well was located in the center of the trench, which was deepened to a depth of 5.5 meters (18 feet) in the vicinity of the well. Adding a low-permeability cover minimized infiltration of surface waters.

After 2 years of operation, approximately 9.8 cubic meters (2,600 gallons) of free-product hydrocarbons were recovered. With a product-to-water ratio of about 1:91, the trench recovered approximately 53.9 liters (14.24 gallons) of petroleum hydrocarbons per day.

4.4.2.2 LNAPL and Dissolved-Phase Recovery, Westminster, Colorado

At a municipal service center in Westminster (15), the site geology consisted of 3 to 3.7 meters (10 to 12 feet) of sandy clay underlain by interbedded sandstones and claystones. Ground water occurred at depths between 3.7 to 6.1 meters (12 to 20 feet) during the operation. In situ slug tests of the upper 3 meters (10 feet) of the saturated zone indicated an average hydraulic conductivity of 7×10^{-5} centimeters per second. Regional ground-water gradient was approximately 0.01. Contamination at the site was free-product gasoline floating on ground water. The gasoline plume covered an area 91.4 to 122 meters (300 to 400 feet) in width and 122 meters (400 feet) in length that was estimated to contain 189 to 379 cubic meters (50,000 to 100,000 gallons) of product (Figure 4-16). A gasoline vapor plume extended 15.2 meters (50 feet) beyond the limits of the liquid plume.

The trench was located nearly normal to the contaminant plume and was constructed using a backhoe with a sliding trench box. The trench was 0.9 to 1.2 meters (3 to 4 feet) wide, 5.5 to 6.1 meters (18 to 20 feet) deep, and 183 meters (600 feet) long. The base of the trench contained 10-centimeter (4-inch) perforated pipe, which sloped at a grade of 0.01 toward a corrugated metal pipe sump in the middle of the trench. The trench was backfilled with 1.9-centimeter (3/4-inch) gravel to within 2.4 meters (8 feet) of the ground surface (688 cubic meters [900 cubic yards] required); the remainder of the trench was filled with materials excavated from the trench. In addition to the trench, two 12.2-meter (40-foot) deep recovery wells were installed elsewhere in the plume.

The thickness of the original plume varied from 0.6 to 1.8 meters (2 to 6 feet). After 1 year of trench operation, most monitoring wells showed less than 15 centimeters (6 inches) of product. Total flow of product and ground water from both the trench and recovery wells was approximately 7.6 cubic meters (2,000 gallons) per day, and after 1 year total product recovery was estimated to be 114 cubic meters (30,000 gallons). It will take an

Table 4-2. Summary of Applications of Trenches for Delivery or Recovery: Site Characteristics

Reference	Site Name	Contaminant	Soil Type	Hydraulic Conductivity	Gradient	Depth
Hydrodynamic Control						<3 m
Piontek and Simpkin, 1992	Laramie Tie	Creosote/pentachlorophenol mixture (DNAPL)	Alluvial sands	0.25-10 cm/sec		
Day and Ryan, 1992	Ohio	Mixed-waste landfill leachate	Glacial till/bedrock			
Ground-Water Remediation						
Mast, 1991	Site A	Free product and dissolved petroleum hydrocarbons	Marine clay	0.0001-0.00001 cm/sec	0.0017	<3 m
Mast, 1991	Site B	Dissolved petroleum hydrocarbon	Clay/sand/clay	<0.0001 cm/sec	0.0625	1 m
Mast, 1991	Site C	Free product and dissolved petroleum hydrocarbons	Deltaic clay/sand	0.003-0.04 cm^2/sec (T)	0.0645	1-3 m
Ganser and Tocher, 1988	Westminster	Free product and dissolved gasoline	Sandy clay/sandstone	0.00007 cm/sec	0.01	4-6.5 m
Rawl, 1994	Rinker Concrete	Dissolved-phase PAHs	Limestone/sandstone	>0.1 cm/sec		1 m
Rawl, 1994	Langley AFB	Free product and dissolved jet fuel (JP-4)	Sands and silts			
Day and Ryan, 1992	Northern California	“Spilled processing chemicals”	Clays, silts			
Vapor Extraction						
Barrera, 1993	Case #1	VOCs (PCE, TCE, TCA)	Clay/sand and gravel			2.5 m
Barrera, 1993	Case #2	BTEX, petroleum hydrocarbons	Clay/silt and fine sand	0.00001-0.0001 cm/sec	0.04	5-6 m
Barrera, 1993	Case #3	Toluene	Sand and silt			5-7 m
Barrera, 1993	Case #4	VOCs (acetone, MEK, toluene, xylene, e-benzene)	Silt and clay/sand	0.0001 cm/sec		1-2 m
Combined Ground-Water Remediation and Vapor Extraction						
Rawl, 1994	Law Center	Free product and dissolved BTX	Sand and clay/granite	0.000007-0.03 cm/sec		
LNAPL Recovery						
Hanford and Day, 1988	San Jose	Free product diesel fuel	Sands, silts, clays			9-11 m
Day and Ryan, 1992	South Texas	Free product waste oil				Shallow
DNAPL Recovery						
Meiri et al., 1990	Rock Creek	TCE	Glacial till/bedrock	0.00002-0.00008 cm/sec	0.02	1-2 m
Rawl, 1994	Gray Iron Works	TCE	Silty clay glacial till	<0.0003 cm/sec		
Sale and Applegate, 1994	Laramie Tie	Creosote/pentachlorophenol mixture	Alluvial sands	0.25-10 cm/saec		<3 m
Flow Barrier						
Rawl, 1994	Star Lake	Free product diesel fuel	Sands, silts, clay			4.5 m

Table 4-3. Summary of Applications of Trenches for Delivery or Recovery: Trench Parameters

Reference	Site Name	Shape	Length	Width	Depth	Fill Material
Hydrodynamic Control						
Piontek and Simpkin, 1992	Laramie Tie	Closed loop	5,100 m			Drainline with bentonite barrier wall
Day and Ryan, 1992	Ohio	Linear (2)		1 m	14 m	Sand, geotextile, bentonite barrier wall
Ground-Water Remediation						
Mast, 1991	Site A	Linear	5 m	1 m	3-4 m	Pea gravel
Mast, 1991	Site B	Linear:				
		N-S	48 m	1 m	3 m	Pea gravel
		E-W	45 m	1 m	3 m	Pea gravel
Mast, 1991	Site C	Linear	9 m	1 m	3.2 m	Pea gravel
Ganser and Tocher, 1988	Westminster	Linear	180 m	1 m	5-6 m	3/4-in. gravel
Rawl, 1994	Rinker Concrete	Linear	15 m	0.3 m	3 m	Sand
Rawl, 1994	Langley AFB	Linear (19)	1,000 m	0.3 m	6 m	Sand
Day and Ryan, 1992	Northern California	Linear		0.75 m	9 m	Gravel with geotextile, slurry wall
Vapor Extraction						
Barrera, 1993	Case #1	Linear (5)	150 m		2.5 m	Pea gravel
Barrera, 1993	Case #2	Linear (8)			3 m	Pea gravel
Barrera, 1993	Case #3	Linear (9)			5 m	Perforated sheet piling
Barrera, 1993	Case #4	Linear (8)			1 m	Pea gravel
Combined Ground-Water Remediation and Vapor Extraction						
Rawl, 1994	Law Center	Linear (7)	360 m	0.3 m	5-7 m	
LNAPL Recovery						
Hanford and Day, 1988	San Jose	Linear (2)	180 m	1-1.5 m	13-14 m	Gravel over sandy gravel
Day and Ryan, 1992	South Texas	Linear	400 m		6 m	Geomembrane panels
DNAPL Recovery						
Meiri et al., 1990	Rock Creek	Model only				
Rawl, 1994	Gray Iron Works	Linear (4)	250 m	0.3 m	7 m	Sand
Sale and Applegate, 1994	Laramie Tie	Linear (12)	670 m			Perforated drain only
Flow Barrier						
Rawl, 1994	Star Lake	Curvilinear	400	0.3 m	4.5 m	40-mil HDPE

Table 4-4. Summary of Applications of Trenches for Delivery or Recovery: Product Recovery

Reference	Site Name	Pump/Well Type	Pump/Well Location	Pump Rate	Product Recovery
Hydrodynamic Control					
Piontek and Simpkin, 1992	Laramie Tie				
Day and Ryan, 1992	Ohio	Recovery wells	In trench	5 gal/min per trench	
Ground-Water Remediation					
Mast, 1991	Site A	12-in. recovery well	Middle of trench	9 gal/min	14 gal/day
Mast, 1991	Site B	12-in. recovery well	Bend in trench	0.5 gal/min	
Mast, 1991	Site C	24-in. recovery wells		0.033 gal/min	
Ganser and Tocher, 1988	Westminster	Metal sump	Middle of trench	1.4 gal/min	30,000 gal, first 12 months
Rawl, 1994	Rinker Concrete	8-in. recovery well	End of trench	0.05-0.16 gal/min	None, below MCL
Rawl, 1994	Langley AFB	8-in. recovery well	End of trench		Not yet on line
Day and Ryan, 1992	Northern California	12-in. recovery well	328-ft intervals in trench		
Vapor Extraction					
Barrera, 1993	Case #1	Vacuum	Out of trench	15 HP/1,000 cfm	100 lbs, first 30 days
Barrera, 1993	Case #2	Vacuum	Out of trench	15 HP/500 cfm	270 lbs/day
Barrera, 1993	Case #3	Vacuum	Out of trench		
Barrera, 1993	Case #4	Vacuum	Out of trench	10 HP/250 cfm	25 lbs, first 120 days
Combined Ground-Water Remediation and Vapor Extraction					
Rawl, 1994	Law Center	8-in. recovery well		30 gal/min	
LNAPL Recovery					
Hanford and Day, 1988	San Jose	12-in. recovery well	100-ft intervals in trench		
Day and Ryan, 1992	South Texas	Recovery wells with skimmers	Wells in trench		
DNAPL Recovery					
Meiri et al., 1990	Rock Creek	N/A	N/A	N/A	N/A
Rawl, 1994	Gray Iron Works	8-in. recovery well	End of trench	5 gal/ min	
Sale and Applegate, 1994	Laramie Tie				280,000 gal (1992-1993) (50% after 30 days; 90% after 90 days)
Flow Barrier					
Rawl, 1994	Star Lake	N/A	N/A	N/A	N/A

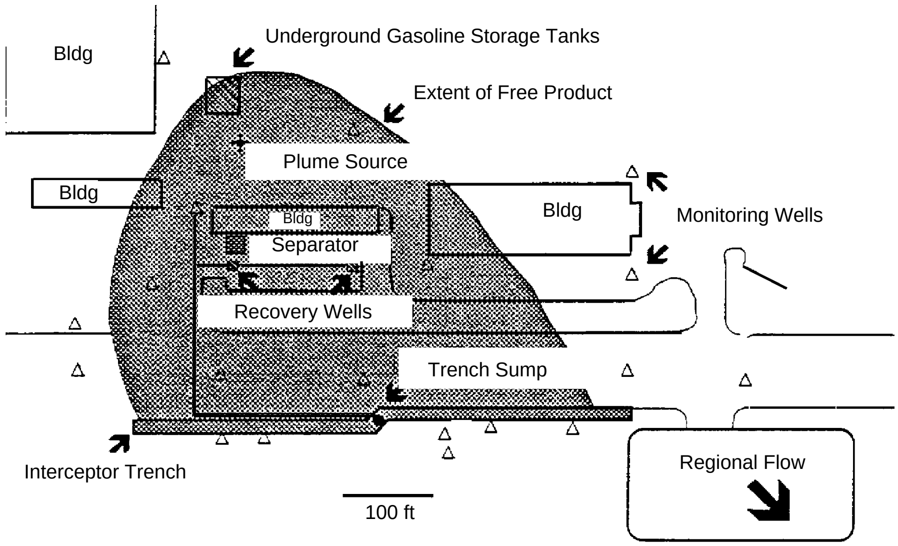


Figure 4-16. Plan of the Westminster gasoline recovery site (15).

estimated 5 years to recover 50 to 70 percent of the product (15).

4.4.2.3 DNAPL Recovery, Laramie, Wyoming

At a former wood treating facility (31) in Laramie, the site geology consisted of approximately 2.4 meters (8 feet) of alluvial sediments underlain by fine-grained sandstone. Surficial alluvial sediments of sands, silts, and clays graded downward to coarse sands and fine gravels at the base. The lower several feet of the alluvial aquifer were contaminated with wood-treating oil (Figure 4-17), a DNAPL that sank below the surface of the ground water. The initial residual oil concentration ranged from 5,000 to 100,000 ppm in soil boring samples (32).

An initial field demonstration was conducted in 1988 to test the effectiveness of product recovery. The demonstration used horizontal drains for waterflooding followed by chemical flooding. Two 4.6-meter (15-foot), parallel horizontal drains were installed 4.6 meters (15 feet) apart, and a sheet piling wall separated them from the surrounding alluvial aquifer. During this demonstration, approximately 6.1 cubic meters (1,600 gallons) of oil were recovered. This was estimated to be 94 percent of the oil in the test cell.

In 1989, a second field demonstration was conducted. A 39.6-meter (130-foot) square sheet pile wall isolated this test cell from the surrounding aquifer. Three 10-centimeter (4-inch) horizontal drains were installed; these drains were oriented parallel, spaced 18.3 meters (60 feet) apart, and located at the aquifer-bedrock contact. The initial volume of wood treating oil was estimated to be approximately 259 cubic meters (68,500 gallons). An initial waterflood removed the mobile phase of the oil; recovery from this step was 151 cubic meters (40,000 gallons.) Chemical flooding removed the residual phase oil; this step removed an additional 90.8 cubic meters (24,000 gallons) of oil. In total, the horizontal drain system coupled with water and chemical flooding removed 242 cubic meters (64,000 gallons) or 93.5 percent of the initially estimated product reservoir.

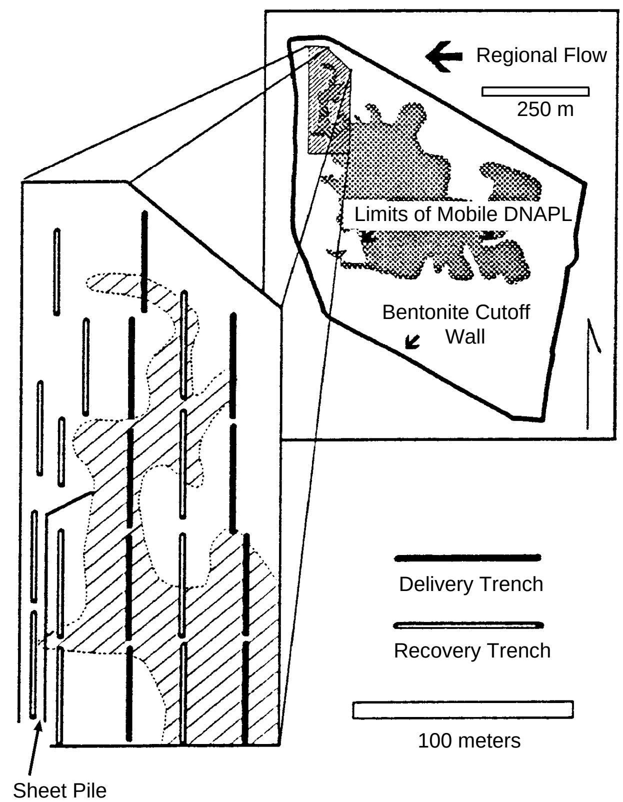


Figure 4-17. Plan of the Laramie DNAPL recovery site (20).

Full field implementation and system operation began in 1991 with installation of 12 oil recovery units. Drainlines in the system were 54.9 meters (180 feet) long, and spaced 27.4 meters (90 feet) apart. During 1991, three units were operated that recovered 227 cubic meters (60,000 gallons) of oil. From the summer of 1992 to the summer of 1993, all 12 units were operated, recovering 1,136 cubic meters (300,000 gallons) of oil. Approximately 3.79 x 10^5 cubic meters (100 million gallons) of water circulated through the alluvial aquifer.

Production records from the 1992-1993 pumping period indicate that 50 percent of the mobile oil was recovered after approximately 30 days of system operation, and 90 percent recovery was achieved in 90 days. Pumping beyond 130 days produced only minor increases in oil recovery.

Total recovery from all pilot studies and the first 2 years of system operations was approximately 3,407 cubic meters (900,000 gallons) of oil.

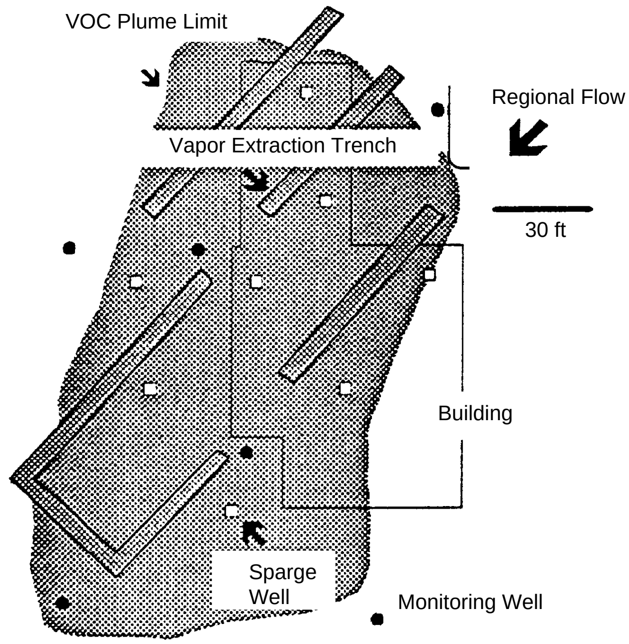
4.4.2.4 Vapor Recovery, Illinois

In northeastern Illinois (24), the site geology consisted of clayey surface sediments underlain by a plastic clay that contained trace coarse-grained materials. A 0.6-meter (2-foot) thick sand and gravel unit occurred near the water table at a depth of about 2.4 meters (8 feet). Contamination at the site included VOCs and semivolatile organic compounds (SVOCs) in the soil and ground water (Figure 4-18).

Initial investigation indicated that dissolved phase VOCs could be removed from the aquifer by air sparging; followup investigations concluded that because of lateral geologic heterogeneities, sparging was not a viable option unless the extraction wells could be placed very near the seasonal high water level. The sand and gravel layer located at the water table would serve as a pathway for VOC removal by vapor extraction.

The implemented system consisted of nine air sparging wells and five vapor extraction trenches with a cumulative length of 168 meters (550 feet). The trenches, which were excavated by backhoe, were 0.9 to 1.2 meters (3 to 4 feet) wide, and 2.1 meters (7 feet) deep (Figure 4-18). Installation of the sparging wells and extraction trenches required about 3 weeks. On the basis of airflow analysis, a 10 horsepower, 5.7 cubic meters (200 cubic feet) per minute blower was selected for sparging, and a 15 horsepower, 28.3 cubic meters (1,000 cubic feet) per minute blower was selected for vacuum extraction. Cost for the system as described was less than $190,000.

The sparging/vapor extraction system removed more than 45.4 kilograms (100 pounds) of VOCs in the first 30 days of operation and reduced VOC concentrations by 75 percent in the first 4 months of operation



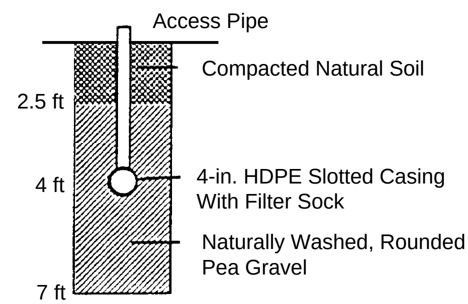


Figure 4-18. Map of the northeastern Illinois vapor extraction site and detail of trench completion (24).

4.4.2.5 TCE Recovery, Modeling, and Field Results, Ohio

Modeling of ground-water flow at a site can be a valuable tool during the design of a delivery or recovery system. Therefore, this case study presents site characterization, predictive numerical modeling to support the design of an interceptor trench system, field data from the installed system, and a comparison of the predicted and observed results. The material presented here has been taken from the following references: Krishnan and Siebers, (33); Meiri and others, (34); Weston, (35-37); and Woodward-Clyde Consultants (33-38).

Geology. The site, located in northeastern Ohio, included two adjacent properties totalling approximately 13 acres (33). The site geology (Figure 4-19) consisted of an upper fractured till unit (upper aquifer 0 to 2.1 meters [0 to 7 feet] below ground surface), a lower till aquitard (2.1 to 3.7 meters [7 to 12 feet] below ground surface), weathered shale bedrock (lower aquifer, 3.7 to 8.5 meters [12 to 28 feet] below ground surface), and competent shale bedrock (34). Depth to ground water in

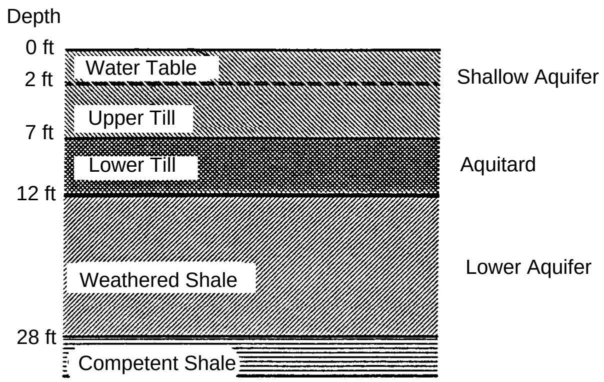


Figure 4-19. Typical subsurface profile (34).

the upper unconfined aquifer ranged from 0.6 to 1.5 meters (2 to 5 feet).

Regarding the site's hydraulic profile, slug tests of wells screened in the upper aquifer indicated hydraulic conductivities of 2×10^{-5} to 8×10^{-4} centimeters per second (0.065 to 2.4 feet per day); porosity was estimated to be 0.30. Regional ground-water gradient in the upper aquifer, determined from water levels in screened wells, averaged about 0.02, with flow to the west. Depth to the piezometric surface of the lower confined aquifer was slightly more than 0.6 meters (2 feet). Pump tests on a well screened in the lower aquifer indicated a transmissivity of about 4.1 square meters (13.5 square feet) per day, or a hydraulic conductivity of about 0.3 meters (0.85 feet) per day (assuming an aquifer thickness of 4.9 meters [16 feet]). Lower aquifer storativity was estimated to be 3×10^{-4}. Regional gradient in the lower aquifer, based on data from three deep wells, was calculated to be 0.01, also to the west. Pump tests using adjacent wells screened in the upper and lower aquifers indicated that the two aquifers were separated hydraulically; the vertical hydraulic conductivity of the aquitard was calculated to be 3×10^{-8} centimeters per second (8×10^{-5} feet per day) (34).

Distribution of Contaminants. Contamination at the site included TCE and heavy metals in soil. The ground water contained TCE, tetrachloroethene, trans-dichloroethene, 1,1-dichloroethene, vinyl chloride, 1,1,1-trichloroethane, ethylbenzene, and xylene (33). TCE was the principal ground-water contaminant. The contaminants apparently leaked from concrete silos (Figure 4-20).

As of 1984, TCE in the upper till aquifer had migrated 45.7 to 76.2 meters (150 to 250 feet) from the probable source area (Figure 4-21). It was assumed that the migration had occurred over an 8- to 10-year period, suggesting an average plume front velocity of about 4.6 to 9.1 meters (15 to 30 feet) per year. Average ground-water flux (based on an average hydraulic conductivity of 0.37 meters [1.2 feet] per day, a regional gradient of 0.02, and a porosity of 0.30) was estimated to be 9.1

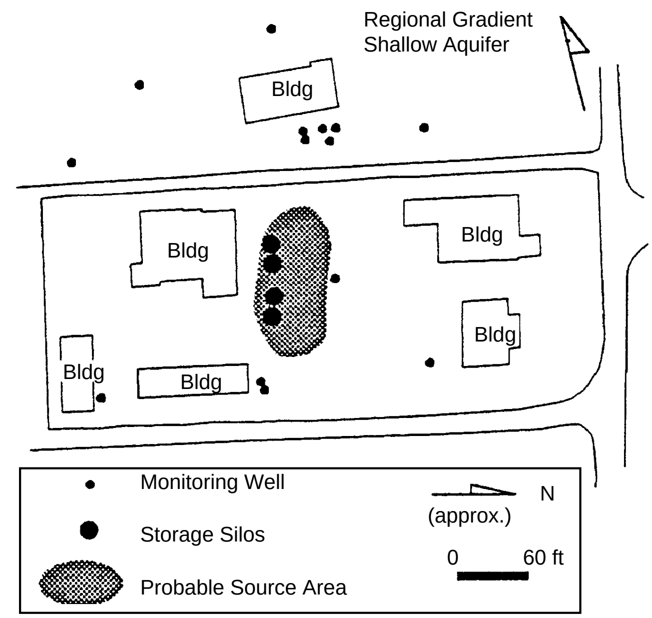


Figure 4-20. Site map showing locations of monitoring wells, storage silos, and probable contaminant source area (34).

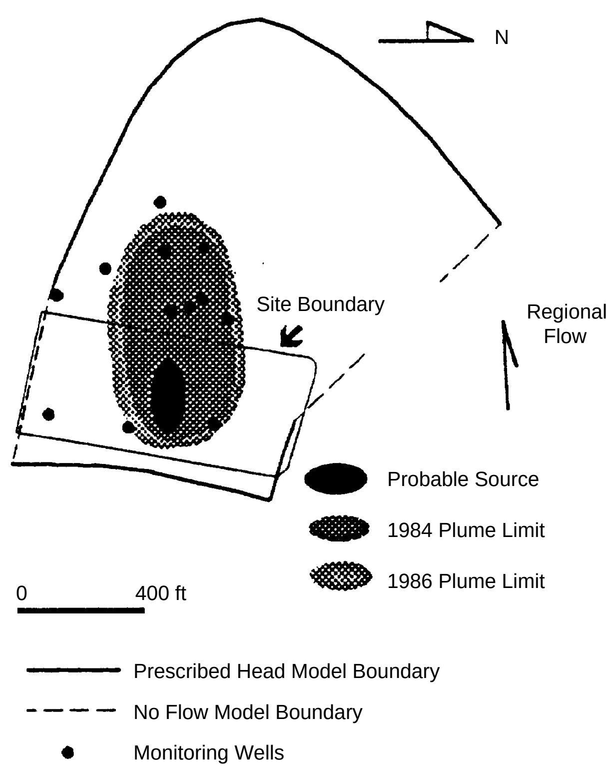


Figure 4-21. Extent of TCE plume in 1984 and 1986; also shown is the ground-water model domain, with prescribed (fixed) head and no-flow boundaries (34).

meters (30 feet) per year. This indicated a retardation factor between ground-water velocity and TCE plume front velocity of 1 to 2. Comparison of plume front position between 1986 and 1984 indicated a retardation factor of 1.2 to 2. Based on the 1986 data, the TCE plume covered an area of approximately 12,077 square meters (130,000 square feet). Assuming a uniform plume thickness of 1.5 meters (5 feet) and a porosity of 0.30, the volume of the plume was approximately 5,522 cubic meters (195,000 cubic feet) (34). Data from the deep weathered-shale aquifer were insufficient to define the extent of the TCE plume.

System Design. Vertical extraction wells and trenches were considered as remedial alternatives. The vertical extraction well system was deemed impractical because modeling indicated that discharge rates would be on the order of 0.4 liters (0.1 gallons) per minute per well. This low rate would limit the radius of influence to a few feet and would require several thousand wells for remediation.

Drains installed in shallow trenches also were considered as a remedial alternative. Two-dimensional ground-water flow and contaminant transport models were used to predict water table drawdown, trench discharge, and TCE concentration in the extracted water. The two-dimensional coupled flow transport models used both advective and dispersive contaminant migration and retardation. Model boundary conditions were based on surface topography and configuration of the water table surface, with boundaries selected beyond the expected region of influence of the trench system (Figure 4-22). The base of the upper till was selected as the bottom of the aquifer. A finite element mesh was established, with 212 node points and 204 elements. All existing shallow monitoring wells were located at nodes.

The flow model was calibrated using empirical data with an assumption of steady-state conditions. Calibration was completed by varying precipitation recharge, initial boundary head values, and hydraulic conductivity. The predicted heads in the final calibrated model differed from the observed field values by 0.3 meters (1 foot) or less.

Proposed trench locations were near the plume front and along the plume center at a depth of 2.1 meters (7 feet) below ground surface (Figure 4-23a). Operation of the trench was simulated as a transient (non-steady-state) system for 420 "model" days. Beyond 420 days, water level and flow rate changes with time were insignificant. Predicted trench discharge rates dropped from an initial value of approximately 37.9 liters (10 gallons) per minute to a steady-state rate of about 3.8 liters (1 gallon) per minute.

Then, a preliminary transport analysis used the flow model to estimate changes in TCE concentration resulting from operation of the trench system. Assumed TCE-related transport model parameters were: retardation factor = 1.5, longitudinal dispersivity = 9.1 meters (30 feet), and transverse dispersivity = 3 meters (10 feet). Distribution of TCE in 1986 was used as the initial concentration for the model. The model simulated

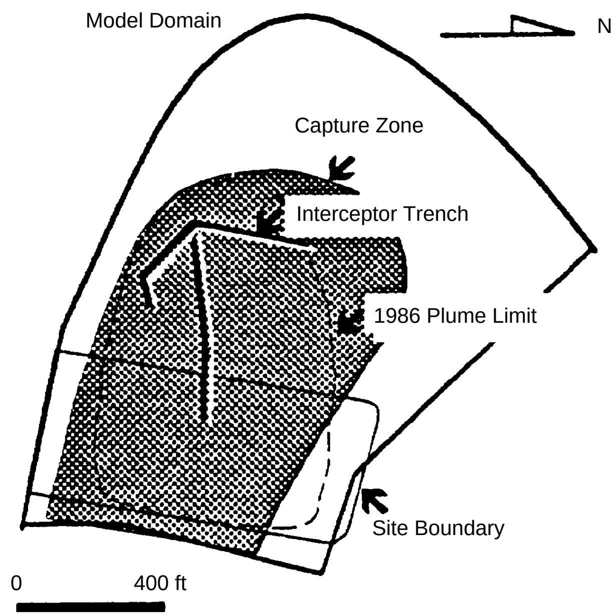


Figure 4-22. Model domain showing location of the interceptor trench, the 1986 TCE plume limit, and extent of the capture zone (34).

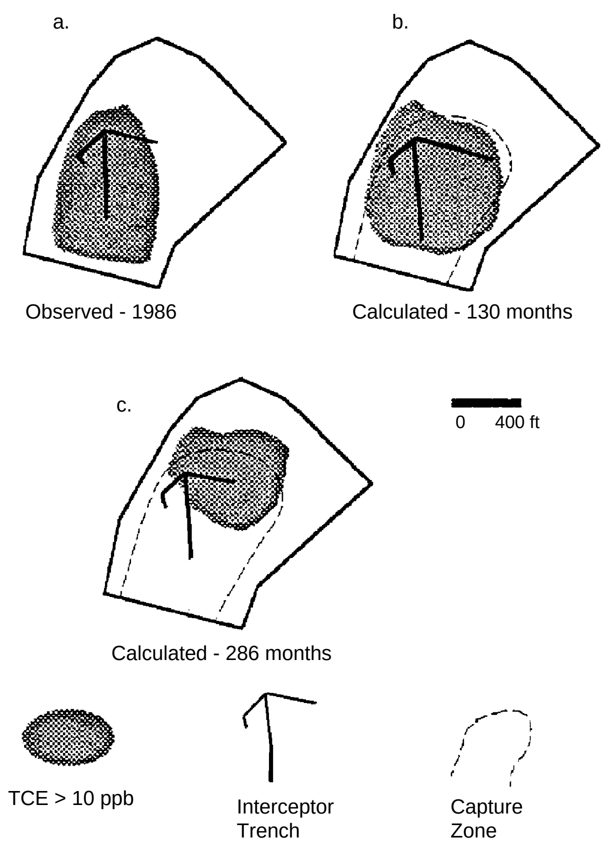


Figure 4-23. TCE concentration distribution through time (Note: TCE >10 ppb outside of capture zone.)

TCE movement for 8,580 days (23.5 years). Results of the preliminary simulation indicated an overall reduction in TCE concentration and predicted locations of contamination during the recovery system operation (Figure 4-23). The results also indicated, however, that some marginal areas of the TCE plume could avoid capture as advective flow and dispersion moved it beyond the trench capture zone.

The transport modeling indicated that the operation would require approximately 24 years to decrease average discharge TCE concentrations to about 8 ppb (from an initial value of about 1,550 ppb). This would require the removal of approximately 9 pore volumes of contaminated ground water. Because the analysis assumed rapid TCE desorption from soil, no TCE transformation or degradation, and other simplifying factors, the estimates presented are rough and to be used only for planning purposes.

Implementation. Plans for constructing and implementing the interceptor trench (Figure 4-24) were developed in 1987 (38). Designs called for all trench segments to be approximately 2.1 meters (7 feet) deep to fully penetrate the shallow aquifer. The initial trench system was approximately 565 feet in total length and consisted of two trench segments 2.1 meters (7 feet) deep, with separate sumps (designated Martin and Henfield sumps on Figure 4-24).

In addition to a depth of 2.1 meters (7 feet), each trench segment was 0.9 meters (3 feet) wide. A filter fabric (geotextile) lined the excavation. Then, 15 centimeters (6 inches) of 1.9-centimeter (3/4-inch) gravel was placed at the bottom of the trench followed by a 15-centimeter (6-inch) diameter, continuously perforated PVC drain pipe (Figure 4-25). The trench was backfilled with 1.9-centimeter (3/4-inch) gravel to within about 0.3 meters (1 foot) of the ground surface. The remaining 0.3 meters (1 foot) of backfill consisted of natural soils to minimize infiltration of surface waters.

Results. The ground-water extraction system began operation in January 1989. Figure 4-26 summarizes the ground-water extraction from the two interceptor trenches in the shallow, upper till aquifer from September 1989 through September 1993. In general, several observations could be noted for this period:

- Data from monitoring piezometers indicated that the regional flow in the shallow aquifer was north-northwest, rather than to the west as assumed during the modeling phase of the project.
- Temporal variations were observed in the concentration of total VOCs (monthly averages typically varied from 1,000 to 6,000 ppb), but no consistent trend of decreasing concentration through time seemed to occur. On the basis of an initial "best fit" first-order rate constant, it was estimated that lowering VOCs to a residual concentration of 20 ppb would take approximately 15 years (an extraction of approximately 1.2 x 10^5 cubic meters [32 million gallons]).

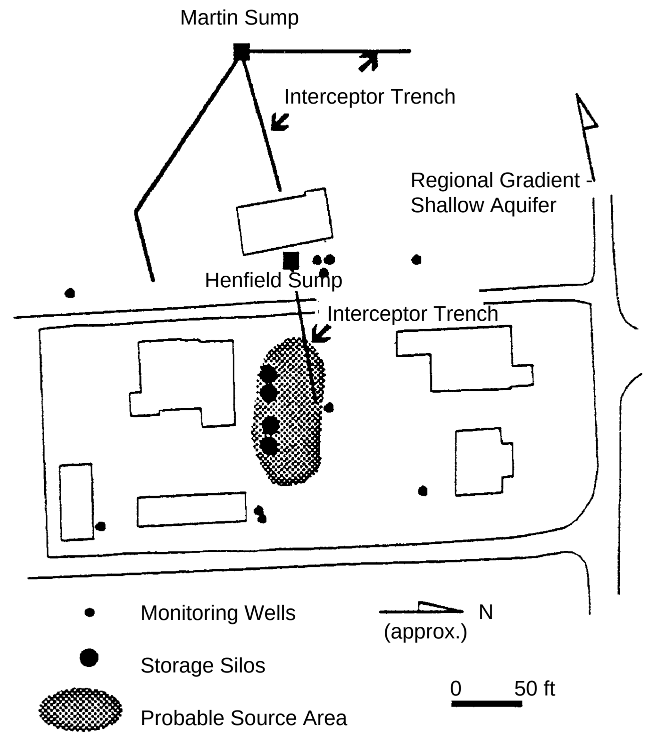


Figure 4-24. Site plan showing locations of initial interceptor trench segments (38).

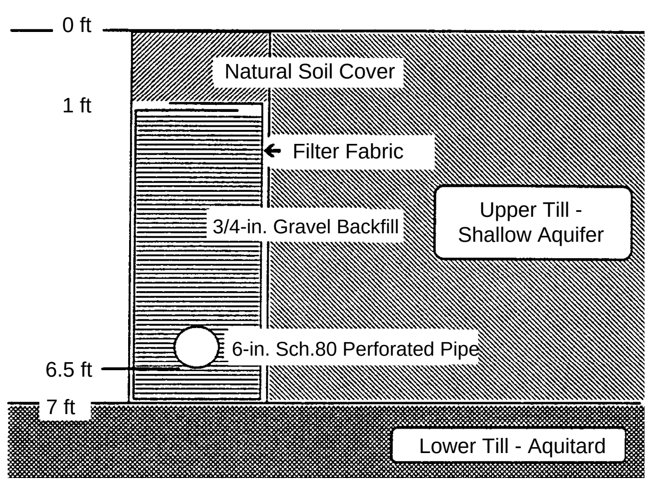


Figure 4-25. Schematic cross section of trench construction (38).

- The property containing the storage silos appeared to be the principal region of contamination of the shallow (upper till) aquifer, but insufficient data existed to generate a valid spatial model.

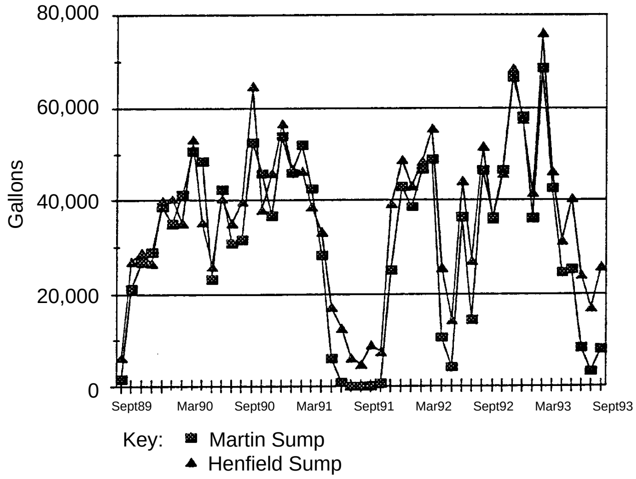


Figure 4-26. Monthly extraction from interceptor trench sumps.

- The initial interceptor trench system was insufficient to capture the VOC plume. Consequently, in December 1991 additional trench segments were considered, followed by a recommendation in December 1992 to construct these segments on an adjacent property. In October 1993, the design of the additional trench segments was completed, and the trenches were installed during the winter of 1994.

- As of September 1993, approximately 40.8 kilograms (90 pounds) of VOCs were treated at the site.

For the first year of operation of the interceptor trench system, the predicted extraction (from modeling) exceeded the actual extraction. After the first year, the actual extraction exceeded the predicted volume. Figure 4-27 compares the actual and predicted volumes. A linear regression through the observed data and fixed at the origin yielded an average flow rate of about 67,000 gallons per month. In contrast, a linear model through the steady-state portion of the predicted data (after the first 8 months) yielded an average flow rate of approximately 164 cubic meters (43,200 gallons) per month.

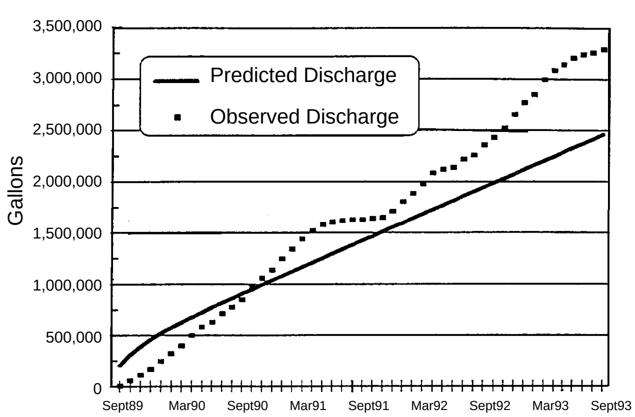


Figure 4-27. Observed and predicted discharges from trench system.

The actual trench system is recovering 155 percent of the predicted value. These differences probably result from parameter estimates that the modeling used, including:

- Rate of recharge by precipitation (model value appears to underestimate the actual value).
- Hydraulic conductivity of the shallow aquifer (model value appears to underestimate the actual value).
- Regional gradient (a different direction as indicted by the observed data).

Additional examination of the data could possibly yield additional causes for this difference.

4.5 References

1. Gilbert, S.G., and J.J. Gress. 1987. Interceptor trenches for positive ground-water control. Ground Water Monitor. Rev. 7:55-59.

2. Hanford, R.W., and S.R. Day. 1988. Installation of a deep drainage trench by the biopolymer slurry drain technique. Proceedings of the National Water Well Association Outdoor Action Conference, Las Vegas, NV.

3. Day, S.R., and C.R. Ryan. 1992. State of the art in biopolymer drain construction. In: Paul, D.B., R.R. Davidson, and N.J. Cavalli, eds. Slurry walls: Design, construction, and quality control. ASTM STP 1129. Philadelphia, PA: American Society for Testing and Materials.

4. LaGrega, M.D., P.L. Buckingham, and J.C. Evans. 1994. Hazardous waste management. New York, NY: McGraw-Hill.

5. Farrell, M. 1993. Breaking new ground in groundwater remediation. Hazmat World (January).

6. Rawl, G. 1994. Personal communication. Horizontal Technologies, Inc., West Palm Beach, FL.

7. Soils. 1993. Heres how it works: Horizontal wells linear contaminant recovery system. Soils (November). p. 48.

8. Bauer Spezialtiefbau. 1994. Diaphragm and cutoff walls. Personal communication with Badwi Khouri, Coastal Caisson Corporation, Clearwater, FL (March).

9. Begor, K.F., M.A. Miller, and R.W. Sutch. 1989. Creation of an artificially produced fractured zone to prevent contaminated ground-water migration. Ground Water 27(1):57-65.

10. Beljin, M., and L.C. Murdoch. 1992. Analytical models for interceptor trenches. Final report. EPA Contract No. 68-C9-0031-WA1.

11. Murdoch, L.C. 1994. Transient analysis of an interceptor trench. Water Resour. Res. In press.

12. Mast, M.K. 1991. The prediction of the effectiveness of interceptor trenches in the remediation of ground-water contamination by petroleum hydrocarbons. M.S. thesis. Texas A&M University.

13. Zheng, C., K.R. Radbury, and M.P. Anderson. 1988. Role of interceptor ditches in limiting the spread of contaminant in ground water. Ground Water 26:734-742.

14. Chambers, L.W., and J.M. Bahr. 1992. Tracer test evaluation of a drainage ditch capture zone. Ground Water 30:667-675.

15. Ganser, D.R., and R.J. Tocher. 1988. Design and construction of a subsurface gasoline recovery system. Presented at FOCUS Conference on Southwestern Ground-Water Issues, Albuquerque, NM. pp. 479-486.

16. Gilham, R.W., and D.R. Burris. 1992. Recent developments in permeable in situ treatment walls for remediation of contaminated ground water. Proceedings of the Subsurface Restoration Conference, Third International Conference on Ground-Water Quality Research, Dallas, TX.

17. Keely, J.F. 1984. Optimizing pumping strategies for contaminant studies and remedial actions. Ground Water Monitor. Rev. 4(3):36-73.

18. Repa, E., and C. Kufs. 1985. Leachate plume management. EPA/540/2-85/004.

19. Piontek, K.R., and T.S. Simpkin. 1992. Factors affecting the practicability of in situ bioremediation at a wood preserving site. Proceedings of the 84th Meeting of the Air and Waste Management Association, Kansas City, MO.

20. Sale, T.C., and D. Applegate. 1994. Oil recovery at a former wood-treating facility. Proceedings of the Innovative Solutions for Contaminated Site Management Conference of the Water Environment Federation, Miami, FL.

21. U.S. EPA. 1985. Leachate plume management. EPA/540/2-85/004.

22. Huling, S.G., and J.W. Weaver. 1991. Dense nonaqeous phase liquids. EPA Ground Water Issue. EPA/540/4-91/002.

23. American Petroleum Institute. 1989. A guide to the assessment and remediation of underground petroleum releases, 2nd ed. API 1628. Washington, DC (August).

24. Barrera, J.A. 1993. Air sparging and vapor extraction as a means of removing chlorinated and BTEX compounds in complex ground-water conditions. Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Groundwater Conference, Houston, TX.

25. Starr, R.C., and J.C. Cherry. 1993. Funnel-and-gate system directs plumes to in situ treatment. Groundwater currents. EPA/542/N-93/006.

26. Starr, R.C., and J.C. Cherry. 1994. In situ remediation of contaminated ground water: The funnel-and-gate system. Ground Water. In press.

27. Pankow, J.F., R.L. Johnson, and J.A. Cherry. 1993. Air sparging in gate wells in cutoff walls and trenches for control of plumes and volatile organic compounds (VOCs). Ground Water 31:654-663.

28. Devlin, J.F., and J.F. Barker. 1994. A semipassive nutrient injection scheme for enhanced in situ bioremediation. Ground Water. In press.

29. Blowes, D.W., and C.J. Ptacek. 1992. Geochemical remediation of ground water by permeable reactive walls: Removal of chromate by reaction with iron-bearing solids. Proceedings of the Subsurface Restoration Conference, Third International Conference on Ground-Water Quality Research, Dallas, TX.

30. Gilham, R.W., S.F. OHannesin, and W.S. Orth. 1993. Metal-enhanced abiotic degradation of halogenated aliphatics: Laboratory tests and field trials. Proceedings of the HazMat Central Conference, Chicago, IL.

31. Pitts, M.J., K. Wyatt, T.C. Sale, and K.R. Piontek. 1994. Utilization of chemical-enhanced oil recovery technology to remove hazardous oily waste from alluvium. Proceedings of the Innovative Solutions for Contaminated Site Management Conference of the Water Environment Federation, Miami, FL.

32. Union Pacific Railroad. 1990. Laramie tie plant: In situ treatment process development program. Milestone IV report (appendices).

33. Krishnan, P., and D. Siebers. 1989. Ground-water remediation at a Superfund site. HMCRI.

34. Meiri, D., M. Ghiasi, R. Patterson, N. Ramanujam, and M. Tyson. 1990. Extraction of TCE-contaminated ground water by subsurface drains and a pumping well. Ground Water 28:17-24.

35. Weston. 1991. Annual evaluation report for Old Mill site, Rock Creek, OH. Submitted to U.S. EPA, Region V, Chicago, IL (December).

36. Weston. 1992. Second annual evaluation report for Old Mill site, Rock Creek, OH. Submitted to U.S. EPA, Region V, Chicago, IL (December).

37. Weston. 1993. Third annual evaluation report for Old Mill site, Rock Creek, OH. Submitted to U.S. EPA, Region V, Chicago, IL (October).

38. Woodward-Clyde Consultants. 1987. Old Mill ground-water extraction system: Henfield, revision 2. Submitted to U.S. EPA, Region V, Chicago, IL.