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How To Evaluate Alternative Cleanup Technologies For Underground Storage Tank Sites

A Guide For Corrective Action Plan Reviewers

Appendix A

Horizontal Remediation Wells

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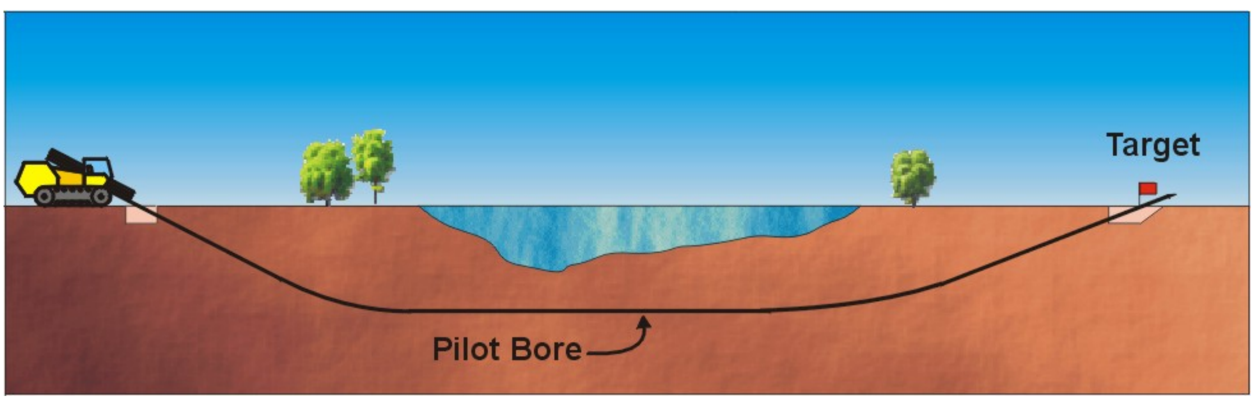
Appendix A
Horizontal Remediation Wells

Introduction

This appendix describes the use of horizontal remediation wells for cleaning up underground storage tank sites. While the chapters in this guide *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers* describe remediation techniques, this appendix describes one well installation technology that can be used to facilitate various remediation techniques.

Horizontal directional drilling (HDD) is a technology widely used to install underground utilities and to extract oil and natural gas. HDD equipment and methods are also used to install wells at environmental cleanup sites; these are known as horizontal remediation wells (HRWs) or horizontal environmental wells. HDD uses a specialized drill rig and drill-head locating equipment to create a curved borehole along a pre-determined borepath, as shown in Exhibit A-1. The drill rig either pulls or pushes the well casing into the curved borehole. A HRW can be installed either using both an entry hole and an exit hole, known as a surface-to-surface, continuous, or double-ended well; or using only an entry hole, known as a blind well. HRWs are able to access locations beneath surface obstructions, and are able to place long well screens in contact with the contaminated area. HRWs wells can be thousands of feet long, with hundreds of feet of well screen.

Exhibit A-1. Schematic Of Typical Horizontal Remediation Well



(Reprinted from Horizontal Directional Drilling Good Practices Guidelines (2008) by the HDD Consortium with permission of the North American Society for Trenchless Technology (NASTT). Copyright 2008 by NASTT. All rights reserved.)

The oil drilling industry developed HDD in the 1930s and continues to update the technology (Bardsley 2014a; Van Heest 2013). HDD was adapted for installing underground utilities in the 1970s (Bardsley 2014a). This use of HDD, known as trenchless technology, is now used to install various underground utilities such as water, sewer, gas, electric, telephone, and fiber optic cables (Directed Technologies Drilling (DTD) 2004; Van Heest 2013).

Starting in the late 1980s, the U.S. Department of Energy sponsored a series of demonstration projects applying HDD technology for the installation of HRWs (U.S. Department of Energy 1998). These demonstration projects helped improve HRW installation technology and techniques (Denham and Lombard 1994). Following the Department of Energy demonstration projects, other federal agencies began to consider the use of horizontal wells for remediation projects (U.S. Army Corps of Engineers 1996; U.S. Environmental Protection Agency 1997). HDD contractors have been designing and installing HRWs for more than 20 years (Van Heest et al. 2013). Thousands of HRWs have been successfully installed in the U.S. (Bardsley 2014a).

Advantages Of Horizontal Remediation Wells

HRWs have two main advantages:

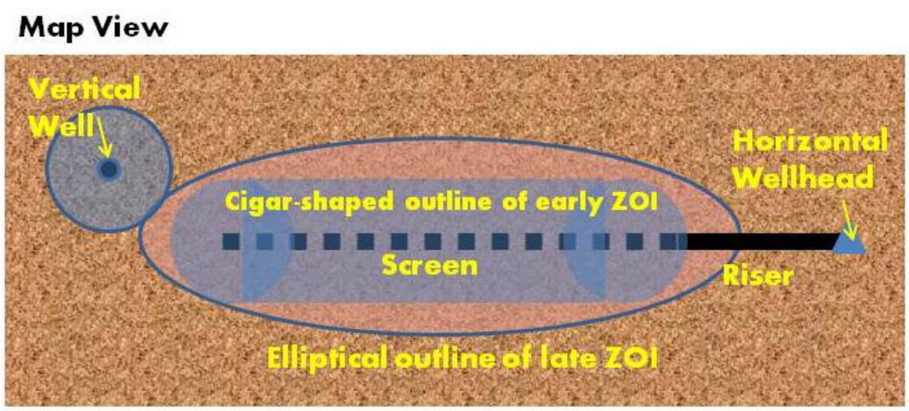
- Ability to access places beneath surface obstructions
- Greater contact with contamination

HDD drill rigs can install wells in locations where conventional vertical drilling or trenching would be undesirable or impractical; for example, they can be used beneath some types of active facilities, buildings, neighborhoods, roads, railyards, airport runways, tank farms, rivers and lakes, and sensitive ecological areas (Bardsley 2014a; Doesburg 2013; Doherty et al. 2000; DTD 2004; Griffin 2004; Lubrecht 2011; Lubrecht 2012; Sequino 2014; U.S. Environmental Protection Agency 2007; Van Heest 2013; Walters 1999/2000).

Most geologic deposits or sediments near the surface have horizontal layers with different vertical strata. This causes fluids in the subsurface to preferentially flow in a horizontal direction. Therefore, contaminant plumes are longer and wider than they are thick. A horizontal well may be installed within a specific stratigraphic layer to maximize contact with the contamination (Bardsley 2014a; DTD 2004; Griffin 2004; U.S. Environmental Protection Agency 2012; Van Heest 2013). Plume geometry is often a main factor when deciding between using HRWs, conventional vertical wells, or other delivery mechanisms; plume geometry determines the number and length of wells, driving the cost comparison. Large, elongated plumes often favor an HRW application.

HRW well screens can be hundreds of feet long (Mott-Smith et al. 2011; Lubrecht 2012). Multiple vertical wells with overlapping zones of influence (ZOI) might be needed to achieve what a single horizontal well can achieve with a single zone of influence, as shown in Exhibit A-2. A typical ZOI for a HRW is about 80 feet or a 40-foot radius around the well. The ZOI can be measured using vertically installed piezometers or wells, as is done for conventional vertical remediation wells. Lundegard et al. (2001) found during a pilot study that at least 30 vertical air sparge wells would be needed to achieve the benefit of one horizontal well with 90 meters of well screen. Installing many vertical wells would have a much greater adverse impact on sensitive surface habitats.

Exhibit A-2. Comparison Of Zone Of Influence Of Horizontal Well Versus Vertical Well



(Reprinted from Directional Drilled Horizontal Wells and Engineered Horizontal Remediation Wells Screens Accelerate Site Closure (2013) by Garry Van Heest, Michael Sequino, and George Losonsky with permission of Directional Technologies, Inc.)

Having a longer well screen in communication with the subsurface contamination, may potentially result in a faster cleanup (Sequino 2014). In addition, HRWs may be less prone to short-circuiting than vertical wells because HRWs are screened within a layer of uniform permeability (Van Heest 2013).

Because the HDD crew steers the drill in three dimensions during the drilling process, the wellbore can follow a curved path to follow plume geometry, target a Non-Aqueous Phase Liquid NAPL layer, target a specific geologic layer, or avoid underground utilities as needed (Bardsley 2014a; DTD 2004; Parmentier and Klemovich 1996).

Depending on site-specific circumstances, additional potential advantages of HRWs include:

- Intersecting multiple fractures, if vertically fractured bedrock is present, (Carlisle et al. 2002; Kinner et al. 2005)
- Reducing disruption in the vicinity of the site by (Bardsley 2014a)
    - Reducing number of wellheads
    - Locating well heads away from existing surface infrastructure
    - Reducing construction time on site
- Reducing time needed for injections, because of the long well screens (Van Heest 2013)
- Resulting in less business disruption because of the smaller footprint (Van Heest 2013)
- Requiring fewer pumps and manifolds than vertical well networks (DTD 2004)
- Helping achieve green and sustainable remediation goals through reduced energy use and less disruption of surface ecology (Lubrecht 2012)

- Recently developed proprietary technology that allows the placement of multiple multi-purpose wells within a single horizontal borehole (EN Rx 2015)

Although installing a HRW is more expensive per foot than installing a vertical well, incorporating horizontal wells may make the overall cleanup project less expensive by reducing the number of wells needed, shortening the time to closure, and reducing disruption to businesses or other activities (DTD 2004; Fournier 2002; Parmentier and Klemovich 1996; Sequino et al. 2012; Van Heest et al. 2013; Walters 1999/2000).

Limitations Of Horizontal Remediation Wells

- Higher installation costs for HRWs than vertical wells
- Design, drilling, and installation of HRWs more challenging than vertical wells

Upfront HRW installation costs are greater per foot than vertical wells (Griffin 2000; Parmentier and Klemovich 1996). Typical HRW costs include: mobilization, $10,000 - $20,000; boring, $90 - $120 per foot; well materials, $10 - $20 per foot; and wire-line tracking, if needed, $30 - $40 per foot. Other potential costs include handling, characterizing, and disposing of the large volume of investigation-derived waste often produced during HRW installation, typically 0.08 cubic yards per foot of drilling, depending on the borehole diameter. Larger projects typically require roll-off containers and frac tanks to containerize drilling waste. If off-site disposal is required, costs range from tens to hundreds of thousands of dollars for moderate to large projects.

Although HRWs have been used for decades, the environmental remediation industry and environmental regulators are more familiar with vertical wells. This can pose a hindrance to the widespread adoption of HRWs (Griffin 2000). While many professionals agree that this technology is sound, there is a lack of published, peer-reviewed literature assessing the performance of HRWs.

A HRW engineer pointed out that “proper development of a horizontal well, drilled with drilling mud, generally takes a higher level of care than developing wells that were constructed using auger drilling technology” (Lubrecht 2012). See additional explanation in Drilling A Horizontal Remediation Well section. Installing HRWs puts great strain on the well materials, and this increases the potential for system failure due to well screen deformation.

HRWs can have limitations based on site features such as, landscape footprint, geometry, and depth. Planning the bore path for a HRW is more complicated than for a conventional vertical well; the horizontal well driller must consider the three dimensional subsurface geology, the location of underground utilities, and where to locate the entry and exit bores (Lubrecht 2011). HRWs typically descend to the desired depth at a shallow angle, so the entry and exit bores may need to be located a large horizontal distance away from the treatment area as shown in Exhibit A-1. At some sites, the required setback distance may place the entry and exit bores off of the contaminated property on parcels owned by other parties. In these cases, one must obtain permission to conduct drilling activities on those properties.

A fluctuating water table can also pose a problem for HRWs screened near the water table as shown in Exhibit A-3. For example, a soil vapor extraction well installed just above the water table could flood if the water table rises. Alternatively, a well installed to extract LNAPL at the water table's surface could fail to extract LNAPL if the water table rises or falls (DTD 2004; see Removal Of LNAPL section).

HRWs are installed by specialty HDD contractors, some of whom are more familiar with utility installation than with the requirements for environmental wells and the procedures for working on cleanup sites (Bardsley 2014b; Griffin 2004). Griffin notes that "Horizontal wells require proper design, construction, and development procedures that are not normally understood by directional drillers" (Griffin 2000). Some researchers have cautioned that horizontal wells could "provide a conduit for contaminated groundwater to be drawn into the well, conveyed a large distance, and injected into an uncontaminated region of an aquifer" (Steward and Jin 2001). For this reason, exercise extra care to prevent cross-contamination when installing HRWs with long screened intervals, as discussed in Planning Activities section.

HRW installers may also face regulatory hurdles. Some states' well construction regulations apply to conventional vertical wells; special permission may be needed to use horizontal wells (Bardsley 2014b). For instance, California has requirements for companies using HDD near a California roadway (Caltrans 2015). Drilling underneath rail lines may also require special permits and fees.

Uses Of Horizontal Remediation Wells

HDD has been used to install extraction, injection, and monitoring wells to address contaminated soil and groundwater (Bardsley 2014b). Less commonly, HDD has been used to collect soil samples. HRWs have been used to address petroleum contamination and chlorinated solvents (U.S. Army Corps of Engineers 2010). HRWs have been used for the following remediation technologies (DTD 2004; Bardsley 2014a; Bardsley 2014c):

- Groundwater extraction
- Soil vapor extraction[1]
- Dual phase extraction[2]
- Free phase contaminant removal
- Air sparging[3]
- Hot air/steam injection
- Bioremediation[4]
- Nutrient injection
- In-situ chemical oxidation[5]
- Electrical resistance heating
- Radio frequency heating
- Permeable reactive barriers
- Infiltration or injection of treated groundwater

A hybrid approach, using both HRWs and vertical wells, may be suitable at some sites depending on plume geometry and project goals.

The following subsections describe the more common uses of HRWs.

Air Sparging And Soil Vapor Extraction

HRWs have been widely used for air sparging (AS). By bubbling air through contaminated groundwater, AS systems transfer volatile contaminants from the groundwater to the overlying vadose zone. AS systems are often used together with soil vapor extraction (SVE) systems, which induce a vacuum within the overlying unsaturated soil or vadose zone to extract contaminated vapors from the subsurface soil gas and then collect them for treatment at the surface, as shown in Exhibit A-3.

For more information, see the following chapters in *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers*

[1] Soil Vapor Extraction, Chapter II

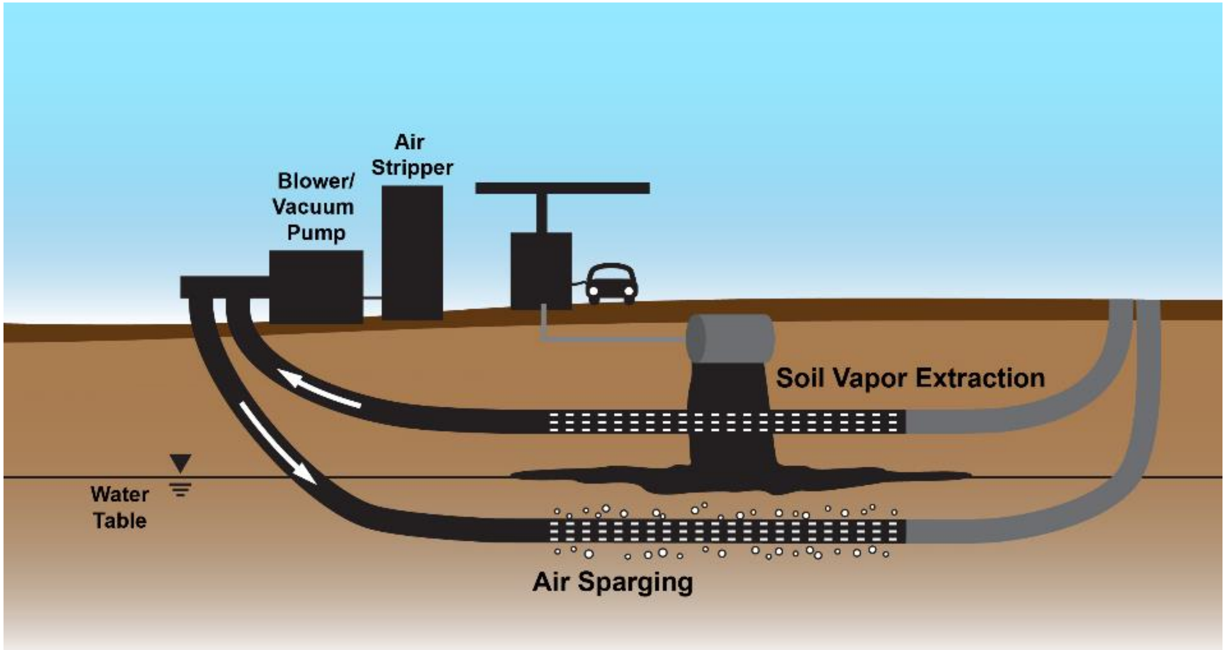
[2] Dual Phase Extraction, Chapter XI

[3] Air Sparging, Chapter VII

[4] Biosparging, Chapter VIII

[5] Chemical Oxidation, Chapter XIII

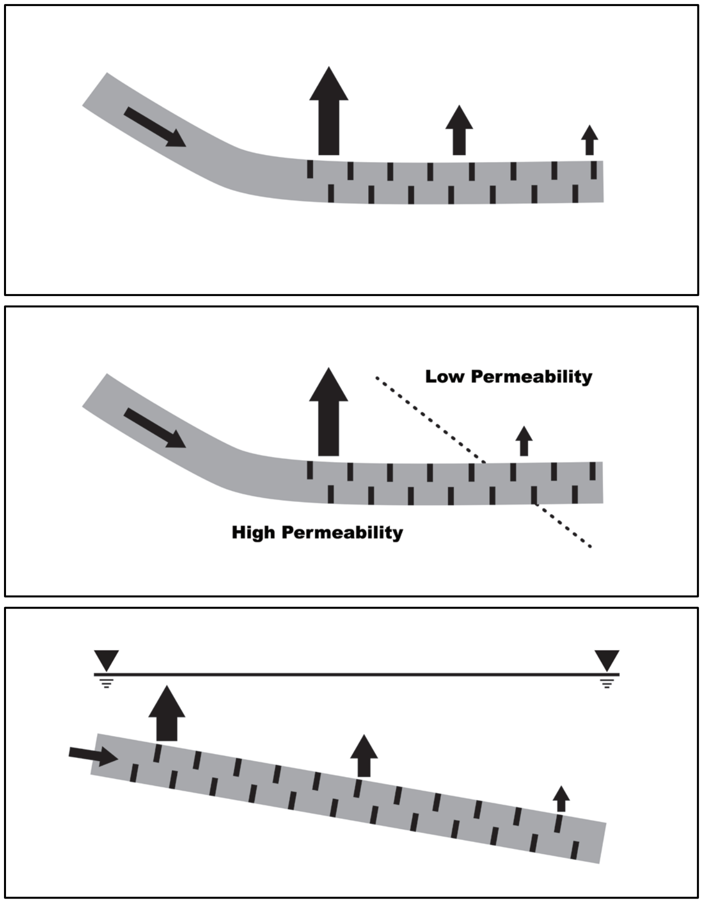
Exhibit A-3. Air Sparging And Soil Vapor Extraction System



HRWs have been used to mitigate the potential for vapor intrusion into buildings (U.S. Environmental Protection Agency 2012; Van Heest et al. 2013). The system works by extracting air from beneath the building's foundation slab, preventing vapor phase contaminants from transferring from the vadose zone into the building. Horizontal drilling can install such a sub-slab depressurization system from outside the building, preventing disruption to building activities (Van Heest et al. 2013).

Horizontal well screens can disperse air broadly across a contaminated area; however, the well must be designed and installed properly to ensure that air will be dispersed as uniformly as possible across the entire screened interval, as shown in Exhibit A-4 (Doesburg 2013; DTD 2004; Lundegard et al. 2001). For both AS wells and SVE wells, well screens with more or larger openings at the end of the screen that are farther from the pump, called zone well screen designs, can help make the flow uniform by equalizing the pressure along the length of the well screen (Doherty et al. 2000). Lundegard et al. (2001) determined that "if the well airflow rates can be estimated, a custom perforation pattern can be designed that will minimize pressure drop within the well and result in effective delivery of air to the formation."

Exhibit A-4. How Horizontal Air Sparge Wells Can Fail To Deliver Air Uniformly



Top: Excessive pressure drop caused by poor screen design

Middle: Excessive pressure drop caused by natural variation in permeability

Bottom: Excessive pressure drop caused by downward slope of well with respect to water table

(Adapted from Effective Air Delivery from a Horizontal Sparging Well (2001) by Paul D. Lundegard, Brent Chaffee, and Doug LaBrecque with permission of the National Ground Water Association.)

When considering horizontal wells for AS and SVE, there are several things to keep in mind. Because groundwater levels fluctuate seasonally, SVE wells should be placed above the seasonal high groundwater elevation to avoid damaging the SVE system by sucking water into the system (Doherty et al. 2000; DTD 2004). One source recommends placing SVE wells at least 6-8 feet above the seasonal high groundwater elevation (Strong 2016). Alternatively, a dual-phase extraction system could be used, in which vacuum suction extracts contaminated groundwater, hydrocarbon vapor, and separate-phase petroleum product from the subsurface.

Several sources have noted that clogging of well screen slots can be a problem for horizontal AS wells, especially when the slots are very small (Butler and Mott-Smith 2011; DTD 2004). Slot sizing should be based on design principles for naturally developed wells (Driscoll 2014). With correct slot sizing, fines intrusion is generally limited, but the potential for well redevelopment to address biological or chemical fouling should be considered, especially for pumping and injection wells (Strong 2016).

Hot Air Or Steam Injection

Some remediation systems inject hot air or steam into the subsurface to volatilize contaminants, such as diesel and fuel oil, that do not readily volatilize at normal temperatures. To avoid problems with oil buildup in the extraction wells, the engineer must design the system to ensure it can deal with condensate in the removal wells (DTD 2004). Methods of handling condensate accumulation issues in piping systems include:

- Designing wellheads with union or flanged connections for ease of redevelopment, well screen cleaning, vacuum removal of accumulated oils,
- Designing surface-to-surface wells to allow pressure flushing of well screen by using surfactants, compressed air, etc.,
- Oversizing well screen diameter to accommodate buildup of condensate.

Bioremediation

HRWs have been used for bioremediation. For example, HRWs were used to inject oxygen gas for the biostimulation of poly aromatic hydrocarbons (PAHs) degradation at a former wood treatment facility (Mott-Smith et al. 2011). HRWs were also used to inject a mixture containing bacteria, enzymes, and oxygen at a leaking underground storage tank site (Clark and Laughlin 2000). See Air Sparging And Soil Vapor Extraction section about ensuring uniform air delivery.

Chemical Injection

HRWs have been used for injecting chemicals "to either reduce the toxicity of contaminants or to prevent their migration" (DTD 2004). Some of these injections are one-time events, so the "wells typically require less extensive well development than longer-term treatment alternatives" (DTD 2004). A 2008 remedial action used horizontal wells to inject permanganate for in-situ chemical oxidation of trichloroethylene (TCE) in groundwater (USACE 2010). Chapter XIII of the EPA's *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers* describes using chemical oxidation at leaking underground storage tank sites.

Corrective action plan reviewers should be aware that because the quantities of oxidants used are typically greater in horizontal wells than in vertical wells, permitting and notification requirements in the National Fire Protection Association's *NFPA 430: Code for the Storage of Liquid and Solid Oxidizers* may be triggered when HRWs are used for in-situ chemical oxidation.

Removal Of Light Non-Aqueous Phase Liquid (LNAPL)

Leaking underground storage tank sites frequently have contaminants present as LNAPL which is often concentrated near the water table interface. Changes in seasons and weather cause the water table to fluctuate, which results in LNAPL accumulating above or below the water table; this is known as the smear zone.

HRWs can be used to pump LNAPL from the subsurface or to sparge LNAPL. For example, a large plume of aviation fuel was removed by three HRWs at the Marine Corps Air Station at Cherry Point, North Carolina (Collins 2014). Another cleanup project captured a gasoline plume by drilling a horizontal collection well to intersect vertical fractures; a vertical recovery well was drilled into the low point of the horizontal well to pump out recovered gasoline and contaminated groundwater (Carlisle et al. 2002).

At sites with highly variable water table elevations, horizontal wells may be less useful than vertical wells for LNAPL removal (DTD 2004). At these sites, consider using a sloped well or nested well configuration with a dual-phase extraction system when attempting to remove LNAPL with a horizontal well. A dual-phase system will extract groundwater or LNAPL when the water table is high and soil vapor when the water table is low (DTD 2004).

Plume Containment

HRWs have been used to contain the migration of groundwater plumes by withdrawing groundwater (Lubrecht 2012; Walters 1999/2000) or air sparging (Sequino et al. 2011). Installing several horizontal extraction wells, one above the other, perpendicular to the direction of groundwater flow, can help contain a groundwater plume. By installing wells at various elevations, this configuration would also help address the concern that a lowering water table could leave a horizontal extraction well stranded above the water table (DTD 2004).

Injection Of Treated Water

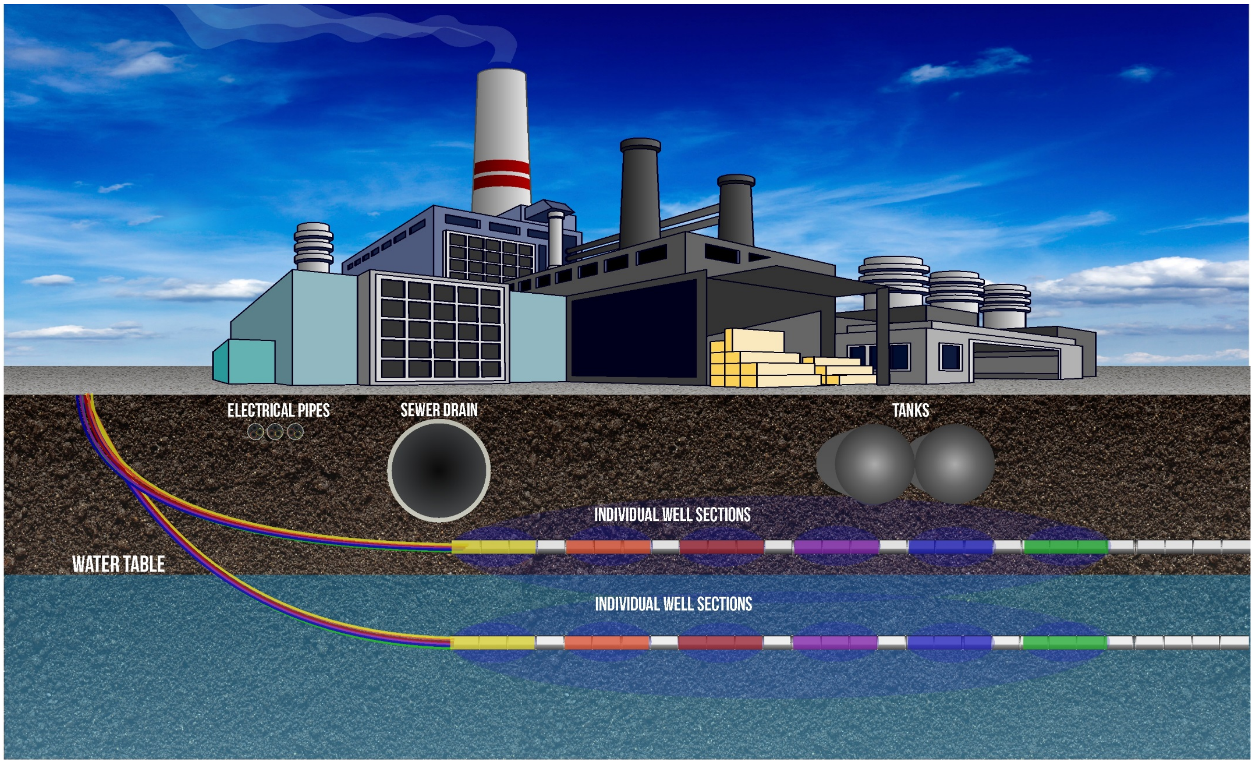
HRWs can be used to infiltrate treated water back into the subsurface (DTD 2004). Horizontal wells may reduce "the potential for local groundwater mounding or other adverse changes in groundwater gradient associated with shallow or deep vertical injection wells" because horizontal wells often have longer screen lengths than do vertical wells, and these screens distribute the injected volume over a longer lateral distance in the aquifer (Lubrecht 2012).

Sampling

Some sampling techniques have been developed for use with HDD equipment; however, HDD sampling is not yet widespread (DTD 2004). Limited soil sampling can be accomplished using HDD equipment, but there are difficulties in keeping the borehole open and retrieving the sample. Some groundwater sampling can also be conducted using HDD equipment. (DTD 2004). New equipment for sampling and site characterization is being developed for use with HDD methods to take advantage of HDD's ability to reach areas not accessible vertically. For example, Ahn et al. (2006) describe the Smart Subsurface Horizontal Investigation Probe (SSHIP) that combines an array of miniature sampling tubes, a logging tool, a miniature resistivity probe, and a miniature cone penetrometer. The SSHIP is controlled from the surface and can transmit data in real-time over a distance of up to 300 meters.

A proprietary technology developed in 2015, allows the placement of multiple multi-purpose wells within a single horizontal borehole, allowing collection of separate samples from different points along the borepath (EN Rx 2015). With this technology, each well is screened in a different location, and the well screens are separated from each other by bentonite and grout as shown in Exhibit A-5; the wells can be used for treatment, sampling, or a combination of the two within a single borehole.

Exhibit A-5. Segmented Horizontal Remediation Wells



(Reprinted from EN Rx, Inc. website (2015) with permission of EN Rx, Inc.)

Drilling A Horizontal Remediation Well

Planning Activities

Weigh various factors when considering and planning a HRW including (Bardsley 2014a; Wampler undated):

- Surface and near-surface constraints
- Treatment objective
- Site geotechnical conditions
- Depth
- Borehole configuration
- Allowable bending radius of drill pipe and well materials
- Locations of underground utilities
- Setback distance required

At some sites, surface constraints, for example a gas station, a tank farm, an active runway, or business operation, may be the primary factor driving the decision to use HRWs. As such, the bore path should be planned to avoid interfering with these types of surface features.

As with vertical wells, understanding the site's geology and developing an accurate conceptual site model are important. At sites where the conceptual model has not yet been well-defined, a pre-design investigation should be conducted using vertical test borings at specified intervals along the proposed bore path. Soil samples should be collected from these borings for grain-size determinations, which are critical for well screen selection. The exploratory borings should be grouted to prevent inadvertent return of drilling fluid. The North American Society for Trenchless Technology's (NASTT) *Horizontal Directional Drilling Good Practices Guidelines* provides advice on how to conduct a site investigation; see Chapter 4 of NASTT 2008.

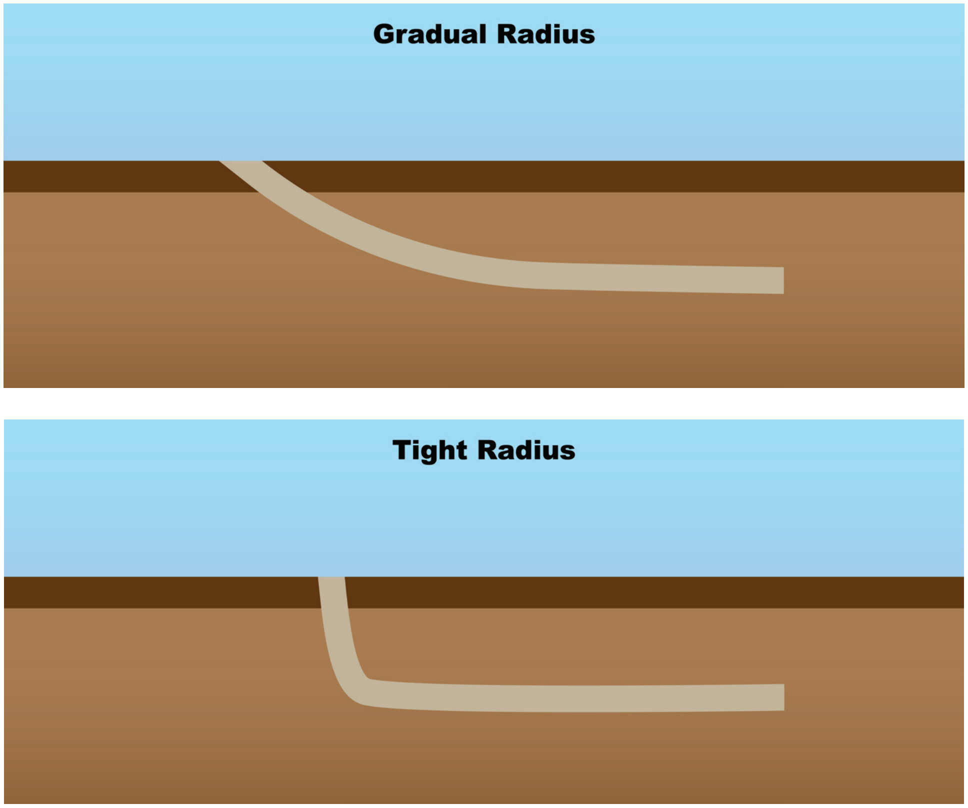
HRWs can also be installed via trenching, rather than drilling at shallower depths, depending on soil type and stability. However, trenching is impractical for deeper applications, such as those deeper than about 20 feet, and for wells to be screened in the saturated zone, due to the increased costs for dewatering and shoring.

Horizontal wells installed at relatively shallow depths typically use walkover navigation methods to determine the location of the drillhead. These battery-powered transmitters are currently inadequate for depths greater than 80-100 feet. Advanced navigation methods for depths exceeding 80-100 feet are more expensive than walkover locators as discussed in Locating Technologies section (Directional Technologies, Inc. (DTI) 2013; DTD 2014a, 2014b).

HRWs are advanced to the desired depth at a shallow angle, approximately 10 to 20 degrees from horizontal, so the entry and exit bores may need to be located a significant horizontal distance away from the treatment area, potentially on a neighboring parcel. This may entail requesting access from adjacent property owners. Horizontal wells typically require approximately 5 feet of setback for every foot of depth. If the well is to be screened at a location 50 feet below a building, the entry point would be located about 250 feet away from the building. If the well is a surface-to-surface well, the exit bore would be about 250 feet away from the other side of the building. The 5:1 setback is a rule of thumb; HRW installers may be able to achieve shorter setbacks depending on the borehole diameter, geology, and type of drill rod (DTI 2013, Strong 2016). The necessary setback distance may be a limiting factor when deciding whether HRWs are practical at a given site, taking into account surrounding land use and access.

A borehole's radius of curvature defines how tightly it curves as shown in Exhibit A-6. A longer radius of curvature puts less stress on the drilling equipment and well materials, but requires a longer borehole and larger setback distances (Kaback 2002). Directional drilling may be more difficult in geologic layers that contain cobbles or boulders, because these may deflect the drill bit away from the desired borepath.

Exhibit A-6. Borehole Radius Of Curvature



Precautions To Take When Planning A Horizontal Remediation Well

Some researchers have cautioned that certain horizontal wells could "provide a conduit for contaminated groundwater to be drawn into the well, conveyed a large distance, and injected into an uncontaminated region of an aquifer" (Steward and Jin 2001). Installing the well parallel to potentiometric isocontours or perpendicular to groundwater flow direction, can help prevent preferential pathway concerns. The corrective action plan reviewer should ensure the plan explains what precautions will be taken to guarantee that the proposed HRW will not act as a preferential pathway to spread contamination. Possible precautions are listed below:

- Wells should not be screened across both contaminated and uncontaminated areas.
- Wells should not perforate competent confining layers where possible, to avoid creating a conduit for contamination of naturally protected saturated zones.

Performance demonstration via groundwater flow or contaminant transport modeling may be needed to alleviate concerns.

Prior to any excavation or boring, drillers should notify the local one call center; www.call811.com for contact information. The one call center will send companies to mark the locations of underground utilities; however, depth information is not usually provided. It is the responsibility of the HDD driller to determine the exact locations of utilities, in order to avoid damaging them (NASTT 2008; Wampler undated).

As with any construction project, the corrective action plan reviewer should ensure plans are in place to mitigate noise and traffic impacts, (NASTT 2008). The corrective action plan reviewer should also ensure a safety plan is in place and addresses safety issues relevant to HDD (NASTT 2008):

- Staying clear of overhead power lines when moving drill rigs and handling drill pipe;
- Verifying location of underground utilities, such as electric cables, gas lines, communication cables, sewer pipes; and
- Following procedures if the drill strikes an underground utility.

HDD Equipment

In horizontal directional drilling, a drill rig, also known as a boring machine, advances the drill rod through the ground, while the drill path is being controlled using one of several locating techniques. The drill rig then pulls the drill string out of the borehole. The sizes of drill rigs are rated based on how many pounds of thrust or pullback capability and torque they have. HDD drill rigs used for environmental applications are grouped into (DTD 2004; NASTT 2008):

- Small rigs: less than 40,000-50,000 pounds of thrust or pullback capacity, used for drilling less than 700 feet as shown in Exhibit A-7; and
- Large rigs: greater than 40,000-50,000 pounds of thrust or pullback capacity, used for drilling 700-2,000 feet as shown in Exhibit A-8.

Small rigs usually have all needed components integrated on the rig, making them more mobile. Small rigs are also able to operate in a much smaller work area (NASTT 2008, Table 3-1). Large rigs can install longer wells, but their setup is more complicated due to their use of separate units for power, drilling fluid mixing, and drill rod handling. Large rigs use a crane to load drill rods, whereas small rigs have integrated automated rod loaders (DTD 2004).

Drill pipe, also known as drill stem and drill rod is hollow and comes in various diameters from about 1 inch to over 6 inches, and segment lengths, 6 feet to over 30 feet (DTD 2004; NASTT 2008). Most drill pipe is made of steel manufactured specifically to withstand the various forces experienced during HDD. These forces include twisting, due to drilling; compression, due to thrusting; tension, due to pullback; and bending, due to following the desired bore path (DTD 2004).

Exhibit A-7. Smaller HDD Drill Rigs

(Reprinted from Directed Technologies Drilling, Inc. website (2015) with permission of Directed Technologies Drilling, Inc.)

Exhibit A-8. Larger HDD Drill Rigs

(Top photo reprinted from Directed Technologies Drilling, Inc. website (2015) with permission of Directed Technologies Drilling, Inc. Bottom photo reprinted from Horizontal Environmental Drilling 101 – An Introduction to the Means and Methods for Horizontal Environmental Well Installation ([2014]) by David Bardsley with permission of Directed Technologies Drilling, Inc.)

The drill-head is located at the leading end of the drill string. The drill-head includes the drill bit and a cavity housing the electronic locating equipment, as shown in Exhibit A-9. Drilling fluid pumped down the drill pipe travels through the cavity to cool the electronics and the drill bit (DTD 2004). Drill bits are available in various styles and sizes; the type of drill bit is selected based on the characteristics of the formation being drilled, as shown in Exhibit A-11. The most common is the duckbill bit, shown in Exhibits A-9 and A-10. The angle of the drill bit allows operators to steer; when the drill pipe is pushed forward without rotation, the angle of the bit causes the borehole to advance at an angle. Other types of drill bits include carbide bits, conical bits, and toothed bits (DTD 2004).

Exhibit A-9. Typical Drillhead (With Cavity Open)

(Reprinted from Horizontal Directional Drilling Good Practices Guidelines (2008) by the HDD Consortium with permission of NASTT. Copyright 2008 by NASTT. All rights reserved.)

Exhibit A-10. Typical Drillhead

(Reprinted from Drill Pipe Inc. website (2015) with permission of Drill Pipe Inc.)

Exhibit A-11. Drill Bit Types

Drill Bit Type	Application
Slant-Face Bits	
Flat spade Bent spade	Clay Sand Organic soils
Modified spade	Hard ground conditions
Rock bits	Soft to medium rock Hardpan
Rotary Rock Bits	
Milltooth tri-cone	Soft rock
Tungsten carbide inserts (TCI) tri-cone with sealed bearings	Medium to hard rock
Drag bit	Soft rock
Percussive Bits	
Eccentric flat-faced with carbide button inserts	Soft to hard rock
Carbide button slant-face	Soft to hard rock Hardpan
Carbide button round face	Soft to hard rock

(Source: NASTT 2008)

Drilling Tools

Several types of drilling tools are used for directional drilling: compaction tools, jetting tools, downhole mud motors, and air hammers.

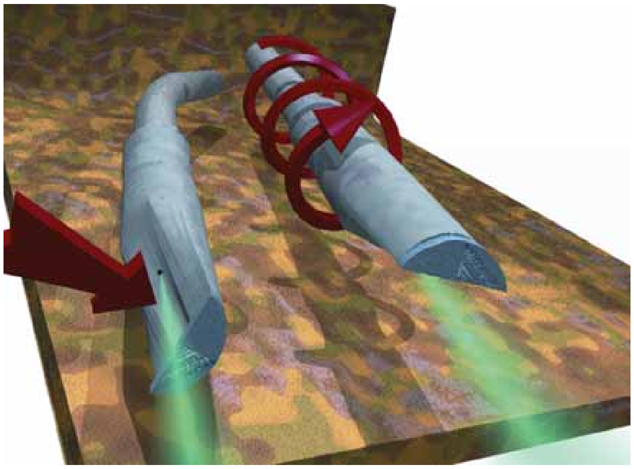
The drilling tools used most commonly for HRWs are compaction tools, such as the duckbill bit as shown in Exhibits A-9 and A-10 and the toothed bit displayed, in Exhibit A-12. Compaction tools work by scraping away the geologic material to form a borehole, much like a wood chisel. The bit is inclined at an angle to the drill pipe, so when the driller applies thrust to the drill pipe without rotation, the borehole turns in the direction of the bit, as shown in Exhibit A-13. When the driller rotates the drill pipe, the borehole advances in a straight line (Bardsley 2014a; DTD 2004; Kaback 2002). Compaction tools are most useful in small boreholes, shallow depths of less than 50 feet, and unconsolidated formations (Kaback 2002). Compaction tools cause reduced permeability surrounding the borehole (Kaback 2002), which must be addressed during the later back-reaming step.

Jetting tools use hydraulic pressure to drill the borehole. The hydraulic jet comes out of a bent housing or from a port on a drill bit attached to a bent subassembly often called a bent sub. Due to the bend, the hydraulic jet comes out at an angle to the axis of the drill pipe. When the drill pipe is not being rotated, the angle of the jet causes boring to proceed in that direction, as shown in Exhibit A-14. When drilling in a straight line, the driller rotates the drill pipe, which prevents the angled jet from establishing a preferred direction (Bardsley 2014a; Kaback 2002).

Exhibit A-12. Toothed Drill Bit

(Reprinted from Directional Technologies, Inc. website (2015) with permission of Directional Technologies, Inc.)

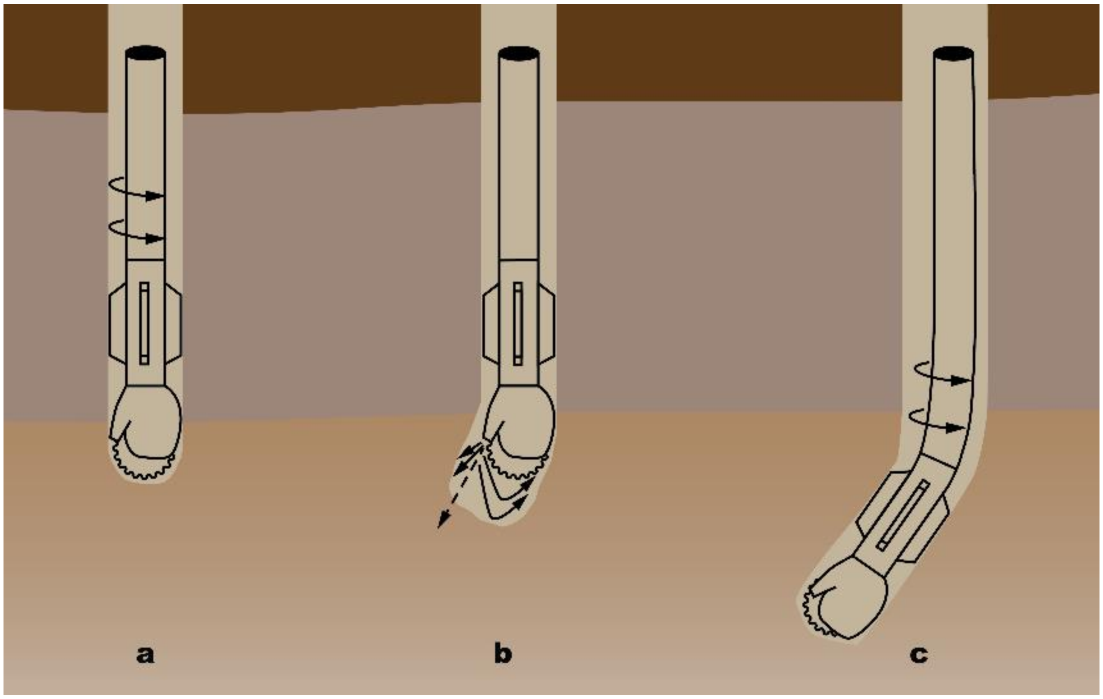
Exhibit A-13. Steering The Borehole



Left: Driller has stopped rotation to steer the bit to the right
Right: Drill pipe is being rotated to drill a straight borehole

(Reprinted from Horizontal Wells for Groundwater Remediation (2013) by Garry Van Heest with permission of Directional Technologies, Inc.)

Exhibit A-14. Use Of Jetting Tool To Drill A Curve



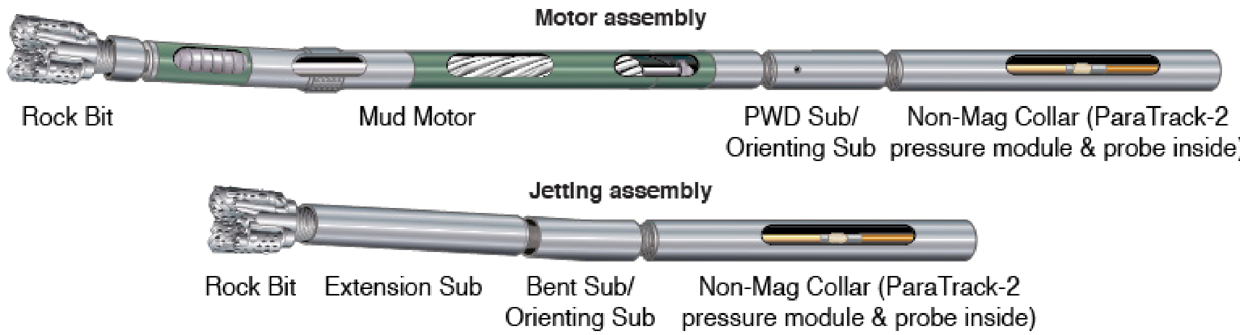
a: Rotary drilling to drill a straight section

b: Hydraulic jetting without rotation to jet a pocket

c: Drillhead advanced into pocket and rotary drilling resumed

Downhole mud motors are a more complex type of drilling tool used to drill in rock or very hard formations, as shown in Exhibit A-15 (DTD 2004; NASTT 2008). Drilling fluid is forced through the mud motor, which causes the motor, and the drill bit attached to the motor to rotate. Percussive drilling systems, such as air hammers, are another type of drilling tool used to bore through rock or very hard formations (DTD 2004; NASTT 2008).

Exhibit A-15. Mud Motor And Hydraulic Jetting Tools



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Two Ways Of Installing Horizontal Wells: Surface-To-Surface And Blind Drilling

A HRW can be installed using either both an entry hole and an exit hole known as a surface-to-surface, continuous, or double-ended well; or by using only an entry hole known as a blind well. To install a surface-to-surface well, the drill enters the ground, descends to the desired depth, traverses the desired distance, rises to the surface, and exits the ground. The drill rig is then used to pull the well casing into place through the exit hole. To install a blind well, the drill enters the ground, descends to the desired depth, traverses the desired distance, and is then withdrawn from the borehole. The drill rig is then used to push the well casing into place through the entry hole. With both types of wells, soil cuttings and drilling fluids are removed from the well during the well development process; contaminated soil and fluids must be handled accordingly; collected, characterized, treated, and properly disposed as necessary, see Drilling Fluids section.

Surface-To-Surface/Continuous Wells

Surface-to-surface drilling is a common way to install HRWs. Surface-to-surface HRWs have achieved depths greater than 200 feet and lengths over 2,850 feet (Bardsley 2014a). In this method, once the drillhead re-emerges from the ground at the exit point, as shown in Exhibit A-16, it is removed from the drill pipe and a back reamer is attached to the drill pipe, as seen in Exhibit A-17. The reamer is then pulled back through the borehole to enlarge it to accommodate the well materials. There are different types of reamers suitable for different soil conditions (NASTT 2008):

- Compaction reamers can be used in clays, silts, sands, and cobbles;
- Mixing reamers can be used in clays and sands; and
- Hole openers can be used in hard soil and rock.

Usually the well materials - well casing and screen, are attached to the reamer and is pulled into place directly behind the reamer, as shown in Exhibits A-18, A-19. The well materials can be attached to the back reamer using a swivel so that the well materials are not forced to rotate during pullback. The reamer alone can also be pulled through the borehole one or more times prior to pulling through the well materials to make pullback easier; this is known as pre-reaming (DTD 2004; NASTT 2008. Pre-reaming may be useful when the well materials have a large diameter or low tensile strength (NASTT 2008; Wampler undated).

Exhibit A-16. Drillhead Emerging From Ground

(Reprinted from Horizontal Environmental Well Handbook (2004) by Directed Technologies Drilling with permission of Directed Technologies Drilling, Inc.)

Exhibit A-17. Process Of Drilling Surface-To-Surface Well

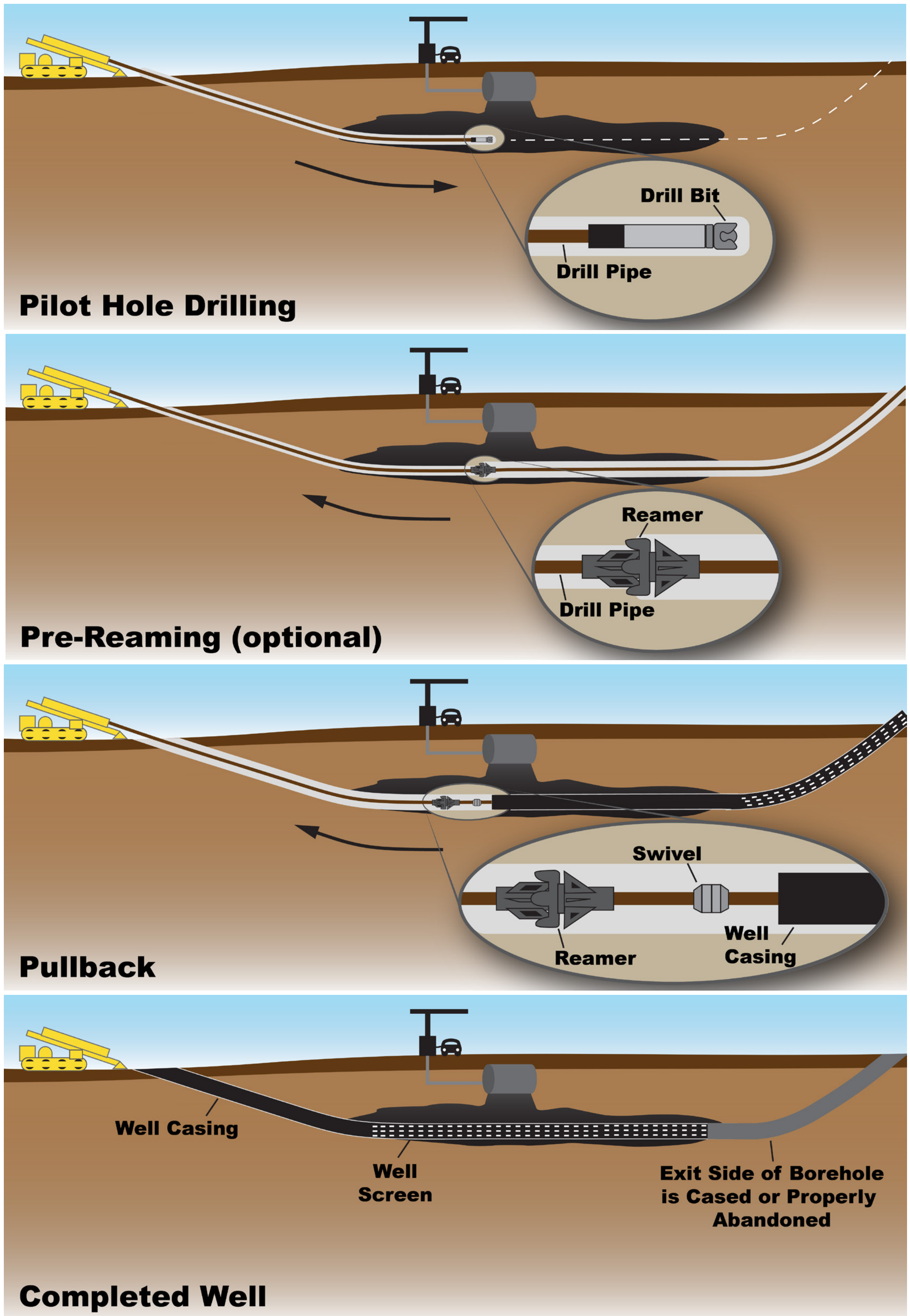


Exhibit A-18. Back Reamer (Right) Attached To Well Casing (Left) Prior To Pullback

(Reprinted from Directed Technologies Drilling, Inc. website (2015) with permission of Directed Technologies Drilling, Inc.)

Exhibit A-19. Back Reamer (Right) Attached To Well Casing (Left) After Pullback

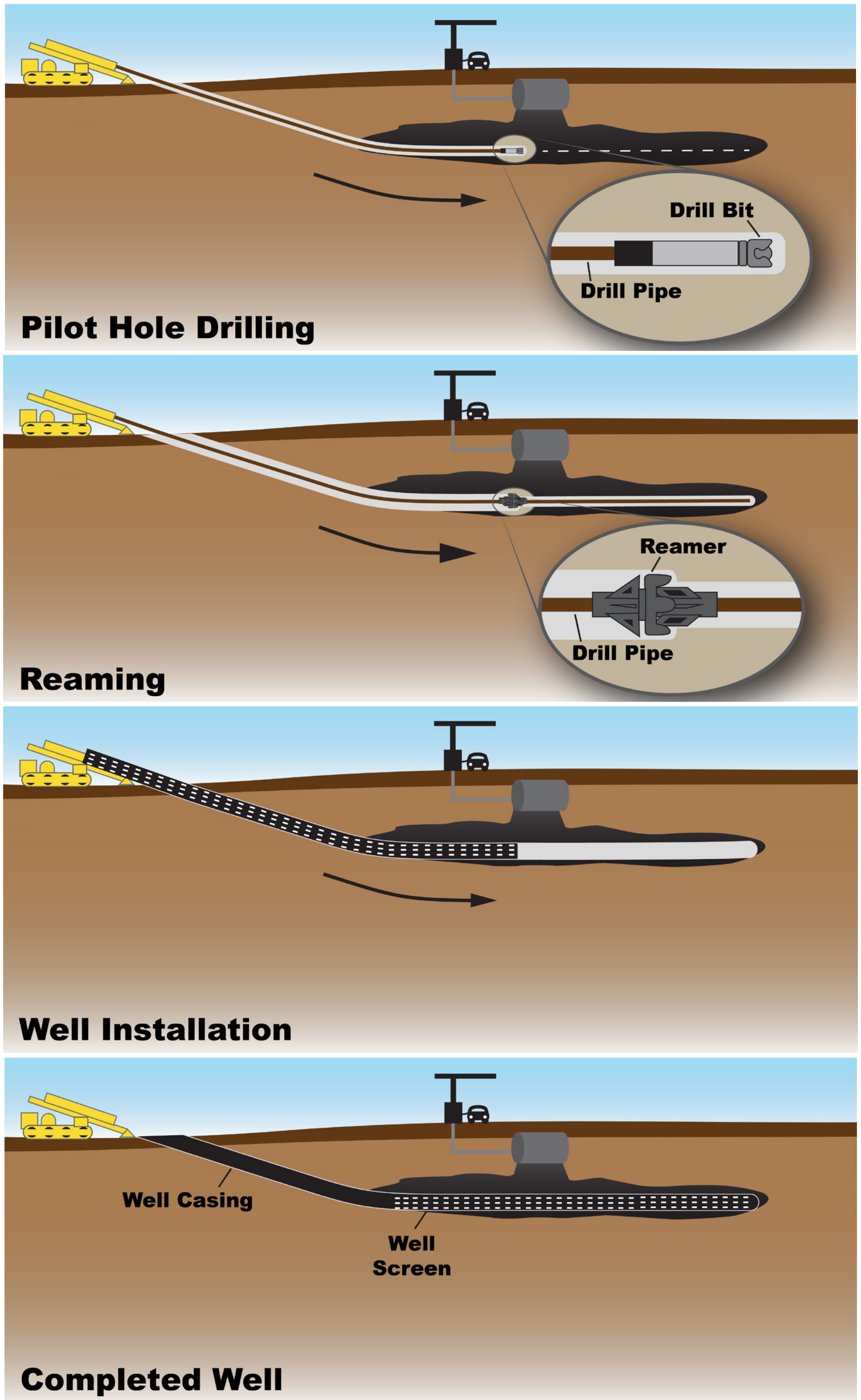
(Reprinted from "Tracer Wire System Importance for HDD" (2013) by Lee Dester with permission of Copperhead Industries, LLC)

Blind Wells

Blind wells are useful when there is no place to locate an exit hole (Sequino 2014; Van Heest et al. 2013). Blind wells have been installed at depths greater than 200 feet and with lengths of over 1,500 feet (Bardsley 2014a). Blind wells cost less than surface-to-surface wells, but have greater uncertainty of successfully installing the well materials. They are used with more confidence where the geology is free of rocks and cobbles.

Two common ways to install a blind well are by completing as an open-hole or using a larger diameter hollow-stem drill casing that encloses the well material. In an open-hole completion, the drillhead enters the ground, descends to the target depth, and is then withdrawn from the borehole, as shown in Exhibit A-20. A reamer is then attached to the drill pipe and is pushed into the borehole to enlarge it. The well materials are then pushed into the borehole. Prior to this step, a carrier casing can be installed in the curved portion of the borehole to prevent the well materials from digging into the side of the borehole (DTD 2004). In some geological materials (such as gravels, cobbles, poorly consolidated sands, and swelling clays) it may be difficult to maintain an open borehole while pushing the well material into the borehole. In these situations, using a larger diameter hollow-stem drill casing surrounding the well material may be useful. Also, commonly used well materials may not be able to withstand the compression forces caused when pushing the well materials into the borehole. Steel is better able to withstand compression, but is much more expensive than polyvinyl chloride (PVC) or high-density polyethylene (HDPE) (Bardsley and Ombalski 2014).

Exhibit A-20. Process Of Drilling Blind Well (Open-Hole Completion)



An example of this larger hollow stem drilling technique is described by Bardsley and Ombalski (2014). It is a proprietary method called knock off technology, in which a large-diameter drill pipe is used with the well materials already inside the drill pipe. Once the desired borehole location is reached, the drill bit detaches from the drill pipe, the drill pipe is withdrawn from the borehole, and the well materials remain in place.

Locating Technologies

The ability to know precisely where the drillhead is located underground is vital to the successful installation of a HRW. Several locating technologies are used in HDD:

- Walkover locators
- Remote magnetic systems
- Gyroscopic steering tools

The type of locating technology used for a particular HRW project is selected "based on bore path, interference risk, depth and cost" (Bardsley 2014a).

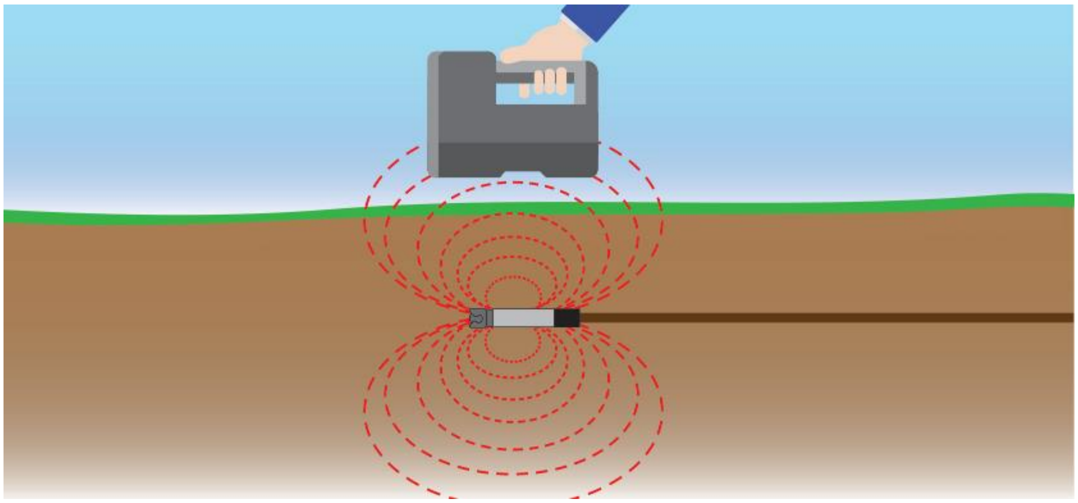
Walkover Locators

Walkover locators are the type of locating technology most often used in HRW installation. A battery-operated transmitter, called a sonde, in the drillhead transmits wireless radio signals that are received by a handheld receiver carried by a crew member on the surface, as shown in Exhibits A-21, A-22. These signals inform the driller about the drill-head's location, depth, and orientation, allowing the driller to adjust the drilling process to keep the drillhead on the desired bore path (Bardsley 2014a; DTD 2004; DTD 2014a; NASTT 2008). The orientation information includes pitch or the angle with respect to horizontal and roll or the rotation of the drillhead.

Exhibit A-21. Walkover Locator Receiver In Use

(Reprinted from Horizontal Environmental Well Handbook (2004) by Directed Technologies Drilling with permission of Directed Technologies Drilling, Inc.)

Exhibit A-22. Walkover Locator (Cross-Section)



Walkover locators have several limitations:

- Walkover locators can be difficult to use at sites with excessive electromagnetic interference for example, interference from reinforced concrete, buried pipelines or drums, power lines, cathodic protection systems, or industrial motors (DTD 2014a; Sequino 2014).
- Walkover locators cannot be used when the boring depth is too great for the signal to reach the surface. The maximum depth at which walkover locators can be used has been reported as about 80 feet (DTD 2014a) to 100 feet (DTI 2013). Although signal strength can be an issue, replacing the battery power with an electrical wire running through the drill pipe can boost the signal, allowing walkover locators to function for deeper boreholes and at sites with electromagnetic interference (DTD 2014a).
- If the battery powering the sonde becomes depleted during drilling, then the drill pipe must be withdrawn from the borehole in order to replace the battery (DTD 2004). Therefore, field personnel should be aware of manufacturers' specifications about battery life expectancy in order to proactively maximize drilling efficiency by changing batteries as necessary.

Remote Magnetic Systems

Remote magnetic guidance systems have a sensor in the sonde that senses its location and orientation relative to a magnetic field, either the Earth's natural magnetic field or an induced magnetic field (DTD 2014a). Most remote magnetic systems create an artificial magnetic field using a coil of wire placed on the ground surface around the borepath; the sensor in the sonde senses its location within this magnetic field (DTD 2014a). The remote magnetic guidance system sends the drillhead's orientation information, including pitch and roll, to the driller through a wire within the drill pipe. The wire also supplies power to the sonde, so battery life is not a concern. Remote magnetic guidance systems are useful in areas where interference makes walkover locators inaccurate and for long and deep borings where battery life is a concern for walkover locators (DTD 2004; DTD 2014a; DTI 2013; Finnsson 2005). Remote magnetic guidance systems can be used at depths of up to 200 feet (DTD 2014a).

Remote magnetic guidance systems are more expensive to use than walkover locators because of the labor needed to lay out and survey the coil and to maintain the wire connection (DTD 2004; DTD 2014a; DTI 2013). Every time an additional length of drill pipe is added to the drill string, the drilling team must re-establish the wire connection. This can either be done manually by wire splicing or by using special drill pipe with cable embedded within the pipe (DTD 2004; Finnsson 2005). There are additional costs for the remote magnetic guidance system as well as the use of specialty drill pipe.

Gyroscopic Steering Tools

Gyroscopic steering tools are a highly accurate type of HDD locating technology that do not require any wireless communication or surface access, as shown in Exhibit A-23. They use optical gyroscopes and accelerometers to track the drill-head's position and orientation (DTD 2014b). All of the information is transmitted to the driller through a wire in the drill pipe. Gyroscopic steering tools are useful for very deep boreholes or where interference is too great to use either walkover or remote magnetic guidance systems (DTD 2004; DTD 2014b; Kaback 2002; Lubrecht 2011; NASTT 2008). However, using a gyroscopic steering tool is much more expensive than the other locating technologies because it requires specialized technicians, a large drill rig, and large drill rods (DTD 2004; DTD 2014b).

Exhibit A-23. Gyroscopic Steering Tool

(Reprinted from Horizontal Technology, Inc. website (2015) with permission of Horizontal Technology, Inc.)

Drilling Fluids

HDD drill rigs pump drilling fluid down the borehole while drilling to maintain borehole stability, remove cuttings, cool the drill-head and bit, and lubricate the well materials to be installed (Bardsley 2014a; DTD 2004; Kaback 2002). Selecting an appropriate drilling fluid is crucial for a successful HRW installation.

Using an improper type or density of drilling fluid may seal the pore spaces in the soil around the borehole, reducing the ability of the HRW to function as intended (Bardsley 2014b). To prevent loss of porosity, some cleanup managers limit the density of drilling fluid that can be used, or require the use of biodegradable drilling fluids (Bardsley 2014b).

Bentonite-based drilling fluid is typically used in general HDD applications. It transports cuttings well and seals the borehole, keeping the drilling fluid from escaping into the surrounding soil. However, bentonite's effectiveness at sealing borehole walls can be a disadvantage when installing a remediation well, which must extract or inject materials from or into the subsurface (Wampler undated). Therefore, bentonite-based drilling fluid must be removed from the borehole during the back-reaming process or during well development (Kaback 2002); see the Well Development section.

Several manufacturers have developed drilling fluids specifically for HRWs. Bio-polymers are an alternative type of drilling fluid that biodegrade after the drilling process to avoid reducing the soil's permeability (Bardsley 2014a; Mott-Smith et al. 2011; Carlisle et al. 2002; Doesburg 2013; DTD 2010). The biodegradation occurs naturally within a few days or can be degraded in one day by adding an enzyme (DTD 2010; Lubrecht 2011). Bio-polymers are more expensive than bentonite (DTD 2010). Care should be taken to ensure that the bio-polymer's breakdown products do not adversely affect the chemistry of the subsurface.

At some HDD projects, drilling fluid is recycled by collecting fluid as it comes out of the borehole, removing drill cuttings from the fluid, and reusing the fluid in the drilling process (DTD 2004; Lubrecht 2012). Recycling the drilling fluid reduces the volume of fluid that must be produced and later disposed of (Bardsley 2015; DTD 2004; Lubrecht 2012). However, at cleanup sites, potential contamination of the drilling fluid may make it preferable not to recycle the fluid (DTD 2004). Small HDD rigs usually do not recycle drilling fluid (DTD 2004). Drilling fluids often contain additives to improve performance (Bardsley 2015; Wampler undated). For example, surfactants can be added to prevent clays from sticking to the drill pipe (Wampler undated). A corrective action plan proposing to use HRWs should include a disposal plan for used drilling fluid and cuttings, as well as ensure additives in the drilling fluid will not adversely affect the chemistry of the subsurface.

For surface-to-surface horizontal wells, if the entry hole and the exit hole are at different elevations, drilling fluid management becomes a concern (Lubrecht 2011). It may be advisable to avoid drilling uphill and prevent drilling fluid from spilling out of the entry hole (Wampler undated).

Containing Contamination

Depending on the nature of the contamination at the site and at the location of the planned borehole, the corrective action plan should include plans for dealing with contaminated drilling fluid and contaminated drilling equipment (Bardsley 2015; DTD 2004). HDD drill rigs wipe mud off the exterior of the drill pipes as they are withdrawn from the borehole. If additional decontamination is needed, specialized drill pipe cleaners that use steam are available (DTD 2004). If drilling fluid encounters contamination and is reused, then the interiors of the drill pipes may need to be decontaminated.

Sometimes during HDD, drilling fluids escape from the ground at unexpected places. These occurrences are called inadvertent returns, or daylighting, as shown in Exhibit A-24. Inadvertent returns can occur due to hydrofractures called frac-outs, existing preferential pathways, such as soil fissures, loose gravel, building foundations; or other causes (Bardsley 2014a; NASTT 2008). Inadvertent returns are more likely to occur under these conditions (Bardsley 2014a):

- High mud weight and pump pressure
- Boring near the surface typically within 10 feet

Corrective action plans that propose to use a HRW should include a plan for dealing with inadvertent returns. Bardsley (2015) recommends the following precautions:

> “Supplies necessary to handle the IR [inadvertent return] must be on site and, often, the IR plan may require one member of the crew to continuously walk the bore path to observe and report any inadvertent returns. The IR plan also must fully detail plans in case the drilling fluid appears in the stream, wetland or river being drilled.”

Use hay bales, silt fencing, sand bags, berms, and vacuum trucks to contain or capture drilling fluid spills (NASTT 2008).

Exhibit A-24. Inadvertent Returns During HDD

(Reprinted from Horizontal Environmental Drilling 101 – An Introduction to the Means and Methods for Horizontal Environmental Well Installation (2014) by David Bardsley with permission of Directed Technologies Drilling, Inc.)

Casing And Well Screen Selection

Well design is one of the most challenging aspects of HRW installation and project success. Well design is highly variable and is based on multiple factors, including design flow rates, length of the screen, total depth, total well length, soil types, and others.

Horizontal well casing materials are similar to those used for vertical wells (Bardsley 2014a):

- HDPE
- Stainless steel
- Carbon steel
- PVC
- Fiberglass

Several general rules apply when selecting casing materials. HDPE is used where design necessitates that significant curving or bending radius is needed. Stainless or carbon steel may be used for high pressure or temperature applications, or where installation requires higher tensile strength. PVC is typically used for shorter or shallower installations.

In general, greater stresses are placed on the well materials during installation of horizontal wells than conventional vertical wells. The well materials are either pulled or pushed into long, curving boreholes, creating high tension or compression, and bending (DTD 2004; Kaback 2002). The pullback strength of HDD rigs greatly exceeds the tensile strength of some casing materials (DTD 2004). The casing material must also be able to withstand the curvature of the borepath. Potential damage includes abrading the well screen during installation, causing reduced permeability, or partial breaking of the well screen, causing the well to admit formation materials (DTD 2004). If the damage is severe, the HRW may not function as intended. Horizontal wells may also be subject to crushing forces from the overlying soils "if poorly-consolidated material is being penetrated or the installation is very shallow, particularly if the casing is longitudinally slotted" (DTD 2004). HRW designers must take into account these stresses when selecting well materials and screen types (NASTT 2008, sections 5.4.6 and 5.4.7).

As for all wells, the diameter of the riser pipe must be large enough to accommodate the submersible pump needed for operation. This is especially important to keep in mind for HRWs because they typically have smaller diameter casings than conventional vertical wells (Soukup 2016).

Proper well screen selection is also crucial for ensuring a well's effectiveness. Well screen selection is highly site-specific and depends on many variables; therefore, the design and selection of the well screen should not be based on untested assumptions. The well screen must be designed to withstand installation stresses, carry out the desired remediation function, and prevent excessive infiltration of sediment into the well. Due to the complexity of well screen design, some HRW drilling firms subcontract well screen design to a materials specialist. Exhibit A-25 presents a typical well screen. Hydrogeologic software is also available to aid in designing the well screen (Van Heest et al. 2013). For horizontal SVE wells, a zone well screen design can be used, with more or larger openings at the end of the screen that is farther from the pump; this helps make the flow uniform by equalizing the pressure along the length of the well screen (Doherty et al. 2000).

Exhibit A-25. Well Screen In HDPE Pipe

(Reprinted from Horizontal Wells for Groundwater Remediation (2013) by Garry Van Heest with permission of Directional Technologies, Inc.)

Conventional well construction techniques call for installing a filter pack to fill the space between the well casing and the borehole, which improves the well's function by preventing clogging. Installing a filter pack in a horizontal well is more difficult than for a conventional vertical well because the horizontal orientation of the well means that a filter pack cannot be poured in place by gravity methods as is done for conventional vertical wells (DTD 2004). Therefore, it is common for HRWs to have no filter pack installed; such naturally developed wells have the well screen in direct contact with the geologic formation (Soukup 2016; Strong 2016). Naturally developed wells work best in coarse, well-graded formations; natural well development is more challenging in fine, uniform material. At sites with fine, uniform material, the well screen slot size must be carefully chosen; openings slightly too small will reduce well yield, and openings slightly too large will cause long-term infiltration of sand and thus increase maintenance (Soukup 2016). Natural well development may also be practical for some types of HRWs where clogging is less likely, such as SVE wells and some injection wells (DTD 2004).

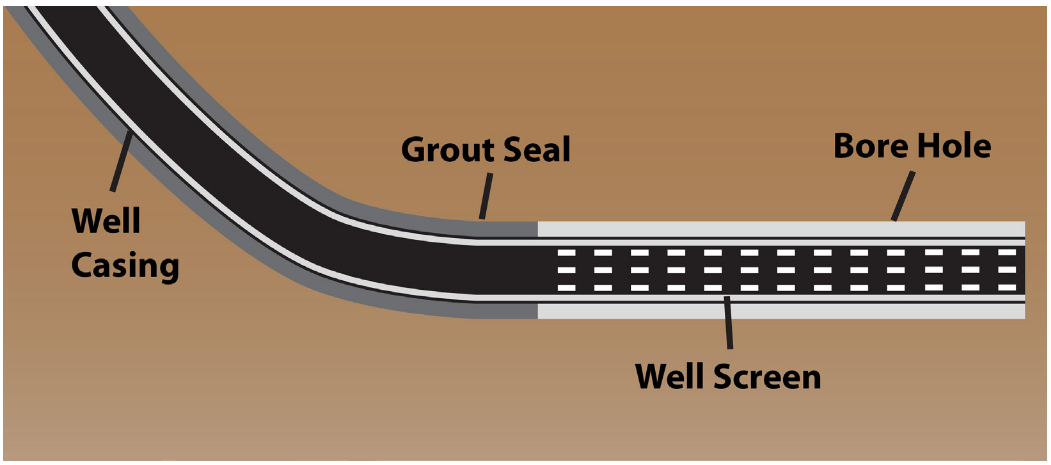
Several manufacturers produce pre-packed well screens specifically for horizontal wells, in which a well screen is manufactured with a filter already in place (DTD 2004). These pre-packed filters are relatively fragile and susceptible to damage during installation; they must be able to withstand the bending, dragging, and other forces imposed during well installation. Pre-packed well screens also require larger boring diameters.

Sealing The Well

After the well materials have been installed in the borehole, the annulus (the space between the riser pipe and the borehole) must be sealed to prevent surface water from entering the well and, for injection wells, to prevent the injected materials from escaping to the surface along the riser pipe (DTD 2004;

Lubrecht 2011). For surface-to-surface wells, both ends of the well need to be sealed. Horizontal wells are typically sealed by pumping cement grout down the borehole using tremie pipes (Exhibit A-26). Prior to pumping the cement grout into the borehole, it may be necessary to block the annular space to prevent the cement grout from flowing down to the screened portion of the well casing. Various materials can be used to block the annular space, including bentonite, sand, polyurethane grout, and pneumatic packers (DTD 2004, pp. 18-20).

Exhibit A-26. Schematic Of Horizontal Well Construction



Horizontal well ends can be designed to be either aboveground or underground; underground well ends are placed within a vault. If using a vault, the well's angle and configuration of the vault must allow all necessary tools and instruments to enter the well (DTD 2004; Lubrecht 2011).

Well Development

After the well materials have been inserted in the borehole and the well has been sealed, well development must take place. One purpose of this step is to remove the soil particles that usually get caught in the well screen openings during horizontal well installation (DTD 2004; Lubrecht 2011). Another purpose of well development is to remove remaining drilling fluid from the well, borehole, and surrounding soil (Bardsley 2014b).

Developing horizontal wells is different from developing conventional vertical wells. Horizontal wells have much longer screens, and these screens are pushed or pulled for long distances through the borehole during installation (DTD 2004). Therefore, developing a horizontal well can take much longer than a conventional vertical well (Kaback 2002).

Two methods for well development are overpressuring and jetting. Overpressuring the well works by capping one end of the well and pumping water into the well at high pressure. The hydraulic pressure forces the clogging soil particles out of the well screen openings. The overpressuring technique is inexpensive and simple, but does not work as well with clayey soils and long well screens. In addition, in screens longer than 200 feet, the pressure may not be great enough to clear all of the openings. The overpressuring technique can be augmented by using inflatable packers to isolate one section of the well screen at a time; each section is then overpressured in turn, rather than overpressuring the entire length of the screen at one time (DTD 2004).

Jetting is the second method commonly used to develop horizontal wells. Jetting entails pushing or pulling a hydraulic jet through the well screen to dislodge soil particles from the well screen openings, as shown in Exhibit A-27. Jetting a well takes longer and is more expensive than overpressuring the well but is typically more effective in removing fines from the annular space and the slots. Jetting is recommended in wells where overpressuring may not be effective for example in clayey soils or in wells using long well screens (DTD 2004).

Exhibit A-27. Hydraulic Jet Used For Horizontal Well Development

(Reprinted from Horizontal Environmental Well Handbook (2004) by Directed Technologies Drilling with permission of Directed Technologies Drilling, Inc.)

Operation And Maintenance

Depending on their use and the subsurface conditions, HRWs typically require less frequent redevelopment than do vertical wells, because it takes more time for the longer well screens of HRWs to be rendered ineffective by clogging. But depending on the geologic formation's particle sizes and the well screen selected, naturally developed HRWs with no filter pack, may experience long-term infiltration of sand and silt, requiring recurring maintenance (Soukup 2016).

Measuring the water level and drawdown is more difficult in a horizontal well due to the angled riser. The contractor must devise a means of manually recording the distance to static level down the riser pipe and converting it to the elevation of the groundwater surface relative to mean sea level. To accomplish this, the borehole's trigonometry needs to be defined using detailed well construction logs with boring angles and casing lengths. To promote accurate well gauging, use results from manual well gauging and pressure transducers to calibrate and refine each other (Soukup 2016).

The angled risers of HRWs also require selecting pumps that are capable of operating at an inclined angle without excessive wear on the motor and impellers (Soukup 2016).

Conclusion

HRWs, like vertical wells, can be used with a variety of cleanup methods. The choice of horizontal wells or vertical wells depends on site-specific conditions and the remediation technology deployed. The main advantages of HRWs are:

- Improved access at sites with surface or near-surface obstructions
- Improved contact efficiency for elongated, relatively shallow plumes
- Reduced site impact
- Reduced operation and maintenance

Disadvantages include:

- Their relatively high initial cost
- The increased complexity of planning, installing, and developing a horizontal well compared to a conventional vertical well
- Limited number of drilling subcontractors with environmental experience
- Limited acceptance and familiarity from the environmental remediation industry and environmental regulators

Depending on site-specific considerations, HRWs may be a viable and cost-effective option to consider during corrective action planning.

References

Ahn, T., E.N. Allouche, and E.K. Yanful. A Multi-purpose Platform for Horizontal Subsurface Investigation. *Geotechnical Testing Journal*, Vol. 29, No. 3. 2006. http://www.astm.org/DIGITAL_LIBRARY/JOURNALS/GEOTECH/PAGES/GTJ12189.htm

Bardsley, David. Horizontal Environmental Drilling 101 – An Introduction to the Means and Methods for Horizontal Environmental Well Installation. 2014 Arizona Institute of Professional Geologists and Arizona Hydrological Society National Conference, September 2014, Prescott, Arizona. 2014a. https://cese.utulsa.edu/wp-content/uploads/2017/06/IPEC-2014-Horizontal-Environmental-Drilling-101.pdf

Bardsley, David S. Horizontal Environmental Wells – Look Before You Leap. *Trenchless Technology*. September 19, 2014. 2014b. http://trenchlessonline.com/horizontal-environmental-wells-look-before-you-leap

Bardsley, David S. HDD Methods for Water Wells, Environmental Wells. *National Driller*. December 9, 2014. 2014c. http://www.nationaldriller.com/articles/89827-hdd-methods-for-water-wells-environmental-wells

Bardsley, David S. Fluids Handling, Safety in Horizontal Drilling Have Evolved. *National Driller*. January 1, 2015. http://www.nationaldriller.com/articles/89845-fluids-handling-safety-in-horizontal-drilling-have-evolved

Bardsley, David and Dan Ombalski. Knock Off Blind Wells – An Innovative Method to Complete Single Ended Horizontal Environmental Wells. 2014 Arizona Institute of Professional Geologists and Arizona Hydrological Society National Conference, September 2014, Prescott, Arizona. Page 35 of Program. http://www.aipg.org/Events/mtg_proceedings/2014annmtg/2014%20Program%20Prescott%20AZ.pdf

Butler, C. and E. Mott-Smith. Horizontal Well Design, Installation and Performance for Biosparging a PAH Plume. 17th Annual Florida Remediation Conference, Orlando, October 2011. 2011. http://www.clu-in.org/products/tins

Caltrans. Encroachment Permits: Guidelines and Specifications for Trenchless Technology Projects. January 2015. http://www.dot.ca.gov/trafficops/ep/docs/HDD_Booklet.pdf

Carlisle, Dana, David A. Cook, and James A. Miller. Successful Use of an Innovative Horizontal/Vertical Well Couplet in Fractured Bedrock to Intercept a Mobile Gasoline Plume. *Groundwater Monitoring and Remediation*, Vol. 22, No. 2. 2002. http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6592.2002.tb00316.x/full

Clark, Brian and David Laughlin. Just “Do It”: The remediation of brownfield sites (abandoned industrial and commercial properties) is frequently complicated by contamination from the constituents of Total Petroleum Hydrocarbon (TPH) from gasoline. *HazMat Management*, April 1, 2000.

Collins, Andrew. Free Product Recovery System Using Horizontal Wells Wins DOD System of the Year: MCAS Cherry Point. 21st Annual International Petroleum Environmental Conference, October 2014, Houston, Texas. 2014. https://cese.utulsa.edu/wp-content/uploads/2017/06/IPEC-2014-Free-Product-Recovery-System.pdf

Cox, Stephen and William Powrie. Horizontal Wells for Leachate Control in Landfill. *New Civil Engineer*, January 1, 2001. http://www.nce.co.uk/horizontal-wells-for-leachate-control-in-landfill/698714.article

Denham, Miles E. and K.H. Lombard. A Synopsis of Environmental Horizontal Wells at the Savannah River Site. WSRC-TR-94-0239. 1994. http://www.osti.gov/scitech/biblio/102269

Directed Technologies Drilling. Horizontal Environmental Well Handbook. 2004. http://horizontaldrill.com/wp-content/uploads/2016/04/DTD_Horizontal_EnvWell_Handbook.pdf

Directed Technologies Drilling. Why Bentonite Hurts Well Production: The Case for Biopolymer Drilling Fluid. 2010. http://horizontaldrill.com/wp-content/uploads/2016/04/StraightTalk-Drilling-Fluid.pdf

Directed Technologies Drilling. Putting the "Direction" in Directional Drilling. *Inflection Points*. April 2014. 2014a. http://horizontaldrill.com/dtds-april-inflection-points-putting-the-direction-in-directional-drilling/

Directed Technologies Drilling. A Different Spin on HDD Navigation. *Inflection Points*. July 2014. 2014b. http://horizontaldrill.com/july-2014-a-different-spin-on-hdd-navigation/

Directional Technologies, Inc. How Deep Can a Horizontal Well be Drilled? 2013. http://www.directionaltech.com/how-deep-can-a-horizontal-well-be-drilled

Doesburg, James. State of the Horizontal Remediation Well Industry. 2013 National Ground Water Association Summit, April-May 2013, San Antonio, Texas. 2013. https://ngwa.confex.com/ngwa/2013gws/webprogram/Paper8988.html

Doherty, Shawn B., Mark A. Lyverse, Tom Peargin, Ashok Katyal, and David Bardsley. Design, Installation, Operation, and Effectiveness of a Horizontal Soil Vapor Extraction Well for an Off-site Hydrocarbon Plume. *Proceedings of the 2000 Petroleum Hydrocarbons and Organic Chemical in Ground Water Conference*, 228–242. 2000.

Driscoll, Fletcher G., editor. Groundwater and Wells. 2nd ed. St. Paul, Minn.: Johnson Division, 2014.

EN Rx. Website Information And Case Studies Regarding Vertebrae Technology. 2015. http://enrx.net/products-services/vertebrae.html

Finnsson, Siggi. The Digitrak Eclipse Locating System: A Flexible And Innovative Approach To Meeting Today's HDD Locating Challenges. 2005. http://www.digital-control.com/support/Articles/2005/NoDig_Rdam_2005.pdf

Fournier, Louis B. Directionally Drilled Horizontal Wells Offer Cost Savings and Technical Advantages Over Alternative Soil and Groundwater Remediation Systems. *Remediation Journal*, Vol. 13, No. 1. 2002. http://onlinelibrary.wiley.com/doi/10.1002/rem.10056/abstract

Griffin, Jeff. Demand Remains Low For HDD Remediation. *Underground Construction*, Vol. 55, No. 7. 2000. http://connection.ebscohost.com/c/articles/3361790/demand-remains-low-hdd-remediation http://www.thefreelibrary.com/Demand+Remains+Low+For+HDD+Remediation.-a063986104

Griffin, Jeff. Horizontal Remediation Wells Complex, Yet Viable Market Niche. *Underground Construction*. July 1, 2004. http://www.highbeam.com/doc/1G1-120043727.html http://www.thefreelibrary.com/Horizontal+remediation+wells+complex,+yet+viable+market+niche.-a0120043727

Kaback, Dawn. Horizontal Environmental Wells – Parts 1-3. *National Driller*. June 1, July 1, August 1, 2002. http://www.nationaldriller.com/articles/84905-horizontal-environmental-wells-part-1 http://www.nationaldriller.com/articles/85982-horizontal-environmental-wells-part-2 http://www.nationaldriller.com/articles/86143-horizontal-environmental-wells-part-3

Kinner, N.E., R.W. Masters, and L.B. Fournier. Fractured Rock: State of the Science and Measuring Success in Remediation. 2005. http://clu-in.org/download/remed/fractured_rock_summary.pdf

Lubrecht, Michael D. Remediation Beneath California Tank Farm. *Trenchless Technology*. September 21, 2011. http://trenchlessonline.com/remediation-beneath-california-tank-farm

Lubrecht, Michael D. Horizontal Directional Drilling: A Green and Sustainable Technology for Site Remediation. *Environmental Science and Technology*, Vol. 46, No. 5. 2012. http://pubs.acs.org/doi/pdf/10.1021/es203765q

Lundegard, Paul D., Brent Chaffee, and Doug LaBrecque. Effective Air Delivery from a Horizontal Sparging Well. *Groundwater Monitoring and Remediation*, pp. 117–123. 2001. http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6592.2001.tb00307.x/abstract

Mott-Smith, Ernest, Cal Butler, Timothy R. Turner, Erik Spalvins, and Sean R. Carter. Injection of Oxygen in Deep Horizontal Wells for the Biostimulation of PAH Degradation at a Former Wood-Treating Superfund Site. International Symposium on Bioremediation and Sustainable Environmental

Technologies (Reno, NV; June 27–30, 2011). 2011. https://projects.battelle.org/bioremediation-symposium/2011Bio_Proceedings/Papers/B-27_Abs.pdf

North American Society for Trenchless Technology (NASTT). Horizontal Directional Drilling Good Practices Guidelines. Third Edition. Principal authors: David Bennett and Samuel T. Ariaratnam. ISBN 1-928984-17-7. 2008.

Parmentier, Paul P. and Ronald M. Klemovich. A New Direction in Remediation. *Civil Engineering–ASCE*, Vol. 66, No. 4. 1996. http://cedb.asce.org/cgi/WWWdisplay.cgi?99248, "available for purchase"

Sequino, Michael. Conquering a Busy Intersection to Install Horizontal Remediation Wells and Protect Indoor Air. 21st Annual International Petroleum Environmental Conference, October 2014, Houston, Texas. 2014. https://cese.utulsa.edu/wp-content/uploads/2017/06/IPEC-2014-Conquering-a-Busy-Intersection.pdf

Sequino, Michael, George Losonsky, James R. Oppenheim, and Kevin W. Martin. Post-Closure Analysis Proves Success of Enhanced Hydrocarbon Bioremediation Using Twelve Horizontal Sparge Wells at Petroleum Products Bulk Terminal. 2011. http://www.directionaltech.com/post-closure-analysis-proves-success-of-enhanced-hydrocarbon-bioremediation-using-twelve-horizontal-sparge-wells-at-petroleum-products-bulk-terminal

Sequino, Michael J., Garry Van Heest, John Collins, and KeeBum Chang. Horizontal Remediation Wells Prove More Cost Effective than Verticals to Install and in Achieving Site Closure at a Northeast Retail Petroleum Site. 19th International Petroleum Environmental Conference, October-November 2012, San Antonio, Texas. 2012.

Soukup, William G. Cornerstone Environmental Group. Peer Review Comments on Draft Appendix: Horizontal Remediation Wells, How To Evaluate Alternative Cleanup Technologies For Underground Storage Tank Sites: A Guide For Corrective Action Plan Reviewers (EPA 510-B-94-003, EPA 510-B-95-007, and EPA 510-R-04-002). Comments prepared for U.S. Environmental Protection Agency (EPA), Office of Land and Emergency Management (OLEM). 2016.

Steward, David R. and Wei Jin. Gaining and Losing Sections of Horizontal Wells. *Water Resources Research*, Vol. 37, No. 11. 2001. http://onlinelibrary.wiley.com/doi/10.1029/2001WR000371/pdf

Strong, Mark. CH2M Hill. Peer Review Comments on Draft Appendix: Horizontal Remediation Wells, How To Evaluate Alternative Cleanup Technologies For Underground Storage Tank Sites: A Guide For Corrective Action Plan Reviewers (EPA 510-B-94-003, EPA 510-B-95-007, and EPA 510-R-04-002). Comments prepared for U.S. Environmental Protection Agency (EPA), Office of Land and Emergency Management (OLEM). 2016.

U.S. Army Corps of Engineers. Horizontal Directional Drilling for Environmental Applications. Technical Letter No. 1110-1-178. December 10, 1996. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA403059

U.S. Army Corps of Engineers. Final Remedial Action Report: Building 165 and Area 18C Groundwater Treatment Pilot Systems, Former Raritan Arsenal Project, Edison, New Jersey. 2010. https://www.epa.gov/sites/production/files/2017-01/documents/raritan_final_remedialaction_report.pdf

U.S. Department of Energy. Innovative Technology Summary Report: Horizontal Wells, Subsurface Contaminants Focus Area. DOE/EM-0378. Office of Environmental Management, Office of Science and Technology. OST Reference #1927. September 1998.

U.S. Environmental Protection Agency. Analysis of Selected Enhancements for Soil Vapor Extraction. EPA-542-R-97-007. 1997. http://clu-in.org/download/remed/sveenhmt.pdf

U.S. Environmental Protection Agency. Air Sparging Through a Horizontal Well at Camp Lejeune in North Carolina. 2007. http://clu-in.org/products/demos/search/vendor_details.cfm?Project_ID=220

U.S. Environmental Protection Agency. Engineering Forum (EF) Teleconference Summary, November 7, 2012. 2012.

Van Heest, Garry. Horizontal Wells for Groundwater Remediation: How a Technology That Revolutionized the Oil Industry Is Used to Remediate Groundwater. *EM Magazine*, June 2013. http://pubs.awma.org/gsearch/em/2013/6/vanheest.pdf

Van Heest, Garry, Michael Sequino, and George Losonsky. Directional Drilled Horizontal Wells and Engineered Horizontal Remediation Wells Screens Accelerate Site Closure. Presented at the 29th Annual International Conference on Soils, Sediments, Water, and Energy, October 21-24, 2013, University of Massachusetts at Amherst. 2013. http://www.directionaltech.com/directionally-drilled-horizontal-wells-and-engineered-horizontal-remediation-well-screens-accelerate-site-closure

Walters, Dick. Kelly AFB Tries Horizontal Wells. *ECOTONE*, Vol. 3, No. 4. 1999/2000. https://clu-in.org/products/tins/tinsone.cfm?id=33544077&&query=GROUNDWATER%20REMEDIATION%20IN%20RESIDENTIAL%20AREAS%20SURROUNDING%20BRAC%20SITES%20&numresults=25&startrow=201

Wampler, David. The Basics of Environmental Remediation Utilizing Horizontal Wells. Undated. http://www.jackson-creek.com/soil-remediation/remediation