Horizontal Environmental Well Design and Installation

PREFACE

Horizontal environmental wells have emerged as one of the robust and proven remediation technologies of the 21st century. Over the past fifteen years, hundreds of horizontal remediation wells have been installed in every conceivable geologic formation. They have been used for groundwater extraction, air sparging, biosparging, nutrient injection, soil vapor extraction and dual phase extraction. The drilling technology used for these applications has been used to take soil samples from beneath buildings and tanks. The U.S. EPA has chosen this technology twice as part of their technology transfer program to foreign scientists and engineers. The track record of successes is sufficiently long to allow us to say this technology, when properly applied, is a very effective tool for the remediation industry.

Horizontal environmental wells are really nothing more than an access technology. Most environmental contamination is planar and usually occurs within 100 feet of ground surface. Vertical wells, the traditional method to access contaminated zones, can only treat a small area of what is usually a large planar feature. Many sites require many vertical wells to treat the contamination zone. The environmental engineer, using horizontal wells, can replace these many vertical wells with a very few horizontal wells. The resulting cost savings can be enormous.

This handbook has been prepared by an experienced team of environmental professionals who have installed more horizontal wells than anyone else in the country. It is based on over fourteen years experience experimenting and improving the technology. It is designed to provide the environmental scientist/engineer with a basic understanding of horizontal drilling and horizontal remediation technology. It should help the scientist/engineer determine whether or not horizontal wells are appropriate for a given problem, and help him/her design a drilling program to achieve their goals.

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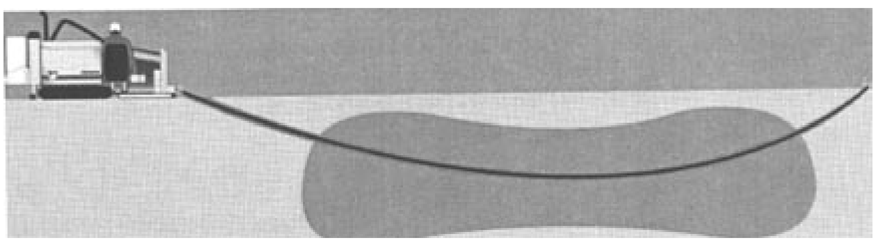
History of Horizontal Drilling

Horizontal Directional Drilling (HDD) has essentially created the trenchless technology market. Today, HDD is a recognized and often preferred method for installing all types of underground utilities such as water, sewer, gas, electric, and telephone. HDD is also well-suited for installing environmental remediation wells. The purpose of this handbook is to familiarize you with the basics of horizontal drilling and how it can be used for environmental remediation.

What Is HDD?

Horizontal directional drilling is a technology allowing the driller to drill in three dimensions. The driller can literally move the drillhead up, down, left or right underground. This is accomplished by drilling a pilot bore into the ground at an angle and then leveling out at a specified depth. Once the proper depth has been reached, the pilot bore is typically advanced horizontally a specified distance and then back to the surface.



Once it exits the ground, the drill head is removed and a back reamer or expander is attached along with a swivel and the slotted well screen. It is then pulled back through the pilot bore to the drilling unit. To better understand it, let's take a look at the individual pieces of the process.

Directional Drilling Machines

Directional drilling machines (also referred to as drill rigs, boring machines, or drills) are available in many sizes. Regardless of the size, they all have three main functions:

rotation, forward thrust, and pullback. The industry-wide standard for rating the size of a machine is the total pounds of pullback capability. Directional drilling machines typically used for environmental applications are categorized as small

(50,000 lbs or less seen on the left) or larger (greater than 50,000 lbs seen on the right). The HDD industry has machines much larger than 1,000,000 lbs, but these are not typically used for horizontal environmental wells.

A small drilling machine usually has integrated components consisting of the power unit, drill pipe, and automated rod loader. The small rigs as seen in the picture above, are quite popular because of the mobility and reduced setup time. A larger drill consists of a power unit that is attached permanently to a truck bed, trailer, or is skid-mounted and has hydraulic hoses running to the drill rack. These larger machines are capable of installing wells several thousand feet in length. They have separate mud mixing and processing units and their drill rods are loaded with a crane rather than an automated rod loader.

More information about drilling equipment can be found on the web. Vermeer Manufacturing is the largest manufacturer of the smaller equipment and can be found at www.vermeer.com. American Augers is the largest manufacturer of larger drilling machines and can be found at www.americanaugers.com.

Drill Pipe

Drill pipe, also known as drill stem, drill rod or drill string, is available in numerous diameters and lengths, depending on the size of the drill rig. Diameters of drill pipe can range in size from just over one inch to six inches or larger. The length of each drill pipe can range from six feet to thirty feet or longer.

Drill pipe is hollow to allow drilling fluids to pass from the drill rig to the drill head. Most rods are made of specially formulated steel capable of withstanding the tensional, compressional and torsional forces experienced during the drilling process. HDD drilling rods are unusual in that they have to accommodate the forces listed above as well as the forces created by bending through the desired bore path.

Drill Heads

Drill heads come in many sizes shapes, and styles. The most common drill heads are the duckbill bit for cutting and steering. This style of head has a cavity in the center to house the electronic locating equipment. Passages for drilling fluid are routed around the center cavity to cool the locating electronics in the head. The duckbill or cutting bit attaches to the front of the drill head at a tapered angle. It is this angle that causes the drill head to change direction of travel when thrusting forward with no rotation.

The drill head is advanced into the soil by pushing and rotating the drill head and drill string. The combination of thrust and rotation cuts the soil, excavating a borehole the diameter of the duckbill. When the driller wants to steer the drill head, he stops rotating the drill string and pushes forward on the drill rods. The tapered angle of the duckbill forces the drill head to deflect from the original path in the direction where the duckbill is pointed. In order for this system to work, the driller must know the location of the drill head and its orientation. This is discussed in the locating system portion of this handbook.

The cutting tool on the drill head is selected specifically for the formation being drilled. Carbide tipped blades, conical bits, and toothed bits are used where necessary. Mud motors are used to drill in rock or very hard formations. Mud motors are more complex than other styles of drill heads and require more support equipment. As the name implies, the drill head is actually a motor that rotates a cutting bit or tri-cone. The rotation of the motor is created by the flow of the drilling fluid (mud) being forced through it. Mud volumes of more than one hundred gallons per minute are common depending on the size of the mud motor. Steering with a mud motor requires a "bent sub" between the mud motor and the drill stem. A bent sub is a short piece of threaded drill stem that has a small bend in it. It is the orientation of the bend in the sub that determines the direction that the head travels.

Several manufacturers have designed air hammers for horizontal directional drilling. These tools allow us to direct the drill in very hard formations. DTD has used directed air hammers to install wells in rock as hard as fractured granite.

Back Reamers

Once the pilot bore is completed, the drill head is removed and a back reamer is attached to the drill string. Back reamers, also known as expanders or hole openers, have two major functions. The first and most obvious is to enlarge the hole to a size large enough to allow room for the installation of the well. The other function is to mix the cuttings with the drilling fluids to create a slurry down hole, thus creating a better environment for installing the product line.

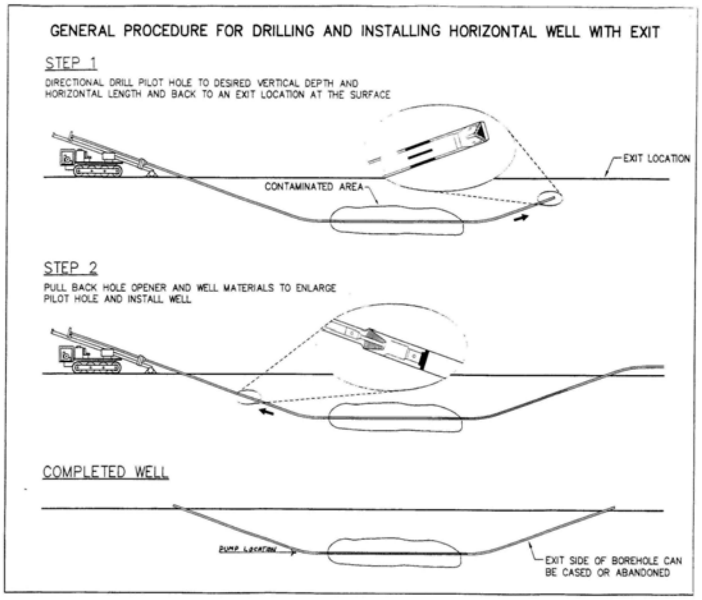
There are numerous styles and sizes of back reamers. Choosing the proper back reamer is dependent on the size of well being installed and the specific soil conditions.

Typical Drilling Approaches

There are two primary methods for advancing horizontal bores: 1) surface to surface drilling; and 2) blind hole drilling. Each method has its advantages and disadvantages as discussed below.

Surface to Surface Drilling

The most common method for installing horizontal wells is to drill surface to surface. In this method, the drilling machine is set up at one end of the bore path with the drill inclined downward pointing into the soil. The drill head is advanced into the ground by pushing and rotating the drill string. Drilling mud is pumped through the drill string and drill head into the formation, cooling the drill head and transporting cuttings up the borehole.



The drillhead is directed downward along a pre-planned path so that at the desired location the well screen portion of the borehole is flat or inclined at a specified grade. The borehole is advanced along the well screen portion and then back to the surface.

Once the drill head has re-emerged at the surface, it is removed from the drill string and replaced with a reamer. The reamer is designed to enlarge the borehole to accommodate the well materials. Typically the well materials are attached directly behind the reamer and pulled into the borehole. Sometimes the reamer is pulled through the borehole one or more times to enlarge the hole or condition it to make the pull back easier.

The methods described above are appropriate for almost any size well. Most environmental remediation wells are eight-inch diameter or less, but larger wells could be installed if necessary. Horizontal wells in excess of 2,800 feet in length have been installed with this method.

Blind Hole Drilling

Blind holes are drilled with the drill head never resurfacing. The drill is advanced downward as with the surface to surface method. Once the drill head has been steered to the end of the well screen, the drill stem is pulled out of the well and a specialized reamer attached. The reamer is pushed into the borehole, enlarging it to accommodate the well materials. In some instances, a carrier casing is installed through the curved portion of the well to prevent the well materials from digging into the side of the borehole. Once the borehole has been prepared, the well materials are pushed into it. Horizontal wells in excess of 1100 feet in length have been installed with this method.

Locating Techniques and Equipment

The ability to locate the drill head is critical to the success of any drilling effort. It is essential to choose the proper locating method for the application at hand. The best way to have a successful installation is to choose an experienced environmental drilling contractor with a proven record of success. Provide the contractor with the desired bore hole path and depth, and ask for a proposed approach to accomplishing the task. A good contractor will be able to provide you with a detailed explanation of their proposed locating system and the limitations of their approach. The following sections discuss some of the basics of current locating technology.

Walkover Locators

The type of locator most commonly used in HDD is a walkover system. Walkover systems, as the name implies, require that the locator operator "walk over" the top of the drill head with the receiver to determine the depth and position of the drill head.

Walkover systems consist of two major components, a receiver and a sonde. The sonde, also known as a transmitter or probe, fits inside the drill head and is powered by "C" cell batteries or, in some instances, by a 12 volt battery. The sonde sends out a signal that is picked up by the receiver. The receiver processes this signal into three important pieces of information: pitch, roll, and depth. Pitch is the inclination of the drill head and can be expressed in degrees or as a percent of slope, depending on the locator being used. Pitch as a percent of slope is used most often by walkover systems. If the pitch is zero, the drill head is level from end to end. If there is a minus pitch reading, the drill head is pointing down. A positive reading means the drill head is pointing up. By knowing what the pitch reading is, it is easy to calculate how much depth change there will be for a given length of bore.

Roll is the rotational position of the duckbill or bent sub and is very important when making a steering correction. Steering changes are made by thrusting forward without any rotation. The rotational position of the duckbill determines which direction the drill head will move. Roll is commonly referred to as the "clock face" in the field. When the operator of the drill faces the direction that the drill is advancing, 12 o'clock is up, 6 o'clock is down, 3 o'clock is right, and 9 o'clock is left. The duckbill can be positioned to move two directions at the same time. An example is the 2 o'clock position. This would cause the drill head to move mainly to the right and a little up. A 7 o'clock steer would cause the drill head to move mainly down and a little to the left.

To determine the depth of the drill head with a walkover system, the receiver usually is placed directly over the top of it. The depth below the receiver is determined by measuring the signal strength. The receiver converts the signal strength coming from the sonde and displays the depth. Depending on the manufacturer, depth can be displayed in inches or feet and inches or in metric units.

Remote Displays

An important part of a walkover locator package is the remote display. Remote displays attach to the drill rack and display the pitch, roll, and depth information that are on the receiver. This makes it possible for the drill rack operator to see what the locating technician is seeing. A remote display is very useful for the drill rig operator when trying to position the drill head at a specific clock position or for determining how much of a pitch change is being made while steering.

Wire-Line Systems

Wire-line locating systems are similar to walkover systems. The major difference is the sonde itself. Instead of being powered with "C" cell batteries, power is provided through an insulated wire that connects the sonde to the drill rig. The wire is attached to a 12V or 24V automotive-type battery. Consequently, the battery life of the sonde is not a problem since the battery is above ground and can be recharged without pulling the drill stem out of the hole. Another advantage of the wire-line system is that the drill head can be located at depths of up to 100 feet. Obtaining depth readings and determining the location of the drill head are done the same as when using a walkover system. However, the pitch and roll information is transmitted up the same wire that powers the sonde and this information goes directly to the remote display on the rack. Wire-line systems are particularly useful for extremely long or extremely deep bores. Boring with a wire-line system is more time-consuming than using a standard walkover system because of the time required attaching a new section of wire every time the rod is changed. Wire line systems are slowly being replaced by systems where the cable is already imbedded in the drill rod.

Steering Tools

Steering tools are a locating technology that has been adapted from the oil field. They are typically larger than the sonde technology and are most commonly used with machines using drill rods greater than three and one half inch in diameter. However, they are very accurate and the head can be located from the drill rig itself without walking over the drill head. Since all of the data is transferred either through the drill stem or through a wire, it is possible to drill in areas where interference is too great for a walkover-type system. They are also good for deep bores where accuracy is crucial. The major downside of a steering tool is the price. They can be many times the price of a walkover system, and they require substantially more training to operate.

Drilling Mud

Drilling mud selection and mixing is a science unto itself. Depending on the size of drilling equipment, the drilling mud can be recycled, saving on disposal costs. In many instances, a single pass of the drilling mud is preferred from a decontamination standpoint and a cost standpoint. The best way to choose the right system is to work with your driller to evaluate the alternatives.

Directed Technologies Drilling Incorporated

Drilling mud is necessary to cool the drillhead and to remove cuttings from the borehole. The ideal drilling mud has the ability to suspend solids, flow easily, maintain the borehole and lubricate the materials to be installed. The mud has to be stable long enough to allow the drilling and well installation to take place. It also has to be easily broken down to allow the well to contact the formation. Ideally, the mud and the break-down chemicals will not adversely affect the permeability of the formation or the chemistry of the soil and groundwater around the well.

Several manufacturers have developed drilling muds specifically for horizontal environmental wells. Baroid, CETCO, and Wyoben are some of the leading companies whose products are widely recognized in the marketplace. Their products are discussed in detail on their respective web pages:

Baroid – www.baroididp.com/baroid_idp_prod/baroid_idp_prod_BIOBORE.asp.
CETCO – www.cetco.com/dpg/pdf/PTDS_CleanDrill.pdf.
Wyoben – www.wyoben.com/z-downloads/product_sheets/borzan.pdf.

Horizontal Well Remediation Technologies

Many technologies have been developed to treat zones of soil or groundwater contamination in place. Although the mechanics of these technologies vary widely, from the injection of microbes that digest contaminants to the vacuum extraction of vapor in the soil, they all share one common requirement --they must come in contact with the contaminated media.

Access to contaminants can be accomplished through trenching or other excavation, vertical drilling (either by auger or rotary methods), or horizontal directional drilling. HDD has many benefits as an access technology, with two significant advantages being:

- An increase in the linear footage of well screen in contact with the contaminated zone, compared to a vertical well screen; and
- The ability to drill beneath surface obstructions or ongoing site operations without disturbance, in contrast to either vertical drilling or trenching operations.

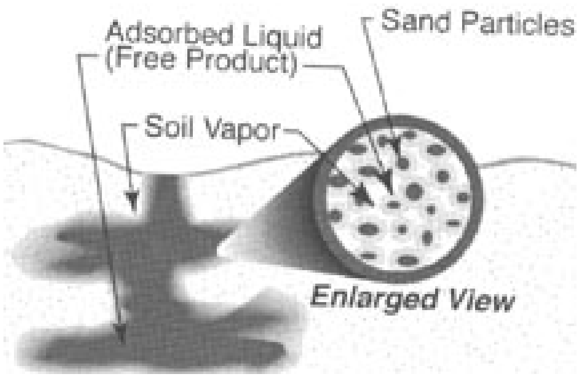
This chapter summarizes the common technologies in use for site remediation that are compatible with horizontal directional drilling.

Vadose Zone Remediation

Extraction cleanup methods remove contaminants from the ground and convey them to the surface where they are treated. This is still the most common technology applied at hazardous material cleanup sites, although some other methods, notably bioremediation, are quite common. Above the water table, horizontal wells are often used for removal of soil vapor, vapors produced by the evaporation of gasoline, volatile solvents or other volatile chemicals that have been released into the soil. Below the water table, horizontal wells can either extract contaminated groundwater directly or can be used to mobilize contaminants for collection elsewhere. Horizontal infiltration or injection wells may be used to reinject treated groundwater back into the subsurface.

Soil Vapor Extraction (SVE)

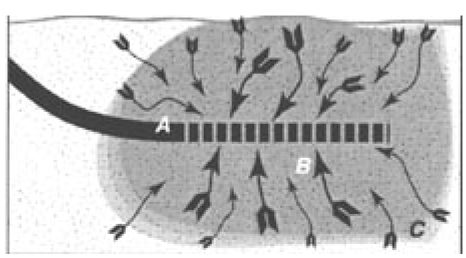
A large portion of the contamination at typical industrial and commercial sites is the result of releases of volatile organic compounds (VOCs). Some of these, such as benzene, toluene, xylene and ethylbenzene are common constituents of gasoline or other petroleum products.



Other volatile contaminants such as jet fuel, fuel additives, and some chemical feed stocks can also be treated with SVE systems. The common denominator is the ability of the contaminant to volatilize.

When these compounds enter the soil as a liquid, much of the liquid is adsorbed as free product onto the surface of the soil particles. The figure above shows a typical distribution of contaminants within the vadose zone, that portion of the soil column that lies above the water table. A portion of the compound evaporates, or volatilizes, to fill the spaces between soil particles, creating soil vapor. The amount of each kind of compound that volatilizes and enters these spaces is governed by several physical laws. If some of this soil vapor is removed, more of the free product evaporates to maintain the equilibrium between liquid and gaseous phases of the compound.

Soil vapor extraction, takes advantage of this behavior to remove contaminants from within the vadose zone. The figure to the right illustrates the extraction process. A soil vapor extraction well is a perforated or slotted well screen placed within the vadose zone to which a vacuum is applied to remove contaminated soil vapor. As this occurs, clean air moves from the surrounding soil to fill the low-pressure region that is created. More of the free product volatilizes and is removed and the process continues until only a residual amount of contaminant remains, tightly bonded to the soil.



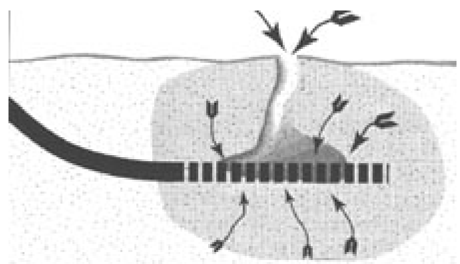
Horizontal wells are often used for soil vapor extraction, particularly at sites located beneath structures such as gas stations, chemical plants and refineries.

The design and installation of SVE wells must address two key site variables: water table fluctuation and leakage into the atmosphere.

If a SVE well penetrates into the water table, the vacuum system will accumulate water when operated, reducing system efficiency and potentially damaging the equipment. Because water tables often rise and fall with the seasons, it is important to be aware of not only the current depth to water but the highest elevation that the water table is likely to reach. If a system must be installed at a site with a fluctuating water table, a dual-phase extraction system, described below, should be considered.

Leakage, or *short-circuiting*, is another potential pitfall for the installer. Soil vapor extraction works because an evenly distributed region of lower vapor pressure (i.e., a partial vacuum) causes liquid contaminants to volatilize and move toward the extraction well. If the soil is homogeneous, with no major fractures or low-porosity zones, the area in which this occurs is usually most effective closer to the well and tapers off in efficiency farther away. A network of wells is usually designed to give even coverage throughout the contaminated zone.

Short-circuiting occurs when a direct pathway forms to the surface. Atmospheric air is drawn into the system because the short circuit has less resistance than the surrounding soil, greatly slowing the remediation process. The figure to the right shows an SVE system that has developed a short circuit due to a frac-out during installation. Short circuits can occur for a variety of reasons, including frac-outs, old roots, porous zones in the soil, proximity to gravel backfill around foundations or buried utilities, or poorly completed well ends. It is difficult to predict if or when a frac out may occur. Ensure your horizontal drilling contractor has a plan and the equipment necessary to deal with frac outs.



Hot Air or Steam Injection

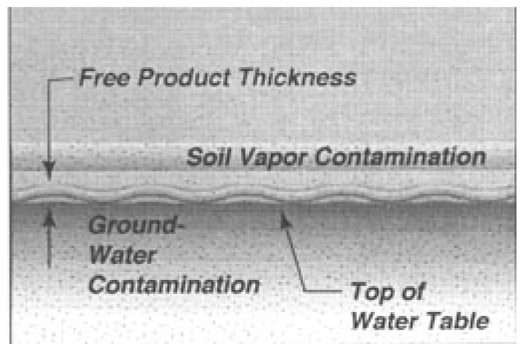
Some contaminants, such as diesel or fuel oil, do not volatilize easily at normal temperatures, making soil vapor extraction ineffective. If additional wells are installed to inject hot air or steam (steam injection wells), the higher temperatures will mobilize these heavier hydrocarbons and permit their removal. This technology has worked at some sites, but there are problems with oil buildup in the extraction wells. The engineer must carefully design the system to ensure it can be deal with condensate in the removal wells.

Free-Product Removal

Many organic compounds such as gasoline or diesel are lighter than water and tend to float on the surface of the water table. When accumulations of the contaminant have sufficient depth (a few inches), they are referred to as free product. The figure below shows how a free-product layer may exist with other phases at a contaminated site. Several types of extraction systems have been devised to remove free-product layers.

Horizontal wells can be used for free-product removal but are less flexible in this application than vertical wells or trenches.

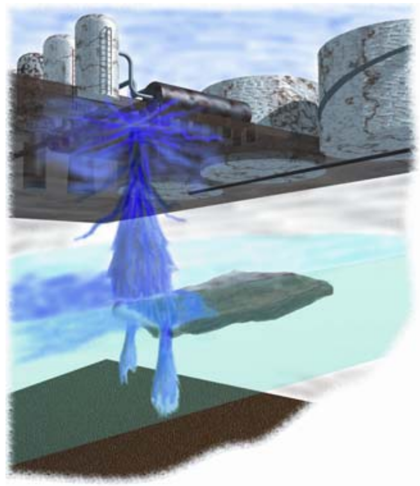
Because the free product usually occurs in a relatively thin, horizontal layer, the well must penetrate it very accurately for extraction to be effective. If the water table moves up or down, because of seasonal effects or groundwater usage, the free product may move out of reach of a horizontal extraction system.



The solution to this is to design a dual-phase extraction system that can withdraw either free product or a mixture of free product and water (which is run through an oil-water separator prior to treatment) when the water table is high, or soil vapor when the water table drops. Dual-phase extraction systems are gaining popularity with designers, particularly as more advanced pumps, separators and treatment systems are being developed.

Another alternative is to drill several horizontal wells in succession, each slightly higher than the other. This type of system, especially when aligned perpendicular to the direction of groundwater flow, can be very effective in stopping contaminant migration.

Groundwater Remediation



Groundwater may be contaminated by a variety of chemical releases, from the VOCs discussed above to metals, pesticides or radioactive materials. Some of these contaminants require sophisticated treatment systems to remove them; others are relatively simple to strip from the water. As in the vadose zone, contaminants that are soluble in water will diffuse throughout a volume of groundwater to equalize their concentration. Unlike most soil vapor, groundwater can flow down gradient, essentially downhill along bedding planes or other geological structures. As the contaminants are swept down gradient with the groundwater from the site of the release, or source area, they form a contaminant plume. One of the main concerns of environmental regulators is that a plume can travel off-site, often for thousands of feet, affecting other users along the way or potentially entering surface waters.

Remediation of a groundwater plume can include removal or in-place destruction of the contaminants, construction of barriers to prevent migration of the contaminated groundwater, or combinations of these technologies. Of the methods typically used for contaminant removal, Groundwater extraction (also called pump-and-treat) and air sparging are the most common.

Groundwater Extraction

Groundwater extraction wells are situated where the highest concentration of contamination is located and water is pumped from that location, treated aboveground, and either reinjected or disposed of in a nearby sewer or surface stream.

Vertical wells have historically been used for this purpose; however horizontal wells are gaining favor because they can place a longer screen in contact with the contaminant plume and may be steered to follow a plume. Horizontal wells also require fewer pumps and manifolds than vertical well networks. Horizontal wells can be placed in almost any orientation, conforming to the dimensions of the plume.

Shallow horizontal wells may also be used to infiltrate treated water back into the ground. This can be of benefit at sites where connection to a municipal sewer is impractical since discharge to the ground surface or to a surface stream is generally highly regulated.

Injection Systems

Air Sparging

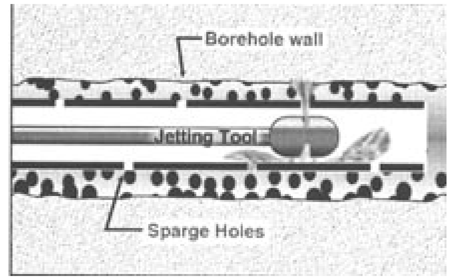
Air sparging makes use of the physical principles outlined in the soil vapor section to remove contaminants that are dissolved in the groundwater. If clean air is bubbled through contaminated groundwater, some of the dissolved contaminant moves into the air (called partitioning) and is transported to the top of the water table and released into the soil vapor.

Air sparging systems may incorporate a pair of wells to promote this mass transfer. The air injection well is placed some distance below the water table and used to inject compressed air into the groundwater column. A soil vapor extraction well is situated vertically above the air sparge well to draw off the volatilized contaminants. Many designs have several sparge and extraction wells at sites where buildings or underground spaces could accumulate volatiles released by the sparged air.

Horizontal wells have several advantages over vertical wells in this application. The ability to gain access to obstructed areas and to follow plumes is described earlier. Horizontal sparge wells have also been demonstrated to be far more effective than vertical wells in dispersing air across a broad area; however, proper design is critical to ensure even air distribution from end to end within the well.

Air sparge wells use either slotted or perforated pipes to distribute air along the length of the well screen. Slotted pipe is typically made with the slots parallel to the long axis of the pipe, although perpendicular slots are sometimes used. The smallest cut slot possible in HDPE pipe is 0.020” in width. Smaller width slots are possible in PVC, fiberglass, or metal pipes. One manufacturer has developed a microslot well screen that is closed until the well is pressurized. These small-width slots can make development and ongoing maintenance of air sparge wells difficult.

Air sparge wells can be difficult to develop because complete removal of drill cuttings and spent drilling fluid may never occur within a reasonable development time frame. The limited open screen area from which to flush, jet, or pump the surrounding formation is the primary limitation. The figure at right shows a cross-section of a typical sparge well which illustrates the problem. If the system is to be operated continuously, that is, air will always be leaving the pipe, lack of development might not be an issue. However, most systems are shut down periodically, either as part of the remediation design or for equipment maintenance. If fine materials surround the sparge well, they will enter the pipe as the air bleeds off and groundwater enters the injection holes. Once inside the casing, fine sand and silt is nearly impossible to remove without redevelopment.



Engineers should consider the use of well screens with an integral filter to avoid this problem, or they can place the properly designed air sparge pipe inside a larger-diameter, conventional well screen. In the first case, development becomes less critical because fine-grained soil is prevented from entering the well. The carrier casing method also has merit because the well can be properly developed; then the sparge pipe can be inserted afterwards.

Chemical Injection

Another form of treatment, particularly for groundwater, is the injection of chemical compounds to either reduce the toxicity of contaminants or to prevent their migration. Chemicals might be introduced to oxidize contaminants to change them into less harmful compounds. Other chemicals might be used to flocculate contaminants or solidify a region of contaminants, e.g., through pressure grouting. Because many of these treatment methods are "one shot" injections, these wells typically require less extensive well development than longer-term treatment alternatives.

Bioremediation

Bioremediation methods include the injection of bacteria or fungal colonies to metabolize the contaminants, or the introduction of air, water or nutrients to enhance the growth of native microorganism populations, which then break down contaminants such as petroleum hydrocarbons. Bioventing is the injection of air at low volume and low pressure to stimulate bacteria growth. Well installation is much the same as for a soil vapor extraction well within the vadose zone, with the same concerns for avoiding short circuits.

Sampling

HDD systems have not been extensively used for sampling. Nevertheless, two sampling applications have been developed. First, soil sampling can be accomplished on a limited scale by attaching a sampling tube to the end of the drill string at intervals during the drilling process, pressing it into the bore-hole face, then tripping out to remove the captured sample. While common in vertical drilling, this sampling has not often been used with HDD due to difficulties in keeping the borehole open and in recovery of the sample. DTD completed a demonstration of the technology at the Fernald site for the Department of Energy in the summer of 2004. This success will likely lead to a greater use of the technology.

Sampling of groundwater can be accomplished within a specific interval within a completed well by using packers to isolate the desired region, then withdrawing a sample with a sampling pump. Alternatively, multiple wells can be pulled into the same bore to collect samples at various locations. HDD wells are also being installed beneath landfills or other infrastructure to contain leak sensors that detect the presence of certain index chemicals.

Well Seals

Horizontal wells enter and exit the ground at an angle, creating new challenges for regulators and engineers. Well seals are usually installed for two purposes: to provide a barrier for surface water migration and to provide a plug to allow cement grout to be installed. We have learned how to install seals using a variety of techniques and materials. There isn't any one sealing method that will work for all applications, but with a little creativity and hard work, an effective seal can be installed.

The first thing to recognize is the horizontal borehole will eventually collapse in virtually every type of soil. Nature abhors a vacuum and the presence of a void in soil is an unnatural condition. Looking at a horizontal well in a cross sectional view, you quickly recognize that a horizontal well is a well that is very wide and quite shallow. For a four-inch diameter well, gravity has only to work on filling a void roughly six inches deep. Left to itself, the borehole will collapse around the well materials.

Another factor in filling the annular space between the well materials and the borehole is the drilling mud. While we use a biodegradeable drilling mud that will break down, the solids carried by the mud (as much as 50%) will not break down. Once the well materials have been pulled into the well, the drilling mud will break and the remaining solids will fill much of the void.

Borehole collapse notwithstanding, there remains the need to seal the well end(s) to prevent surface water from moving via a preferential pathway into the well, or, in some instances, to prevent sparge air or other gasses from migrating up the well. There are several methods we have used to seal the well ends including bentonite plugs, sand bridges, polyurethane grout, cement grout, and pneumatic packers. We have provided a brief description of these techniques below.

Bentonite Plugs

Bentonite chips or pellets can be used in horizontal wells much the same as in vertical wells. The bentonite fills the annulus when it swells, blocking the hole. The difference is in how to install the bentonite. A typical horizontal environmental well is installed at an angle approximately minus 12 degrees or minus24 percent from horizontal. Unlike vertical wells where you simply drop the bentonite chips into the hole being careful not to bridge in the annulus, you must push the chips into the horizontal hole. We have tried bags of chips attached to the well materials, air injection methods, two by fours and PVC tubing to push the chips into the annulus. There does not appear to be any "best" method to get the bentonite into the hole. With the exception of the air injection method, most bentonite seals can be installed no further than ten feet from the end of the borehole. Typically what happens is the bentonite sticks to the sides of the borehole (the sides are wet from the drilling mud) and begins to swell. Even as you are pushing the bentonite into the borehole, the hole is collapsing, making it difficult to get the chips into it.

We have used an air injection method to blow bentonite granules into a borehole with some success. This only works above the water table and in zones where there is limited risk to volatilization of contaminants. In this method, we use an air eductor to entrain the bentonite, blowing it down a tremie pipe. Once the tremie becomes even slightly wet from drilling mud or groundwater, this method ceases to work.

Sand Bridges

The purpose of the bentonite is to block the hole so the cement grout will not flow into the screened interval. The same goal can be achieved using a sand bridge, providing the bridge is strong enough to withstand the pressure of the cement. We have used air and water to flow sand into the borehole annulus. These methods have worked for distances up to 30 or 40 feet from the end of the well. We typically try to place a bridge ten feet in length in order to hold back the cement grout.

Polyurethane Grout

We have had some success with polyurethane grouts, primarily in shorter applications. The grout we use is designed to expand on contact with water. We have been able to inject the polyurethane above and below the water table, but have found it difficult to pump it beyond 100 feet. The polyurethane is used to form an annular block to hold back cement grout.

Cement Grout

We use a cement grout the same as with vertical wells. Cement is pumped into the annulus by positioning a tremie pipe approximately one foot above the annular block. We typically use 5 lbs bentonite/94 lbs cement/7 gallons of water mixture. We use a grout pump or rig pump to mix the grout and to pump it into the borehole. The key to getting the cement grout into the borehole is to have your tremie pipes pre-positioned, or even attached to the well materials before they are pulled into the well. The sealing operation has to proceed very quickly in order to be successfully accomplished.

Pneumatic Packers

One method to ensure the well annulus is blocked is to install a pneumatic packer in line with the well materials. The advantage of a pneumatic packer is that it can be installed a long way from the well ends and it completely blocks the annulus. The primary disadvantage is the air lines needed to inflate the packers. The air lines are relatively weak and often do not survive the pullback.

Well Ends

Horizontal wells offer other challenges once they have been installed. Since they exit the ground at an angle, traditional completions are not appropriate. Like vertical wells, they can be

completed above ground or below ground.

Above ground completions offer the user the advantage of working on the well at waist height. Bailers and other devices relying on gravity are difficult or impossible to use in horizontal wells. We have specialized tools for developing and purging horizontal wells that work well with above ground completions. These completions are obviously best at sites where traffic isn't a concern.

Below ground horizontal well completions are similar to vertical well completions in that they use vaults, but the similarity ends there. Horizontal vaults have to accommodate the near horizontal well screen. The vault has to be designed so pumps and other tools can slide into the well without snagging on the vault. Engineers must examine the length of the pumps and instrumentation to ensure it fits within the vault.

Well Performance and Casing Selection for Horizontal Wells

Well screen selection is nearly always a compromise, balancing the desire to optimize flow rate with the need to control sedimentation within the well. Horizontal remediation well designers must juggle these same variables, but must also consider the difficulties of construction to a greater extent than they would in a vertical well.

Well Performance: Key Factor in Well Design

Well performance is, not surprisingly, the key issue for designers. A successful well design (including the screen, filter pack and development methodology) should accomplish several tasks simultaneously:

- It should optimize the connection with the surrounding aquifer or soil vapor reservoir. Performance is generally enhanced when a well-graded filter pack, either placed during construction or created during development, bridges the gap between the well screen and the borehole walls.
- It should minimize flow restrictions across the permeable section of the casing itself. The more open area available, generally, the better for most applications (with the exception of air sparging).
- It should resist clogging by sediments, corrosion, mineral deposits, or microorganisms. Slot size, in particular, must be large enough to permit adequate

development, but not so large as to permit intake of fine-grained sediments indefinitely.
- It should resist chemical degradation by *in situ* contaminants and/or native groundwater constituents.

Although materials and techniques have long been established to address these criteria in the construction of vertical wells, they do not always transfer easily to a horizontal configuration. Differences in construction between the two applications result in the need to consider additional factors in horizontal well design. The two most significant differences are the tensile and bending stresses felt by the casing during installation of the well assembly and the constraints of a horizontal configuration on well completion and development methods. Under some circumstances, compressive strength can be a factor as well, for example, in single-ended well completions where the casing is pushed into the well bore. Resistance to crushing by overburden soils (ring stiffness) can also be important if poorly-consolidated material is being penetrated or the installation is very shallow, particularly if the casing is longitudinally slotted.

Casing Durability: Tensile strength, Stiffness, and Abrasion

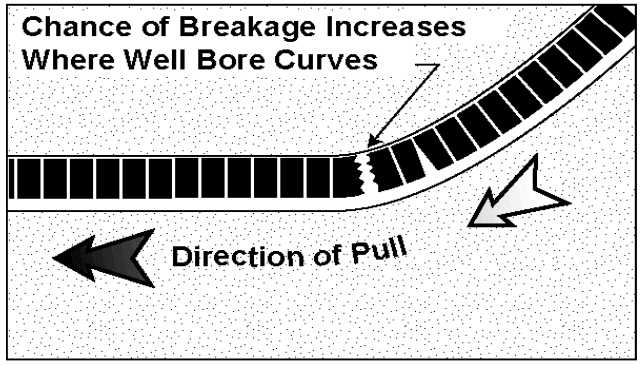
Horizontal well casings are subject to higher stresses and greater potential for damage during installation than vertical wells of similar dimensions. The pullback power of horizontal drill rigs, measured in tens of thousands of pounds, can easily exceed the tensile strength of most plastic well casings. This is particularly true where stress is concentrated on one portion of the casing as it moves through a curved section of the well bore. In vertical wells the tensile strength of the pipe is not generally a factor unless the well is very deep, since the casing must only withstand gravitational forces as it is lowered into the well. Drag along the well bore during horizontal well installation can also damage the casing surface, even if total failure does not occur; this may occur as abrasion or breakage within localized areas of the screen section.

Tensile Strength

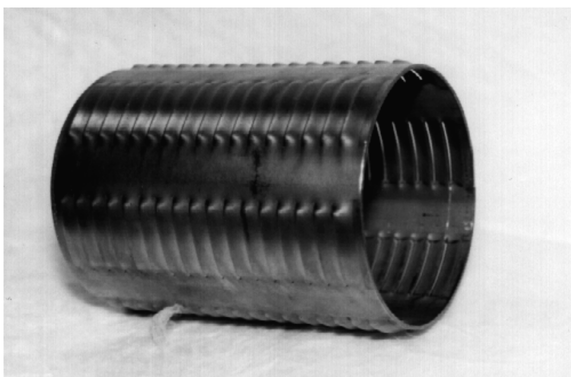
Designing for maximum tensile strength is a relatively straightforward exercise, made on the basis of material type (e.g., steel is stronger than HDPE), wall thickness (e.g., Schedule 80 pipe is stronger than Schedule 40), and slot type and spacing. Beyond these fundamental choices the designer must make sure that the screen’s other strength parameters are adequate to survive installation in a horizontal well.

Directed Technologies Drilling Incorporated

Tensile strength is one important consideration; pipe stiffness and bending characteristics are of nearly equal importance. Early in the application of directional drilling to remediation wells, installers discovered that the wire-wrapped, rod-based well screens that work well for vertical wells are easily damaged in horizontal installations. Failure typically occurs at the pipe ends where the rods are welded to the threaded coupling box,



usually as the casing flexes through a curve in the well bore path, as shown at right. Stress transmitted along the stiff pipe is focused at this joint, causing breakage or buckling of the rods at the weld.



This weakness can be avoided by using a pipe-based screen. But overbuilding the casing to achieve sufficient tensile strength can result in a stiff casing that resists conforming to the well bore, creating increased friction during installation. For instance, Roscoe-Moss micro-louvered casing (pictured left) works well in horizontal wells at diameters of four inches or less, but the manufacturer doesn’t recommend its use in larger diameters because its greater stiffness and heavier gauge metal actually increase the likelihood of failure through buckling during installation.

Stiffness

Screen designs using pipe-based thermo-plastic materials, e.g., PVC pre-pack screens, must also be constructed and installed very carefully since stress can be concentrated at inherently weak threaded couplings. Pipe breakage in PVC screens has also occurred where baffle assembly screws have been placed too close to the slots during manufacture, causing failure through the slots.

Extremely stiff casing *can* be installed, but requires that the well bore be drilled with very straight sections and a very smooth and gradual transition from the surface launch angle to the horizontal screen section. Often this transition must be extended in order to arrive at a workable bend radius for the pipe. It may also require that the well bore be reamed to several times the pipe diameter. In the first instance, longer transitions require more setback and more riser pipe, resulting in higher costs and greater pressure or vacuum loss in sparging or soil vapor extraction systems. In the second case, an oversized well bore increases drilling costs and makes the completed well more difficult to develop.

Abrasion Resistance

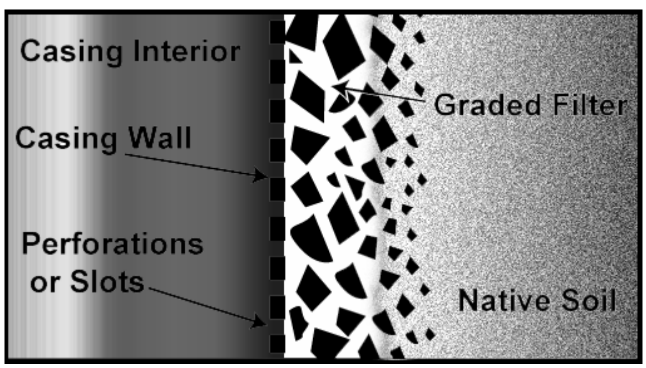
Surface damage of the screen due to drag during installation is avoidable, but difficult to monitor. Damage can result in a breach in the screen, allowing formation materials to enter the well unrestricted, or can result in diminished permeability.

Brittle well screen materials, such as PVC, can have sections of slots broken out relatively easily during installation, without causing complete parting of the screen. This damage may not be noticed until the well sands in or a pump is damaged at a later time. Geotextile filters, wrapped around the pipe and factory banded or fastened with steel banding in the field, can create an effective filter but can tear or be dislodged, exposing the slotted pipe beneath, if snagged during installation.

These problems have been addressed in several products recently introduced to the horizontal well industry, as well as through special installation techniques. Both of these developments are explored in more detail below.

Filter Packs: Natural, field constructed, and integrated

In an ideal well design, vertical or horizontal, there is a well screen situated within a well bore of somewhat larger diameter, with a graded filter bridging the gap to progressively block fines from reaching the screen as fluid travels from formation to well. In a vertical well this filter is commonly composed of loose sand. The screen slot size and sand gradation are selected to provide filtration on the basis of the grain size distribution of the surrounding soil.



This is a proven construction technique in vertical wells. Centralizers, a type of spacer, may be used to keep the well screen centered within the vertical well bore to allow even distribution of the sand around the screen. Gravity aids in the placement of the sand, which may be poured into the well bore from the surface or placed using a tremie pipe. Well development removes fine grained sand and soil particles close to the well screen, creating a graded filter, from coarse to fine, that extends outward from the screen to the well bore.

Horizontal wells present different challenges:

- Unless centralizers are used, the screen will certainly rest on the well bore invert. This thwarts any attempt to create a sand pack completely surrounding the casing.
- If centralizers are used, they must be sturdy enough to support the weight of the well screen in a horizontal position; most off-the-shelf centralizers are not.
- Depending on the stiffness of the screen and the straightness of the well bore, centralizers must be closely spaced to adequately support the screen. However,

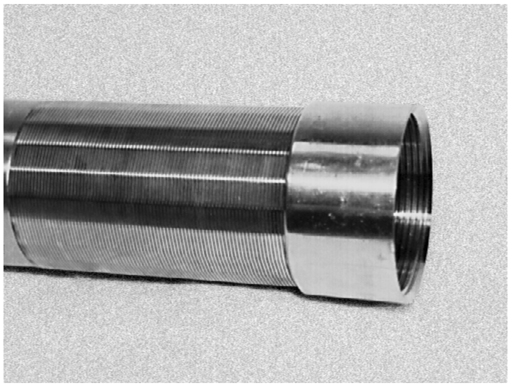
attaching several centralizers to the well screen will cause significant drag during the casing installation.

- Unlike the placement of sand in a vertical well, the sand pack in a horizontal well must be emplaced along the screened interval using a sand injection device or as slurry, using a tremie pipe, since gravity alone won't move the sand laterally through the well bore. With centralizers attached to lift the casing, pushing injection tubes or tremies into the well bore annulus is a high-risk, difficult undertaking.

The following subsections describe some of the considerations and available products for installing horizontal wells with a natural filter pack, field-constructed filters, and manufactured, integrated filter systems.

Natural pack

Since a sand filter pack like that used in vertical wells is impractical to construct in horizontal wells, designers must look at other options. The simplest is no filter at all, a "natural pack" completion. Depending on the end use of the well and the grain size distribution of the soil, this can work quite well or may result in immediate well clogging. The well screen used can be of any appropriate material from PVC to stainless steel (pictured left).



Soil vapor extraction wells, used for removing contaminated soil vapor above the water table, are good candidates for natural pack completions. Since the viscosity and density of air are much lower than that of water, air's carrying capacity to move particulates into a well screen is significantly reduced compared to that of groundwater. In practical terms, this means that soil vapor installations are unlikely to suffer from sedimentation within the screen unless the soil is dry, non-cohesive, fine-grained, and the entry velocity of the soil vapor is high. Occasionally, pulses of water (e.g., precipitation, irrigation water) that move downward through the vadose zone towards the water table may also mobilize sediments into the screen.

Groundwater extraction wells are more prone to sedimentation than soil vapor wells. Slot or perforation sizes and grain size distributions must be considered carefully before deciding to construct these wells without some type of filtration. Most groundwater extraction wells benefit from some form of filtration.

Injection wells must be considered on a case by case basis. Bioventing installations within the vadose zone rarely require a filter. But air sparge or steam injection wells, unless operated continuously, can become silted or sanded in if the injection operations are cycled or temporarily suspended. For them, filter systems help insure continued operation.

Field Constructed Filters

One method that has been used for constructing a functional filter system is to wrap geotextile, usually of the non-woven variety, around the outside of the well screen. Although this method, sometimes called a "filter wrap," provides an added measure of filtration, factory construction is expensive and field construction is both expensive and time consuming. Geotextile is robust, resisting tearing during installation, but does increase the skin friction and drag of the screened interval during installation. If snags occur, the casing may break or the fabric can be dislodged, leaving gaps through which soil can enter the screen.

Integrated Systems

Pre-Pack Screens

Pre-packed well screens are manufactured by several companies, in a variety of forms, and are based on a variety of pipe materials, including PVC, HDPE, and stainless steel. Basically a completed-well-on-a-pipe, pre-pack screens may be custom built in nearly any configuration to meet project needs.

This versatility does not come without a cost. Pre-pack screens are expensive per linear foot and are more difficult to install than other solutions. Installation difficulties are primarily due to the weight and stiffness of a pre-pack casing section. Unless a pipe-based design is used, as mentioned above, even steel pre-pack may not survive the rigors of installation in a horizontal well.

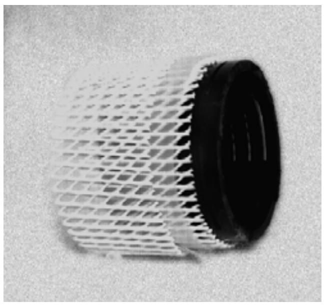
Innovations in Horizontal Screen Design

Some well screen materials have been developed recently to address many of the strength and performance issues mentioned above. For lack of an industry-standard term, these are referred to here generically as "filter screens," since they incorporate a filtration system designed to eliminate the need for an external sand pack.

EnviroFlex (Manufacturer: Titan Industries, Inc.)

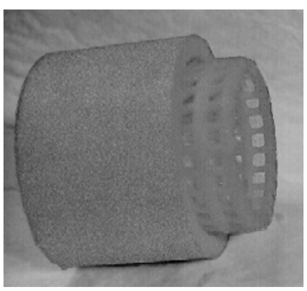
Introduced after testing on numerous horizontal well installation projects, EnviroFlex was designed specifically for direct-pull (as opposed to carrier casing) horizontal well installations. Using a composite filtration system, comprising a non-woven geotextile, a geogrid supporting mesh or a porous polyethylene tube bonded to the *inside* of a perforated well screen, and an inner PVC screen, EnviroFlex maintains high tensile strength while protecting the filtration layers from installation damage. The outer casing is available in a variety of material types (steel, PVC, or HDPE) to permit matching the screen type to installation and chemical resistance requirements. The Enviroflex screen is also economical, about midway in price between standard slotted screen and pre-pack screen for a given diameter.

HydroQuest (Manufacturer: TerraFilter)



This filter screen system uses a synthetic pipe base with wide slots, covered with an external, tubular composite of filtration materials. It has the potential to achieve excellent hydraulic performance. The composite, consisting of a layer of fine, medical-grade synthetic mesh sandwiched between two layers of heavier mesh, is factory-installed on the base pipe, with heat shrink tubing bonded to the ends. During construction, this material is susceptible to damage by tearing, bunching, or other failure of the external membrane. Direct installation in a well bore is difficult due to the poor bonding of the filter to the base pipe, so installation using a carrier casing (described below) should be considered.

Schumasol (Manufacturer: Schumacher/U.S. Filter)



A filter screen constructed of sintered polyethylene resin beads, Schumasol was developed to maximize the open area of the screen while maintaining filtration properties that meet or exceed pre-pack performance. It achieves excellent filtration characteristics, but the porous construction of the screen limits its tensile strength. Installation using a carrier casing is specified by the manufacturer. Schumasol has been successfully installed on several major remediation projects in the U.S.

Stratapac (Manufacturer: Pall Well Technology)

Originally designed for the petroleum drilling industry, the Stratapac filter screens are another composite, with several layers of stainless steel mesh coated with metallic particles bonded between inner and outer perforated metal casings. Test results reported by Pall indicate good hydraulic performance and the material is available in sizes practical for horizontal installations. The Stratapac screen, with its all-steel construction, is reportedly resistant to damage during installation, without the need for specialized installation techniques. Its drawbacks include relatively heavy weight and stiffness, coupled with high cost.

Well Development

Horizontal wells are sufficiently different from vertical wells to require careful examination of development methodology. Typically, we develop wells by stressing them, bringing fine materials into the well and creating a graded filter around the well screens. Indeed, well screens are typically designed to allow a percentage of the formation materials to enter the well. The challenge is to develop a development method that takes into account the effects of long screens and the installation methodology of horizontal wells.

Overcoming Installation Damage

Vertical wells are typically lowered into a borehole, with little or no chance for the slots or perforations to be plugged by formation materials. Horizontal wells are either pushed or pulled into the boreholes, often for hundreds if not thousands of feet. Pulling the well materials into the borehole inevitably results in the slots or perforations becoming blocked with formation materials.

The two most common methods for removing the formation materials from the slots are to either overpressure the well or to jet the well. Either method is appropriate depending on the formation and length of the well.

Overpressuring the Well

Overpressuring the well is simply applying enough hydraulic pressure to force fluid and formation materials out of the slots and back into the borehole. This can be accomplished by capping one end of the well and injecting water into the other end. Diaphragm pumps are particularly useful for this technique as they provide a pulsing motion to the water. We typically use this method in sandy soils with relatively short well screens. This method can be used to inject breaking solutions into the well at the same time.

The overpressuring approach works well where the soil materials do not have a lot of clay and are typically much larger than the slots in the well materials. This technique is not appropriate for longer screens (greater than 200 feet) where the pressure can dissipate before all of the slots are clear. The primary advantage to this technique is its low cost and simplicity.

Jetting the Well

Jetting is recommended in clayey soils or in wells where the screens are longer. Jetting can be accomplished using a drilling rig to push drill rods and jets into the well or by pulling a jetting tool into the well using a cable. Because this technique requires tools inside the well, it is typically more time consuming and more expensive.

We have found that commercial sewer jets work well for cleaning the slots. We typically use the mud pump on the drilling machine to run the sewer jet as these pumps can produce the necessary volumes and pressures to clear the screens. Because the screens often have multiple curves and may have sediment inside them, we most often use a cable installed inside the well to assist moving the jet through the well. We typically use multiple passes of the jetting tools to ensure complete treatment of the well screen.

Pumping with Packers

The overpressuring technique can be complemented by isolating parts of the well screen with packers to focus the energy of the pumping system. In this instance, a double packer system is pushed or pulled into the well with a discharge pipe attached to a pump. The assembly is placed in the screen and inflated. The interval between the packers is subjected to the injection and pumping action to clear the screen and remove fines from the annulus. This technique is quite effective, but requires additional expense and equipment.

Jetting and Pumping

We have found that the techniques listed above are not always sufficient to accomplish the development desired. We have incorporated jetting and pumping tools into a development assembly that is capable of treating horizontal wells in excess of 2,000 feet in length. This assembly combines a high-pressure jet with a down-hole pump to jet the well and simultaneously remove the dislodged material. This apparatus is the most effective method to develop or redevelop horizontal wells.

Safety

All construction managers and workers are familiar with Occupational Safety and Health Administration (OSHA) requirements for protecting the health and safety of everyone on the job. Experienced professionals in the horizontal drilling business know about protecting themselves from electrical strikes, confined-space entry and work in excavations. Unlike vertical environmental drilling, however, horizontal drillers have additional risks not normally encountered in past practices.

This section of the handbook is designed to provide scientists and engineers with an overview of requirements that are not necessarily covered in Hazardous Waste Site Operations and Emergency Response (HAZWOPER) training (40 hours health and safety training). We will discuss specific issues to take into consideration when planning a horizontal environmental drilling project. This section is not a comprehensive guide and should only be used for planning purposes. Consult a safety professional for a more complete health and safety program for your company.

Health and Safety Program

Every contractor working on projects covered by 29 CFR 1910.120 must have an established health and safety program that describes procedures for good health and safety practices in keeping with state and federal occupational health and safety standards and that represents the minimum standard of safe work practices to be observed. Many horizontal drillers do not have such a program in place and may not be prepared to conform to the requirements of environmental drilling. Engineering firms should make certain the driller they select is familiar with and experienced in implementing an environmental safety plan.

PPE

The purpose of PPE is to shield or isolate individuals from exposure to chemical, physical, biological and radiological hazards via skin contact and potential dermal or ingestion. When properly selected and used, PPE can effectively reduce and/or eliminate such hazards. Improper use of PPE can give workers a false sense of security; it can contribute to the spread of contamination and can actually create greater hazards than it prevents.

PPE requirements for horizontal drilling on hazardous waste sites are similar to those for vertical drillers. In most instances, a horizontal drill operator will have less exposure to hazardous materials than a vertical driller. This is due in large part to the equipment and drilling practices employed in horizontal drilling.

Most of the smaller equipment typically used by horizontal drillers have automated rod loaders. The rod loaders allow the driller to operate the equipment without touching the metal coming in contact with the underground contamination. The operator sits at a console, many feet away from the entrance pit where contaminated cuttings are emerging from the borehole.

The drilling mud is usually not recycled in smaller horizontal drilling machines. This means the inside of the drill rods never come in contact with contamination. The drill rods pass through various types of wiping systems before they are pulled from the ground, ensuring that they are free from contamination. In areas where there are serious concerns about decontamination, specialized rod cleaners that steam clean the rods can be used. This means there is very little decon required for a horizontal directional drilling machine and there is very little exposure for the operator. Prior to selecting a HDD contractor, engineers should ensure the contractor has an acceptable system to clean the drill rods as they are pulled from the ground.

Larger drilling rigs typically do not have automated rod loaders. These rigs usually load the drill rods with a crane, requiring additional workers and the risks associated with heavy loads overhead. The drill rods typically are brought to the rig on a trailer and there are issues with working above ground without a place to tie off.

The larger drill rigs are just that, larger. Workers making connections on the drill rods are often more than six feet in the air on a narrow, potentially slippery, catwalk. Safety harnesses can actually become hazards on this type equipment as the workers have to mount and dismount the catwalk many times during a well installation.

Larger rigs also have potential problems with overhead electrical and telephone wires. The automated rod loaders typically are less than eight feet in height and do not pose a serious threat to overhead obstructions. The cranes on the larger rigs reach many feet into the air and can pose a serious threat to the health and safety of the workers.

The locating technician typically does not come near the entrance or exit pits. This person walks over the drill head, noting its location and orientation. Unless the ground surface is contaminated, this person rarely comes into contact with contaminated materials. The laborer who assists with pumping the pits and attaching the various drilling tools usually comes into contact with contaminated materials. This person, and anyone who may work with them in the pits, will often require PPE.

The actual PPE required for the job is site specific of course. Typically, the driller and the locating technician work in Level D with hard hats, safety glasses and steel toed boots. The driller usually needs hearing protection. The laborer will typically need Tyvek coveralls, rubber boots and gloves.

Definitions and Abbreviations

Key Definitions

Air sparging – remediation technique – typically used to strip volatile contaminants from ground water by injecting air below the water table. Often combined with soil vapor extraction. Some engineers sparge to increase dissolved oxygen in the groundwater and soil to enhance biodegradation. (See bioventing)

Air stripping – remediation technique – typically used to strip volatile contaminants from ground water by injecting air below the water table. Essentially the same as air sparging. Often combined with soil vapor extraction.

Back reamer – drilling tool – a tool designed to enlarge a pilot hole. Typically employed by attaching to the drill string once it exits the ground (surface to surface installation). Can be used to forward ream a hole.

Bentonite – drilling material – an additive used with water to lubricate, stabilize, and clear drill cuttings from a borehole. Bentonite is a naturally occurring mineral used in the drilling process.

Bioaugmentation – remediation technique – typically used to degrade environmental contaminants by introducing organisms to enhance cleanup.

Bioremediation – remediation technique – typically used to degrade environmental contaminants using native organisms.

Bioventing – remediation technique – typically used to enhance bioremediation by providing oxygen to native *in situ* organisms.

Bore or borehole – drilling term – the elongated cavity created by the drilling process. Often the borehole is not a void, but rather a hole filled with drilling mud and cuttings.

BOREGEL™ – drilling material – a drilling mud manufactured by BAROID consisting of bentonite, polymer, and soda ash. Typically used in horizontal directional drilling for utilities. Because it contains bentonite, BOREGEL is usually not suitable for environmental applications.

Box – drilling term – the female thread portion of a drill rod.

Bubbling pressure or air entry value or threshold pressure – remediation term – the pressure at which air will enter the saturated zone.

Cable sonde – drilling tool – a downhole transmitter or probe that is powered by electricity generated at the surface.

Chinese finger – drilling equipment – a woven wire device typically used to pull materials into a bore. The finger is placed over the material. When it is pulled, it tightens on the material, becoming tighter the harder it pulls.

Compactor reamer – drilling tool – a tool used to enlarge the borehole by compressing the soil. Since this type of tool typically will decrease the permeability of the soil, it may not be suitable for horizontal wells.

CON DET® - drilling material – a water soluble anionic surfactant manufactured by BAROID used to prevent formation materials from sticking to drilling tools.

Deflection – drilling term – the amount of flex exhibited by the drill rods. The drill head is typically steered by pushing it into the formation without rotation. There are limits to which the rods can be pushed before they deflect excessively.

Dry hole – drilling term – a condition that occurs when the drilling tools advance beyond the drilling mud. Typically caused by trying to drill too fast.

EZ MUD® - drilling material – a polymer additive used to increase viscosity and gel strength of bentonite drilling mud.

Filter cake – drilling term – the wall cake that forms from the platelets in bentonite-based drilling mud. Filter cake is the barrier between the borehole and the formation, limiting the amount of drilling mud needed to complete the borehole.

Frac out – drilling term – during normal drilling operations, drilling fluid travels up the borehole into a pit. When the borehole becomes obstructed or the pressure becomes too great inside the borehole, the ground fractures and fluid escapes to the surface.

Front locate point – drilling term – walkover locating systems determine the azimuth of the drill head using the magnetic field created by the down hole transmitter. This magnetic field is hourglass in shape, and the magnetic field changes at the top and bottom of the hourglass. The point at the front of the hourglass is the front locate point.

Gel strength – drilling term – the property of drilling fluid that permits it to suspend and transport drill cuttings from the borehole.

High Density Polyethylene (HDPE) – well screen material – HDPE is often used for horizontal environmental wells because of its flexibility, chemical resistance, and high tensile strength.

Hydro-lock – drilling term – A condition where the well casing and screens become "locked" in the borehole during pullback. This occurs when fluid becomes trapped inside the borehole behind the well materials. Suction increases to the point where the drill can no longer pull the casing into the hole.

Locator – drilling equipment – The above-ground component of a walkover locating system. The locator includes one or more antennae and a receiver to detect the signal transmitted by the downhole transmitter, and a microprocessor to decipher and display the downhole data

Lubricity – drilling term – the lubrication properties of a given material. Certain drilling mud additives improve the lubricity in a borehole.

Negative locate – drilling term – the locate point midway between the forward and rear locate points, at the center point of the "hourglass".

Pitch – drilling term –deviation from a horizontal plane is measured as pitch. When the drill is directed downward, the pitch is negative. When it is directed toward the surface, the pitch is positive.

Pothole – drilling term – a small hole excavated from the surface to a buried utility in order to provide positive verification of its location..

Rear locate – drilling term – the point along the drilling path opposite the front locate point.

Remote – drilling equipment – walkover equipment typically includes a direct reading receiver held by the locating technician and a remote unit that is a repeater for the locator. The remote is located at the drilling machine and enables the driller to see the same information as the locator.

Rod wiper – drilling equipment – A rubber or synthetic grommet placed over the drill rods during pullback to strip excess mud from the rods before they are stowed.

Sonde – drilling equipment – The downhole component of an electronic locating system. Same as a transmitter.

Strike alert – drilling equipment – A protective device used while drilling that sounds an alarm if the drill string contacts a buried electrical utility.

Swivel – drilling equipment – the fitting at the top of the drill string enables the flow of drilling mud into the drill rods while simultaneously permitting them to rotate.

Thread compound – drilling material – An anti-seizing compound, frequently a high-pressure, copper-based grease, used to prevent the drill rods threads from seizing.

Transmitter – drilling equipment – The downhole component of an electronic locating system. Same as a sonde.

Wing cutter – drilling equipment – A reaming tool with wing-shaped extensions, used to expand the pilot hole to its final diameter.