Ohio Environmental Protection Agency

Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring

Chapter 15

Use of Direct Push Technologies for Soil and Ground Water Sampling

John R. Kasich, Governor
Mary Taylor, Lt. Governor
Craig W. Butler, Director

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Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring

Chapter 15

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Ohio Environmental Protection Agency
Division of Drinking and Ground Waters
P.O. Box 1049
50 West Town Street
Columbus, Ohio 43216-1049
Phone: (614) 644-2752
epa.ohio.gov/ddagw/

Preface

This document is part of a series of chapters incorporated in Ohio EPA's *Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring* (TGM), which was originally published in 1995. DDAGW now maintains this technical guidance as a series of chapters rather than as an individual manual. These chapters can be obtained at ***epa.ohio.gov/ddagw/gw_support.aspx***

The TGM identifies technical considerations for performing hydrogeologic investigations and ground water monitoring at potential or known ground water pollution sources. The purpose of the guidance is to enhance consistency within the Agency and inform the regulated community of the Agency's technical recommendations and the basis for them.

Ohio EPA utilizes ***guidance*** to aid regulators and the regulated community in meeting laws, rules, regulations and policy. Guidance outlines recommended practices and explains their rationale. The methods and practices described in this guidance are not intended to be the only methods and practices available to an entity for complying with a specific rule. Unless following the guidance is specifically required within a rule, the Agency cannot require an entity to follow methods recommended within the guidance. The procedures used should be tailored to the specific needs and circumstances of the individual site, project and applicable regulatory program, and should not comprise a rigid step-by-step approach utilized in all situations.

Changes from the February 2005 TGM

Ohio EPA's *Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring* (TGM) was first finalized in 1995. Chapter 15 (Use of Direct Push Technologies for Soil and Ground Water Sampling) was added as a new chapter in February 2005. This is the first revision to the chapter.

Section numbers were added to make the document easier to read.

References were updated, in particular, the references to ASTM standards.

Additional information has been added on:

- Hydrogeologic Section (4.3) added new subsection on the hydraulic profiling tool (4.3.2).
- Analytical Section (4.4) added paragraph on newer Optical Image Profiler system tool.
- Terminology changed throughout document to make concepts flow better and easier to understand.

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Chapter 15
Use of Direct Push Technologies for Soil and Ground Water Sampling

Direct push (DP) technology devices are investigation tools that drive or push small-diameter rods and tools (typically not exceeding four inches in diameter) into the subsurface by hydraulic or percussive methods. DP can be used for a number of applications. Specialized DP probes may be used to collect *in-situ* geophysical, geochemical and geotechnical measurements. Applications include soil sampling, ground water sampling, geophysical sensing, geochemical sensing and soil gas sampling. The purpose of this guidance document is to discuss the applications of DP to soil and ground water sampling.

DP tools such as the cone penetrometer have been used for assessing site geology for many years. With the invention of the Hydropunch(TM) in 1988, (Edge and Cordry, 1989) an alternative to monitoring wells for collecting ground water samples was developed. DP technology became more popular in the 1990s in response to a growing need to assess sites more quickly and cheaply. A growing number of inquiries from the public about DP during this time prompted Ohio EPA to form a Direct Push Technologies Workgroup in June of 1998 to evaluate DP as they relate to site characterization.

Depending on site conditions, DP methods may offer an attractive alternative to traditional sampling methods such as hollow-stem augering with split spoon sampling. Advantages include the smaller size of the DP rigs, which allows for sampling in spaces that would be impossible for larger, conventional hollow-stem auger (HSA) rigs; and quicker penetration, allowing for more efficient and economical site characterization. DP methods also produce fewer cuttings, and the smaller diameter holes require fewer materials for well installation or probe hole sealing. An additional benefit is a minimal amount of waste material is produced when compared to traditional drilling methods. The speed and mobility advantages of DP soil sampling may allow a more complete and accurate investigation of site geology. Similarly, when investigating ground water, the speed of investigation and a lack of a need for well materials may allow for a more thorough characterization of the hydrogeology of the site. Purge water disposal volumes are smaller, since the volume of water extracted during well development and purging is much less than it would be for a conventionally installed well due to the smaller radius of disturbed aquifer around the well.

DP is applicable in unconsolidated sediments. It is most applicable for shallow depths (less than 100 feet), but may be able to go deeper depending on site conditions. Because of the lighter weight and therefore limited downward force, penetration may be difficult in sediments containing a high percentage of gravels and cobbles or in dense, highly compacted sediments (such as over-consolidated till). Alternative drilling methods may be advisable in situations of unfavorable conditions.

This chapter addresses the use of DP in the applications of both stratigraphic investigations and chemical analysis. The primary sources of information for this document include: ASTM Method D6282; U.S. EPA (1997); ASTM Method D6001; ASTM Method D6724; ASTM Method D6725 and U.S EPA (2005). This chapter pertains to samples collected with rigs and not hand-driven samples.

1.0 Equipment for Advancing DP Technology Rods

DP devices may be driven by manual, mechanical or hydraulic methods, and may be truck-mounted or stand-alone. A DP tool string includes the sample collection tool and extension rods for advancement and retrieval of the sample tool. There are two types of rod systems: 1) single-tube and 2) dual-tube. Both allow for soil, soil gas and ground water sampling. Single- and two-tube systems have overlapping applications and can be used in many of the same environments. However, strengths and limitations associated with each should be considered.

1.1 Single-Tube

Single-tube rod systems use a single string of rods to connect the probe or sampling tool to the rig. The rod diameters are smaller than the sampler and typically range from 1.25 to 4.5 inches. For collection of soil samples, once a sample has been collected, the entire string must usually be removed from the probe hole. If subsequent sample collection at greater depths is required, the process must be repeated by re-entering the probe hole with an empty sampler. Figure 15.1 shows a visual representation of this process.

1.2 Dual-Tube (Cased, Two-Tube)

Dual-tube systems advance concentric tubes: an outer tube, or casing; and a separate inner rod with the sampler attached (Figure 15.2). The outer tube is used for borehole stabilization. The inner extension rod is used for sampler recovery and insertion. Because dual tubes are advanced simultaneously, outer tube diameters are relatively large, typically 2.5 inches; however, they can range between 2.25 and 4.5 inches. The outer casing and inner extension rod with sampler are advanced simultaneously for the length capacity of the sampler. The sampler is removed from the probe hole and a new sample barrel or plug bit is inserted for each increment of depth. Because the hole is cased, continuous sampling is simplified and expedited.

Withdrawing the tool string from the probe hole is accomplished by applying a retractive force on the tool string assembly. The drill string can either be withdrawn by direct mechanical pull through use of a hydraulic system, or by line-pull using mechanical or hydraulic-powered winches or cathead and rope windlass type devices.

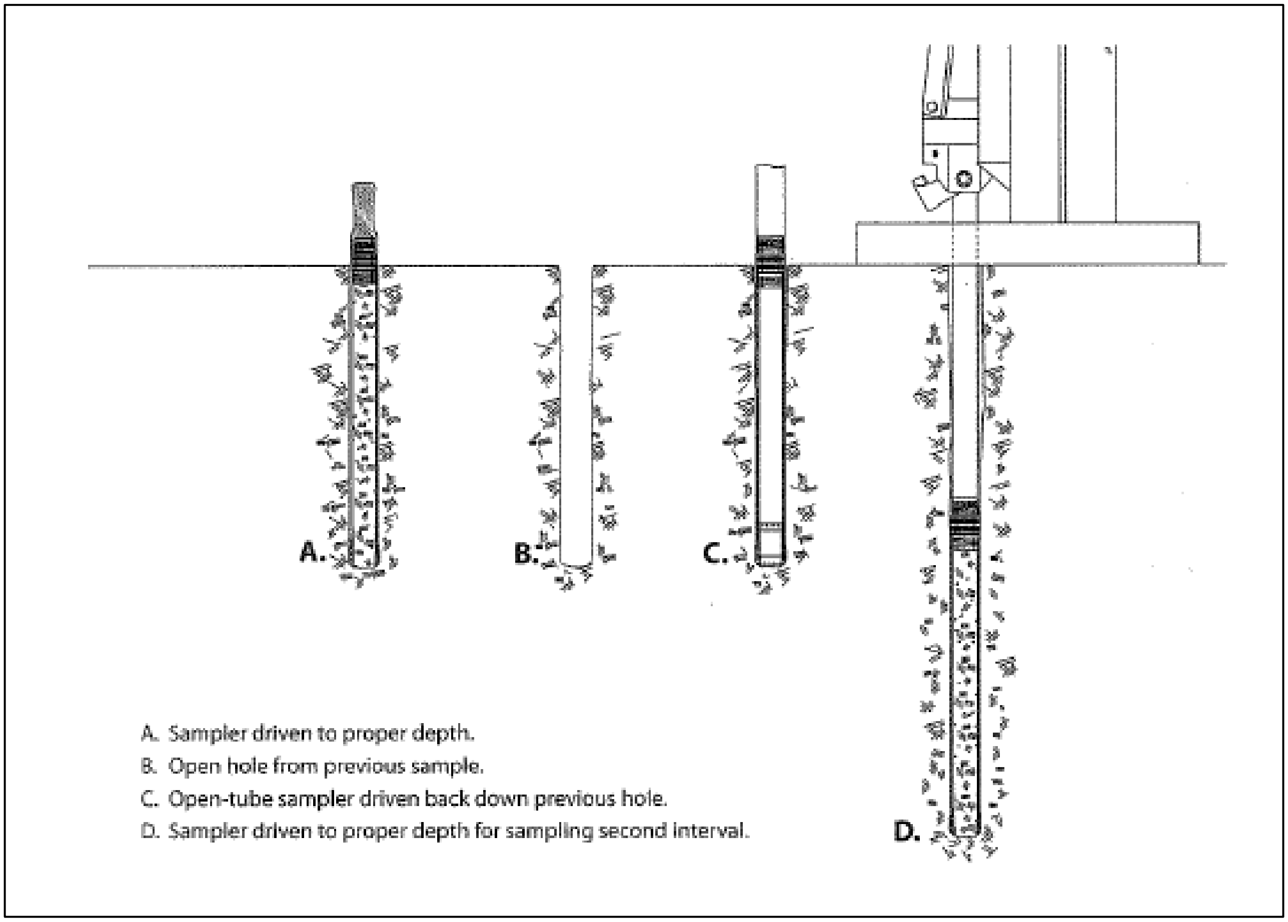

Figure 15.1 Figure of a typical open-ended sampling device used for continuous coring. From Geoprobe® Systems (2015)**.**

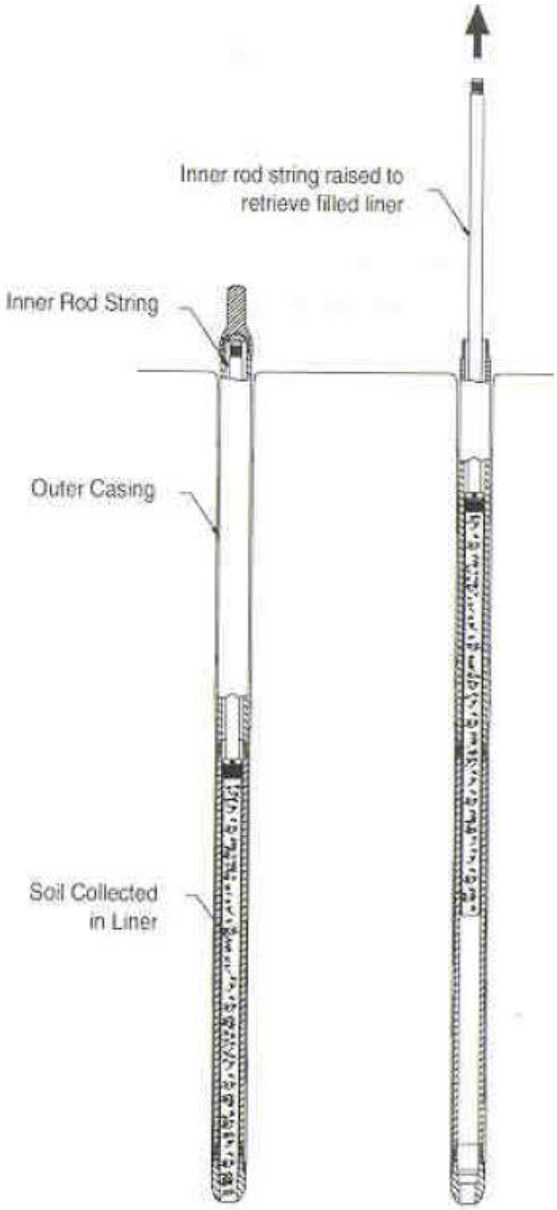

Figure 15.2 A dual-tube rod system. The outer tube and inner rod assembly are driven to depth as one unit. Once proper interval is reached, the inner tube and sample are withdrawn. From Geoprobe® Systems (2015).

2.0 Soil Sampling

The primary sources of information on soil sampling used in this document may be found in ASTM Method D6282 and U.S. EPA (1997).

2.1 Samplers

In general, there are two types of soil samplers used with DP rigs: non-sealed and sealed. Non-sealed soil sampling tools remain open as they are pushed to the target depth. Three non-sealed samplers are: 1) open solid-barrel; 2) split-barrel (or split-spoon); and 3) thin-walled (Shelby tube). However, the split-barrel and thin-wall are not commonly used with DP rigs. Sealed soil samplers remain closed until they reach the sampling depth. A commonly used sealed sampler is a closed barrel sampler. Many of these samplers allow for a liner to be inserted to contain the sample interval and allow for easy extraction from the sample barrel. Additional information on soil samplers can be found in Chapter 6 — Drilling and Subsurface Sampling, of the *Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring* (Ohio EPA, 2007).

2.1.1 Open Solid-Barrel Samplers

Open solid-barrel samplers consist of a drive head assembly, a non-sealed barrel and a cutting shoe. The sampler is attached to the DP rods at the head assembly. A check valve, which allows air or water to escape as the barrel fills with soil, is located within the head assembly. The check valve improves the amount of soil recovered in each sample by allowing air to escape. With the use of liners, samples can be easily removed for volatile organic compound (VOC) analysis or for observation of soil structure.

2.1.2 Split-Barrel Samplers (Split-Spoon Samplers)

Split-barrel samplers are also often used with hollow-stem augers, and are similar to open solid-barrel samplers except the non-sealed barrels are split longitudinally so the sampler can be easily opened. The primary advantage of split-barrel samplers is they allow direct observation of soil cores without the use of liners and without physically extruding the soil core. As a result, split-barrel samplers are often used for geologic logging. Split-barrel samplers, however, may cause more soil compaction than open solid-barrel samplers because the tool wall thickness is often greater. Although liners are not compatible with all split-barrel samplers, they may be used to reduce the need for decontamination. Additional information on the use of split spoon samplers with hollow-stem augers may be found in Chapter 6 — Drilling and Subsurface Sampling, of the *Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring* (Ohio EPA, 2007).

2.1.3 Thin-Walled Tube Samplers (Shelby Tubes)

Thin-walled tube samplers, similar to larger diameter samplers known as Shelby tubes, are used with both DP and hollow-stem augers for collecting undisturbed samples. The non-sealed sampling tube is typically attached to the sampler head using recessed cap screws or rubber expanding bushings. The sampler walls, made of thin steel with a sharpened cutting edge, minimize soil compaction compared to other types of samplers. Relatively undisturbed samples are required for certain geotechnical analyses such as permeability and triaxial shear tests. More information on the use of thin wall samplers may be found in Chapter 6— Drilling and Subsurface Sampling, of the *Technical Guidance Manual for Hydrogeologic*

Investigations and Ground Water Monitoring (Ohio EPA, 2007) and ASTM Method D1587.

2.1.4 Closed-Barrel Samplers (Piston Samplers)

Closed-barrel or piston samplers (Figure 15.3) are similar to open solid-barrel samplers, except the barrel opening is sealed with a rigid, pointed piston that displaces soil as it is advanced. Sometimes referred to as discreet-depth samplers, the samplers are pushed to the desired depth (without the need to collect shallower soil cores), the piston is unlocked by releasing a retaining device, and subsequent pushing or driving forces soil into the sampler. The assembly can then be removed and soil extracted. Piston samplers are typically air and water tight; however, if O-ring seals are not maintained, leakage may occur.

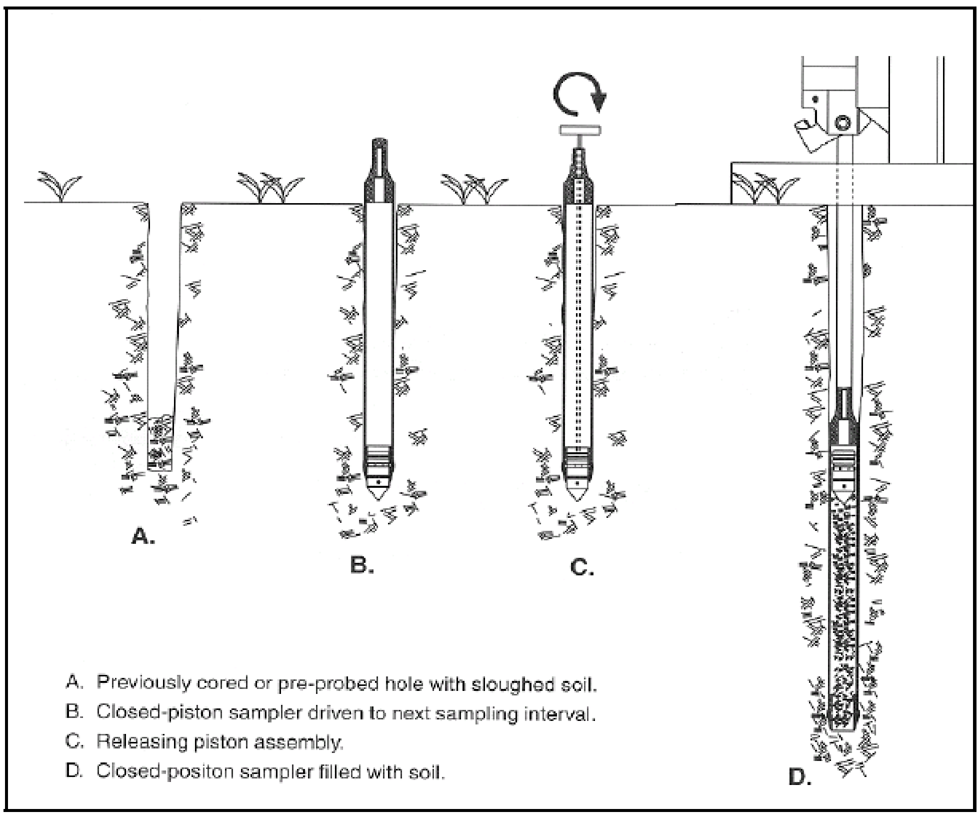

Figure 15.3 Figure of a typical closed-barrel sampling device (e.g., MC5 system) used for discrete depth sampling. From Geoprobe® Systems (2016)**.** These samplers are used most often for single events (discrete point sampling) when a sealed sampler is required to avoid cross-contamination or where probe hole wall stability cannot be assumed (ASTM D6282).

2.2 Soil Sampling Method Evaluation

DP offers many advantages for soil sampling, including fast site assessment, rig mobility and greater efficiency than conventional drilling methods. Use of available sampler lengths of up to five feet can allow for more continuous sampling intervals than are possible with conventional split-spoon samplers. In general, DP is applicable in unconsolidated sediments that are conducive to withdrawing sufficient soil volume for analysis. Where sample quality or quantity may not meet sampling objectives, alternatives such as switching to a different sampling method (for example, a hollow-stem auger) or a different sampling tool (for example, a wider diameter sampler) should be employed.

2.2.1 Single-Rod Sampling Considerations

Because only one string of rods is used, single-rod systems are not as heavy as dual-tube systems and enable quicker rod connection. Because of the lightweight rod string, situations in which a single sample is desired or with shallow sampling depths in cohesive formations can be sampled quickly and easily with few complications. Open barrel, single-tube samplers (Figure 15.1) are not recommended for use in non-cohesive formations or saturated sands where formation slough or collapse can compromise sample quality and integrity. Closed barrel, single tube samplers (Figure 15.3) often will be preferred under non-cohesive formation conditions (ASTM D6282).

However, the lack of hole casing can cause some complications when continuous sampling to depths greater than 10 feet is desired in non-cohesive formations. Sampling with single tube rods can be slower because the probe hole may collapse or slough without the stabilization of an outer casing rod. A second drawback of single-rod systems is the potential for formation or saturated zone cross-contamination during continuous sampling. Because the probe hole is uncased during rod retraction and reinsertion, the open probe hole can serve as a conduit for potentially contaminated soils or ground water from overlying zones that may slough or migrate to otherwise uncontaminated lower zones. Cross-contamination is of particular concern if NAPLs (non-aqueous phase liquids) are present, since they could migrate down the probe hole. Also, when multiple samples are taken, repeated entry can deform or skew the alignment of the probe hole. This can create problems when sealing the probe hole if a skewed hole prevents complete insertion of a tremie pipe or permits bridging of bentonite pellets or granules. Under these conditions the operator may drive or lower a string of drive rods with an expendable tip to the base of the sampled boring. Then a grout slurry can be pumped down the rods as the tool string is retracted to effectively seal the boring from bottom to top (ASTM D6262).

With no outer casing in place to guard the open-tube sampler during rod reinsertion, sample biasing may be exacerbated by probe hole collapse, probe hole sloughing or probe hole smearing. Thus, the sampler may collect soil samples from varying zones as it is advanced to the target depth. If the displaced material is contaminated or contains analytes at levels higher than the target depth, the target sample may be biased high. Conversely, if the collapsed material is cleaner or contains analytes at concentrations lower than the target depth, the target sample may be biased low. In either case, the sample collected is not representative of the target depth.

Depending on site conditions, the collection of undisturbed samples using thin-walled samplers with DP may or may not be feasible. Typically, DP rigs are mounted on lighter trucks than hollow-stem auger rigs, and do not have hydraulic systems that are capable of generating as much downward force as hollow-stem auger rigs. Consequently, hollow-stem auger rigs are better equipped to push thin-walled sample tubes to greater depths and have better recovery over a wider range of soil conditions than DP rigs. Closed-piston single-tube samplers may be preferred when encountering heaving sands and for preventing cross contamination of soil within a ground water plume.

2.2.2 Dual-Tube Sampling Considerations

The use of the outer casing in a dual-tube system has several advantages. Dual-tube systems are faster than single-rod systems for continuous sampling at deeper sampling depths (for instance, depths greater than 10 feet). Because only the inner sample barrel is removed, and not the entire rod string, reaching the target depth is not complicated by probe hole sloughing and collapse. In addition, the outer casing maintains the probe hole's alignment during multiple insertions of the sampling rod. This helps assure a proper grout seal. Because the outer casing is never removed during sampling, the probe hole remains sealed, reducing the potential for sloughing of contaminated soil or migration of contaminated fluids down the hole. The outer casing also protects non-sealed samplers from sample biasing caused by smearing. In addition, the outer casing enables the use of non-sealed samplers for vertical contaminant profiling above the saturated zone.

Use of the outer casing in a dual-tube system also has disadvantages. It is heavier, requiring twice as much rod and a heavier rig, thus making it more cumbersome. The dual-tube system is also more susceptible to soil friction because of its larger diameter, slowing boring and sampling. An oversized cutting shoe is sometimes used to reduce friction and buckling but may increase the risk of contamination migration down the probe hole. Even using heavier driving equipment, penetration depths are often not as great as those possible with single-rod systems due to the increased friction.

2.2.4 Soil Sampling Recommendations

DP techniques are appropriate for soil sampling when:

- Its use and methodologies are consistent with the data quality objectives of the sampling program.
- Unconsolidated sediments are to be sampled.
- Materials to be sampled contain a low percentage of gravel and cobbles and are not dense or highly compacted.
- Materials to be sampled are less than 100 feet in depth. DP techniques may be able to probe deeper in some circumstances.

If using DP:

- Dual-tube sampling should be used whenever possible. This is especially important if there is a potential for sloughing to a lower zone. If a single-tube is used for vertical profilers, it is imperative sealed samplers are used.
- Closed-barrel samplers should be used for most applications. The only situation where non-sealed samplers would be acceptable is with single sample collection events above the saturated zone.
- If recovery of samples or cave-in of the probe hole is problematic, the data quality objectives should be supplemented or different sampling techniques employed.

- Probe holes should be sealed using retraction grouting with a tremie tube and a liquid slurry material. Sealing probe holes by surface pouring of dry granular bentonite is acceptable if: (1) the boring has penetrated no further than the top of the uppermost saturated zone; and (2) the soils overlying the uppermost saturated zone do not contain waste material or free product.

3.0 Ground Water Sampling

There are two common types of ground water sampling equipment used in DP methods: tools for obtaining one-time grab samples, and wells installed using DP for short-term or long-term sampling. Most sampling devices used with DP tools are composed of stainless steel or other inert metals. Well screen materials may be composed of stainless steel, polyvinyl chloride, polyethylene or polytetrafluoroethylene. The primary sources of information on ground water sampling used in this document are ASTM Method D6001-05, ASTM Method D6724-04, ASTM Method D6725-04, and the U.S. EPA guidance *Groundwater Sampling and Monitoring with Direct Push Technologies* (2005).

3.1 Ground Water Grab Samplers

Grab samplers are used to rapidly collect samples to define ground water conditions during one sampling event. They are typically used during site characterization to help identify plume boundaries, hot spots, preferred pathways or other monitoring points of interest. This data will facilitate in placement of permanent monitoring wells.

DP grab ground water samplers can be grouped into two classes: 1) sealed protected screens (closed samplers) or 2) exposed screens (open samplers). There are also two types of drive systems: single-rod and dual-rod. As described in section 2.2.1, single-tube systems have only one drive rod. Dual-tube systems have an inner and outer drive rod. The inner rods are removed to obtain a sample. Dual-tube systems allow for some protection of cross-contamination, therefore, are more advantageous if multiple level sampling is desired from a single boring.

3.1.1 Exposed-Screen (Open) Samplers

Exposed-screen samplers (Figure 15.4) consist of a well screen, ports, or milled slots to allow the influx of ground water and a riser pipe permitting the extraction of a water sample. In practice, exposed-screen samplers are driven to the approximate sample depth below the ground surface. A ground water sample is taken by extracting water with either a bailer or tubing/pump combination. Purging and development must be conducted prior to sampling to prevent cross-contamination and obtain a representative sample of the ground water. Because the exposed-screen sampler can be pushed to different depths, multi-level water samples can be taken without having to remove the tool string. This can be a significant time savings, especially where three-dimensional plume mapping is a data quality objective.

However, exposed-screen samplers may have significant disadvantages. Clogging of the well screen or milled slots can occur when sampling formation water in silty or clay-rich soils as well as ground water high in suspended solids. For this reason, exposed-screen samplers are commonly used in geologic formations composed of sands and gravels. If soil is contaminated above the saturated zone of interest, draw-down by the tool string of contaminated soil may produce false-positive results. Contaminated ground water trapped in some sampler designs can also be drawn from one zone to another, potentially biasing sampling results at the point of interest. The initial ground water withdrawn from the sampler can be turbid because of the disturbance of the formation while using DP tools. In addition, because of the small screen diameter, as well as not having a sand pack to aid filtering out fine particles, development of the formation can be difficult when abundant fines are present in the screened interval.

Figure 15.4 Photograph of a typical exposed-screen sampler

To prevent plugging of the screen or sampling portholes, some exposed-screen samplers (Waterloo Profiler ®) are designed so the pumping direction can be reversed and a small amount of water injected into the screen to maintain a positive pressure on the screen and prevent clogging of the sampling ports. Only clean, potable water of known chemical quality transported from off-site should be used. The pump flow is again reversed once the next sampling depth is reached, and another ground water sample is taken from that depth. Once all samples are taken, the probe hole may be sealed by pumping grout through the profiler. Figure 15.4 shows a typical ground water profiler assembly.

Whenever multiple depths are sampled, there is a possibility of drawing contamination to deeper depths, potentially biasing results. While pumping water into the screen during driving may decrease the chances of this, the practice can create some problems of its own. Even though the water is pumped into the sampler under low pressure, some water may be introduced into the formation. Alternatively, when the next sample is withdrawn, the clean water may mix with the formation water and cause samples to be biased low. Care should be taken to note the volume of water pumped into the sampler to ensure the same volume of water is withdrawn. In addition, because of the small diameter and because multiple samples are obtained from one pushing event, it is unlikely the formation can be sufficiently developed prior to obtaining the sample.

3.1.2 Sealed-Screen (Closed) Samplers

Closed-screen samplers (Figure 15.5) are protected, sealed sampling devices consisting of a well screen housed within a protective sheath to which are attached an expendable drive point, drive rod(s) and drive head. The assembly is initially driven with the outer casing in place. Rubber O-rings keep the device water tight, eliminating the threat of formation fluids entering the screen before deployment and assuring sample integrity. Once the desired depth is reached, the screen is held in place and the outer casing is retracted to expose the screen to formation water. After a sample is obtained, the expendable drive point is left in place and the sampling assembly is removed. Screen length can vary from one to five feet and are generally composed of PVC or stainless steel.

Since the screen is only exposed after the tool has been placed at the target depth, susceptibility of the screen to clogging is reduced. The O-ring seals make the sampler water tight and reduce the likelihood of cross-contamination by preventing water from entering the sampler as it is advanced to depth. In addition, some closed-screen samplers have been specifically designed to leave the outer casing and screen with an attached riser (usually PVC) in place for weeks and up to a year as a temporary monitoring device.

Turbid samples may be caused both by the disturbance of the formation while driving DP tools, and by the initial entrance velocity of water into the sampler before the water level inside the sampler reaches equilibrium with the formation water. As with exposed screen samplers, development of the formation can be difficult due to the small screen diameter when significant amounts of fines are present. A problem can also occur if extension rods aren’t used to hold the base of the screen on place, the screen may completely fail to deploy or only partially deploy.

Vertical profiling can be accomplished with a single-tube closed-screen sampler or dual-tube inner rod screen in a single non-cohesive ground water zone by sampling from the shallowest to deepest intervals. Profiling is started at the shallowest interval, then advancing the tools string down to subsequent sampling intervals. Prior to sample collection at each interval, the sampler must be retracted, decontaminated, reassembled and redeployed to new target depth, and then a sufficient volume of water must be purged to best obtain the formation water at the new sample interval. The sampling may be conducted in a single borehole or new borings located a couple of feet from the original boring.

3.2 DP-Installed Wells

DP used for advancing probe rods can be adapted to install wells for long- and short-term monitoring of ground water. Once the desired sampling interval has been evaluated and determined, the preferred and most common approach is to push the probe rods or the drive casing to the desired depth with a sacrificial tip. The screen and well casing are usually inserted into the rods or drive casing to the total depth. This protects the screen from becoming plugged with soil and being exposed to any overlying zones of contamination. The annulus of the boring is sealed to prevent migration of contaminants into the ground water zone. ASTM D6725-04 Practice for Direct Push Installation of Pre-packed Screen Monitoring Wells in Unconsolidated Aquifers (2010) provides additional guidance on DP well installation.

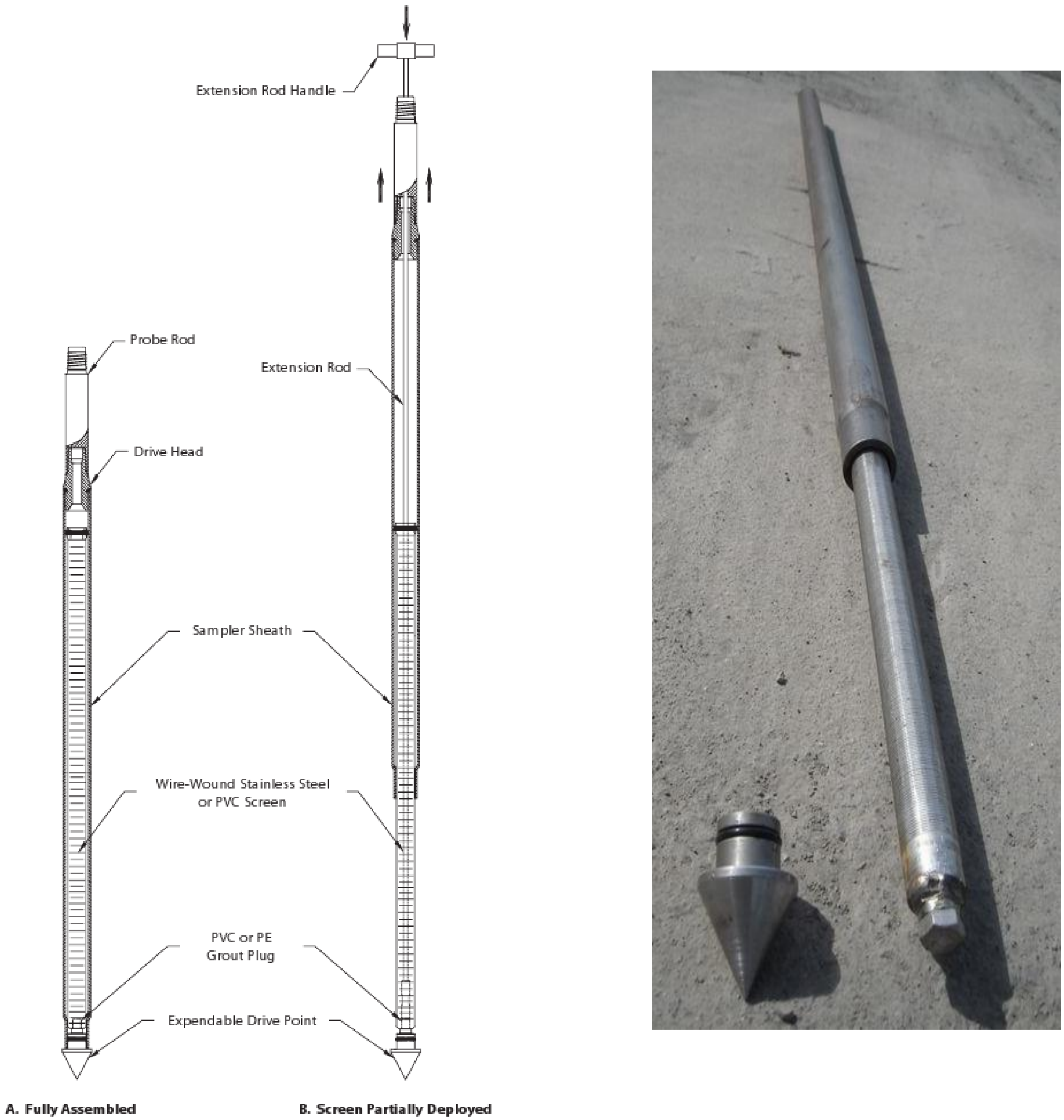

Figure 15.5 Typical closed-screen sampler assembly. From Geoprobe® Systems (2015)**.**

3.2.1 Conventionally Screened and Packed Wells

The inside diameter of probe rods or temporary drive casings used for DP well installations range from 1.5 to 4.5 inches. Wells can be installed using conventional well production casing (screened completion casing connected to and hung on blank casing) with inside diameters up to two inches, provided the well can be properly packed and sealed. If the production casing is installed in non-cohesive formation material, it may collapse around the screened completion casing as the rods or outer casing are removed, possibly eliminating the need for placement of the filter pack. If the formation is stable or cohesive soil, filter pack material is placed around the outside of the screen by pouring it into the annular space between the production casing and the temporary drive casing as the temporary drive casing is pulled from the borehole, resulting in filter pack material between the annular space of the screened completion casing and borehole wall. The well is sealed by pouring granular bentonite into the annular space or pumping bentonite slurry through a tremie line ran downhole in the annular space to the top of the filter pack. The well is grouted from the bottom up by pumping bentonite slurry through the tremie line as the temporary drive casing is removed from the hole.

3.2.2 Pre-Packed Screen Wells

Wells can also be installed using pre-packed well screens on the production casing, which help to eliminate problems with small diameter wells in the placement of filter pack around the screen. A pre-packed screen is an assembly consisting of an inner slotted screen surrounded by a wire mesh sleeve which acts as a support for filter media (Figure 15.6). The pre-packed screen assemblies can either be shipped with filter media already packed within the mesh sleeve or can be shipped without filter media and packed with filter sand in the field. Refer to ASTM D5092-02 (2005) for appropriate sizing of filter pack material. The wells are sealed and grouted using same procedure described for conventionally completed DP wells. ASTM D6725-04 (2010) provides additional guidance on the use of pre-packed well screens (Figure 15.7).

Figure 15.6 Direct push pre-packed monitoring well screen. From Geoprobe® Systems (2015)**.**

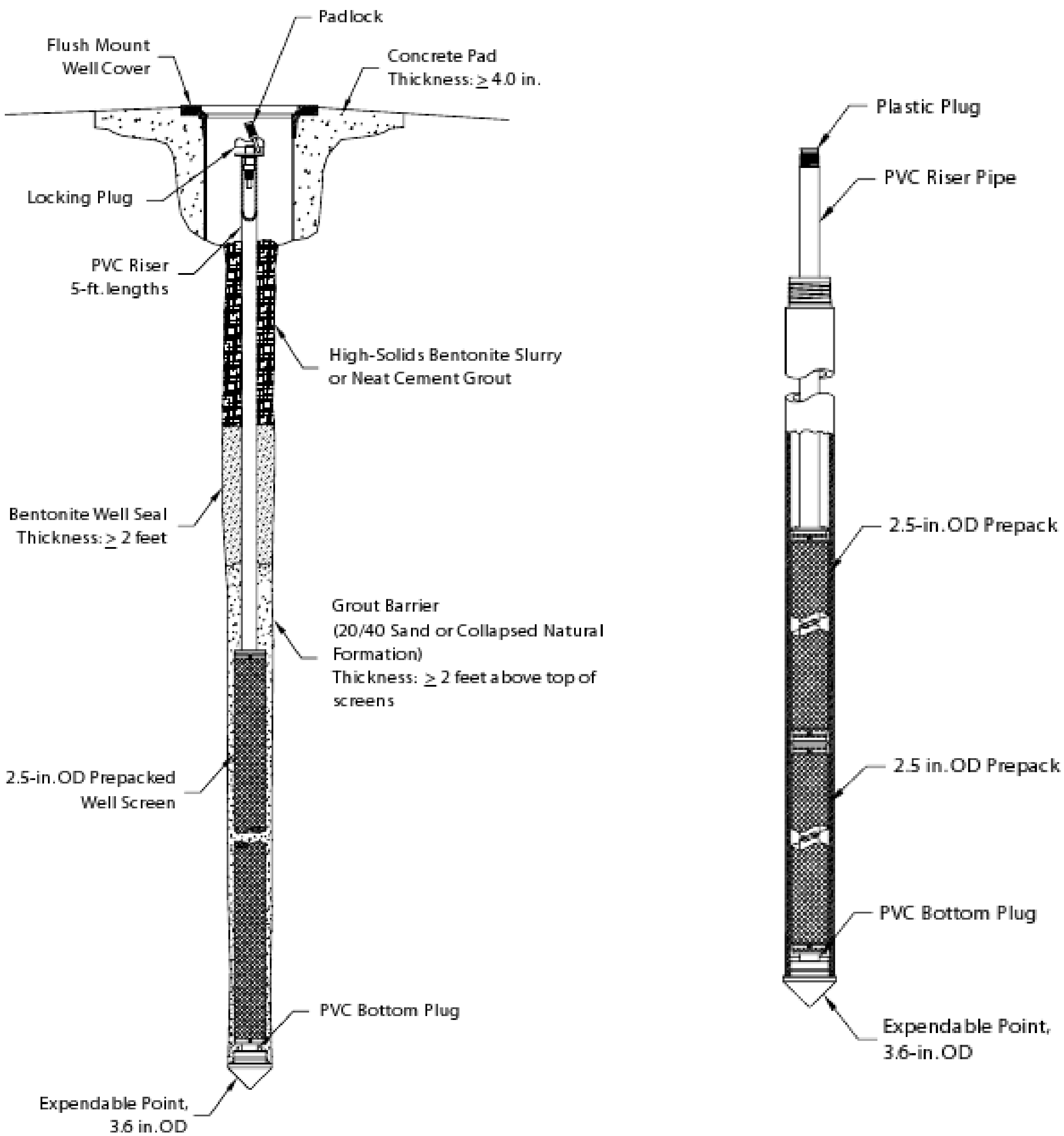

Figure 15.7 Typical pre-packed screen well assembly. From Geoprobe® Systems (2015).

3.2.3 Development of DP Wells

Due to the effects of DP installation on the soils around the well, development of each well is needed to ensure representative samples. Development of DP wells helps repair damage done to the formation during the driving of DP tools, and increases the hydraulic communication between the well and the formation. Due to the small casing diameters, the equipment available to develop small diameter wells is limited to small capacity bailers, inertial pumps (inertial check valve and tubing systems), peristaltic pumps and small diameter bladder pumps. Inertial check value and tubing is effective when used for development of coarse-grained sediments. The downward stroke of the inertial lift pump provides a surging of the water column and loosens the fines in the formation. The following upward stroke of the pump simultaneously removes the loosened fines, preventing them from clogging the screen. However, in finer-grained formations, over surging should be avoided to prevent clogging the screen with fines. It may be necessary to perform additional purging with a non-surging pumping device to attain lowered turbidity levels for wells installed in fine-grained formations (ASTM D 6725-04, 2010).

Development should not be implemented until the seal has cured and settled to prevent pulling uncured grout into the sand pack. The time interval between well installation and development is a function of well construction, type of grout and conditions under which the grout was installed. For example, neat cement (Type 1) generally cures within 48 hours (Gaber and Fisher, 1988: State Coordinating Committee on Ground Water, 1996). However, if the cement grout column is located mostly above the water column, then 24 hours may be sufficient. Bentonite-based grouts tend to set within 24 to 48 hours. Bentonite granules, chips or pellets, above the sand pack will reduce the potential for contaminating the sand pack with grout during development activities and thus reduce the time interval between construction and development. A 0.75-inch direct-push well installed with dry granular bentonite grout may require less than 24 hours

Ideally, a time of 48 hours is recommended (U.S. EPA, 2001). However, shorter time frames may be acceptable as discussed above. If a shorter time frame is used, then justification for using less than 48 hours should be documented. It is ultimately the responsibility of the professional to demonstrate ground water samples collected from the well are representative of the formation water and are not impacted by grout contamination.

Similar to conventional wells, drawdown and field stabilization parameters (for example, specific conductance, dissolved oxygen, pH and turbidity) should be monitored during development to determine when the formation and ground water have stabilized (see Chapter 8 — Monitoring Well Development, Maintenance and Redevelopment and Chapter 10 — Ground Water Sampling, of the *Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring* (Ohio EPA, 2009 and 2012, respectively)

3.2.4 Probe Hole and Monitoring Well Sealing

Because any open hole can act as a conduit for contaminants to the subsurface, all probe holes and monitoring wells shall be appropriately sealed and abandoned in accordance with Ohio Administrative Code Rule 3745-9-10, Abandoned well sealing. Due to the small diameter of DP probe holes, sealing the probe holes offers a few special challenges. It is important to select appropriate sealing methods based on the site-specific conditions, such as position relative to the water table, presence or absence of NAPL, or risk of sloughing. An inadequately sealed probe hole or monitoring well can create a preferential pathway for the infiltration of contaminants to previously uncontaminated zones. The procedures for borehole sealing in Chapter 9 —Sealing Abandoned Monitoring Wells and Boreholes, of the *Technical Guidance Manual for*

Hydrogeologic Investigations and Ground Water Monitoring (Ohio EPA, 2009) should be followed for all probe hole sealing. Additional information about the methods discussed below may be obtained from U.S. EPA (1997).

Grouting machines are available for use with small diameter wells to allow the operator to properly seal monitoring well installations and seal soil and ground water sample holes. The use of grouting machines reduces problems of grout bridging and incomplete seals associated with adding grouting materials from the ground surface.

3.3 Ground Water Sampling Method Evaluation

The various types of ground water samplers and wells used with DP are evaluated in the following sections.

3.3.1 Grab Samples

With respect to site screening investigations in which ground water samples are not being collected for compliance purposes, grab samplers may delineate site-wide hydrogeology more quickly and efficiently than monitoring wells. Because they are easy to use and do not require well materials, grab samples typically have a significant advantage over traditional monitoring wells as site screening tools. In addition, they often facilitate hydrogeological evaluation and plume mapping, and can be very helpful in optimizing the location and construction of permanent monitoring wells.

Conversely, with respect to obtaining representative ground water samples to generate accurate and verifiable data, the use of grab samplers does present a few challenges. Correct placement of the screened interval is particularly important given the short screen and discrete sampling interval, so contaminant layers are not missed. The short time frame of many DP investigations is often insufficient for adequate well development and equilibration with the surrounding formation water. Because there is no filter pack installed around a DP sampling tool, fines may clog the well screen when sampling in fine-grained formations, preventing ground water from reaching the sampler. Clogging of the screen could cause samples to be biased lower than actual contaminant concentrations. Problems with turbidity may be due to the inability to adequately develop the sample zone. Finally, when sampling objectives include trend analysis and monitoring of remediation efforts as goals, the one-time sampling inherent in samples taken with DP tools is often not appropriate for these longer-term monitoring requirements. For these applications DP monitoring wells may be installed to conduct long term monitoring and trend analysis.

When a closed-screen sampling tool is opened for sampling, the entrance velocity of water into the screen can be high due to the hydraulic head of the formation water. This initial high entrance velocity can induce degassing of the sample as well as turbidity. Because of these concerns, significant purging of the sampler and the sampling zone should be performed before sampling to reduce bias. As a general rule, multi-level sampling can be accomplished only with repeated advances of a sealed-screen sampler, especially when using a single-tube rod system. Since the probe hole must stay open between advances of the sampler, cross-contamination may be a problem between sampling events. Sealed-screen samplers used within a cased dual-tube rod system can eliminate the problems with cross-contamination when multi-level sampling. However, even when using tools to reduce the potential for cross-contamination, all sampling equipment should be decontaminated between sampling intervals.

Some exposed-screen manufacturers solve the problem of screen clogging by pumping distilled or deionized organic-free water into the screen during advancement. This prevents ground water from entering the exposed screen and may be an ideal choice when a detailed vertical characterization of contaminant plumes is desired. Additionally, exposed-screen samplers may be used to pinpoint a location of highest vertical contamination for more precise placement of well screens. However, the addition of water into the subsurface may lead to sample biasing. Care should be taken to ensure water representative of the formation is collected when sampling.

3.3.2 Wells

DP-installed wells allow for long-term monitoring of ground water trends, while grab samplers do not. Since they can be installed with filter pack, they allow for more thorough well development and lower sample turbidity than grab samplers. Wells installed using DP also offer several advantages over wells installed with conventional methods. The speed and mobility of DP sampling allow a more complete and accurate investigation than would be available with conventional wells. Commercially available screen lengths as short as two feet allow DP wells to be installed in a vertically precise manner, avoiding excessive or inadequate screen lengths. Drilling cuttings and purge water volumes are lower as a result of the smaller well diameters. Several studies have comparing DP-installed wells with conventionally installed wells found no significant difference in the quality of samples taken from DP wells as compared to conventionally installed wells (U.S. EPA, Technology Innovation Office, Hanscom AFB Comparison Study, 2003: Kram, Lorezana, Michaelsen, Lory, 2001).

The limitations of DP-installed wells are a consequence of the small diameter of such wells. The inside diameter (ID) of probe rods or temporary drive casing used for DP wells ranges from 1.5 to 3.5 inches. The smaller well diameters limit the choices of purging and sampling equipment. Several types are currently available, including check valve (inertial lift) pumps, peristaltic pumps, small-diameter bladder pumps and small-diameter electric submersible pumps. New small-diameter pumps are continually being developed. As with all DP applications, installation of wells with DP is limited to unconsolidated sediments, and may be limited by depth or the presence of gravels or cobbles. These limitations should be considered in site sampling and analysis plans.

Because of the smaller diameter of the probe hole with DP, the annulus around the riser and screen is smaller than with conventional drilling methods. This smaller annulus (less than two inches) makes it more difficult to ensure filter material is placed evenly around the screen when using gravity placement of the filter material. Because of this limitation, bridging of the filter sand can result. Bridging can create voids in the filter pack, leading to turbid samples. In addition, the presence of voids can potentially allow the bentonite seal to be drawn into the screened zone, contaminating the well.

Wells installed with pre-packed well screens allow for more control over placement of the filter pack. Because the filter media is placed around the screen at the surface, pre-packed screens allow more control over the filter pack grain size and eliminate bridging of the filter media. Use of pre-packed screens may make it possible to use finer grain filter pack sand than is used for conventional well filter pack, providing less turbid samples.

3.4 Applications of DP for Ground Water Sampling

3.4.1 Considerations for Use as a Screening Tool

Screening can be defined as a reconnaissance investigation used to identify site-specific matrix types and hydrogeology, determine the presence and the extent of contamination, and select sampling locations for permanent well installation. Screening samples are not intended to meet the same data quality objectives as compliance samples. Because a reconnaissance investigation is used for selecting screening samples, data quality objectives may be less stringent than those utilized for other investigations, but still satisfy the purpose of defining the extent of contamination and selecting sampling locations for more compliance sampling. Depending on the time frame of the project, screening samples can be either evaluated in the field using a field instrument (e.g., flame ionization device, photoionization device, or portable gas chromatograph), or sent to a laboratory for analysis.

DP has many advantages making it ideal for use as a ground water screening tool. Screening applications DP would work well for include: detecting the presence of ground water contaminants; assessing the relative concentrations of contaminants; investigating pathway completeness; conducting three-dimensional plume definition; and guiding the installation of monitoring points.

Any type of DP sampler or well can be used for screening applications, depending on the desired goals and data objectives. The limitations of each type should be kept in mind when planning the sampling exercise. The project goals, data objectives, and site conditions will dictate which type is used. Vertical depth sampling is best done using a sealed grab sampler with a dual tube rod system to prevent cross-contamination. A ground water profiler may also be used. If only a single sample is needed, either a closed or open screen sampler is appropriate. The user should be aware of the potential for clogging of the screen when using an open screen sampler. When no analysis of concentration trends over time is needed, grab samplers can be used. If an analysis of contaminant of concern concentrations over time is desired for site screening, temporary or permanent wells can be installed. All probe holes shall be properly sealed when sampling is complete. The preferred method of sealing is using retraction grouting with a tremie tube and a liquid slurry material. However, surface pouring may be appropriate for shallow probe holes (less than 10 feet deep) in cohesive formations.

3.4.2 Considerations for Collection of Compliance Samples

Compliance samples are collected to meet regulatory requirements, which often include standards such as "protective of human health and the environment." Such standards generally assume quality assurance/quality control (QA/QC) objectives to ensure laboratory results with a high degree of accuracy and precision. Sample collection and analytical techniques used should be recognized as those producing valid, repeatable, representative data by U.S. EPA, Ohio EPA, and environmental professionals. Definitive samples and their associated laboratory results should meet all required QA/QC criteria, including those for use in risk assessments, and should be scientifically valid, legally defensible, repeatable, and representative of subsurface conditions (Puls and Barcelona, 1996). An example is ground water sampling for hazardous and municipal solid waste landfills as required by Ohio Administrative Code (OAC) chapters 3745-54-90 through 3745-55-01 and OAC 3745-27-10, respectively.

DP technology can be used to collect compliance ground water samples if the data quality objectives are met. Since reproducibility is necessary to the proper collection of compliance samples, grab samples representative of a one-time sampling event cannot be reproduced over time and are thus not appropriate for use in compliance sampling. The sample point should be a permanent or temporary well. Samples from properly constructed DP wells should be equivalent in accuracy to conventional ground water samples. To achieve this equivalency, the well should be properly constructed, sealed, developed, purged and sampled. Ohio EPA believes the only way to achieve this level of data quality using DP is with DP wells installed using pre-packed well screens. Because the filter media is placed around the screen at the surface, pre-packed screens allow more control over the filter pack grain size and eliminate bridging of the filter media.

Another consideration of using DP wells as an alternative to conventional monitoring wells for collecting compliance ground water samples is the yield of DP wells will be lower due to their smaller diameter (typically 0.5 to < 2 inches; conventional well diameters are generally > 2 inches). Depending on the sampling technique, sample volume, formation permeability, and ground water yield, more time may be required to extract a relatively large-volume ground water sample from a DP well than an equivalently screened conventional monitoring well.

DP-installed wells are not recommended in situations when a well must be installed to monitor a zone of unknown ground water quality underlying a contaminated zone. A multi-cased well should be installed to prevent cross-contamination, and the upper water-bearing zone should be drilled, cased and grouted separately. DP cannot be used to install a multi-cased well because the well annulus is too small to allow for sufficient grout sealing (U.S. EPA, 2004).

4.0 Specialized Measurement and Logging Tools

Specialized direct push probes may be used to collect *in-situ* geotechnical, geophysical and analytical measurements or soil gas samples. A number of tools are available, and more are being developed. The following is a discussion of some of the tools used in conjunction with site characterization and contaminant detection. The tools and technologies noted in this section are used for screening investigations. To properly interpret the information collected with these instruments, soil and ground water data (for example, soil type, presence of NAPL, laboratory analysis, etc.) are generally needed for comparison to the instrument response. Data from the analysis of previously collected soil and ground water samples may be used. If such data is not available, a limited number of soil borings will likely be needed to provide soil and ground water data.

Additional information about the technologies discussed in this section, including illustrations, is presented in U.S. EPA (1997), *Direct Push Technologies,* in *Expedited Site Assessment Tools for Underground Storage Tank Sites*; draft U.S. EPA guidance *Groundwater Sampling and Monitoring with Direct Push Technologies*; and the Field Analytic Technologies Encyclopedia (FATE). FATE is an online encyclopedia providing information about technologies for field sampling, sensing and analysis of contaminated media. The website is provided by the U.S. EPA Office of Superfund Remediation and Technology Innovation and may be accessed at ***http://clu-in.org/characterization/technologies/***.

4.1 Geotechnical

Cone penetrometer technology (CPT) may be used to quickly and efficiently evaluate soil stratigraphy. CPT characterizes the subsurface lithology by testing the response of the soil to the force of a penetrating cone. Sensors mounted in the tip of the rod send electronic signals to a computer at the ground surface, where the information is processed. CPT cones are pushed rather than vibrated into the subsurface. They may be used either with a CPT rig or in conjunction with a DP platform with pushing capabilities. The data should be correlated to site-specific boring data.

The most commonly used type of CPT cone is called a three-channel cone. It contains sensors that measure soil resistance on both the end of the cone and the friction sleeve, which is a cylindrical sleeve on the side of the penetrometer tip. The tip resistance to sleeve resistance ratio, called the friction ratio, can be used to estimate the soil type. The resistance data are recorded in real time at the surface to show relative density with depth. A continuous vertical profile of stratigraphy can be inferred from these data through comparison with existing drilling and soil sampling information. ASTM D6067 (2010) reports CPT rigs typically reach depths of 66-130 feet, but can reach as deep as 230 feet when heavier equipment is used. However, the maximum depth of investigation is always dependent on site conditions and the specific drilling, sampling and logging equipment being used.

4.2 Geophysical

Geophysical logging probes can be used with DP rods to evaluate subsurface conditions. A limited amount of drilling and soil sampling information in the immediate vicinity of the geophysical logging locations are needed to correlate geophysical responses with known site stratigraphy and subsurface conditions. Two examples of standard geophysical logging tools that may be used with CPT and DP rigs include:

Electrical conductivity (or resistivity) probes are used to evaluate stratigraphy, locate ground water zones and identify the presence of ionic contaminants (e.g. brines) or injected remediation fluids such as high concentration sodium persulfate. Clay layers are more conductive than sand due to the greater number of positively charged ions on the surfaces of clay minerals. Conductivity fluctuations are also affected by soil moisture content and the ionic strength of ground water.

Nuclear logging tools are used to evaluate stratigraphy, ground water conditions and subsurface contaminant distribution. Two types of nuclear logging tools include: (1) those which measure the natural radioactivity of a formation; and (2) those which emit radiation and measure the corresponding response of the formation. The first type of tool measures gamma radiation emissions from naturally occurring uranium, thorium and radioactive potassium present within clay minerals, and are useful in distinguishing clay-rich strata from sand-rich strata. The second type of tool exposes the boring walls to a relatively strong radiation source (gamma rays or neutrons), and measures the formation response which depends on its density (or porosity), water content and the presence or absence of hydrocarbons.

4.3 Hydrogeological

Several tools for obtaining vertical hydrogeologic profiles are discussed in the following subsections. Data from these tools can help determine where to place and screen conventional (bored) monitoring wells to obtain samples (soil and water) for analysis.

4.3.1 Piezocone

A piezocone is similar to a three-channel CPT cone with the addition of a pressure transducer mounted in the cone. Measurements of pore water pressure using a piezocone can determine the depth of the saturated zone and the relative permeability of the saturated sediments. A piezocone can also be used to perform dissipation tests. The downward advancement of the probe is paused to measure the change in pore water pressure over time while the cone is held stationary. Dissipation tests are useful for estimating (within an order of magnitude) hydraulic conductivity.

4.3.2 Hydraulic Profiling Tool

The hydraulic profiling tool (HPT) allows the user to create a continuous profile of the soil hydraulic properties in both fine- and coarse-grained material. While most soil profiling methods infer permeability from parameters like grain size or geotechnical properties, the HPT system can measure high resolution data on hydraulic permeability directly by injecting water into the formation. The system consists of two sensors: a sensitive downhole transducer to record dynamic pore pressure and an electrical conductivity sensor providing information on lithology.

HPT can be used to:

- Identify the ground water zones and confining units
- Locate and define better migration pathways for contaminants
- Target specific regions for injection of remediation material
- Select well screen intervals

Additionally, the HPT can conduct static dissipation tests at individual depths. This data is used to determine static water level (or head pressure in confined aquifers) and estimate hydraulic conductivity over a limited range (approximately 0.1 ft/day to 100 ft/day). To verify estimates of hydraulic conductivity obtained with the HPT, DP ground water samplers and pneumatic slug testing (ASTM Standard D7242) may be conducted at discrete targeted intervals.

4.4 Analytical

A number of chemical sensors can be used in combination with DP methods to provide screening level analysis of contaminants at depth.

Induced fluorescence systems use ultraviolet light to induce fluorescence of polynuclear hydrocarbons (PAHs). With ***laser-induced fluorescence (LIF)***, UV light is emitted from a nitrogen laser through a sapphire window into the soil. The UV light induces fluorescence of PAHs. The fluorescence signal is then transmitted to the surface via a fiber-optic cable. The ***fuel fluorescence detector (FFD)***, works in a manner similar to LIF except a mercury lamp is used as the light source. FFD can be configured to target detection of a number of different hydrocarbon contaminants.

An ***Optical Image Profiler (OIP) system*** is also available for investigation of petroleum fuels and related hydrocarbons. The OIP uses an ultraviolet LED and down hole camera to log images of UV induced fluorescence. The OIP probe includes a visible light LED and electrical conductivity dipole.

A ***membrane interface probe (MIP)***, also called a semipermeable membrane sensor, heats the soil to promote volatile constituents to diffuse across a thin permeable membrane on the probe's side. Once inside the probe, an inert carrier gas carries the chemicals to the surface where they can be analyzed by an in-line on-site gas chromatograph. The presence or absence of VOCs and their relative distribution can be estimated. See ASTM D7352 (2012), Standard Practice for Direct Push Technology for Volatile Contaminant Logging with the Membrane Interface Probe (MIP), for additional information.

The U.S. Army's ***Site Characterization Analysis Penetrometer System (SCAPS) Hydrosparge*** is similar to the MIP except the SCAPS Hydrosparge actively purges VOCs from the ground water rather than allowing them to diffuse into the sampler. The SCAPS Hydrosparge uses an inert gas to purge VOCs from ground water. The carrier gas then carries the VOCs to the surface for real-time analysis. As with data from the MIP, the Hydrosparge detects the presence or absence and relative distribution of VOCs (California EPA, 2000).

The ***thermal desorption VOC sampler*** (TDS) works similarly to the MIP and Hydrosparge samplers. The TDS system employs a special DP probe for collecting a soil sample into a chamber at depth where it is then heated, causing VOCs in the sample to desorb from the soil. A pneumatic system then employs a carrier gas to transport the VOCs to the surface for qualitative analysis.

XRF, or x-ray fluorescence, emits x-rays onto subsurface soils to induce fluorescence of the elements in the subsurface. The elements present in a sample are excited by the x-rays and emit fluorescent x-ray with a characteristic energy signature. The x-rays are then detected in the probe tip.

Explosive Sensor (ES) uses electrochemical sensors to respond to the presence of compounds characteristic of explosives (RDX, TNT and HMX) and their breakdown products. The tool is used along with geophysical sensors to determine soil lithology.

4.5 Soil Gas Sampling

Soil gas sampling is used to indicate areas of contamination in the subsurface. Due to the complex partitioning behavior of volatile organic compounds from liquid phases to the soil atmosphere, and transportation of soil gas through the vadose zone (Ullom, 1995), results from soil gas sampling can provide an indication of soil or ground water contamination. However, because soil gas analytical results provide a qualitative indication of contamination, they are best suited for site screening purposes. Conventional activities such as ground water sampling of monitoring wells and performance of soil borings will always be necessary to confirm and/or monitor subsurface contamination. Depending on the type of sampler employed, soil gas samples are retrieved either directly through the probe rods or through tubing (nylon or Teflon®) inserted into the probe rods.

For sample collection and evaluation of soil gas, the reader is referred to Ohio EPA guidance on *Sample Collection and Evaluation of Vapor Intrusion to Indoor Air for Remedial Response and Voluntary Action Programs* (2010).

4.5.1 Soil Gas Samplers

Using DP solely as a means to deliver a gas sampler to the target depth(s), the following describes types of samplers that may be utilized for collection of soil gas samples.

Expendable tip samplers have an expendable tip that separates from the DP rods once the desired sampling depth is reached and the rods are withdrawn a few inches to expose the soil. Tubing with a connector adapter attached is then inserted down the rods and connected to the expendable point holder for sample collection. To sample deeper, the probe must be withdrawn and another expendable tip attached, which can make this a time-consuming sampling method if multiple depth sampling is desired.

Retractable tip samplers can be attached to the end of the probe rods by a steel connecting tube that is screened or slotted to allow for gas to enter the probe rods. To sample, the rods are withdrawn a few inches, exposing the sampler to the target zone of interest. When sampling multiple depths in a single probe hole, the probe rod should be withdrawn and the sampler cleaned to assure a proper seating of the retractable tip.

Exposed screen samplers have a slotted or screened terminal end fitted onto the probe rods, similar to exposed screen samplers used for ground water sampling. Exposed screen soil gas samplers allow rapid sampling of multiple depths in the same probe hole. A disadvantage to these samplers is cross-contamination of the sample slot or screen can occur if the probe is pushed through contaminants prior to the targeted sampling depth.

4.5.2 Retrieving Soil Gas Samples

No matter which sampler system is chosen, the samples can be retrieved by one of two methods. The soil gas may be drawn directly through the probe rods, or soil gas can be sampled through a sampling tube inside the probe rods. Sampling through the probe rods is a fairly simple method. A disadvantage of this method is the large volume of air within the probe rods must be purged prior to collecting a sample. Sampling through the probe rods also increases the chances of sampling of atmospheric gases instead of the intended sample interval. In addition, because the connections between the rods may not be air-tight, soil gas may be drawn from subsurface intervals other than the targeted zone.

Withdrawing the samples through tubing can overcome these problems. Using nylon or Teflon® tubing for sampling reduces the purge volumes required and eliminates the possibility of drawing air from the joints between rod sections. Typically, a 0.125- to 0.25-inch tubing is used when sampling with this method.

5.0 References

ASTM D1587, 2016. Standard Practice for Thin-Walled Tube Sampling of Fine-Grained Soils for Geotechnical Purposes. ASTM International, West Conshohocken, Pennsylvania.

ASTM D5092, 2005. Standard Practice for Design and Installation of Groundwater Monitoring Wells in Aquifers. ASTM International, West Conshohocken, Pennsylvania.

ASTMD6001, 2005. Standard Guide for Direct-Push Water Sampling for Geoenvironmental Investigations. ASTM International, West Conshohocken, Pennsylvania.

ASTM D6282, 2005. Standard Guide for Direct-Push Soil Sampling for Environmental Site Characterizations. ASTM International, West Conshohocken, West Pennsylvania.

ASTM D6067, 2010. Standard Practice for Using the Electronic Piezocone Penetrometer Tests for Environmental Site Characterization. ASTM International, West Conshohocken, Pennsylvania.

ASTM D6724, 2010. Standard Guide for Installation of Direct Push Ground Water Monitoring Wells. ASTM International, West Conshohocken, Pennsylvania.

ASTM D6725, 2010. Standard Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers. ASTM International, West Conshohocken, Pennsylvania.

ASTM D7242, 2006. Standard Practice for Field Pneumatic Slug (Instantaneous Change in Head) Tests for Determining Hydraulic Properties of Aquifers with Direct Push Samplers. ASTM International, West Conshohocken, Pennsylvania.

ASTM D7352, 2012. Standard Practice for Direct Push Technology for Volatile Contaminant Logging with the Membrane Interface Probe (MIP). ASTM International, West Conshohocken, Pennsylvania.

California EPA, 2000. Hazardous Waste Technology Certification Program Evaluation Report: Site Characterization and Analysis Penetrometer System Hydrosparge VOC Sensor (SCAPS HS) as an in-situ field screening technology for the detection of selected volatile organic compounds in groundwater. Department of Toxic Substances Control.

Edge, R. W. and K. Cordray, 1989. The Hydropunch(TM): An In Situ Sampling Tool for Collecting Ground Water from Unconsolidated Sediments, Groundwater Monitoring and Remediation, Vol. 9, No. 3, pp. 177-183.

Geoprobe Systems, 2015. ***http://geoprobe.com***

Kram, M., D. Lorezana, J. Michaelsen, and E. Lory, 2001. Performance Comparison: Direct-push Wells Versus Drilled Wells, NFESC Technical Report TR-2120-ENV. NAVFAC, Washington, DC.

Ohio EPA, 2012. Ground Water Sampling and Analysis. Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring. Ohio Environmental Protection Agency, Division of Drinking and Ground Waters.

Ohio EPA, 2010. Sample Collection and Evaluation of Vapor Intrusion to Indoor Air for Remedial Response and Voluntary Action Programs. Ohio Environmental Protection Agency, Division of Environmental Response and Revitalization.

Ohio EPA, 2009. Monitoring Well Development, Maintenance and Redevelopment. Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring. Ohio Environmental Protection Agency, Division of Drinking and Ground Waters.

Ohio EPA, 2009. Sealing Abandoned Monitoring Wells and Boreholes. Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring. Ohio Environmental Protection Agency, Division of Drinking and Ground Waters.

Ohio EPA, 2007. Drilling and Subsurface Sampling. Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring. Ohio Environmental Protection Agency, Division of Drinking and Ground Waters.

Puls, R. W. and M. J. Barcelona, 1996. Low-flow (Minimal Drawdown) Ground-Water Sampling Procedures. EPA Ground Water Issue, EPA/540/S-95/504, Ada, Oklahoma.

Ullom, W. L., 1995. "Soil Gas Sampling: In: *Handbook of Vadose Zone Characterization and Monitroing*. L.G. Wilson, L.G. Everett, and S. J. Cullen (eds.). Lewis Publishers, Ann Arbor, Michigan.

U.S. EPA, 2005. Groundwater Sampling and Monitoring with Direct Push Technologies. Solid Waste and Emergency Response OSWER No. 9200, 1-51 EPA 540/R-04/005, Washington, DC

U.S. EPA Technology Innovation Office, 2003. *Field Analytic Technologies Encyclopedia*. Direct-Push Analytical Systems, ***http://clu-in.org/characterization/technologies/***.

U.S. EPA, 2001. Handbook for Suggested Practices for the Design and Installation of Monitoring Wells, EPA 600/4-89/034, Washington, DC.

U.S. EPA, Office of Solid Waste and Emergency Response, 1998. Innovations in Site characterization Case Study: Hanscom Air Force Base Operable Unit 1 (Sites 1, 2, and 3). Technology Innovation Office, EPA-542-R-98-006, Washington, DC.

U.S. EPA, 1997. Direct Push Technologies. In: Expedited Site Assessment Tools For Underground Storage Tank Sites. Solid Waste and Emergency Response, EPA 510-B-97-001, Washington, DC.