NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

SCIENCE ADVISORY BOARD

FINAL REPORT
HORIZONTAL DIRECTIONAL DRILLING

Prepared by:

Water Quality & Quantity Standing Committee

Approved by:

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EXECUTIVE SUMMARY

This report of the New Jersey Science Advisory Board Water Quality & Quantity Standing Committee addresses charge questions focused on the following:

- Does horizontal direction drilling (HDD) present a threat to the groundwaters of the State?
- What does the current science say about impacts of HDD?
- What steps are appropriate to minimize any threat?

Based on this review, HDD represents a potential risk to groundwater as well as to surface water and sensitive ecological receptors. The current science regarding impacts from HDD indicates fugitive drilling mud and fluids, referred to as "Inadvertent Returns" (IR) can include contaminants or otherwise become a source of pollution in groundwater, surface water/sediments, and/or ecologically sensitive areas. HDD may also facilitate translocation and/or cross-contamination of contaminants in otherwise separate subsurface aquifers, especially when performed proximal to contaminated sites. The Committee found that guidance is available on how to deploy HDD. However, New Jersey has no regulatory requirements pertaining to oversight of HDD. In contrast, conventional vertical wells are regulated in N.J.A.C. 7:9D. As a result of the significant negative impacts resulting from IRs and unsuccessful HDDs that have been documented in surveys of HDD projects and the potential for future risks to groundwater, surface water, and ecological areas associated with using this technology, management of HDDs throughout the process of planning, construction, installation, and decommissioning should be considered to prevent potential impacts and minimize risk. The Committee notes that any regulations of HDD could be patterned after those codified to govern conventional well installation, given the potential threats posed by HDDs, with input from experienced HDD contractors. As a result of the potential for environmental impact posed by HDD, areas for management of HDD recommended by the Committee include pre-drill planning, entry and exit hole management, and abandonment planning.

1. Introduction

Horizontal directional drilling (HDD) is a trenchless construction process for drilling boreholes and installing pipe without disturbing the surface and area under which the pipeline is needed. HDDs are often used to cross sensitive areas or difficult to construct areas that involve, for example, roads, wetlands, and waterbodies (CenterPoint Energy, 2013). This methodology has distinct advantages in not disturbing surface conditions. However, as is the case with any type of construction, the HDD process requires developing a sound plan that includes contingencies for any potential problem encountered and an approach for preventing long-term environmental impact.

The New Jersey Science Advisory Board's Water Quality and Quantity Standing Committee (WQ&Q) was charged with addressing the following questions by the New Jersey Department of Environmental Protection (NJDEP):

- Does horizontal direction drilling present a threat to the groundwaters of the State?
- What does the current science say about impacts of HDD?
- What steps are appropriate to minimize any threat?

This report summarizes the Committees response to the charge by addressing the following points:

- Background and benefits of HDD
- Key considerations in HDD well development to prevent problems encountered at sites and reduce environmental impacts posed by using HDD
- Recommendations

A general consensus among the committee members is that while there is clear guidance from industry groups and government entities on how to implement HDD projects, the operational process of planning, construction, installation, and monitoring lacks regulatory requirements, oversight, and enforcement in New Jersey. New Jersey has codified requirements for conventional (vertical) wells (N.J.A.C. 7:9D). These regulations specify detailed methods to be employed during drilling and requirements for decommissioning of abandoned wells. The methods and requirements mitigate the potential for improperly constructed or decommissioned wells to serve as conduits for transport of groundwater contaminants to previously protected aquifers. HDDs are currently not subject to these New Jersey regulations.

Because of the significant problems that may occur and have been documented from past experiences[1], a management framework should be considered for the entire HDD process from planning to construction, installation, and decommissioning. The guidance document developed by DOE (2019) for natural gas applications provides a detailed foundation for developing HDD installation procedures. However, additional requirements should be considered to minimize and

[1]In a survey of 54 HDD installation projects, inadvertent returns (IRs) were documented in approximately 50% (Skonberg, et al., 2008); in a discussion of HDD installations on County utility projects in Florida, the authors state: "Those projects have experienced many successes; however, there have also been many failures, such as lost drill tools, hydrofracture (IRs), failed drill stems, and other abnormal events." (Peters, et al., 2014).

mitigate potential impacts that have resulted from documented failures and unintended releases during past HDD installations. The Committee's recommendations can provide guidance for development of a framework for management of HDD projects.

2. Background and benefits of HDDs

The first applications of HDD technology are credited to Martin Cherrington, a utility construction contractor in Los Angeles, California, who built his own drilling rig in the early 1960s for angled boreholes (Farr, 1992). Cherrington completed the first river crossing using HDD equipment in 1971. The use of HDDs grew slowly until the late 1980s, when advancements in magnetic steering technology provided greater reliability in the location of the drill head in the subsurface and better control of the drilling path (Farr, 2012). The use of HDDs has increased exponentially over the last three decades, as continuing improvements in drilling and steering technology increased the reliability and range of HDD installations.

Early on, environmentalists expressed support for the development of HDD applications. HDD technology provided an alternative to the then-prevailing methods of installing utility pipelines and cables. Prior to the 1960s, petroleum and gas pipelines and other utilities were installed across rivers by open trenching, which had the potential to damage aquatic biota and suspend and redistribute historically deposited contaminants in river-bed sediments. Similarly, pipelines were installed across sensitive wetlands and marshes by trenching through the wetlands; the trenching and the placement of wooden platforms ("matting") to facilitate the mobilization of heavy equipment caused significant damage to these ecosystems. As several researchers and practitioners have pointed out, HDDs provided a method to advance utility pipelines at considerable depth underneath these environmental features, eliminating the disruptive threats (Skonberg et al., 2008; Yan et al., 2018).

HDD methods provide an efficient technology for utility installation under congested urban and industrial settings. Advancing open-cut trenching in these environments can be challenging and disruptive, given the density of existing utilities and inherent traffic control challenges caused by open-cut trenching in urban streets. HDDs offer the capability of advancing pipelines under these features, at depths that avoid existing infrastructure. HDDs have been employed to avoid disruption of other features, such as canals and roadways (Peters et al., 2014) as well as irrigation ditches and railroads (Price et al., 2015).

Installing a utility using HDD methods, because of the depth of installation, also provides increased pipeline security and protection from potential damage during subsequent construction events and natural disasters (Skonberg et al., 2008).

On a smaller scale, HDD technology has revolutionized the installation of smaller-diameter utilities, such as small gas, water, and sewer lines and electric and fiber optic cables. Small directional drilling rigs are able to install these utilities under buildings, structures, wetlands, and other obstructions and sensitive areas. The use of this technology has increased dramatically since the 1990s, even more so with the demand for fiber optic cables in the digital age (Utility Contractor Staff, 2018).

In the area of site remediation (i.e., the cleanup of soil and groundwater contamination), HDD applications have provided remediation practitioners the ability to enhance access to contamination under buildings, structures, and other relatively inaccessible impacted areas. The U.S.

Environmental Protection Agency (USEPA, 2017) issued guidance for regulators and other reviewers to evaluate the application of Horizontal Remediation Wells (HRWs); this guidance, an appendix to a larger guidance manual, identifies the technical aspects and advantages and disadvantages of using HRWs to remediate contaminated sites (USEPA, 2017). Angled and nearly horizontal wells have been installed through contaminated soil and groundwater to allow for the injection of air, oxygen, hot water, steam, oxidizing reagents, and amendments that foster bioremediation of impacted media, and to extract contaminant vapors, contaminated groundwater, and nonaqueous phase chemical product in otherwise inaccessible locations. In addition to allowing for installation in otherwise inaccessible areas, HRWs also can provide more direct contact with contaminated media than conventional vertical wells, thereby enhancing the distribution of amendments and the recovery of contaminants (USEPA, 2017; Lubrecht, 2010).

The discussion above indicates that there are several different applications for HDD technology, and different sizes of HDD installations. This report focuses primarily on the aspects and potential impacts of the larger HDDs. Generally, the larger HDD projects are associated with long distances (greater than 1,000 feet in length) and are designed for the installation of large diameter pipelines for transport of liquid petroleum and natural gas along with fiber optics and other communication cables. Their diameters are typically greater than 1 foot (12 inches).

Smaller HDDs are used for local installation of utility lines and communication cables, and for remediation wells. These are typically less than 1,000 feet in length and usually have diameters less than 12 inches. While some potential impacts can be associated with both large and small HDD installations, the larger HDDs are more subject to the problems and environmental impacts that will be identified throughout this report. Any efforts to expand existing New Jersey well regulations to include HDDs should recognize the differences between larger and smaller HDDs, and that not all regulatory requirements applied to larger HDDs may be applicable to smaller HDDs.

3. Key considerations in HDD well development to prevent problems and reduce environmental impact

This section reviews important considerations in HDD well development that should be part of the operational plan for larger HDDs: Inadvertent Returns, Environmental Impact, Geotechnical Investigations, Monitoring, Setbacks, Drilling Mud, and Grouting Material.

A. Inadvertent Returns

The HDD process uses the flow of large volumes of drilling slurry (primarily bentonite and water) to remove drill cuttings from the borehole; stabilize the walls of the borehole and prevent borehole collapse; and, cool and lubricate the drilling bit. Inadvertent returns (IRs) occur when the drill slurry seeps up through fractures and other conduits in overlying soils or rock. There are several factors that can increase the likelihood of IRs, including:

- The presence of loose, sandy soils;
- Poorly compacted soils and anthropogenic fill;
- Shallow borehole alignments with insufficient soil cover; and,
- The presence of disturbed soil by such features as tree roots, pilings, and previous boreholes.

Some factors evaluated did not have an effect on the frequency of IRs; these included slurry type, slurry viscosity, or the pumping rate employed to circulate the slurry.

The release of bentonite slurries into sensitive environments such as surface water bodies and wetlands can cause impacts that are difficult to mitigate effectively (Skonberg et al., 2008). A survey of large HDD installations determined that IRs occur at all stages of an HDD project – the initial pilot borehole, the reaming of that pilot hole to the final diameter, and the pullback of the assembled pipe through the reamed hole. The majority of IRs evaluated in the survey, more than 60%, occurred during the drilling of the initial pilot hole (Skonberg et al., 2008).

Several authors have recommended measures to reduce the potential for IRs during HDD projects. Peters et al. (2014) recommended the following steps:

- Collect sufficient geologic and geophysical data along the HDD alignment to identify soil and bedrock conditions.
- Off-set geotechnical borings from the alignment centerline to avoid creating conduits for slurry seepage directly over the HDD (an off-set of 25 feet was recommended).
- The HDD design requires diligent planning, accounting for geologic complexity. The plan should include the selection of the appropriate drilling rig, drill head, slurry type, and locating system; the selection and use of an industry-accepted drilling software; and, a plan to inspect and ensure that the drilling equipment has been properly maintained and is in good working order.
- Avoid overly aggressive design, in particular overly aggressive curves, and “3-dimensional” curves (i.e., curves that bend both in the horizontal plane and vertically simultaneously).
- Regulatory and local agencies need to assign properly trained inspectors to monitor HDD installations to identify indications of potential IRs.

- Develop an IR response and mitigation plan. Other authors have indicated that a mitigation plan should include obtaining access (in the form of rights-of-way or easements) to the first and last 200 linear feet of the HDD alignment, as this is where the majority of IRs have occurred (Skonberg et al., 2008).

B. Environmental Impact

HDD is a strategy whereby pipelines and cables are installed underground without open trenches. The execution of much of this process underground is less disruptive to the surrounding rivers and creeks, neighborhoods, flora, and fauna and ultimately safer and more protective of the environment. However, significant environmental considerations need to be addressed during these projects to ensure that the drilling process can be both effective and safe, minimizing potential threats to groundwater, surface water, and sensitive ecosystems. Although many environmental precautions and considerations can be project- or site-specific, it is apparent that there are some common concerns that should be addressed during the planning, preparation, and execution of HDDs.

As discussed in the earlier section on Inadvertent Returns, drilling muds serve many functions including preventing influx of various fluids such as oil, gas, or water from any permeable rocks that may be penetrated in the process. In addition, drilling fluid is used to maintain the stability of the borehole, maintain pressure around the borehole to prevent any blowouts, and reduce friction between the sides of the hole and the drill string (Caenn and Gray, 2017).

HDDs have the potential to cause damage to groundwater resources. As with conventional (vertical) wells, the creation of a continuous conduit through different geologic deposits and rock formations can interconnect groundwaters of different qualities and introduce contaminants from an impacted geologic unit into previously unimpacted aquifers that are used, or have the potential to be used, for water supply. The potential for contaminant transport is present during pilot-hole drilling, reaming, and pipe pullback; that potential is influenced by the ability of the drilling mud to create a “cake” on the borehole walls and prevent fluid migration.

Failed and abandoned HDD projects present a greater risk for contaminant transport, since there are currently no requirements in New Jersey for proper decommissioning of abandoned HDD boreholes. The non-aqueous components of drilling muds left in abandoned boreholes will tend to separate over time, resulting in a decrease in the sealing properties of the mud, thereby increasing the ability of the abandoned borehole to provide a conduit for contaminant transport between different, previously separated geologic units.

One of the most cited environmental concerns associated with HDD is the risk of IRs and drilling mud leakage into the soil and nearby bodies of surface and groundwater (Slade, 1998; George Washington National Forest, 2021). Drilling mud, classified as a contaminant by the Clean Water Act when released, has the potential to negatively impact freshwater ecosystems by increasing water turbidity, altering overall water chemistry, and introducing harmful chemicals to plants and animals that could cause injury (Slade, 1998; Kwast-Kotlarek et al., 2018; Tetra Tech Incorporated, 2016a; Lubrecht, 2012). Strategies to prevent IRs or other releases that could pose a threat to groundwater and surface water include pre-drill planning, entry and exit hole management, emergency response planning, and sealing of bore holes (i.e., abandonment).

A recent spill occurred during the construction of the Marine East II Pipeline, where Sunoco released roughly 8,000 gallons of drilling mud into Marsh Creek Lake (Pennsylvania Department of Environmental Protection, 2021). This type of release can increase the salinity and conductivity of a body of water, alter the overall chemistry of the water, and impact the existing freshwater ecosystems (i.e., George Washington National Forest). The type and severity of the impacts of the drilling mud to the surrounding environment, however, vary largely based on the type used (Fink, 2015). When a spill impacts source water for drinking water treatment systems, rapid response and communication is required to not only minimize the contamination, but also inform all county and state officials to prevent exposure and impacts. As a result, the composition of all chemicals used on site should be documented and thoroughly researched to understand all possible interactions that may occur in the case of a small-scale leak or a large-scale spill or rupture.

IRs associated with drilling projects performed adjacent to or beneath bodies of surface water can disrupt aquatic wildlife and water supplies used for agriculture and drinking water. Drilling mud migration during HDD projects through aquifers utilized for water supply can locally reduce an aquifer's permeability and reduce flow to water supply wells. At the locations of HDD entry and exit holes, storm events can result in transport of drilling mud and cuttings from mud pits and cuttings storage areas. The land surface should be surveyed at the entry and exit holes to assess this risk, and preventative measures implemented where warranted.

Overall, impacts from HDD projects, especially related to IRs, present a greater risk to surface water systems and sensitive ecological habitats, such as wetlands. The potential impacts to groundwater resources from migration of drilling muds associated with HDD projects are likely to be less frequent and be limited in areal extent. Of greater threat to groundwater resources is the potential for HDD boreholes to serve as a conduit for the migration of groundwater contaminants from an impacted groundwater unit to previously uncontaminated aquifers.

C. Geotechnical Investigations

A successful HDD project requires a detailed understanding of the subsurface characteristics along the alignment. A subsurface investigation for an HDD project should include these two main elements: utility and obstruction investigation and a geotechnical investigation.

i. Utility and obstruction investigation

The presence of existing obstructions could impact HDD design. The HDD operator has no view of the ground ahead; therefore, the identification of potential obstructions and utility clearances must be as complete and accurate as possible. ASCE Standard 38-02 and OSHA Safety and Health Information Bulletin 031318 provides guidance on subsurface utility research; considerations include:

- Identification of utilities, adjacent structural foundations, or other man-made subsurface obstructions. Particularly important in urban environments/densely populated areas with a complex subsurface utility infrastructure (pipes, conduits, cables). This research should include a review of available public records and utility maps, communicating with utility companies (directly, when possible), and field inspection for evidence of subsurface utilities.

- If the HDD alignment is expected to pass within 10 feet of utilities it is recommended that a physical confirmation of the utilities is done prior to starting the HDD operations. Existing confirmation methods include pipe locators; geophysical surveys (e.g., ground penetrating radar; magnetometer survey; seismic survey); probing; manual excavation and/or vacuum excavation (potholing).

ii. Geotechnical investigations

A detailed subsurface geotechnical survey is critical to minimize risks of failure during HDD construction (Strater and Dorwart, 2015). The geotechnical survey should:

- Provide the basic data necessary to make critical design and construction decisions.
- Provide the basis for a proper risk assessment and identification of potential mitigation measures.
- Identify areas of potential geologic risk.

A geotechnical evaluation should be completed by a qualified soil or geotechnical engineer to determine (Pipeline Design for Installation by HDD, 2014):

- Subsurface stratigraphy.
- Particle size distribution in unconsolidated materials (particularly percent gravel and cobble).
- Strength properties (cohesion, internal angle of friction) and soil classification.
- Plastic and liquid limits (clays), expansion index (clays), soil density, and penetration tests.
- Determination of bedrock depth.
- If the HDD is going to traverse bedrock, a thorough characterization of the bedrock is necessary; it should include bedrock type, rock strength (UCS), weathering, hardness, and jointing (intensity – rock quality designation and orientation). Identification of the contact between different rock types can be a critical element of HDD design.
- Identification of groundwater level and characterization of groundwater conditions (permeability, heterogeneity, and other properties), local and regional.
- Areas of suspected and known contamination should be identified and characterized. If any contamination is encountered in subsurface samples, it should be documented.

It is common practice to conduct a site investigation in phases. The initial phase of field investigations should consist of detailed review of geological conditions along the HDD alignment and in its general environs. This should include a desk top study of available data including remote sensing imagery, aerial photography, published geologic information, and a field reconnaissance. This review of geologic conditions on a regional and alignment-specific scale should be directed by a qualified geologist; qualifying credentials should be equivalent to a Professional Geologist license awarded by certain states.

The information obtained during the geologic review should be used as a guide in planning the subsequent geotechnical exploration. Field reconnaissance frequently reveals challenges and potential obstacles that may be expected in later exploration phases; these challenges should influence the type, number, and locations of borings required. Even though site investigation will vary from project to project, it should be as comprehensive as possible, and include and address the following (Pipeline Design for Installation by HDD, 2014; ASCE, 2007).

- Geotechnical borings should be adequate in number and spacing – depends greatly on the project and site characteristics –and be tailored to suit the complexity of HDD being designed. The geotechnical investigation program should consider site-specific factors such as the general geology of the area, availability of access, availability of existing data, cost, and others.
- Borings with sufficient depth (should go below the proposed alignment).
- Boreholes should be offset from the drilled path center line to minimize the possibility of drilling fluid inadvertently surfacing through the borings during HDD operations.
- Abandonment of exploratory boreholes: should be backfilled in a manner to minimize vertical fluid migration through the boreholes. A mixture containing cement grout and a bentonite product to promote expansion, which will minimize the possibility of migration, is recommended in critical portions of the borehole. Cuttings from the drilling operation may be incorporated into the backfill if considered beneficial.
- Sufficient lab testing of samples. The calculation of the maximum allowable mud pressures to model potential IRs is a key element of the design. An IR occurs when the mud pressure exceeds the strength of the surrounding ground and allowing the drilling mud to escape through induced fractures or fissures in the surrounding ground. to calculate the maximum allowable pressures (i.e., geotechnical parameters such as unit weight, cohesion, friction angle, and Young's modulus should be determined during the investigation) (for details on how to calculate the maximum allowable pressure during HDD see e.g. Luger and Hergarden, 1988).
- Identification of "problematic" formations that may present risk to trenchless installations. For example, glacial till deposits should be expected to contain cobbles and boulders, even if they are not encountered by the test borings.
- Heterogenous conditions (e.g., the project must bore through rapidly changing conditions).
- Additional exploratory boreholes should be considered if substantial variations in soil conditions are identified in the geologic review or during initial geotechnical investigations (e.g., the presence of gravel, cobble, and/or boulders).

D. Steering and Monitoring

Steering and monitoring are crucial during HDD. Since the drilling head is underground and not visible to the operator, it is essential to make sure that the operator always knows the location of the drilling head for a controlled drill. Uncontrolled drilling can have devastating consequences that include impacts to the safety of the public and workers, environmental issues, damage to surface structures, and striking obstructions such as other underground structures or utilities, which can contribute to bore failure.

There are three main systems for locating the drilling head during construction: walk-over, wireline, and gyro-based locating systems (Younkin, 2019, English, 2018, Benett and Ariaratnam, 2017). Site conditions and characteristics of the HDD project will often determine which system is the most suitable.

- **Walk-Over Locating Systems** use a transmitter, or sonde, placed behind the drill head sends an electromagnetic signal through the ground to a receiver positioned on the surface. The signal provides information relating to direction, angle, rotation, and more. The receiver is usually a handheld unit which allows the operator to follow the path of the bore. Because the system uses an electromagnetic signal to relay data, it works best in locations where there are few obstructions to block the signal. They are relatively easy to set up and are best suited when there are not many obstructions near the bore path as interferences impact their effectiveness, particularly near sources of water or in areas with many existing utility lines. The accuracy of these systems is limited to shallow bores (depth is one of its limitations). The more advanced versions provide real-time remote guidance and can work on multiple frequencies. However, this technology is still limited by the depth to which it can detect the drill head and its susceptibility to interference.

- **Wireline Locating systems** use magnetic guidance and a wire grid to read relevant information which is sent via wire, inside the drill pipe, to a receiver. Some systems use a gyroscope in addition to magnetic guidance, but gyro-based systems are a separate class. Like walk-over systems, the data sent to the receiver determines the depth, angle, rotation, and direction of the drill head. However, magnetic wire-line systems can monitor the head from a greater distance, since they are a non-walk over system Additionally, the in-ground wire's signal can bypass some potential interference. These factors make these systems more accurate when locating and steering as well as safer to the operator. A surface coil can be used to improve tracking accuracy. This consists of an energized wire that is laid out around the perimeter of the site. Measurements can be taken from known surveyed points within the coil. That information is used to improve tracking and steering accuracy of bore. Wireline systems are more costly and time-consuming to implement than the walk over systems, as a result its selection will depend on the length of the bore and site conditions.
- **Gyro-Based Locating Systems** are wireline locating systems that gyroscopes to track the location of the drill bit. They are the most accurate locating systems (English, 2018). One of their great advantages is limited susceptibility to magnetic interference. It can be the optimal choice when the bore needs to cover long distances, and when the HDD alignment runs under structures (e.g., high voltage cables) that can interfere with a magnetic coil on the surface, or when a high degree of accuracy of the position location is needed (e.g. parallel HDD bores) . Creating a magnetic field above lakes and rivers can be difficult. In these cases, project managers may opt for gyro steering instead of magnetic steering, as they do not require surface access to bore path. Gyro steering is also used in areas considered environmentally sensitive where a magnetic field may disturb the surrounding environment or habitats. If an HDD project requires the use of casing when completing the initial drill or a portion of the drill, then Gyro steering tools may be better suited as they are insensitive to magnetic disturbances and interferences that may be caused by casing. Gyro-based locating systems are the most expensive of the three locating systems but are

the most suitable for longer distances, they are the most accurate, have limited susceptibility to interferences and have no depth restrictions.

In addition to locating the drill head during construction, monitoring of the drilling fluid pressure inside the bore during construction is essential for a real-time IR risk management. Pressure monitoring can be used with any of the tracking systems described above.

E. Setbacks

In the planning of HDD projects, owners and contractors understand the importance of securing sufficient workspace at the locations of the exit and entry holes to allow for the placement of drilling equipment, the creation of mud pits, the management of drilling wastes, and the fabrication of the pipe for the pullback through the drilled boring. Often the largest space requirement is prompted by the area needed to fabricate the pipe (i.e., weld together the sections of pipe prior to pullback to minimize interruptions for welding during the pullback operation) (Whisler et al., 2013). This workspace is secured through various means, including procurement of easements and rights-of-way, and property acquisition.

In addition to the workspace needs at the entry and exit holes, project planners should also obtain access, through rights-of-way, easements, or other means, to the sections of the alignment where there is a potential for IRs, to facilitate rapid response and cleanup. According to Skonberg et al. (2008), IRs occur in about half of all HDD installations the authors surveyed, and they occurred most frequently in the initial 200 linear feet from the entry and exit holes. The authors recommend obtaining rights-of-way in these 200-foot segments of the alignment, and that the project planners have response plans in place and the necessary equipment to rapidly mitigate the impacts caused by IRs.

F. Drilling Mud

Drilling mud is a critical contributor to the overall success of an HDD project. The wrong drilling mud can cause serious problems such as IRs and borehole collapse. Hence, it is imperative that the right drilling mud is chosen based on site conditions for an HDD project to run smoothly and efficiently (Mishra, 2019). Usually, a drilling mud is injected into the bore during cutting and reaming to stabilize the bore hole and to remove soil cuttings. The mud reduces drilling torque and gives stability and support to the bored hole. The mud must have sufficient gel strength to keep cuttings suspended for transport, to form a filter cake on the borehole wall, and to provide lubrication between the pipe and the borehole on pullback. Drilling muds are usually thixotropic (i.e., exhibit a time-dependent, shear-thinning viscosity; thicken or are viscous under static conditions), and thus thicken when left undisturbed after pullback (Plastic Pipe Institute, 2021).

Generally, the drilling mud is of two types based on the primary fluid constituent: water-based mud (WBM) and synthetic-based mud (SBM), where the synthetic fluid is typically low-toxicity non-petroleum-based oil (Mishra, 2019). Petroleum-oil based mud (OBM) is no longer used extensively in HDD projects because of their relatively low biodegradability and environmental impact.

- **WBM:** The primary constituent of WBM is water; additives constitute only about 3-4%. The quality of water affects the final drilling mud. The water is typically sourced from local creeks, rivers, or municipal water utilities. Additives are more effective when the pH of the water is between 8.5 and 9.5 and the calcium content is lower than 100 ppm (Mishra, 2019). The primary clay used for drilling mud is sodium montmorillonite (bentonite). Properly ground and refined bentonite is added to water to produce the "mud" (Plastic Pipe Institute, 2021). The gelatinous form and cake-like texture of WBM help seal the borehole walls, preventing the fluid from escaping through crevices in the wall, thereby mitigating the potential for IRs. The final constituent of drilling mud is an additive. Several additives are available, and each is suited for different conditions. Polyaluminum chloride (PAC) is an additive commonly used in sand and cobbles. Partially hydrolyzed polyacrylamide (PHPA) polymers work better in reactive clays than bentonite. Polymers with larger molecular weights are most suitable for rocky soils (Mishra, 2019).

- **SBM:** Also known as low toxicity oil-based mud (LTOBM), SBM is an invert emulsion mud with synthetic oil as the base constituent instead of petroleum-derived mineral oils, which do not biodegrade easily. There was a need to develop a drilling fluid that could match the high performance of OBMs but would be more environmentally friendly. This led to the development of SBM that was formulated with greater biodegradability and reduced toxicity (Mishra, 2019). Similar to petroleum OBMs, SBMs can maximize the rate of penetration, increase lubricity in directional and horizontal wells, and reduce problems related to wellbore instability such as in reactive shales (Mishra, 2019).

Among the additives, surfactants are used to lubricate downhole tooling, reduce torque on the drill string, and inhibit reactive clays and shales. Xanthan Gum at low concentrations is used to boost the drilling fluid viscosity, without substantially increasing the fluid density (Sauls et al., 2018). Flocculating agents are used to help the clay particles aggregate so they are transported in larger sand- and gravel-sized particles. Sodium carbonate is used to increase the pH of the drilling fluid makeup water and aid in the hydration of the bentonite. However, sodium carbonate in the drilling fluid can increase the groundwater pH and carbonate concentration around the drilling holes. If aquifer sediments or soils contain elevated arsenic and uranium concentrations, high pH and high carbonate concentrations can increase the release of these toxic chemicals from the sediments and soils into the groundwater. Therefore, the use of sodium carbonate in drilling fluid is not recommended in areas with high naturally occurring arsenic and uranium, even though the impacted groundwater area may be small. Foam is used primarily in drilling through rock when small, uniform, rock flakes have to be transported to the entry pit (Sauls et al., 2018).

Drilling mud composition varies from one HDD project to another. Finding the right drilling mud mix for any HDD project requires proper understanding of the soil conditions along the alignment. The wrong mud composition can cause the fluid to break through the sidewall, causing an IR. The more thorough the geotechnical investigation of the proposed HDD path, the more precisely the ideal drilling mud formula can be determined (Mishra, 2019). Drilling muds are designed to match the soil and cutter (Plastic Pipe Institute, 2021). The order of mixing also plays a role. Adding polymers before the bentonite has thoroughly mixed can cause balling. PAC polymers should be added before PHPA polymers and dry polymers before liquid polymers (Mishra, 2019).

The components of drilling muds, both WBM and SBM, are essentially non-hazardous materials. WBMs are primarily water-bentonite mixtures, sometimes with non-toxic polymer additives to maintain specific viscosity, density, or other properties. Bentonite is a naturally occurring type of clay that is non-toxic and commonly used in farming practices (New York State Department of Public Service [NY DPS], 2019). SBMs are composed of synthetic oils that are biodegradable and non-toxic. The additive materials are required to be chemically inert, biodegradable, and non-toxic, and petroleum-based additives should not be used (Plastic Pipe Institute, 2021). However, these materials may become a cause for potential concern when an HDD is used to cross beneath sensitive habitats, waterways, and/or cultural or historic resource areas. The release of drilling mud into a stream or similar (especially clear water) habitat may subject benthic invertebrates, aquatic plants, and/or fish and their eggs to sedimentation or suspended solids that can potentially be detrimental to their populations (NY DPS, 2019). Drilling muds can also become toxic when drilling in an area known to contain toxic pollutants (Plastic Pipe Institute, 2021). In such cases, disposal must be in accordance with local laws and regulations, and it may be necessary to dewater the spoils, transport the solids to an appropriate disposal site, and treat the water to meet disposal requirements (Plastic Pipe Institute, 2021). It may also be necessary to add grout to the drilling fluid to ensure proper sealing of the bore hole to eliminate a possible passage for contaminants or install a surface casing to seal the contaminated media from the borehole. Special drilling fluid pumps may then be required (Plastic Pipe Institute, 2021). It should also be recognized that bentonite-based drilling muds are inorganic and hence not biodegradable, and therefore can have undesirable effects on the environment. For example, after a directional drilling run using conventional drilling fluid, a pool of thick sludge forms at the exit and/or entry site. If not cleaned up or recycled, it solidifies into a hard, clay material (Harr, 2013).

Researchers at Oklahoma State University performed an in-depth chemical and physical characterization of spent HDD muds (Daniel and Penn, 2017). A total of 56 samples from 28 different states were received and analyzed for total solids, pH, total salts, sodium, plant available nutrients, and heavy metals. Two field studies were conducted to examine any potential agronomic or environmental impact resulting from the land application of spent HDD mud (Daniel and Penn, 2017). The first study involved surface application of HDD mud to a typical Bermudagrass hay followed by measurements of soil chemical properties and resulting biomass production. The second field study involved the application of HDD mud to a bare ground, which was meant to represent a highly disturbed construction site. Bermudagrass seed was then spread on both mud-amended and unamended soils. Daniel and Penn (2017) reported that after 60 days, cover for the plots that received 10 tons of solids per acre was significantly higher than the unamended control plot. The authors concluded that land application of spent HDD mud is a viable option for disposal because there is nothing chemically limiting unless a driller is boring through historically contaminated sites (Daniel and Penn, 2017).

With respect to the process for the use of drilling fluids and additives, NSF/ANSI 60 certified chemicals are recommended. Furthermore, consistent with Pennsylvania's "HDD IR Assessment, Preparedness, Prevention and Contingency Plan" it is recommended that the composition of drilling muds proposed for use be submitted for NJDEP approval (Tetra Tech, Inc., 2016b).

G. Grouting Material

When HDD drilling operations or pipe installation fail, the drill hole must be abandoned. Most of the HDD guidance and contingency plans specify that the abandoned drill holes will be filled or sealed (Miami Dade County, 1999; CALTRANS, 2015; Emerald Coast Utilities Authority, 2014; Maryland Department of the Environment, 2021). However, in Michigan's HDD Guidance (2014), only drill holes greater than 3 inches in diameter need to be filled. In addition, CenterPoint Energy (2013) recommends only 30 linear feet at each end a drill hole needs to be sealed. CALTRANS (2015) requires backfilling the abandoned drill hole if it is beneath a road to prevent future subsidence. Currently New Jersey does not have regulations requiring the proper abandonment of failed HDDs.

Appropriate grouting material, including cement and bentonite, should be used to fill the entire length of an abandoned well and annular space of a completed well to prevent the potential pathways of water flow through it and to prevent the connection of different groundwater aquifers and contaminant sources. The grouting material should ensure permanent low permeability of the filled well. It should not contain organic and inorganic pollutants and should be stable in the environment. Fly ash containing heavy metals such as arsenic and mercury should not be used in grouting material. Because drilling fluids may contain pollutants and additives that prevent the grouting material from forming stable and low-permeable solids, they should not be used as grouting material and should be removed from bore holes before grouting.

Type I cement and bentonite are the most common materials used for making grout slurries (Michigan Department of Environmental Quality, 2019). The cement grout slurry forms a hard and stable solid that will not be washed away by groundwater in porous soils and fractured rock formations. Proper water-cement ratio is an important factor in the preparation of cement grout slurry because as the water-cement ratio increases, the compressive strength of the cement decreases and shrinkage and permeability of the cement increase.

Bentonite is an aluminum silicate clay that has the ability to absorb large quantities of water to form highly thixotropic colloidal suspension or gel, which increases its volume by up to a factor of eight (Jackson, 1997). It is commonly used to make drilling mud because of its excellent plasticity and lubricity. Bentonite grout offers low permeability. However, the colloidal suspension or gel can be washed away by groundwater in highly porous soils and fractured rock formations. In the unsaturated zone, it shrinks significantly, creating cracks and allowing groundwater to flow through. The solids in dilute bentonite grout can settle, resulting in an open upper bore hole and annulus. Therefore, high solids bentonite grouts (9.4 lbs/gal) are required, and bentonite grouts should not be used in porous formations (Michigan Department of Environmental Quality, 2019). The State of California has issued a notice of exclusion on the use of bentonite slurries as a sealing material for annular seals for the construction and the decommissioning of wells (County of San Diego Department of Environmental Health, 2016). Only high solids bentonite grout and non-slurry bentonite are recommended. The State of California also reported that bentonite may not perform adequately in unsaturated zones.

4. Recommendations

Currently, HDDs are not regulated in New Jersey. In contrast, conventional vertical wells - for example, water supply wells, monitoring wells, and groundwater heat-pump wells - are regulated in N.J.A.C. 7:9D. These regulations specify, in great detail, how vertical wells are to be permitted, constructed, and decommissioned, and specify licensing requirements for drillers who install and decommission wells.

The Committee recommends that any regulations drafted for HDD be patterned after those codified in N.J.A.C. 7:9D, with appropriate input from experienced HDD practitioners, to manage the installation of HDDs given the potential threat posed to groundwater and surface water.

The following items are suggested as areas for management of HDD to address issues and concerns identified in the above response to the charge questions:

A. Pre-Drill Planning

A certain amount of due diligence and pre-drill investigation is critical for the design of a successful HDD. The planning efforts should include:

- Compiling information about potential historical subsurface structures along the alignment.

- Conducting a survey of subsurface utilities and other obstructions along the alignment.

- Environmental due diligence of the sites of the entry and exit holes, to identify any soil and groundwater contamination impacts that could require additional protective design measures. Information on naturally occurring toxic chemicals, such as arsenic and uranium, in groundwater aquifers along the entire length of the borehole should be obtained to take necessary measures to prevent the mobilization of the toxic chemicals from the aquifer sediments into groundwater and to prevent the connection of contaminated and clean aquifers. Recommendations for due diligence for projects that transect multiple properties are included in the NJDEP's Linear Construction Technical Guidance (NJDEP, 2012).

- A geotechnical investigation along the proposed alignment to determine geologic conditions, with emphasis in identifying sensitive areas and problematic ground conditions (e.g., loose sandy soils and gravel, swelling clays, transition zones, preferential paths for IR such as fractures and karst features) to support a successful HDD design and minimize the risk of IRs. One of the factors contributing to IRs is the presence preferential paths, such as fractures, cracks, or karst features. A proper geotechnical investigation should be able to identify these features, and, if possible, these features should be avoided by the alignment. Other measures to mitigate the risk from IRs due to preferential paths include the use of drilling fluid additives, casing off the zone, or grouting.

- Adequate analytical analysis of fluid pressures versus depth of cover can be used to determine adequate depth of cover required to minimize IRs. A detailed and careful calculation of maximum allowable and minimum required drilling fluid pressures is vital to reduce and mitigate the risk of IRs. Furthermore, the difference between these two thresholds needs to be reasonably apart otherwise the design should be modified to reduce the risk of IRs.

- An appropriate steering system and monitoring plan. The risk of IR can be mitigated by adopting good drilling practices, which include: 1. experienced drillers; 2. standard process and procedures in place for drilling, data collection, and communication; 3. proper drill fluid monitoring (fluid properties, fluid volume and flow, and downhole annular pressure).

- Development of an IR response plan, so that equipment and trained personnel are in place for rapid response.

- Acquisition of rights-of-way or easements for at least the first 200 linear feet from both the entry and exit holes so that no access-related delays are incurred to respond to IRs.

B. Entry and Exit Hole Management

- Large HDD projects require managing large volumes of drilling mud and other fluids and the cuttings generated during drilling. HDD constructors should develop plans to manage drilling fluids to minimize impacts to soil and groundwater quality at the entry and exit hole sites.

- The constructors should have plans in place for the disposal of drilling muds and cuttings and ensure that such disposal complies with all federal and state waste disposal laws and regulations.

- At sites with known soil and groundwater contamination impacts, additional design precautions are needed to minimize the potential for the HDD to become a conduit for the transport of contamination occurring in shallow strata into deeper, unimpacted geologic formations and potential water-bearing aquifers. Such design precautions should include the installation and grouting in place of larger diameter casings to isolate and prevent migration from the contaminated strata.

- Cuttings from the contaminated portions of the HDD and drilling fluids that come into contact with them should be sampled and classified for proper waste disposal in accordance with all federal and state waste disposal laws and regulations.

C. Abandonment

- Abandonment procedures should be included in an HDD operation plan and should be approved by the appropriate permitting and regulatory agencies prior to their implementation.

- An abandoned drill hole should be completely filled with clean and low-permeability materials to prevent the creation of migration pathways and the interconnection of different groundwater aquifers and contaminant sources. This is especially necessary if there are potential sources of pollutants in the abandoned drill hole area, such as wastewater pipes, landfills, contaminated soil and groundwater, and naturally occurring toxic substances. Naturally occurring arsenic is commonly found some soils, geologic formations, and aquifers in New Jersey. Connection of impacted aquifers by abandoned drill holes may contaminate clean aquifers. In addition, connection of anaerobic and aerobic aquifers can result in oxidative release of arsenic from arsenic-containing pyrite minerals and reductive release of arsenic from arsenic-containing iron oxide minerals.

- Clean and low-permeable filling materials, such as cement and bentonite, should be used to fill abandoned drill holes. Because fly ash may have heavy metal contamination, including mercury and arsenic, it is not recommended to use fly ash as a component of filling materials and grouts. The composition of filling materials and grouts should be reported in the abandonment procedures.

- Drilling fluids and additives should include only NSF/ANSI 60 certified chemicals and it is recommended that proposed use of variations from the certified additive composition of drilling muds be submitted for review and pre-approval.

- If drilling fluids contain additives that prevent filling materials from forming stable and low-permeable solids, the fluids should be removed from abandoned drill holes before filling them.

- For successful HDDs, it may still be advisable to replace the drilling mud with a thicker bentonite or cement/bentonite slurry that will harden to form a low-permeability grout in the annular space between the casing and the borehole. This replacement could occur concurrently with pipe pullback. At a minimum, a high-density grout should replace the drilling mud for the first 50 to 100 linear feet from both the entry and exit holes, and under roadways and other structures that could be damaged by subsidence.

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