

Chapter 12

Horizontal Directional Drilling

Introduction

The Horizontal Directional Drilling (HDD) Industry has experienced so much growth in the past two decades that HDD has become commonplace as a method of installation. One source reported that the number of units in use increased by more than a hundred-fold in the decade following 1984. This growth has been driven by the benefits offered to utility owners (such as the elimination of traffic disruption and minimal surface damage) and by the ingenuity of contractors in developing this technology. To date, HDD pipe engineering has focused on installation techniques, and rightfully so. In many cases, the pipe experiences its maximum lifetime loads during the pullback operation.

The purpose of this chapter is to acquaint the reader with some of the important considerations in selecting the proper PE pipe. Proper selection of pipe involves consideration not only of installation design factors such as pullback force limits and collapse resistance, but also of the long-term performance of the pipe once installed in the bore-hole. The information herein is not all-inclusive; there may be parameters not discussed that will have significant bearing on the proper engineering of an application and the pipe selection. For specific projects, the reader is advised to consult with a qualified engineer to evaluate the project and prepare a specification including recommendations for design and installation and for pipe selection. The reader may find additional design and installation information in ASTM F1962, "Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of PE Pipe or Conduit Under Obstacles, Including River Crossings," and in the ASCE Manual of Practice 108, "Pipeline Design for Installation by Directional Drilling."

Background

Some of the earliest uses of large diameter PE pipe in directional drilling were for river crossings. These are major engineering projects requiring thoughtful design, installation, and construction, while offering the owner the security of deep river bed cover with minimum environmental damage or exposure, and no disruption of river traffic. PE pipe is suited for these installations because of its scratch tolerance and the fused joining system which gives a zero-leak-rate joint with design tensile capacity equal to that of the pipe.

To date, directional drillers have installed PE pipe for gas, water, and sewer mains; communication conduits; electrical conduits; and a variety of chemical lines.

These projects involved not only river crossings but also highway crossings and right-of-ways through developed areas so as not to disturb streets, driveways, and business entrances.

PE Pipe for Horizontal Directional Drilling

This chapter gives information on the pipe selection and design process. It is not intended to be a primer on directional drilling. The reader seeking such information can refer to the references of this chapter. Suggested documents are the “Mini-Horizontal Directional Drilling Manual”⁽¹⁾ and the “Horizontal Directional Drilling Good Practices Guidelines”⁽²⁾ published by the North American Society for Trenchless Technology (NASTT).

Horizontal Directional Drilling Process

Knowledge of the directional drilling process by the reader is assumed, but some review may be of value in establishing common terminology. Briefly, the HDD process begins with boring a small, horizontal hole (pilot hole) under the crossing obstacle (e.g. a highway) with a continuous string of steel drill rod. When the bore head and rod emerge on the opposite side of the crossing, a special cutter, called a back reamer, is attached and pulled back through the pilot hole. The reamer bores out the pilot hole so that the pipe can be pulled through. The pipe is usually pulled through from the side of the crossing opposite the drill rig.

Pilot Hole

Pilot hole reaming is the key to a successful directional drilling project. It is as important to an HDD pipeline as backfill placement is to an open-cut pipeline. Properly trained crews can make the difference between a successful and an unsuccessful drilling program for a utility. Several institutions provide operator-training programs, one of which is University of Texas at Arlington Center for Underground Infrastructure Research and Education (CUIRE). Drilling the pilot hole

establishes the path of the drill rod (“drill-path”) and subsequently the location of the PE pipe. Typically, the bore-head is tracked electronically so as to guide the hole to a pre-designed configuration. One of the key considerations in the design of the drill-path is creating as large a radius of curvature as possible within the limits of the right-of-way, thus minimizing curvature. Curvature induces bending stresses and increases the pullback load due to the capstan effect. The capstan effect is the increase in frictional drag when pulling the pipe around a curve due to a component of the pulling force acting normal to the curvature. Higher tensile stresses reduce the pipe’s collapse resistance. The drill-path normally has curvature along its vertical profile. Curvature requirements are dependent on site geometry (crossing length, required depth to provide safe cover, staging site location, etc.) But, the degree of curvature is limited by the bending radius of the drill rod and the pipe. More often, the permitted bending radius of the drill rod controls the curvature and thus significant bending stresses do not occur in the pipe. The designer should minimize the number of curves and maximize their radii of curvature in the right-of-way by carefully choosing the entry and exit points. The driller should also attempt to minimize extraneous curvature due to undulations (dog-legs) from frequent over-correcting alignment or from differences in the soil strata or cobbles.

Pilot Hole Reaming

The REAMING operation consists of using an appropriate tool to open the pilot hole to a slightly larger diameter than the carrier pipeline. The percentage oversize depends on many variables including soil types, soil stability, depth, drilling mud, borehole hydrostatic pressure, etc. Normal over-sizing may be from 1.2 to 1.5 times the diameter of the carrier pipe. While the over-sizing is necessary for insertion, it means that the inserted pipe will have to sustain vertical earth pressures without significant side support from the surrounding soil.

Prior to pullback, a final reaming pass is normally made using the same sized reamer as will be used when the pipe is pulled back (swab pass). The swab pass cleans the borehole, removes remaining fine gravels or clay clumps and can compact the borehole walls.

Drilling Mud

Usually a “drilling mud” such as fluid bentonite clay is injected into the bore during cutting and reaming to stabilize the hole and remove soil cuttings. Drilling mud can be made from clay or polymers. The primary clay for drilling mud is sodium montmorillonite (bentonite). Properly ground and refined bentonite is added to fresh water to produce a “mud.” The mud reduces drilling torque, and gives stability and support to the bored hole. The fluid must have sufficient gel strength to keep cuttings suspended for transport, to form a filter cake on the borehole wall that

contains the water within the drilling fluid, and to provide lubrication between the pipe and the borehole on pullback. Drilling fluids are designed to match the soil and cutter. They are monitored throughout the process to make sure the bore stays open, pumps are not overworked, and fluid circulation throughout the borehole is maintained. Loss of circulation could cause a locking up and possibly overstressing of the pipe during pullback.

Drilling muds are thixotropic and thus thicken when left undisturbed after pullback. However, unless cementitious agents are added, the thickened mud is no stiffer than very soft clay. Drilling mud provides little to no soil side-support for the pipe.

Pullback

The pullback operation involves pulling the entire pipeline length in one segment (usually) back through the drilling mud along the reamed-hole pathway. Proper pipe handling, cradling, bending minimization, surface inspection, and fusion welding procedures need to be followed. Axial tension force readings, constant insertion velocity, mud flow circulation/exit rates, and footage length installed should be recorded. The pullback speed ranges usually between 1 to 2 feet per minute.

Mini-Horizontal Directional Drilling

The Industry distinguishes between mini-HDD and conventional HDD, which is sometimes referred to as maxi-HDD. Mini-HDD rigs can typically handle pipes up to 10" or 12" diameter and are used primarily for utility construction in urban areas, whereas HDD rigs are typically capable of handling pipes as large as 48" diameter. These machines have significantly larger pullback forces ranging up to several hundred thousand pounds.

General Guidelines

The designer will achieve the most efficient design for an application by consulting with an experienced contractor and a qualified engineer. Here are some general considerations that may help particularly in regard to site location for PE pipes:

1. Select the crossing route to keep it to the shortest reasonable distance.
2. Find routes and sites where the pipeline can be constructed in one continuous length; or at least in long multiple segments fused together during insertion.
3. Although compound curves have been done, try to use as straight a drill path as possible.
4. Avoid entry and exit elevation differences in excess of 50 feet; both points should be as close as possible to the same elevation.

5. Locate all buried structures and utilities within 10 feet of the drill-path for mini-HDD applications and within 25 feet of the drill-path for maxi-HDD applications. Crossing lines are typically exposed for exact location.
6. Observe and avoid above-ground structures, such as power lines, which might limit the height available for construction equipment.
7. The HDD process takes very little working space versus other methods. However, actual site space varies somewhat depending upon the crossing distance, pipe diameter, and soil type.
8. Long crossings with large diameter pipe need bigger, more powerful equipment and drill rig.
9. As pipe diameter increases, large volumes of drilling fluids must be pumped, requiring more/larger pumps and mud-cleaning and storage equipment.
10. Space requirements for maxi-HDD rigs can range from a 100 feet wide by 150 feet long entry plot for a 1000 ft crossing up to 200 feet wide by 300 feet long area for a crossing of 3000 or more feet.
11. On the pipe side of the crossing, sufficient temporary space should be rented to allow fusing and joining the PE carrier pipe in a continuous string beginning about 75 feet beyond the exit point with a width of 35 to 50 feet, depending on the pipe diameter. Space requirements for coiled pipe are considerably less. Larger pipe sizes require larger and heavier construction equipment which needs more maneuvering room (though use of PE minimizes this). The initial pipe side "exit" location should be about 50' W x 100' L for most crossings, up to 100' W x 150' L for equipment needed in large diameter crossings.
12. Obtain "as-built" drawings based on the final course followed by the reamer and the installed pipeline. The gravity forces may have caused the reamer to go slightly deeper than the pilot hole, and the buoyant pipe may be resting on the crown of the reamed hole. The as-built drawings are essential to know the exact pipeline location and to avoid future third party damage.

Safety

Safety is a primary consideration for every directionally drilled project. While this chapter does not cover safety, there are several manuals that discuss safety including the manufacturer's Operator's Manual for the drilling rig and the Equipment Manufacturer's Institute (EMI) Safety Manual: *Directional Drilling Tracking Equipment*.⁽³⁾

Geotechnical Investigation

Before any serious thought is given to the pipe design or installation, the designer will normally conduct a comprehensive geotechnical study to identify soil formations at the potential bore sites. The purpose of the investigation is not only to determine if directional drilling is feasible, but to establish the most efficient way to accomplish it. With this information the best crossing route can be determined, drilling tools and procedures selected, and the pipe designed. The extent of the geotechnical investigation often depends on the pipe diameter, bore length and the nature of the crossing. Refer to ASTM F1962, Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings⁽⁴⁾ and ASCE MOP 108, Pipeline Design for Installation by Horizontal Directional Drilling⁽⁵⁾ for additional information.

During the survey, the geotechnical consultant will identify a number of relevant items including the following:

- a. Soil identification to locate rock, rock inclusions, gravelly soils, loose deposits, discontinuities and hardpan.
- b. Soil strength and stability characteristics
- c. Groundwater

(Supplemental geotechnical data may be obtained from existing records, e.g. recent nearby bridge constructions, other pipeline/cable crossings in the area.)

For long crossings, borings are typically taken at 700 ft intervals. For short crossings (1000 ft or less), as few as three borings may suffice. The borings should be near the drill-path to give accurate soil data, but sufficiently far from the borehole to avoid pressurized mud from following natural ground fissures and rupturing to the ground surface through the soil-test bore hole. A rule-of-thumb is to take borings at least 30 ft to either side of bore path. Although these are good general rules, the number, depth and location of boreholes is best determined by the geotechnical engineer.

Geotechnical Data For River Crossings

River crossings require additional information such as a study to identify river bed, river bed depth, stability (lateral as well as scour), and river width. Typically, pipes are installed to a depth of at least 20 ft below the expected future river bottom, considering scour. Soil borings for geotechnical investigation are generally conducted to 40 ft below river bottom.

Summary

The best conducted projects are handled by a team approach with the design engineer, bidding contractors and geotechnical engineer participating prior to the preparation of contract documents. The geotechnical investigation is usually the first step in the boring project. Once the geotechnical investigation is completed, a determination can be made whether HDD can be used. At that time, design of both the PE pipe and the installation can begin. The preceding paragraphs represent general guidance and considerations for planning and designing an HDD PE pipeline project. These overall topics can be very detailed in nature. Individual HDD contractors and consultant engineering firms should be contacted and utilized in the planning and design stage. Common sense along with a rational in-depth analysis of all pertinent considerations should prevail. Care should be given in evaluating and selecting an HDD contractor based upon successful projects, qualifications, experience and diligence. A team effort, strategic partnership and risk-sharing may be indicated.

Product Design: PE Pipe DR Selection

After completion of the geotechnical investigation and determination that HDD is feasible, the designer turns attention to selecting the proper pipe. The proper pipe must satisfy all hydraulic requirements of the line including flow capacity, working pressure rating, and surge or vacuum capacity. These considerations have to be met regardless of the method of installation. Design of the pipe for hydraulic considerations can be found in Chapter 6. For HDD applications, in addition to the hydraulic requirements, the pipe must be able to withstand (1) pullback loads which include tensile pull forces, external hydrostatic pressure, and tensile bending stresses, and (2) external service loads (post-installation soil, groundwater, and surcharge loads occurring over the life of the pipeline). Often the load the pipe sees during installation such as the combined pulling force and external pressure will be the largest load experienced by the pipe during its life. The remainder of this document will discuss the DR (Dimension Ratio) selection based on pullback and external service loads. (PE pipe is classified by DR. The DR is the “dimension ratio” and equals the pipe’s outer diameter divided by the minimum wall thickness.) A more detailed explanation of the DR concept is provided in Chapter 5.

While this chapter gives guidelines to assist the designer, the designer assumes all responsibility for determining the appropriateness and applicability of the equations and parameters given in this chapter for any specific application. Directional drilling is an evolving technology, and industry-wide design protocols are still developing. Proper design requires considerable professional judgment beyond the scope of this chapter. The designer is advised to consult ASTM F 1962, Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit



Under Obstacles, Including River Crossings⁽⁴⁾ when preparing an HDD design. This methodology is applied to designing municipal water pipe crossings as shown in Petroff⁽⁶⁾.

Normally, the designer starts the DR selection process by determining the DR requirement for the internal pressure. The designer will then determine if this DR is sufficient to withstand earth, live, and groundwater service loads. If so, then the installation (pullback) forces are considered. Ultimately, the designer chooses a DR that will satisfy all three requirements: the pressure, the service loads, and the pullback load.

Although there can be some pipe wall stresses generated by the combination of internal pressurization and wall bending or localized bearing, generally internal pressure and external service load stresses are treated as independent. This is permissible primarily since PE is a ductile material and failure is usually driven by the average stress rather than local maximums. There is a high safety factor applied to the internal pressure, and internal pressurization significantly reduces stresses due to external loads by re-rounding. (One exception to this is internal vacuum, which must be combined with the external pressure.)

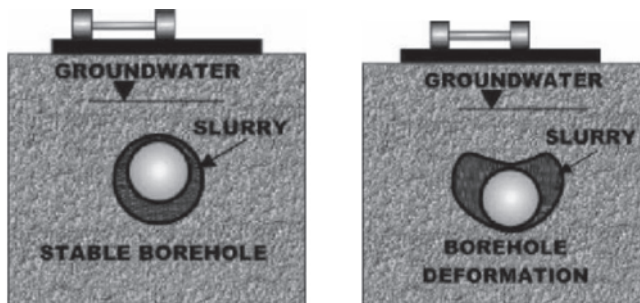


Figure 1 Borehole Deformation

Design Considerations for Net External Loads

This and the following sections will discuss external buried loads that occur on directionally drilled pipes. One important factor in determining what load reaches the pipe is the condition of the borehole, i.e. whether it stays round and open or collapses. This will depend in great part on the type of ground, the boring techniques, and the presence of slurry (drilling mud and cutting mixture). If the borehole does not deform (stays round) after drilling, earth loads are arched around the borehole and little soil pressure is transmitted to the pipe. The pressure acting on the pipe is the hydrostatic pressure due to the slurry or any groundwater present. The slurry itself may act to keep the borehole open. If the borehole collapses or deforms substantially, earth

pressure will be applied to the pipe. The resulting pressure could exceed the slurry pressure unless considerable tunnel arching occurs above the borehole. Where no tunnel arching occurs, the applied external pressure is equal to the combined earth, groundwater, and live-load pressure. For river crossings, in unconsolidated river bed soils, little arching is anticipated. The applied pressure likely equals the geostatic stress (sometimes called the prism load). In consolidated soils, arching above the borehole may occur, and the applied pressure will likely be less than the geostatic stress, even after total collapse of the borehole crown onto the pipe. If the soil deposit is a stiff clay, cemented, or partially lithified, the borehole may stay open with little or no deformation. In this case, the applied pressure is likely to be just the slurry head or groundwater head.

In addition to the overt external pressures such as slurry head and groundwater, internal vacuum in the pipe results in an increase in external pressure due to the removal of atmospheric pressure from inside the pipe. On the other hand, a positive internal pressure in the pipe may mediate the external pressure. The following equations can be used to establish the net external pressure or, as it is sometimes called, the differential pressure between the inside and outside of the pipe.

Depending on the borehole condition, the net external pressure is defined by either Eq. 1 (deformed/collapsed borehole) or Eq. 2 (open borehole):

$$(1) P_N = P_E + P_{GW} + P_{SUR} - P_I$$

$$(2) P_N = P_{MUD} - P_I$$

WHERE

P_N = Net external pressure, psi

P_E = External pressure due to earth pressure, psi

P_{GW} = Groundwater pressure (including the height of river water), psi

P_{SUR} = Surcharge and live loads, psi

P_I = Internal pressure, psi (negative in the event of vacuum)

P_{MUD} = Hydrostatic pressure of drilling slurry or groundwater pressure, if slurry can carry shear stress, psi

(Earth, ground water, and surcharge pressures used in Eq. 1 are discussed in a following section of this chapter.)

$$(3) P_{MUD} = \frac{g_{MUD} H_B}{144}$$

WHERE

g_{MUD} = Unit weight of slurry (drilling mud and cuttings), pcf

H_B = Elevation difference between lowest point in borehole and entry or exit pit, ft

(144 is included for units conversion.)

When calculating the net external pressure, the designer will give careful consideration to enumerating all applied loads and their duration. In fact, most pipelines go through operational cycles that include (1) unpressurized or being drained, (2) operating at working pressure, (3) flooding, (4) shutdowns, and (5) vacuum and peak pressure events. As each of these cases could result in a different net external pressure, the designer will consider all phases of the line's life to establish the design cases.

In addition to determining the load, careful consideration must be given to the duration of each load. PE pipe is viscoelastic, that is, its effective properties depend on duration of loading. For instance, an HDD conduit resists constant groundwater and soil pressure with its long-term apparent modulus stiffness. On the other hand, an HDD force-main may be subjected to a sudden vacuum resulting from water hammer. When a vacuum occurs, the net external pressure equals the sum of the external pressure plus the vacuum. Since surge is instantaneous, it is resisted by the pipe's short-term apparent modulus,, which can be four times higher than the long-term apparent modulus.

For pressure lines, consideration should be given to the time the line sits unpressurized after construction. This may be several months. Most directionally drilled lines that contain fluid will have a static head, which will remain in the line once filled. This head may be subtracted from the external pressure due to earth/ groundwater load. The designer should keep in mind that the external load also may vary with time, for example, flooding.

Earth and Groundwater Pressure

Earth loads can reach the pipe when the borehole deforms and contacts the pipe. The amount of soil load transmitted to the pipe will depend on the extent of deformation and the relative stiffness between the pipe and the soil. Earth loading may not be uniform. Due to this complexity, there is not a simple equation for relating earth load to height of cover. Groundwater loading will occur whether the hole deforms or not; the only question is whether or not the slurry head is higher and thus may in fact control design. Thus, what loads reach the pipe will depend on the stability of the borehole.

The designer may wish to consult a geotechnical engineer for assistance in determining earth and groundwater loads, as the loads reaching the pipe depend on the nature of the soil.

Stable Borehole - Groundwater Pressure Only

A borehole is called stable if it remains round and deforms little after drilling. For instance, drilling in competent rock (rock that can be drilled without fracturing and

collapsing) will typically result in a stable borehole. Stable boreholes may occur in some soils where the slurry exerts sufficient pressure to maintain a round and open hole. Since the deformations around the hole are small, soil pressures transmitted to the pipe are negligible. The external load applied to the pipe consists only of the hydrostatic pressure due to the slurry or the groundwater, if present. Equation 4 gives the hydrostatic pressure due to groundwater or drilling slurry. Standing surface water should be added to the groundwater.

$$(4) \quad P_{GW} = \frac{g_w H_w}{144}$$

WHERE

P_{GW} = Hydrostatic fluid pressure due to ground and surface water, psi

g_w = Unit weight of water, pcf

H_w = Height to free water surface above pipe, ft (144 is included for correct units conversion.)

Borehole Deforms/Collapse With Arching Mobilized

When the crown of the hole deforms sufficiently to place soil above the hole in the plastic state, arching is mobilized. In this state, hole deformation is limited. If no soil touches the pipe, there is no earth load on the pipe. However, when deformation is sufficient to transmit load to the pipe, it becomes the designer's chore to determine how much earth load is applied to the pipe. At the time of this writing, there have been no published reports giving calculation methods for finding earth load on directionally drilled pipes. Based on the successful performance of directionally drilled PE pipes, it is reasonable to assume that some amount of arching occurs in many applications. The designer of HDD pipes may gain some knowledge from the approaches developed for determining earth pressure on auger bored pipes and on jacked pipes. It is suggested that the designer become familiar with all of the assumptions used with these methods. For additional information on post installation design of directionally drilled pipelines see Petroff⁽⁹⁾.

O'Rourke et. al.⁽⁷⁾ published an equation for determining the earth pressure on auger bored pipes assuming a borehole approximately 10% larger than the pipe. In this model, arching occurs above the pipe similar to that in a tunnel where zones of loosened soil fall onto the pipe. The volume of the cavity is eventually filled with soil that is slightly less dense than the insitu soil, but still capable of transmitting soil load. This method of load calculation gives a minimal loading. The method published here is more conservative. It is based on trench type arching as opposed to tunnel arching and is used by Stein⁽⁸⁾ to calculate loads on jacked pipe. In Stein's model, the maximum earth load (effective stress) is found using the modified form of Terzaghi's equation given by Eq. 6., Petroff⁽⁹⁾. External groundwater pressure must be added to the effective earth pressure. Stein and O'Rourke's methods

should only be considered where the depth of cover is sufficient to develop arching (typically exceeding five (5) pipe diameters), dynamic loads such as traffic loads are insignificant, the soil has sufficient internal friction to transmit arching, and conditions are confirmed by a geotechnical engineer.

Using the equations given in Stein, the external pressure is given below:

$$(5) \quad P_E = \frac{k g_{SE} H_C}{144}$$

$$(6) \quad k = \frac{1 - \exp\left(-2 \frac{KH_C}{B} \tan\left(\frac{\delta}{2}\right)\right)}{2 \frac{KH_C}{B} \tan\left(\frac{\delta}{2}\right)}$$

WHERE

P_E = external earth pressure, psi

g_{SE} = effective soil weight, pcf

H_C = depth of cover, ft

k = arching factor

B = "silo" width, ft

δ = angle of wall friction, degrees (For HDD, $\delta = f$)

f = angle of internal friction, degrees

K = earth pressure coefficient given by:

$$K = \tan^2\left(45 - \frac{f}{2}\right)$$

The "silo" width should be estimated based on the application. It varies between the pipe diameter and the borehole diameter. A conservative approach is to assume the silo width equals the borehole diameter. (The effective soil weight is the dry unit weight of the soil for soil above the groundwater level, it is the saturated unit weight less the weight of water for soil below the groundwater level.)

Borehole Collapse with Prism Load

In the event that arching in the soil above the pipe breaks down, considerable earth loading may occur on the pipe. In the event that arching does not occur, the upper limit on the load is the weight of the soil prism ($P_E = g_{SE}H_C$) above the pipe. The prism load is most likely to develop in shallow applications subjected to live loads,

boreholes in unconsolidated sediments such as in some river crossings, and holes subjected to dynamic loads. The “prism” load is given by Eq. 7.

$$(7) \quad P_E = \frac{g_{SE} H_C}{144}$$

WHERE

P_E = earth pressure on pipe, psi

g_{SE} = effective weight of soil, pcf

H_C = soil height above pipe crown, ft

(Note: 144 is included for units conversion.)

Combination of Earth and Groundwater Pressure

Where groundwater is present in the soil formation, its pressure must be accounted for in the external load term. For instance, in a river crossing one can assume with reasonable confidence that the directionally drilled pipe is subjected to the earth pressure from the sediments above it combined with the water pressure.

Case 1 Water level at or below ground surface

$$(8) \quad P_E + P_{GW} = \frac{g_B H_W + g_D (H_C - H_W) + g_W H_W}{144}$$

Case 2 Water level at or above ground surface (i.e. pipe in river bottom)

$$(9) \quad P_E + P_{GW} = \frac{g_B H_C + g_W H_W}{144}$$

WHERE

H_W = Height of Ground water above pipe springline, ft

H_C = height of cover, ft

g_B = buoyant weight of soil, pcf

g_W = weight of water, pcf

g_D = dry unit weight of soil, pcf

Live Loads

Wheel loads from trucks or other vehicles are significant for pipe at shallow depths whether they are installed by open cut trenching or directional drilling. The wheel load applied to the pipe depends on the vehicle weight, the tire pressure and size, vehicle speed, surface smoothness, pavement and distance from the pipe to the point of loading. In order to develop proper soil structure interaction, pipe subject to vehicular loading should be installed at least 18” or one pipe diameter (whichever is