Best Practices for Third Party Crossings Under Railway Tracks

by

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Abstract

Third party utility and pipeline crossings are common construction projects in the railroad industry. Trenchless construction methods are typically used for the installation of third party crossings within a railroad right-of-way. The American Railway Engineering and Maintenance-of-Way Association develops manuals which provides recommended guidelines for trenchless design and construction. All Class I railroads in North America have developed their own standards and processes for accommodating third party utility crossings within their right-of-way.

Three case studies were examined to review historical utility and pipeline crossings within a railway right-of-way. The first case study provided an example of a well-executed microtunnelling crossing technique while the remaining two case studies provided examples of microtunnelling and guided boring techniques within the railway right-of-way.

Best practices to minimize impacts due to third party crossings under railway tracks have been provided. The recommendations for best practices were mainly focused on improving controls related to soil investigations, settlement assessments, monitoring plans, site supervision and monitoring. These recommendations include implementation of the observational method, sufficient soil info at critical locations, standardized coordinate system for settlement trough monitoring at the base of the rails, minimum installation depth for utility crossings, vibration monitoring and consideration for surveying accuracy.

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1.0 Introduction

Presently, there are close to 45,000 km of operating railway lines in Canada [1]. Third party pipeline and utility crossings are commonly designed and constructed within an operating railway Right-of-Way (ROW). Conventional methods for pipeline and utility installations typically consisted of open-cut construction methods that would require the suspension of railway traffic at the construction locations. Due to advancements in technology, improvements in obtaining geotechnical data; developments of new equipment have led to techniques and methods that prove to be less intrusive [2].

Trenchless technologies have provided many benefits such as less trenching, less footprint, smaller environmental impact; with enhancements to productivity, safety, and cost effectiveness throughout construction [2]. Even with the benefits noted above, trenchless technology construction presents many engineering challenges such as obtaining and implementing reliable geotechnical design parameters, settlement assessments, field monitoring planning, in addition to site supervision and monitoring.

The American Railway Engineering and Maintenance-of-Way Association (AREMA) develops manuals annually for the railway industry which provides recommended guidelines for trenchless design and construction. The Class I railroads in North America have all developed their own standards and processes for accommodating third party utility crossings within their ROW. The relevant AREMA guidelines and standards from the North American Class I railroads have been summarized within this report. Based on the AREMA guidelines, several Class I railway standards and three case studies; this report presents best practices for third party crossings under railway tracks.

2.0 Literature Review

Initially, a review of the commonly used trenchless construction methods was conducted. Research was also conducted by obtaining the existing utility accommodation standards from the Class I railroads in North America and relevant guidelines provided by AREMA. Table 2.1 below provides a list of the Class I railways in North America.

Table 2.1: Class I Railroads [3]

BNSF Railway Co. (BNSF)
Canadian National Railway Co. (CN)
Canadian Pacific (CP)
CSX Transportation (CSX)
Kansas City Southern Railway (KCS)
Norfolk Southern Corp. (NS)
Union Pacific Railroad (UP)

2.1 Horizontal Auger Boring

Auger boring also known as bore and jack method, is a common trenchless construction method used to install underground pipelines and utilities. This method consists of advancing casing and horizontal augers from a driving shaft to a reception shaft or alternatively utilizing boring pits. An auger boring machine is setup at the base of the driving shaft or boring pit and provides torque which rotates the cutting head that is attached to the horizontal augers.

Soil spoils are transported by the augers from the cutting head to the boring machine where the spoils are removed. It is common practice to use a water level to make any required corrections to the vertical alignment throughout installation. Bentonite or polymer lubricants may be applied to the outer annulus of the casing pipe to reduce friction during installation [2].

Segment lengths are restricted to the accommodating sizes of the bore pit or driving shaft dimensions. As the casing and augers are advanced, additional casing will be spliced on to the installed casing next to the boring machine where additional auger segments are added. The process is repeated until the casing and augers reach the receiving bore pit or reception shaft.

Installed casing diameters are typically limited to a maximum of 60 inches (1.5 m) and maximum installation lengths of 600 feet (183 m). The longest recorded installation length is 900 feet (274 m). An installed as-built accuracy ±1 percent of the length of bore can usually be accomplished [2]. Table 2.2 below provides a list of the major advantages and constraints for horizontal auger boring. Figure 2.1 below provides a photograph of a typical horizontal auger boring setup.

Table 2.2: Horizontal Auger Boring Advantages and Constraints [2]

Advantages	**Constraints**
Casing is installed as the bore hole is excavated	Bore pits or launch and reception shafts required
Used in a variety of soil conditions	Not successful in unstable soils
Successful in weathered rocks, clay and granular soils up to 100 mm diameter particle size	Dewatering is required

Figure 2.1: Horizontal Auger Boring Construction [4]

2.2 Pipe Jacking

Pipe jacking is an installation technique used to install a prefabricated pipe through the ground from a driving shaft to a reception shaft [2]. The jacking operation is located in the driving shaft. A jacking force is transmitted through the pipe to the excavation face. Soil spoils are transported through the installed pipe and removed from the driving shaft. The spoil removal process does not require water to transport the spoil material. However, pipe jacking requires workers to be located inside the pipe, which differentiates pipe jacking from microtunnelling and other methods. Bentonite or polymer slurry may be applied to the outer annulus of the casing pipe to reduce friction during installation [2]. Figure 2.2 shown below provides a schematic of a typical pipe jacking operation.

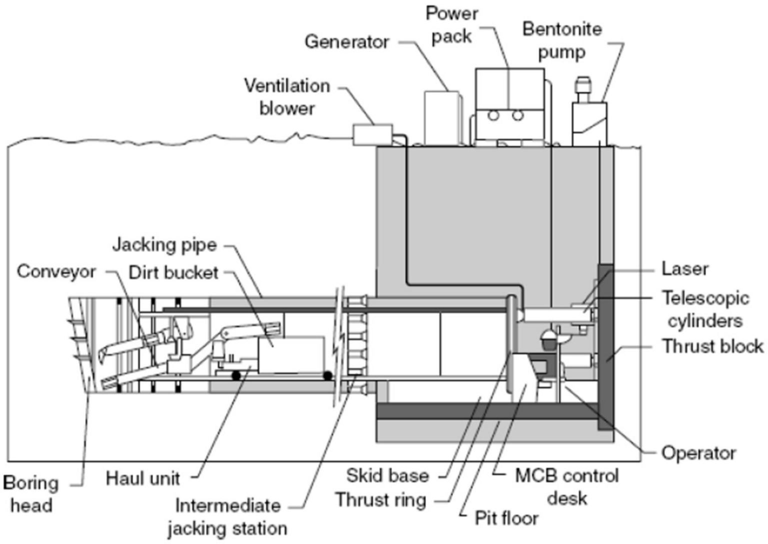


Figure 2.2: Pipe Jacking Schematic [5]

Installed pipe jacking diameters commonly range from 48 inches (1.2 m) to 72 inches (1.8 m) with common installation lengths up to 1,000 feet (305 m). The longest recorded installation length is 3,500 feet (1.07 km). An installed as-built accuracy of ±2 inch (50 mm) for grade and ±3 inch (75 mm) for alignment can usually be accomplished [2]. Table 2.3 below provides a list of the major advantages and constraints for pipe jacking.

Table 2.3: Pipe Jacking Advantages and Constraints [2]

Advantages	Constraints
High installation accuracy	Not successful in saturated dense sands
Used in a variety of soil conditions	High degree of planning required
Successful in clay and granular soils up to 100 mm diameter particle size	Pipe and liners must be engineered to resist jacking forces

2.3 Pipe Ramming

Pipe ramming is a trenchless installation method that typically uses a pneumatic percussion hammer and a dynamic force to drive the pipe into the soil [2]. Open-face and closed-faced are the two major categories for pipe ramming. The closed-faced method requires a cone-shaped driving shoe to be welded to the first segment of the pipe to be rammed. One major benefit of closed-faced pipe ramming is the ability to densify the adjacent soils during the installation process.

Open-faced pipe ramming requires the driving face of the pipe to remain open which allows for a cased bore hole where the soil is excavated within the pipe. Only a small amount of soil densification occurs during the open-faced pipe ramming installation. Lubricants such as water or bentonite can be applied inside and outside of the casing to reduce friction during installation. After installation soil spoils are removed by compressed air or water [2]. Figure 2.3 shown below provides a schematic of a typical pipe ramming operation.

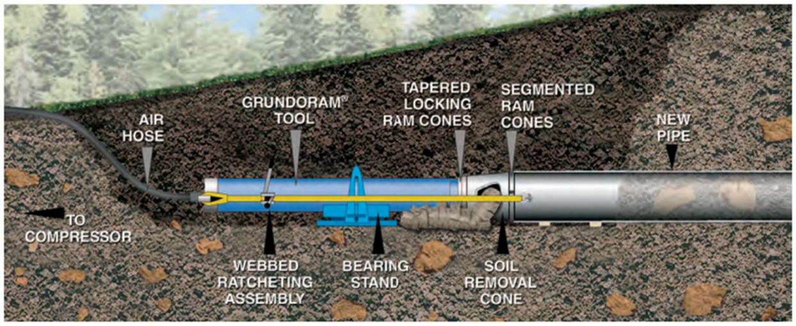


Figure 2.3: Pipe Ramming Schematic [6]

Installed pipe ramming pipe diameters commonly range from 4 inches (100 mm) to 60 inches (1.5 m) with common installation lengths up to 200 feet (60 m). Longer installation lengths up to 400 feet (122 m) have been recorded. Once the pipe ramming process is initiated there is limited control in altering the direction of the bore [2]. Table 2.4 below provides a list of the major advantages and constraints for pipe ramming.

Table 2.4: Pipe Ramming Advantages and Constraints [2]

Advantages	**Constraints**
Used in a variety of soil conditions	Not successful in saturated dense sands
Effective for larger diameter pipes	Pipe can deflect on dense soils (eg. boulders)
Successful in clay and granular soils larger than 100 mm diameter particle size	Accuracy depends on initial setup. Limited control over alignment and grade
Does not require thrust reaction structure	High noise levels and vibrations

2.4 Horizontal Directional Drilling (HDD)

HDD is a technology that originated from the oil and gas industry in the 1970. Since the inception of HDD, this method has evolved into a steerable system for the installation of pipe, conduits and cables launched from ground surface. Three major classifications include large-diameter HDD, medium-diameter HDD and small-diameter HDD [2].

During the first stage, a small-diameter pilot hole a few inches in diameter is drilled along the desired alignment. In stage two, the pilot hole is enlarged to the desired pipeline or utility diameter. Throughout this same stage the pipe is pulled through the pilot hole. It should be noted for large-diameter HDD, several back-reaming passes may be required to enlarge the hole to the desired diameter with pullback operations being performed separately [2]. After reaming, the hole is typically swabbed one or more times with the reaming tool to check the condition of the hole prior to the pullback operations [8].

Drilling fluids called mud, are used to transport spoil out of the bore hole, stabilize the bore hole and provide lubrication during the drilling process [2]. Drilling fluid is primarily water with bentonite and or polymer additives. Figure 2.4 shown below provides a schematic of a typical HDD installation process.

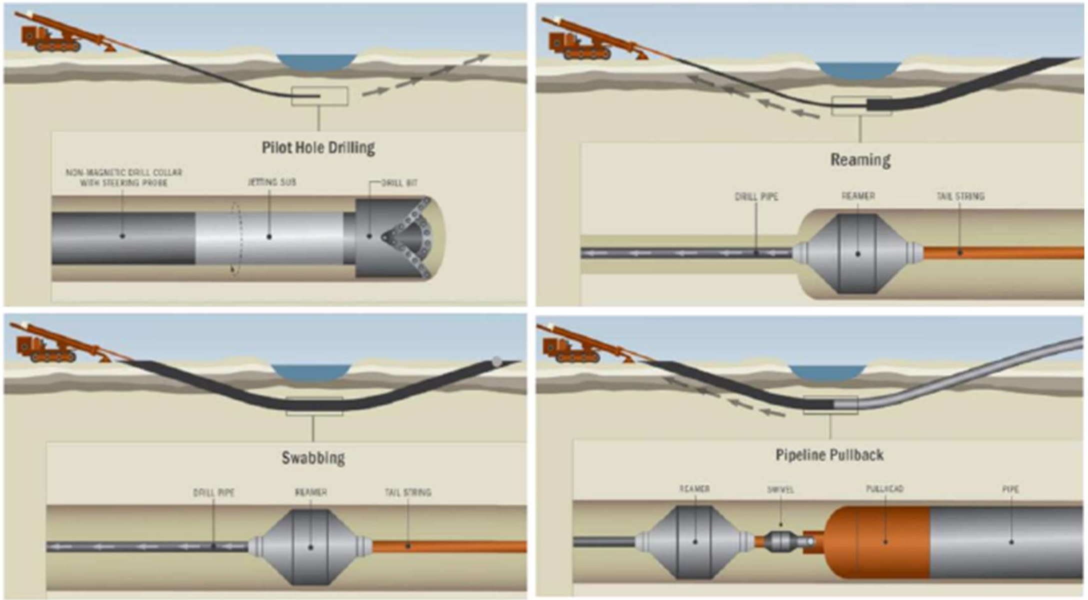


Figure 2.4: Typical HDD Installation Process [7]

HDD installation diameters commonly range from 3 inches (75 mm) to 48 inches (1.2 m) with common installation lengths up to 400 feet (122 m). Longer installation lengths up to 6,000 feet (1.8 km) have been recorded. Installation depths typically range from 15 feet (4.6 m) to 200 feet (61 m) [2]. An installed as-built accuracy within 1 m to 3 m of the designed exit trajectory can usually be achieved. Table 2.5 below provides a list of the major advantages and constraints for HDD.

Table 2.5: Horizontal Directional Drilling Advantages and Constraints [2]

Advantages	**Constraints**
Used in a variety of soil conditions	Disposal of drilling mud is required
Steering capability	Extensive site investigation required
Successful in clay and granular soils up to about 100 mm diameter particle size	Potential for frac-out
Does not require bore pits or launch and reception shafts	Potential for drill head to exit off target

2.5 Microtunnelling (MT)

Microtunnelling is a trenchless installation method that can install pipelines and utilities below ground surface by jacking a pipe behind a steerable, guided, remotely-controlled, articulated microtunnel boring machine (MTBM). Microtunnelling originated in Japan in the 1960’s [2].

MTBM can be used in a wide range of soil conditions to achieve accurate installation tolerances for horizontal alignment and vertical grade from the driving shaft to reception shaft or alternatively boring pits can be utilized [2]. Boulders up to one-third of the diameter of the MTBM can be handled by the cutter wheel on a cone shaped crusher on the MTBM [12]. The two main MT categories include slurry method and auger method.

2.5.1 Slurry MTBM

The slurry method provides continuous support to the excavation face by applying fluid pressure to balance earth and groundwater pressures. Advantages of the slurry system include using this method below the groundwater table or in unstable soil conditions [12].

2.5.2 Auger MTBM

The auger method provides continuous support to the excavation face by applying mechanical pressure to balance earth and groundwater pressures. The auger method is typically used above the groundwater table or with limited groundwater pressure [12]. Figure 2.5 shown below provides schematic of the groundwater, earth and counteractive pressures during installation.

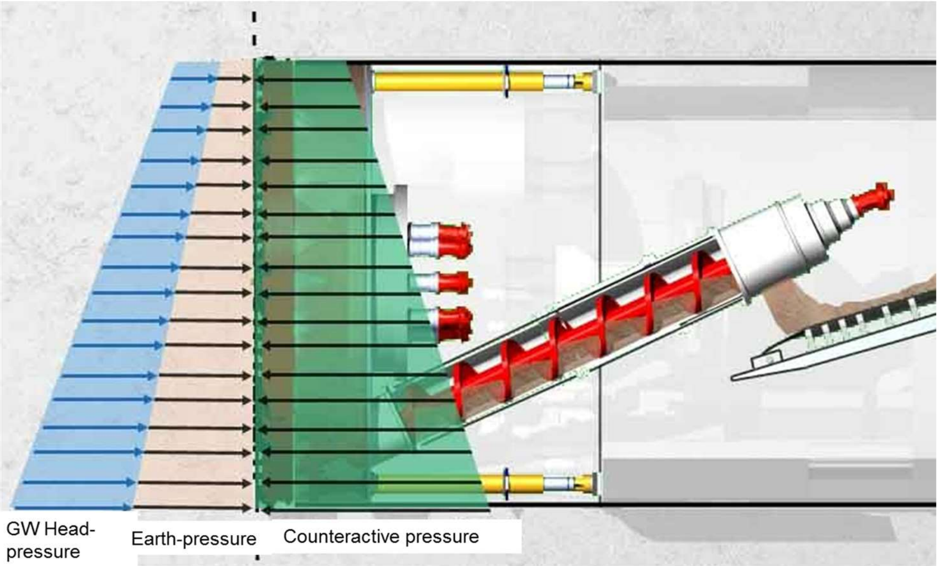


Figure 2.5: MTBM Earth Groundwater, Earth and Counteractive Pressures [9]

Microtunnelling installation diameters commonly range from 10 inches (250 mm) to 136 inches (3.5 m) with common installation lengths up to 500 feet (152 m). Longer installation lengths up to 1,500 feet (457 m) have been recorded for slurry MTBM installation. A minimum installation depth of 5 feet (1.5 m) is recommended to provided sufficient cover with a depth of cover to diameter ratio of 3 is commonly used. An installed as-built accuracy ±1 inch (25 mm) have been recorded with laser guided system controls [2]. Table 2.6 below provides a list of the major advantages and constraints for microtunnelling.

Table 2.6: Microtunnelling Advantages and Constraints [2]

Advantages	Constraints
Used in a variety of soil conditions	Expensive
Highly accurate	MTBM can refuse on large boulders
Successful in clay and granular soils larger than 100 mm diameter particle size	Cannot install low strength or flexible PVC pipes

2.6 Pilot Tube Guided Boring (PTGB)

Pilot tube guided boring was introduced in the 1990's. PTGB is classified as a unique trenchless construction method as it is able to accurately install pipelines and utilities to design grades and alignments by using a guided pilot tube [2]. Similar to horizontal auger boring, the PTGB method uses augers for excavation, soil spoil removal and jacking force for pipeline and utility installation. PTGB uses an accurate guidance system composed of a theodolite and camera which aligns the pilot boring. The hole is then reamed to install the auger casing followed by the installation of the product pipe. Figure 2.6 shown below provides a schematic of a typical PTGB installation process.

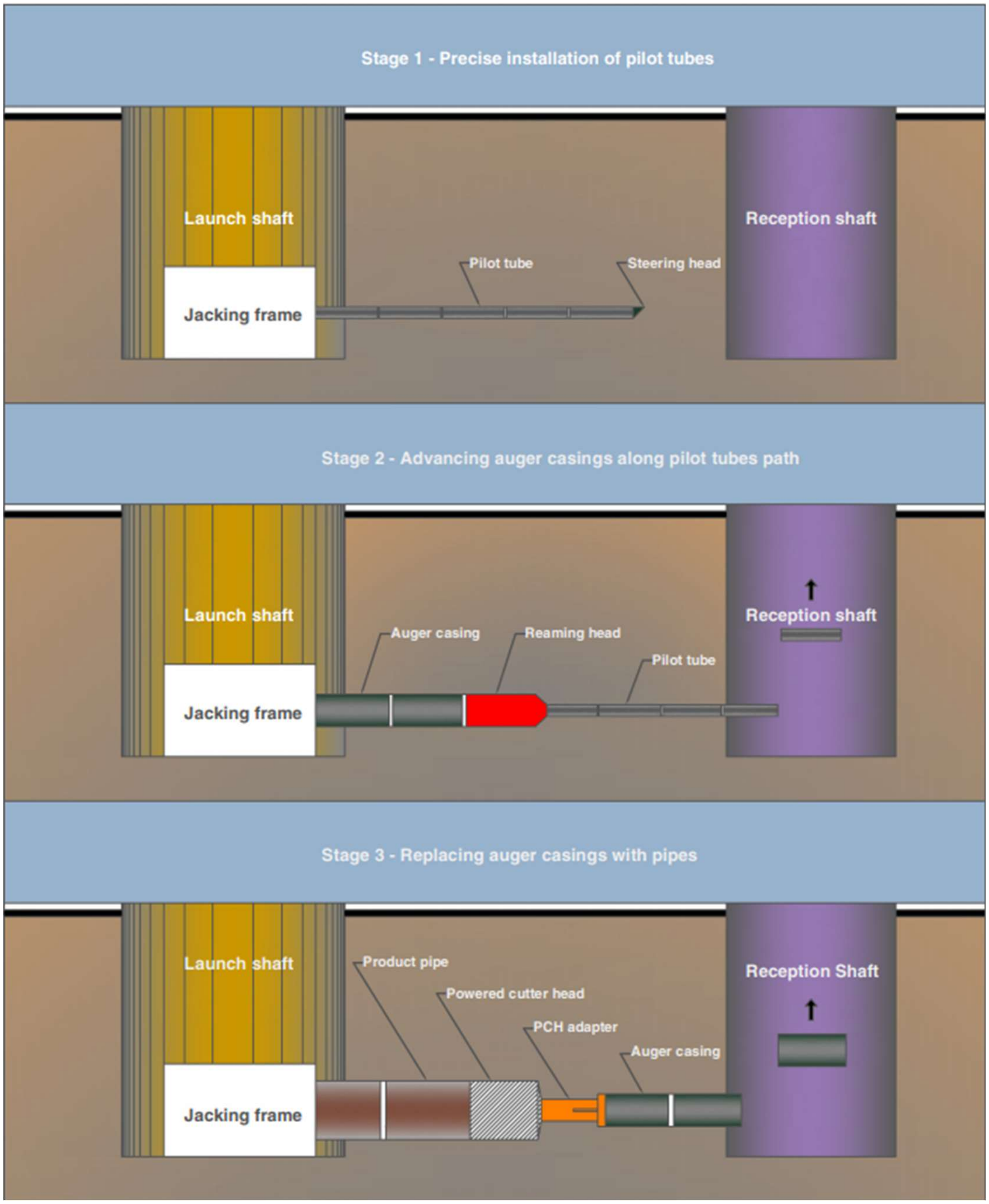


Figure 2.6: Typical PTGB Installation Process [10]

PTGB installation diameters commonly range from 4 inches (100 mm) to 30 inches (762 mm) with common installation lengths up to 300 feet (91 m). Longer installation lengths up to 400 feet (122 m) have been recorded. An installed as-built accuracy ±0.25 inch (6 mm) have been recorded for 300 feet (152 m) pipe length installations [2]. Table 2.7 below provides a list of the major advantages and constraints for PTGB.

Table 2.7: Pilot Tube Guided Boring Advantages and Constraints [2]

Advantages	Constraints
Can be used below and above the water table	Bore pits or launch and reception shafts required
Highly accurate	MTBM can refuse on large boulders
Successful in clay and granular soils up to about 100 mm diameter particle size	Unsuccessful in weathered and unweathered rocks

2.7 ShapeArray

ShapeArray is a patented technology by Measurand Inc. The SAAX instrument is purpose-built for heavy duty rail-line horizontal deformation monitoring applications. Figure 2.7 shown below provides a photograph of a ShapeArray SAAX installed for railroad applications.

Figure 2.7: ShapeArray SAAX Railroad Application (Courtesy of Measurand Inc.)

Horizontal ShapeArray’s can be installed along the base of the rail to provide settlement monitoring data throughout trenchless construction projects. ShapeArray’s can also be installed below ground surface to monitor subsurface deformation. The instruments can be read onsite and can also be accessed remotely when installed to a power source, data logger, modems and ethernet connectivity. Accuracy of the SAAX instrument is ± 1.5 mm for 32 m length of SAAX. The specification sheet for the SAAX instrument is provided in Appendix B, attached to this report.

The ShapeArray system can also be reused for multiple projects when the equipment is not damaged and can operate sufficiently. The system can also be setup to provide email notifications alerts to a distribution list when settlement monitoring alarm thresholds values are exceeded. Visual and auditable alarms can also be equipped onsite to notify field personnel when the settlement monitoring alarm thresholds values are exceeded. Installation of the monitoring system can typically be completed onsite within 10 hours. The system can also be setup to automatically take readings after trains pass the instruments.

Additional advantages of the SAAX system include increased safety during data sampling by not requiring a survey crew near the railway tracks. The main disadvantage of the monitoring system are the associated costs with installation being in the range of $10,000 to $15,000 [11]. Additional disadvantages include risk of damage and specialized personnel required for installation.

2.8 AREMA Guidelines

Each year AREMA publishes well established guidelines for the railroad industry in their annual Manual for Railway Engineering. These guidelines are reviewed, adopted and in select cases modified by the Class I railroads in North American to form independent engineering standards developed by each Class I railroad.

2.8.1 General and Construction Guidelines

AREMA recommends that pipelines should cross railroad tracks preferably at right angles but not less than 45 degrees. Wirelines should cross railroad tracks preferably at right angles but not less than 60 degrees. The crossings should not be located within 45 feet (13.72 meters) to structures. For bored or jacked installation, the bore hole diameter should be the same size as the installed utility [12].

2.8.2 Guidelines for Pipelines Conveying Flammable Substances

AREMA recommends that flammable pipeline installation depths below the base of rail should be 5’1/2” feet (1.68 meters) and 4’1/2” feet (1.38 meters) for primary and secondary tracks, respectively. When casings are not used, the pipeline installation depth below the base of rail should be 10 feet (3.05 meters) [12].

2.8.3 Guidelines for Uncased Gas Pipelines Within the Railroad ROW

AREMA recommends that when casings are not used, the gas pipeline installation depth below the base of rail should be 10 feet (3.05 meters) [12].

2.8.4 Guidelines for Pipelines Conveying Non-Flammable Substances

AREMA recommends that non-flammable pipeline installation depths below the base of rail should be 5’1/2” feet (1.68 meters) and 4’1/2” feet (1.38 meters) for primary and secondary tracks, respectively. When casings are not used, the pipeline installation depth below the base of rail should be 4’1/2” feet (1.38 meters) [12].

2.8.5 Guidelines for Wireline Crossings on Railroad ROW

AREMA recommends that wireline installation depths below the base of rail should be 4’1/2” feet (1.38 meters) for steel casings and 12 feet (3.66 meters) for non-metallic casings. All HDD installation depths below the base of rail should be 12 feet (3.66 meters). Wirelines (carrying 750 volts or less) should be installed 3 feet (0.91 meters) below ground surface in other areas of the railroad ROW. Wirelines (carrying more than 750 volts) should be installed 4 feet (1.2 meters) below ground surface in other areas of the railroad ROW [12].

2.8.6 Guidelines for Fiber Optic Construction on Railroad ROW

For all trenchless installation methods with the exception for HDD, the minimum installation depth below the base of rail is 5’1/2” (1.68 meters). For fiber optic utilities, the minimum HDD installation depth below the base of rail is 12 feet (3.66 meters) [12].

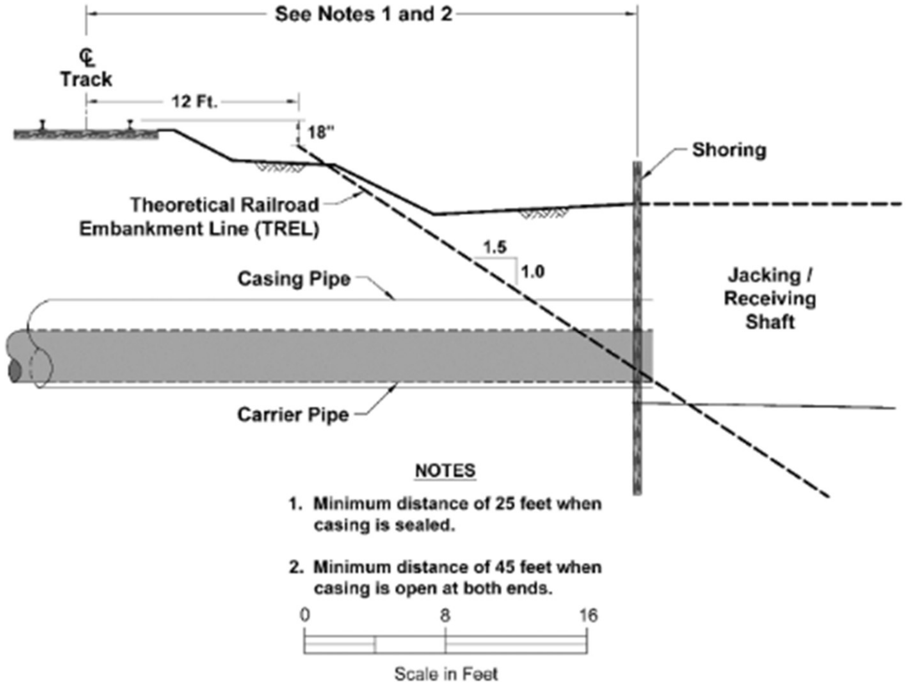
2.8.7 General Guidelines for HDD Construction within Railroad ROW

The minimum HDD installation depth below the base of rail is 12 feet (3.66 meters) and should be aligned at right angles to the railroad tracks. The borings should be located at least 150 feet (45.72 meters) from existing structures with the boring/jacking pits located at least (9.14 meters) away from the railroad tracks. The bore hole diameter should only be up to 2 inches (50.8 mm) larger than the outside diameter of the installed utility with a maximum allowed outside diameter of 36 inches (0.91 meters) [12].

General construction guidelines include using HDD specific drilling fluids and having a frac-out contingency plan. If voids develop within the soil during construction, all voids should be backfilled with grout. The pull back operations should only be completed by the HDD rig; other construction equipment such as dozers should not be used for this task. It should be noted that HDD tools may need to be abandoned in place and grouted if they cannot be retrieved from the bore hole. The boring path should also be recorded about every 10 feet (3.05 meters) along the boring alignment during installation [12].

2.8.8 Microtunnelling

The minimum depth of installation below the base of rail for slurry microtunnelling is at least two times the diameter of the utility. Microtunnelling installation should be located at least 45 feet (13.7 m) away from existing structures. For settlement monitoring, the alert threshold "warning" of ¼ to ¾ inch (6 to 19 mm) and alarm values ranging from ½ to 1 inch (12 to 25 mm) are recommended. Tunnel casings installed without shoring should be extended beyond the theoretical railroad embankment line, see Figure 2.8 below [12].



NOTES

1. Minimum distance of 25 feet when casing is sealed.
2. Minimum distance of 45 feet when casing is open at both ends.

Figure 2.8: Theoretical Railroad Embankment Line [12]

2.8.9 Settlement Control

Before construction starts, a settlement plan should be established that outlines the types of settlement points and frequency of measurements. The plan should check for settlement or heave at the railroad track surface and below the track. The monitoring systems can be conducted with traditional methods or automated systems. The alert threshold warning and alarm limits should be established before construction. [12]

a) "Reaching the alert threshold may trigger the following actions" [12]:
    i. "Discussion of the data and its implications."
    ii. "Increase in the frequency of monitoring."
    iii. "Independent confirmation of the monitoring data."
    iv. "A review of trenchless construction means and methods to determine if changes are required to mitigate further movement."

b) "Reaching the alarm limit may trigger the following actions" [12]:
    i. "Immediate stoppage of construction and notification to the railroad."
    ii. "Independent confirmation of the movement."
    iii. "Review of trenchless construction means and methods and implementation of contingency plans, if needed."
    iv. "Re-evaluation of critical structures in the area and installation of additional monitoring devices if needed."

2.9 North American Class I Railroad Standards and Processes

All Class I railroads have developed their own standards for pipeline and utility accommodation. Each Class I railroad have independent processes for handling utility applications and site monitoring. Some Class I railroads handle these processes internally while others contract out these activities. Table 2.8 below provides a summary of the Class I railroad processes for handing pipeline and utility accommodation.

Table 2.8: Class I Railroad Pipeline and Utility Accommodation Processes

Railroad	Utility Permit Application Review	Construction Monitor
BNSF	External	External
CN	Internal/External	External
CP	Internal/External	External
CSX	Internal	Internal
KCS	External	External
NS	External	External
UP	Internal	External

The following sections provides a summary of the Class I railroad pipeline and utility crossings standards.

2.9.1 BNSF Railway Co.

This section provides a summary of the BNSF underground pipeline and utility installation standards. An engineering review matrix based on the BNSF standard is provided in Table A.1 in Appendix A [13].

a) Geotechnical study not required for jack and bore. Geotechnical study required for all other installation methods that are greater than 26 inch (660 mm) in diameter and within 6 to 10 feet (1.83 m to 3.0 m) depth within base of rail.
b) Settlement alert threshold “warning” of ¼ to ¾ inch (6 to 19 mm) with maximum alarm values ranging from ½ to 1 inch (12 to 25 mm).
c) HDD: 0.0% grade beginning 25 feet (7.62 m) minimum from centerline of track until it reaches a point 25 feet (7.62 m) minimum from centerline of track.

2.9.2 Canadian National Co.

This section provides a summary of the CN (Southern Region) underground pipeline and utility installation standards. An engineering review matrix based on the CN standard is provided in Table A.2 in Appendix A [14].

a) Core line settlement alert threshold “warning” of 5 mm (approximately 3/16 inch) with a maximum alarm value of 10 mm (approximately 3/8 inch), respectively.

b) Branch line settlement alert threshold “warning” of 8 mm (approximately 1/3 inch) with a maximum alarm value of 16 mm (approximately 2/3 inch), respectively.

c) Pile driving vibration monitoring: induced vibrations limited to 3.5”/sec (89 mm/sec) measured in 3 perpendicular directions and induced amplitudes less than 1/128” (1/3.25 m).

d) Vibration monitoring within 150 feet (45 m) of fiber optic cables shall be less than 1.5”/sec (38 mm/sec).

2.9.3 Canadian Pacific

This section provides a summary of the CP underground pipeline and utility installation standards. An engineering process identification matrix based on the CP standard is provided in Table A.3 in Appendix A [15].

2.9.4 CSX Transportation

This section provides a summary of the CSX underground pipeline and utility installation standards. An engineering review matrix based on the CSX standard is provided in Table A.4 in Appendix A [16]. A summary of the CSX HDD standard is provided below [17].

a) Bundling is prohibited. All inner ducts must have an outer casing pipe.

b) All commodity pipes with an outside diameter exceeding 8 inches (200 mm) shall be installed a minimum depth of 25 feet (7.62 meters) below base of rail. For natural gas, fiber optics, and electrical installations within a pipe/conduit with an outside diameter of 8 inches (200 mm) or less shall be installed a minimum depth of 15 feet (4.57 meters) below base of rail.

c) The contractor must provide a detailed frac-out contingency plan.

d) A construction monitor is required to monitor the ground and track for movement during the drilling, reaming, and pullback processes. The construction monitor will be provided by CSX at the applicant's sole cost and expense.

e) A subsurface exploration is required for bores 20 inches (508 mm) or larger.

2.9.5 Kansas City Southern Railway

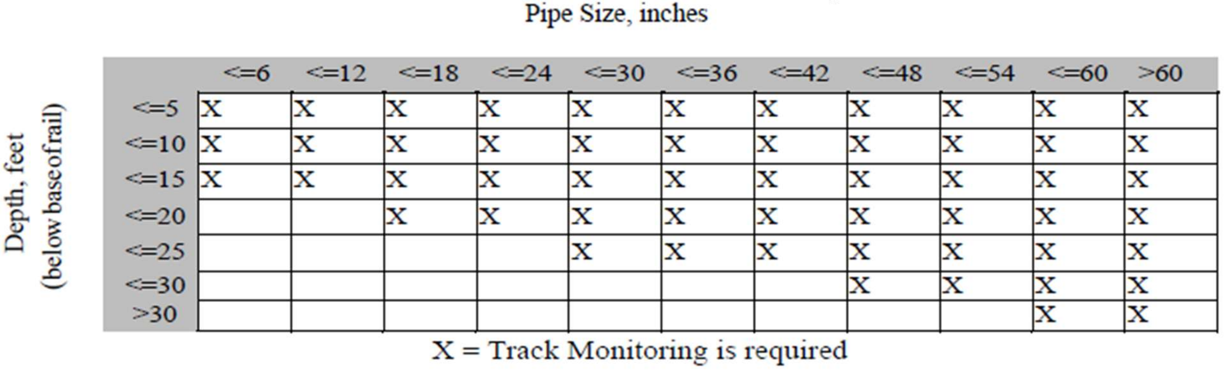
This section provides a summary of the KCS underground pipeline and utility installation standards. An engineering review matrix based on the KCS standard is provided in Table A.5 in Appendix A [18].

2.9.6 Norfolk Southern Corp.

This section provides a summary of the NS underground pipeline and utility installation standards. An engineering review matrix based on the NS standard is provided in Table A.6 in Appendix A [19] [20].

Table 2.9 below provides the Norfolk Southern settlement monitoring schedule and requirements based on pipe size and installation depth below base of rail.

Table 2.9: Norfolk Southern Settlement Monitoring Schedule [19]



Pipe Size, inches

Depth, feet (below base of rail)	<=6	<=12	<=18	<=24	<=30	<=36	<=42	<=48	<=54	<=60	>60
<=5	X	X	X	X	X	X	X	X	X	X	X
<=10	X	X	X	X	X	X	X	X	X	X	X
<=15	X	X	X	X	X	X	X	X	X	X	X
<=20			X	X	X	X	X	X	X	X	X
<=25					X	X	X	X	X	X	X
<=30								X	X	X	X
>30										X	X

X = Track Monitoring is required

a) Track monitoring shall not require track access other than to place the track monitoring targets.

b) Threshold value 1/8 inch (approximately 3 mm) vertical or horizontal deflection and installation shutdown ¼ inch (approximately 6 mm) vertical or horizontal deflection (class 3 or 4).

c) Threshold value ¼ inch (approximately 6 mm) vertical or horizontal deflection and installation shutdown ½ inch (approximately 13 mm) vertical or horizontal deflection. (class 1 or 2).

Underground wireline installations are subject to the following NS standards [19] [20]:

a) Conduits shall maintain a minimum horizontal clearance of 4 feet (1.2 meters), or if within 4 feet (1.2 meters) vertical clearance of 10 feet (3.05 meters) from the base of any railroad signal apparatus.

b) HDD method "A" consists of setting up specialized drilling equipment on existing grade (launching and receiving pits are not required). HDD method "B" consists of using hydraulic jacking equipment to push a solid steel rod under the railroad from a launching pit to a receiving pit.

c) Minimum depth of installation standard is provided in Table 2.10 below.

Table 2.10: NS Wireline Minimum Depth of Installation

Material	Bore & Jack	HDD-A	HDD-B
Steel	5'1/2" (1.68 m)	10' (3.05 m)	5'1/2" (1.68 m)
Plastic	15 feet* (4.57 m)		

*Within 25 feet (7.62 m) of centerline of the closest track and a minimum depth of 10 feet (3.05 m) anywhere else on NS property.

2.9.7 Union Pacific Railroad

For HDD and pipeline installations, UP follows the AREMA Manual for Railway Engineering Chapter 1 – Part 5 pipeline guidelines [21]. Union Pacific has adopted Table 2.9 as part of their guidelines for abandonment of subsurface utility structures [22]. An engineering review matrix based on the UP standard is provided in Table A.7 in Appendix A [21].

3.0 Case Studies

A total of three case studies were examined to assess the performance of existing guidelines and standards. The first case study is an example of a well-executed microtunnelling project which included a soil investigation, settlement assessment, monitoring plan, site supervision and testing. The remaining two case studies summarize the initial events and investigation findings from subsurface failures induced by trenchless construction installations.

3.1 Microtunnel Boring Machine

In 2017, the construction of a concrete lined trenchless storm trunk crossing took place within a railroad ROW. A Herrenknecht AVN1800 MTBM was used to construct the 2.2 m outside diameter, 63 m long tunnel, with 6 m cover above the tunnel under the railway track [23].

3.1.1 Soil Investigation

Two test holes were drilled on both sides of the railway tracks and were advanced with solid stem augers through the surficial soils to the termination depths into the underlying bedrock. Groundwater levels were measured upon completion of drilling both test holes. The soil stratigraphy encountered in the bore holes generally consisted of a surficial layer of topsoil, overlying low plastic clay and/or silt or cohesionless sand, overlying medium plastic glacial clay till, overlying bedrock. Groundwater level readings indicated groundwater levels at approximately 0.8 m below existing ground surface, about 3 m above the tunnel crown [23].

3.1.2 Settlement Assessment

A semi-empirical method described by O'Reilly and New [26] was used to conduct the settlement trough assessment under the railway tracks. This method assumes that the volume of the settlement trough at the surface is equal to the volume loss at the tunnel. Figure 3.1 below provides a schematic of a typical surface settlement induced by tunnelling. The method uses the following equations:

$$S = S_{max} \times \ e^{\left(-\frac{x^2}{2i^2}\right)} \text{ [24]}$$

$$S_{max} = \frac{AV_L}{100} \frac{1}{\sqrt{2\pi}i} \text{ modified from [25]}$$

$$i = K \ \times Z \text{ [26]}$$

Where:
S = theoretical settlement (m)
S_{max} = maximum settlement (m)
x = transverse horizontal distance from the tunnel center line (m)
i = point of inflection (m)
A = excavated area (m³/m)
V_L = volume loss (%)
Z = tunnel axis depth (m)
K = empirical constant of proportionality

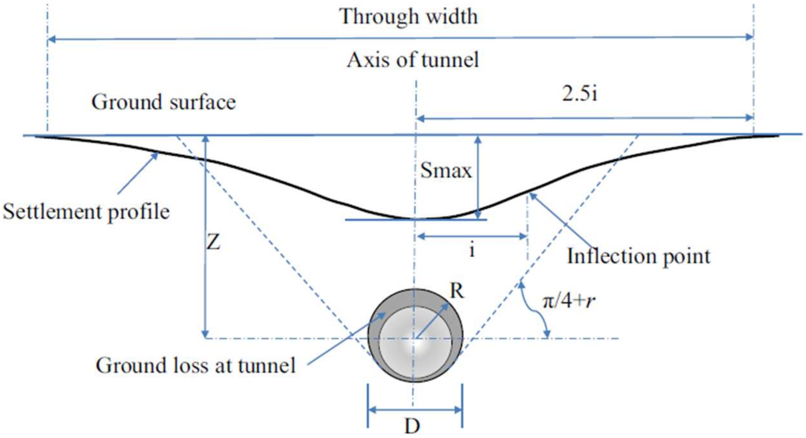


Figure 3.1: Typical Section of the Surface Settlement Induced by Tunnelling [27]

There cases of volume loss (0.5%, 1.0% and 1.5%) were considered for the maximum settlement estimates and the results are presented below in Table 3.1 and Figure 3.2, respectively. Tunnelling estimates suggest 1.0% volumes loss is a conservative approach for microtunnelling projects.

Table 3.1: Estimated Maximum Surface Settlement [23]

0.5 % volume loss	1.0 % volume loss	1.5 % volume loss
3 mm	5 mm	8 mm

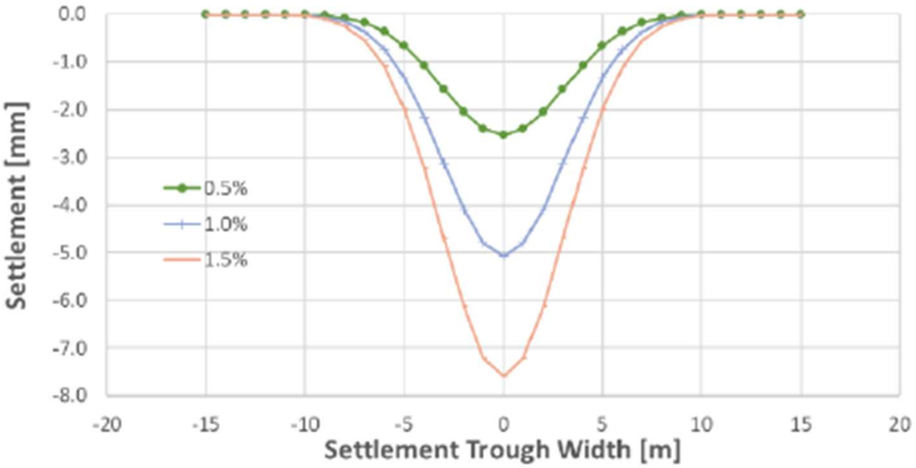


Figure 3.2: Predicted Settlement Trough [23]

3.1.3 Monitoring Plan

Settlement monitoring was completed by establishing surface settlement monitoring points for measuring potential vertical movements along the base of the railroad tracks. A total of 22 monitoring points were established to monitor the settlement trough induced by the MTBM operations. Figure 3.3 shown below provides a plan view of the survey points that were monitored for settlement. Warning and critical alarm thresholds used for the settlement monitoring were 10 mm and 19 mm, respectively.

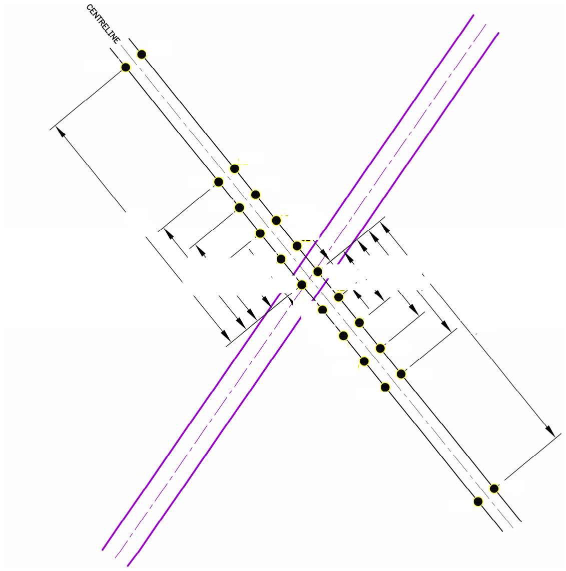


Figure 3.3: Survey Monitoring Points [23]

3.1.4 Site Supervision and Monitoring

The survey points were monitored by an experienced surveying team with a surveying optical level. The maximum settlement due to the tunnelling construction at the survey points was 5.2 mm. It should be noted that the maximum observed settlement compared well with the 1.0% volume loss predicted settlements shown in Figure 3.4 below.

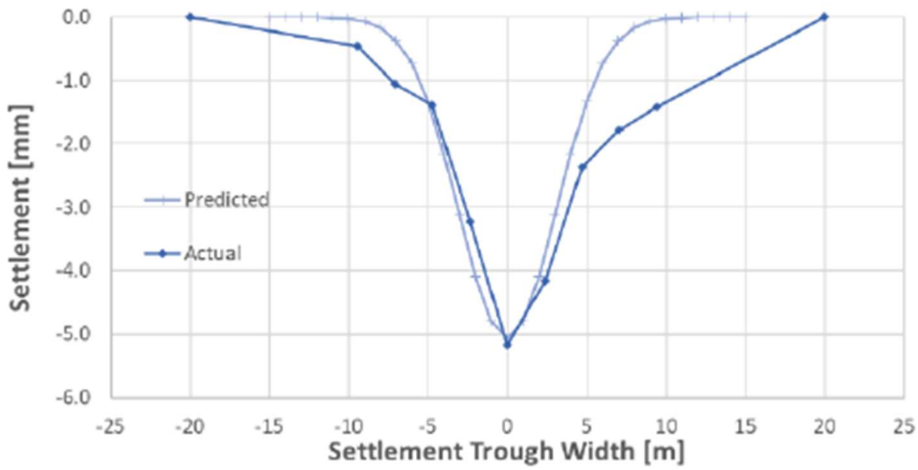


Figure 3.4: Actual and Predicted Settlement [23]

3.2 Microtunnel Boring Machine Failure

3.2.1 Background

The scope of this project was to install utilities under four (4) sets of railway tracks. The trenchless method selected for the installation was microtunnelling. During tunnelling activities on night shift, a sinkhole developed (38 m from the launch shaft) underlying the west most railroad tracks "Track 1" shown below in Figure 3.5. A geotechnical investigation indicated that dense to very dense, silty, poorly graded fluvial gravel underly Track 1. A photograph of the sinkhole is shown in Figure 3.6 below.

Figure 3.5: Site Plan [28]

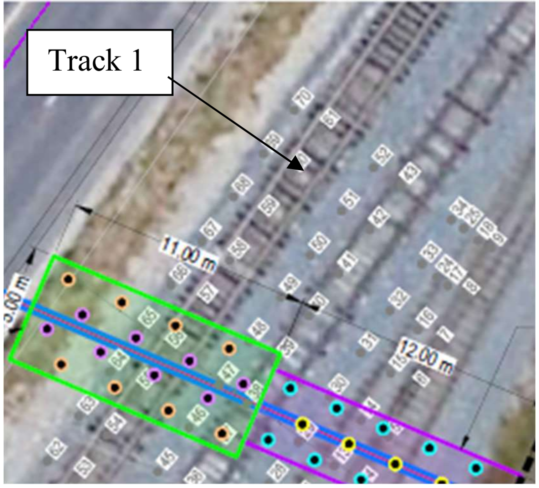


Figure 3.6: Sinkhole Underlying Track 1

A MTBM was used to construct the 1.490 m outside diameter reinforced concrete lined tunnel extending across an approximately 23 m wide railroad ROW at depths ranging from 6.8 m to 7.1 m below the base of rail. It should be noted that the total length of the tunnel extended well beyond the railroad ROW.

3.2.2 Investigation

An investigation was conducted to determine the causes for the failure and the findings are summarized below:

a) Operator error and complacency while operating the MTBM.
b) Difficult tunnelling ground conditions which resulted in over excavation at the face of the MTBM.
c) Geotechnical Engineer of Record was not onsite full-time to conduct settlement monitoring while tunnelling operations commenced.

3.3 Guided Boring Failure

3.3.1 Background

Two steel casings (Casing A and Casing B) were installed under railroad tracks using the guided bore trenchless construction method. The installations were designed to be advanced through loose to compact, fine grained sand with trace amounts of gravel. During the installations of Casing A and Casing B the above referenced soils were encountered with the exception for Casing B where cobbles and boulders were also encountered [29].

By the completion of the settlement monitoring program, significant settlements were not encountered at the Casing A crossing. However, up to 39 mm of track settlement were observed at the Casing B crossing which had also affected the track above Casing A. Settlement monitoring was extended post construction. Three sinkholes along the Casing B alignment centerline had developed [29]. Photographs of the sinkholes are provided in Figures 3.7 through Figure 3.9 shown below.

Figure 3.7: Smaller Sinkhole [29]

27 Mar 2017, 1:46 PM

Figure 3.8: Larger Sinkhole [29]

27 Mar 2017, 1:50 PM

Figure 3.9: Third Sinkhole [29]

3.3.2 Investigation

A post construction investigation was conducted to determine the causes for the settlement and sinkholes. A summary of the investigation findings are provided below [29]:

a) Dynamic settlement of cohesionless soils induced by vibrations from the installation of the Casing B.

b) Slow advancement of the Casing B casing could have introduced soil mobilization into the casing.

c) Displacement of a boulder during casing installation could have been pushed and created subsurface voids.

d) Frozen soil at grounds surface could have “bridged” resulting in a surface settlement monitoring program not being able to detect the development of subsurface voids and subsurface track settlement.

e) Spring thaw can potentially increase the soil water content and trigger a collapse of existing voids.

f) Potential groundwater flow causing subsurface soil erosion.

4.0 Recommendations for Best Practices

Upon review of the relevant guidelines, case studies and industry standards, the recommended best practices for third party pipeline and utility crossings are provided in the following sections. The best practices have been subdivided into the following sections: soil investigation, settlement assessment, monitoring plans, site supervision and monitoring.

In general, it is good practice to apply the observational method to third party pipeline and utility crossing construction projects. A great definition of the observational method is described by CIRIA 185 [30] “The observational method in ground engineering is a continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve great overall economy without compromising safety”.

The eight key ingredients for the observational method are provided below [31]:

a) There must be sufficient site investigation
b) Design is developed on most probable (best estimates) to predict behavior
c) Develop monitoring strategy on calculated values for best case
d) Perform calculations on most unfavorable conditions
e) Identify contingency plans for most unfavorable conditions
f) Monitor and evaluate actual conditions
g) Modify design to suit actual conditions if triggers are exceeded
h) Observational method can only be done if there is adequate time to make decisions and implement

4.1 Soil Investigation

Initially, in the request for proposal phase of any project the scope of work needs to be clearly defined. It is important that consultants bidding on the project understand the scope of work so they can initiate any required preparations which also results in increased accuracy for cost estimates in the proposal phase of the project.

The geotechnical engineering consultant should provide the following site-specific information:

a) Field drilling program
b) Bore hole logs
c) Site plan showing bore hole locations
d) Feasible trenchless installation methods
e) Bore pit construction and backfilling recommendations (if applicable)
f) Temporary shoring (if applicable)
g) Construction inspections

Based on the lessons learned from the select case studies, bore holes should be advanced on both sides of the proposed crossing to confirm the soil stratigraphy, regardless of the crossing length. The bore holes should be near the infrastructure being crossed [29]. Best practices would suggest that two bore holes should be located on the railroad property as close to the boring path as possible. Geotechnical bore holes should be located a sufficient lateral distance from the boring path if pressurized drilling fluids will be used during installation of the crossing.

4.2 Settlement Assessment

Initially a coordinate system should be established for the settlement assessment and remain consistent with the coordinate system used for the settlement monitoring. It is common practice to designate positive values of movement (+) to represent heave and negative values of movement (-) to represent settlement.

The geotechnical engineering consultant should provide the expected surface settlement induced by the trenchless installation method before construction is started. Frac-out contingency plans for HDD drilling methods should be submitted and reviewed prior to construction.

4.2.1 Utility Installation Depth

Using the semi-empirical method described by O'Reilly and New [26] the maximum surface settlement below the base of rail was analyzed for varying utility diameters, installation depths and soil conditions. The settlement trough results are provided in Figures C.1 to C.4 in Appendix C of this report. The equations used in the analysis are provided in section 3.1.2 of this report. Table 4.1 shown below provides a summary of the assumptions and parameters used for the minimum two times and minimum three times the diameter installation depths (Z=2D and Z=3D) below the base of rail analyses. Settlement warning and alarm values of 10 mm and 19 mm respectively were considered as part of the analyses.

Table 4.1: Summary of Assumptions and Parameters

Scenario	**Radius (m)**	**Diameter (m)**	**K**	**Z=2D (m)**	**Z=3D (m)**	**V_L (%)**	**A (m^3/m)**
Cohesive Small Diameter	0.15	0.3	0.5	1.5⁽¹⁾	1.5⁽¹⁾	1.0	0.071
Cohesive Medium Diameter	0.75	1.5	0.5	3.0	4.6⁽³⁾	1.0	1.77
Cohesive Large Diameter	1.5	3.0	0.5	6.1⁽²⁾	9.1⁽³⁾	1.0	7.07
Cohesionless Small Diameter	0.15	0.3	0.3	1.5⁽¹⁾	1.5⁽¹⁾	1.0	0.071
Cohesionless Medium Diameter	0.75	1.5	0.3	3.0	4.6⁽³⁾	1.0	1.77
Cohesionless Large Diameter	1.5	3.0	0.3	6.1⁽²⁾	9.1⁽³⁾	1.0	7.07

Note: (1) tunnel axis depth of 1.524 m (5 feet) was used for the small diameter scenarios
(2) tunnel axis depth approximately two times the diameter of the tunnel
(3) tunnel axis depth approximately three times the diameter of the tunnel

The maximum surface settlement results for the Z=2D and Z=3D installation depths below the base of rail are provided on the semi-natural logarithm plots shown below in Figures 4.1 and 4.2, respectively. The settlement "warning" threshold of 10 mm is included in Figures 4.1 and 4.2.

The maximum surface settlement result in Figure 3.4 from the case study provided in section 3.1 of this report has been plotted on Figure 4.2 since the installation depth for this case study was approximately equal to three times the diameter of the tunnel (Z=3D). The overlying soil stratigraphy for the case study tunnel installation in section 3.1 was predominantly medium plastic clay and compares well with the trendline for clay soils shown below in Figure 4.2.

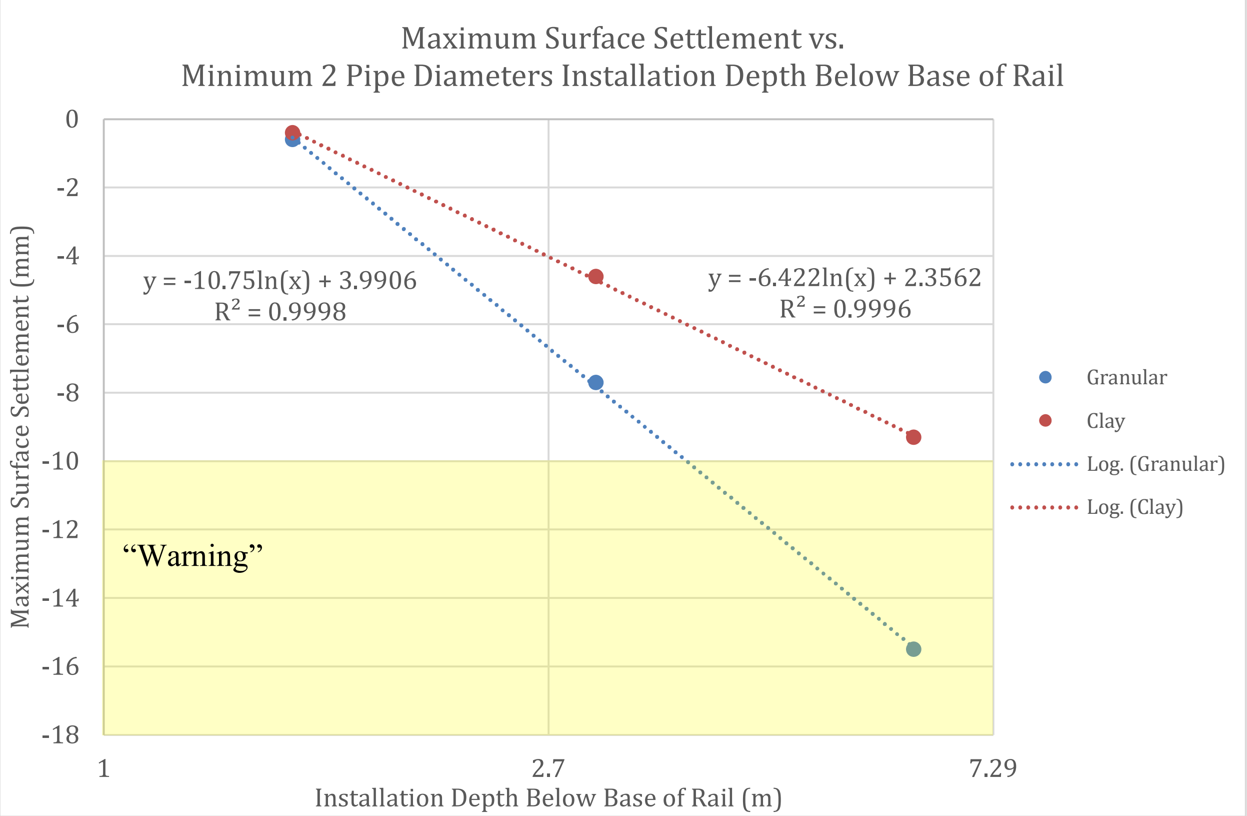


Figure 4.1: Maximum Surface Settlement vs. Installation Depth Below Base of Rail (Z=2D)

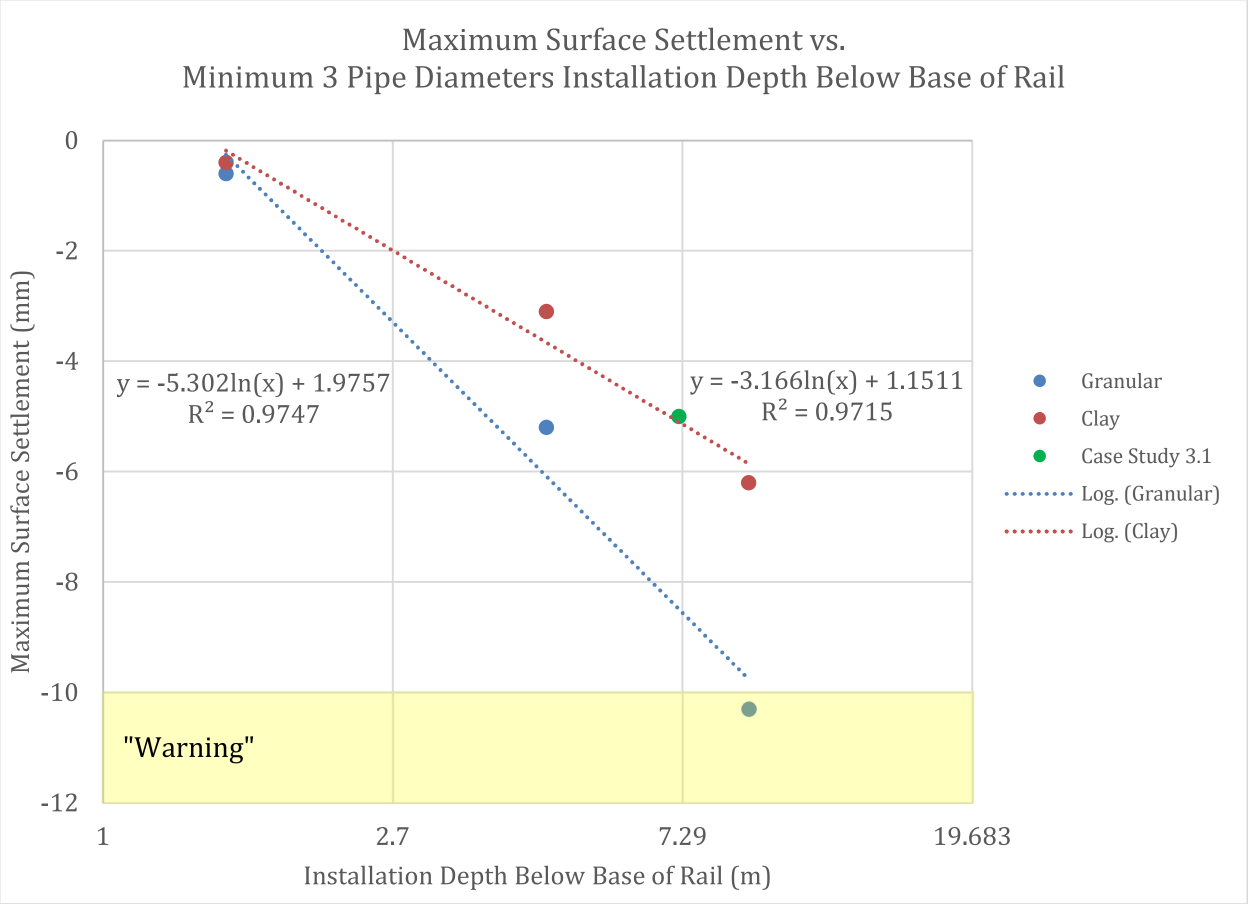


Figure 4.2: Maximum Surface Settlement vs. Installation Depth Below Base of Rail (Z=3D)

The trendlines shown in Figures 4.1 and 4.2, represent the upper and lower limits expected for the maximum surface settlements below the base of rail for mixed soil conditions of varying thicknesses and varying percentages of cohesive and cohesionless soils. Monte Carlo simulations were run to simulate mixed soil site conditions. It should be noted that the Monte Carlo simulations were run for the Z=2D and Z=3D installation depths below the base of rail using the data points (not the trendline equations) shown in Figures 4.1 and 4.2.

Mixed soil stratigraphy histogram plots of the predicted maximum surface settlements for the Z=2D and Z=3D installation depths below the base of rail are provided below in Figure 4.3 and Figure 4.4, respectively.

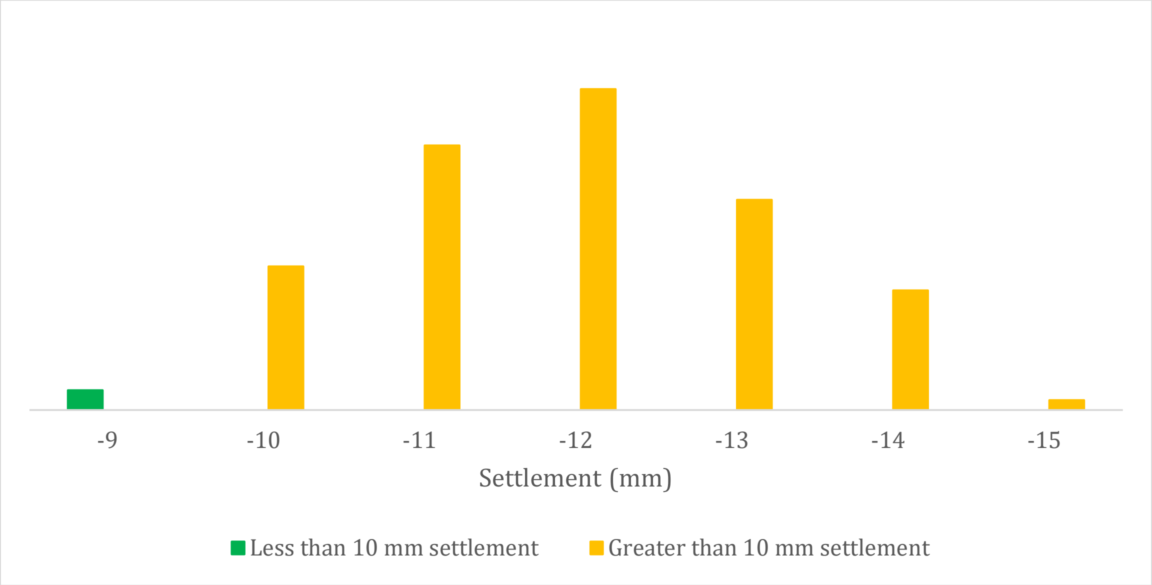


Figure 4.3: Maximum Surface Settlement Histogram for Mixed Soil Stratigraphy (Z=2D)

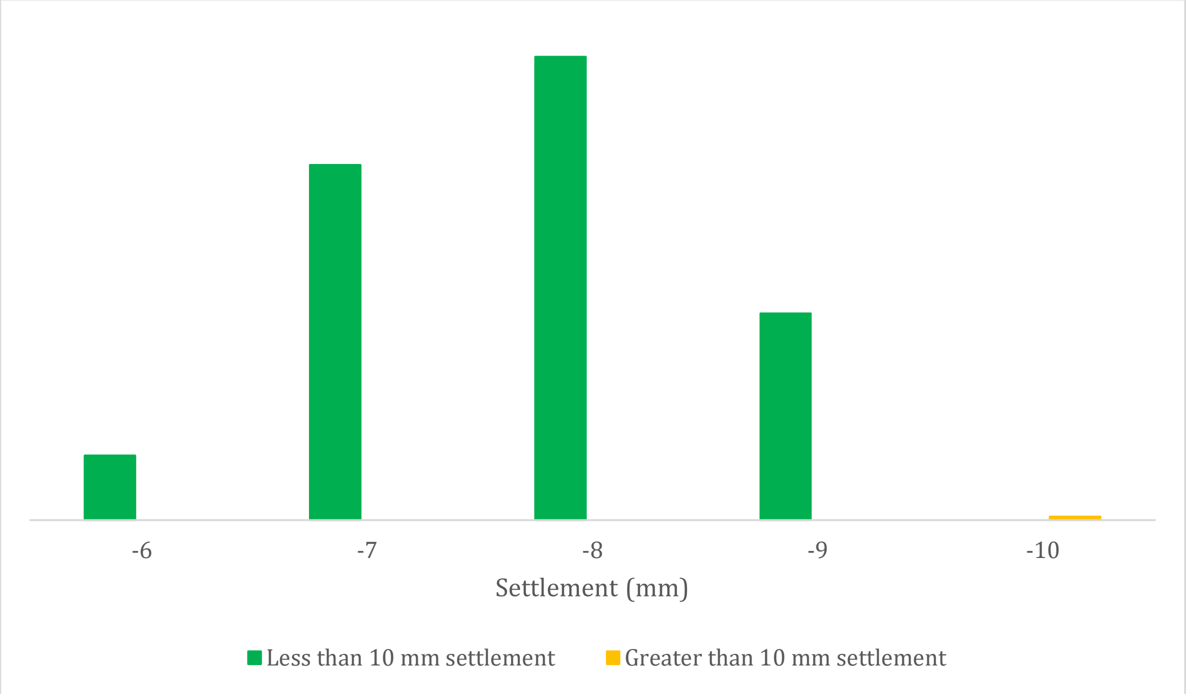


Figure 4.4: Maximum Surface Settlement Histogram for Mixed Soil Stratigraphy (Z=3D)

Based on the input parameters and assumptions used for these analyses, the Monte Carlo simulation results suggest the following:

- There is a 99 percent chance that the maximum surface settlement will exceed 10 mm for large diameter tunnels installed in mixed soil stratigraphy with minimum two times the diameter installation depth below the base of rail.
- There is a 2 percent chance that the maximum surface settlement will exceed 10 mm for large diameter tunnels installed in mixed soil stratigraphy with minimum three times the diameter installation depth below the base of rail.

Mixed soil stratigraphy cumulative density function (CDF) plots of the predicted maximum surface settlements for the Z=2D and Z=3D installation depths below the base of rail are provided below in Figures 4.5 and 4.6, respectively.

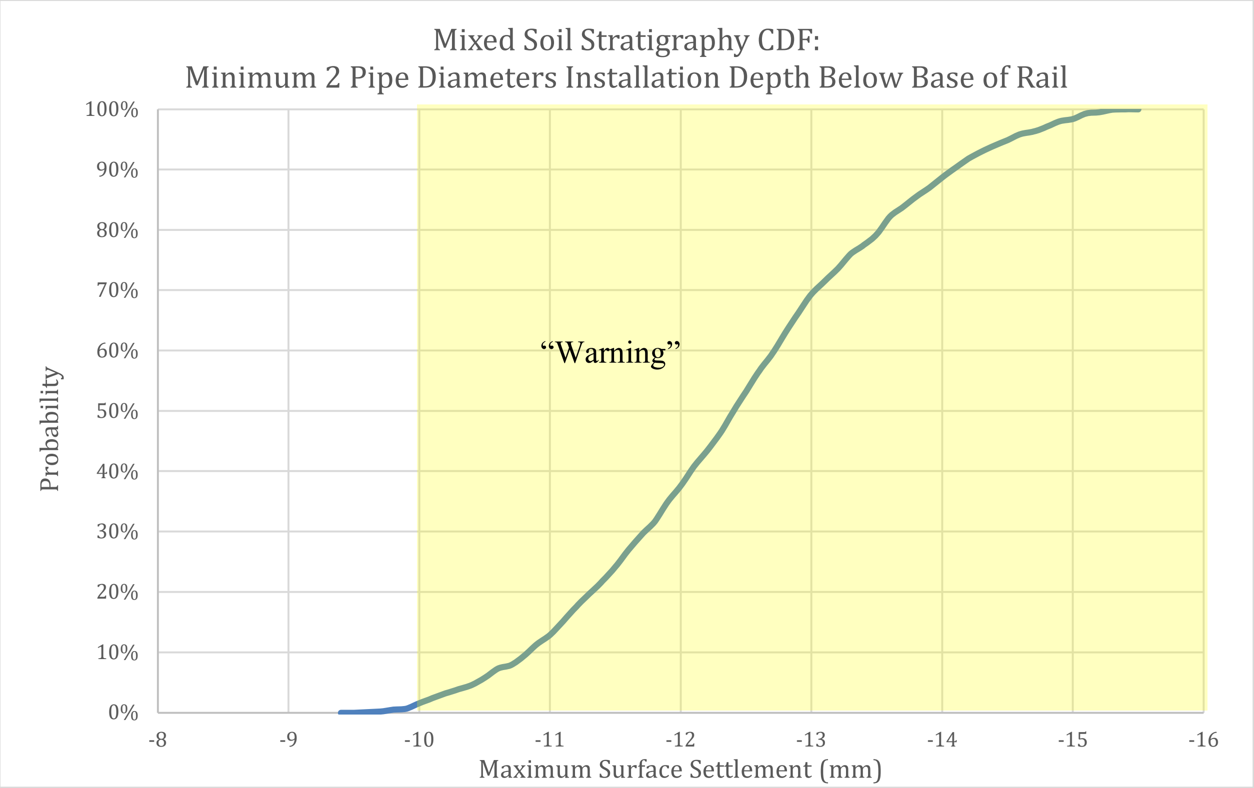


Figure 4.5: Maximum Surface Settlement CDF for Mixed Soil Stratigraphy (Z=2D)

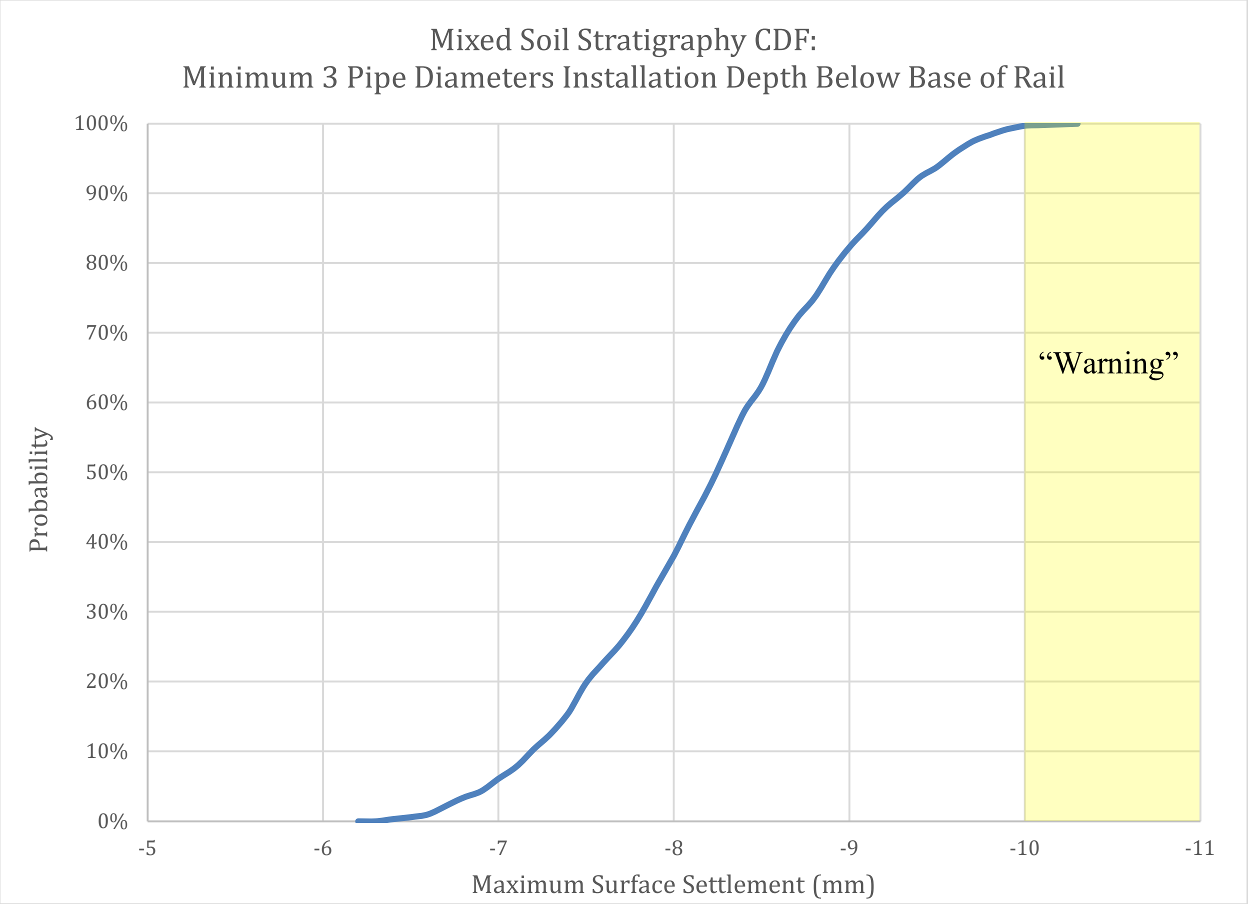


Figure 4.6: Maximum Surface Settlement CDF for Mixed Soil Stratigraphy (Z=3D)

With the exception for the HDD method, the recommended minimum installation depth below the base of rail for third party utility crossings under railway tracks is 1.5 m (5 feet), or three times the diameter of the installed utility, whichever is greater.

AREMA provides the recommended minimum installation depth of 3.66 m (12 feet) below the base of rail for HDD method for third party utility crossings under railway tracks [12].

4.3 Monitoring Plans

Settlement monitoring plans are critical programs for obtaining relevant ground surface and subsurface settlement data throughout trenchless construction projects.

Consideration for vibration monitoring plans may be required for pipe ramming operations near existing facilities, utilities or pipelines. Vibration monitoring plans might also be required for other trenchless construction methods that can induce large vibrations near existing facilities and utilities. Vibration monitoring may also be considered to monitor vibration levels related to dynamic induced settlements and dynamic induced liquefaction in cohesionless soils.

4.3.1 Settlement Monitoring Plan

Best practices for settlement monitoring plans include:

a) Settlement monitoring plan be prepared by the pipeline or utility applicant, at the applicant’s sole cost and expense.

b) Settlement monitoring and settlement mitigation plans should be submitted and reviewed before construction. The plans should outline but not be limited to the construction sequence, proposed survey instrument, settlement/heave threshold limits, frequency and location of survey readings, reporting procedures and settlement/heave mitigation methods.

c) At ground surface, soils can bridge over underlying voids [12]. Therefore, subsurface settlement monitoring along the boring path at locations overlying the ground surface should be considered. This could potentially detect construction induced subsurface soil voids earlier than conventional (surface only) settlement monitoring programs.

d) Survey background readings should be conducted before the start of construction. The background readings should be resurveyed if the background readings are not consistent.

e) Settlement monitoring survey readings should be taken on consecutive days after the installation of the crossing to confirm that all settlement has ceased.

4.3.2 Vibration Monitoring Plan

Best practices for vibration monitoring plans include [32]:

a) Vibration study be prepared by the pipeline or utility applicant, at the applicant's sole cost and expense.

b) Vibration study be completed before construction and may include measuring background vibration levels and/or computer modeling to predict vibration levels.

c) A minimum of two vibration background readings be taken before the start of construction. The background readings should be rerecorded if the background readings are not consistent.

d) Vibration monitoring threshold warning and alarm limits should be established prior to construction. For residential structures, it is common industry practice to adopt vibration monitoring threshold warning and alarm limits of 10 mm/sec and 50 mm/sec, respectively [32].

e) Vibration monitoring and mitigation plans should be submitted and reviewed before construction. The plans should outline but not be limited to the vibration causing equipment, construction sequence, proposed instrument for vibration monitoring, vibration threshold limits, frequency and location of vibration readings, reporting procedures and vibration mitigation methods.

4.4 Site Supervision and Monitoring

Site supervision and monitoring should be carried out by qualified personnel. The North American Class I railroads have established independent process for site supervision and monitoring. For Canadian Class I railroads, these tasks are commonly contracted to consultants.

Alternatively, CSX provides the construction monitor for track settlement monitoring at the applicant's sole cost and expense [17]. The approach taken by CSX has some advantages being that CSX can assign their own schedule, assign their internal construction monitor and CSX will acquire the fees associated with the supervision and monitoring program. However, disadvantages include staffing the construction monitor, assuming risk and liability.

4.4.1 Survey Method

Automated survey systems such as utilizing ShapeArray's or robotic total stations for collecting the settlement monitoring survey data should be considered. Based on the Norfolk Southern standards, track access is only permitted to place the survey targets. By incorporating survey systems that do not require track access to the railway, the railway flagmen would not need to be onsite for the final days of survey readings upon completion of the crossing installation.

It is common practice for the field review monitor to submit daily construction observation reports. It is recommended that the daily construction observation reports note the survey method used to record the settlement monitoring data. The accuracy of the survey data varies based on the survey method. The accuracy of the survey methods can vary from multi-millimeter to submillimeter accuracy.

In situations where the settlement data is a millimeter below the alarm thresholds i.e. “warning” and “critical”, immediate actions may need to be triggered depending if the survey instrument achieves multi-millimeter accuracy. Alternatively, immediate actions may not be required when more confidence is associated with the accuracy of the survey data.

4.4.2 Vibration Monitoring

Two common strategies to conduct vibration monitoring include spot checks or full-time continuous site monitoring. Advantages of spot checks include a cost-effective approach for collecting data for the key construction vibration causing activities onsite while having a construction monitor onsite to document the observed activities. If not implemented correctly this approach can miss data collection of the maximum construction induced vibrations onsite.

A cost-effective solution for third party pipeline and utility construction projects would be to utilize the construction monitor conducting the full-time settlement monitoring to oversee the full-time vibration monitoring program onsite.

5.0 Acknowledgements

I would like to thank Dr. Michael Hendry (University of Alberta) for his supervision that ensured the successful completion of this project. I would also like to thank Remco Kleinlugtenbelt (Thurber Engineering Ltd) for answering my questions and providing relevant reference materials for this project.

6.0 Conclusion

Trenchless technologies have been adopted as a common installation method for installing utilities and pipelines under railroad ROWs. Common trenchless methods include horizontal auger boring, pipe jacking, pipe ramming, HDD, MT and PTGB. The railroad industry has well established guidelines that are published annually by AREMA. The Class I railroads in North American have all developed their own independent utility and pipeline accommodation standards and processes.

The AREMA depth of installation guidelines for utility and pipeline crossings under railway tracks can be adopted as is for small diameter utilities and pipelines. However, for larger diameter utilities and pipelines, the depth of installation of three times the diameter of the utility or pipeline should be considered.

The installation of utility crossings under railway tracks during weekends and night shifts can create added challenges. Full-time settlement monitoring should be conducted whenever construction activities are being conducted. Furthermore, key decision makers should always be available whenever construction activities are being conducted to help troubleshoot any problems.

Trenchless crossings under railway tracks in soft silty deposits are more sensitive to volume losses and should require thorough site investigations, settlement assessments and settlement monitoring. Vibration monitoring should also be considered for trenchless construction methods that induce high vibrations during installations in cohesionless soils, to monitor for risks associated with dynamic induced settlements and dynamic induced pore pressures. Lastly, settlement monitoring, vibration monitoring and contingency plans should be submitted and reviewed prior to construction of trenchless crossings.

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APPENDIX A: North American Class I Railroad Utility Accommodation Standard Summary

Table A.1: BNSF Engineering Review Matrix [13]

STANDARD REQUIREMENTS		UNDERGROUND	CASING	OFFSET FROM TRACK	PROXIMITY TO STRUCTURES
UTILITY CROSSING	WATER LINE XING	6' (1.83 m) BNG	ENCASEMENT SHALL BE STEEL WHERE APPLICABLE. THE CASING SHALL EXTEND THE FULL WIDTH OF THE ROW AND MUST MEET AREMA STANDARDS FOR E80 CASING W&W/O COATING AND CATHODIC PROTECTION	-	UTILITY CROSSING SHALL NOT BE PLACED WITHIN 150' (45.7 m) OF THE END OF ANY RAILROAD BRIDGE, CENTERLINE OF ANY CULVERT OR SWITCH AREA
	CRUDE OIL XING	6' (1.83 m) BNG		-	
	SEWER LINE XING	6' (1.83 m) BNG AND 5'1/2" (1.68 m) BELOW BASE OF RAIL AND 10' (3.05 m) BELOW BASE OF RAIL FOR HDD INSTALLATION.		MANHOLES 25' (7.62 m) MINIMUM FROM MAINLINE	
	ELEC LINE XING	3' (0.91 m) BNG		-	
	HV ELEC LINE XING (> 450 kV)	4' (1.2 m) BNG		-	
	COMM LINE XING	4' (1.2 m) BNG		-	
	FIB OPT LINE XING	4' (1.2 m) BNG		-	
	GAS LINE XING	6' (1.83 m) BNG AND 5'1/2" (1.68 m) BELOW BASE OF RAIL AND 10' (3.05 m) BELOW BASE OF RAIL FOR HDD INSTALLATION.	** STEEL CASING CAN BE OMITTED IF XING IS 30' (9.14 m) OR MORE BELOW BASE OF RAIL AND MAINTAIN 6' (1.83 m) BNG	-	

*UTILITIES SHALL NOT BE PLACED WITHIN CULVERTS OR UNDER RAILROAD BRIDGE ABUTMENTS, BUILDINGS, OR OTHER IMPORTANT STRUCTURE NOR ATTACHED TO BRIDGES

** CARRIER PIPE MUST BE STEEL AND THE WALL THICKNESS MUST CONFORM TO E-80 LOADING FOR CASING PIPE SHOWN IN THE TABLES AS INCLUDED IN THE AREMA MANUAL CHAPTER 1, PART 5 FOR PIPELINE CROSSINGS

Table A.2: Canadian National (Southern Region) Engineering Review Matrix [14]

STANDARD REQUIREMENTS		**DRY JACK AND BORE**	**UNCASED UTILITY**	**DIRECTIONAL BORE**	**CASING**	**PROXIMITY TO STRUCTURES**
UTILITY CROSSING	WATER LINE XING	MAIN TRACKS 6' (1.83 m) BELOW BASE OF RAIL, INDUSTRIAL TRACKS 6' (1.83 m) BELOW BASE OF RAIL, 4' (1.2 m) BELOW ROAD SURFACE, 5' (1.52 m) BELOW DITCH BOTTOM	MAIN TRACKS 10' (3.05 m) BELOW BASE OF RAIL, INDUSTRIAL TRACKS 10' (3.05 m) BELOW BASE OF RAIL, 6' (1.83 m) BELOW ROAD SURFACE, 6' (1.83 m) BELOW DITCH BOTTOM	MAIN TRACKS 15' (4.57 m) BELOW BASE OF RAIL, INDUSTRIAL TRACKS 15' (4.57 m) BELOW BASE OF RAIL, 5' (1.52 m) BELOW ROAD SURFACE, 6' (1.83 m) BELOW DITCH BOTTOM	ENCASEMENT SHALL BE STEEL WHERE APPLICABLE. THE CASING SHALL EXTEND THE FULL WIDTH OF THE ROW OR 50 FEET (15.2 M) WHICHEVER IS GREATER AND MUST MEET AREMA STANDARDS FOR E80 CASING W&W/O COATING AND CATHODIC PROTECTION	UTILITY CROSSING SHALL NOT BE PLACED WITHIN 100' (30.5 m) OF THE END OF ANY RAILROAD BRIDGE, CENTERLINE OF ANY CULVERT OR SWITCH AREA
	CRUDE OIL XING					
	SEWER LINE XING					
	ELEC LINE XING					
	HV ELEC LINE XING					
	COMM LINE XING					
	FIB OPT LINE XING				** STEEL CASING CAN BE OMITTED IF XING IS 15' (4.57 m) OR MORE BELOW BASE OF RAIL	
	GAS LINE XING				** STEEL CASING CAN BE OMITTED IF XING IS 10' (3.05 m) OR MORE BELOW BASE OF RAIL	

*UTILITIES SHALL NOT BE PLACED WITHIN CULVERTS OR UNDER RAILROAD BRIDGE ABUTMENTS, BUILDINGS, OR OTHER IMPORTANT STRUCTURE NOR ATTACHED TO BRIDGES

** CARRIER PIPE MUST BE STEEL AND THE WALL THICKNESS MUST CONFORM TO E-80 LOADING FOR CASING PIPE SHOWN IN THE TABLES AS INCLUDED IN THE AREMA MANUAL CHAPTER 1, PART 5 FOR PIPELINE CROSSINGS

Table A.3: Canadian Pacific Engineering Process Identification Matrix [15]

		Process Levels		
		1. Minimum[1]	**2. Intermediate**	**3. Detailed**
Dimension	Outside diameter of pipe	Less than 300 mm (12 in.)	300 mm (12 in.) to 1500 mm (59 in.)	Greater than 1500 mm (59 in.)
	Cover between BOR and top of pipe	Greater than 1.5 m (5 ft.) or three (3) pipe diameters whichever is greater	Greater than 1.5 m (5 ft.) or two (2) pipe diameters whichever is greater	Less than 1.5 m (5 ft.) or two (2) pipe diameters
	Adjacent structures including switches and signals	Greater than 10 m (32.8 ft.) from centerline	Within 2.5 times, cover between BOR and top of pipe	
	Depth of pipes outside ZPTL	Refer to SP-TS 2.39 All pipes will be at least 0.91 m (3 ft.) below ground (below sub-ballast layer) where pipes are not below the ZPTL	Less than 0.91 m (3 ft.) burial within ZPTL	
Excavation Criteria	Excavation close to CP track(s)	Jacking/access pits shall be more than 10 m (32.8 ft.) from the closest track centerline and shall not encroach on the ZPTL	Excavations or jacking/access pits within 10 m (32.8 ft.) of the closest track centerline	
	Crossing angle	Less than 45 degrees off perpendicular to the track	More than 45 degrees off perpendicular to the track	
Construction Method		Trenchless method[2]		All methods considered
		Pipe bursting will only be considered where the predicted heave is less than 10% of the movement that would result in a change of FRA or TC track class		
Approval Process		Public Works - Utility group to approve with no geotechnical submission	Full review of design, geotechnical and construction method Applicant to pay for the review cost of CP approved service provider	

[1] Move to next class if one or more criteria are not met

[2] Trenchless methods include Auger Boring (AB), Pipe Jacking, Pipe Ramming (PR), Horizontal Directional Drilling (HDD) except high pressure fluid jetting method, Microtunnelling (MT) but exclude any type of mining techniques where any stand up time is required before the tunnel support is placed

Table A.4: CSX Transportation Engineering Review Matrix [16]

STANDARD REQUIREMENTS		UNDERGROUND	CASING	OFFSET FROM TRACK	PROXIMITY TO STRUCTURES
UTILITY CROSSING	WATER LINE XING	5'1/2" (1.68 m) BELOW BASE OF RAIL	ENCASEMENT SHALL BE STEEL WHERE APPLICABLE. THE CASING SHALL EXTEND THE FULL WIDTH OF THE ROW AND MUST MEET AREMA STANDARDS FOR E80 CASING W&W/O COATING AND CATHODIC PROTECTION	-	UTILITY CROSSING SHALL NOT BE PLACED WITHIN 45' (13.72 m) OF THE END OF ANY RAILROAD BRIDGE, CENTERLINE OF ANY CULVERT OR SWITCH AREA
	CRUDE OIL XING	6' (1.83 m) BNG AND 10' (3.05 m) BELOW BASE OF RAIL FOR UNCASED NATURAL GAS PIPELINES. CASING PIPES 5'1/2" (1.68 m) BELOW BOR AND 3' (0.91 m) BNG		-	
	SEWER LINE XING	5'1/2" (1.68 m) BELOW BASE OF RAIL		MANHOLE LOCATED OUTSIDE OF RAILROAD ROW WHERE POSSIBLE	
	ELEC LINE XING	5'1/2" (1.68 m) BELOW BASE OF RAIL		-	
	HV ELEC LINE XING	5'1/2" (1.68 m) BELOW BASE OF RAIL		-	
	COMM LINE XING	5'1/2" (1.68 m) BELOW BASE OF RAIL		-	
	FIB OPT LINE XING	5'1/2" (1.68 m) BELOW BASE OF RAIL		-	
	GAS LINE XING	6' (1.83 m) BNG AND 10' (3.05 m) BELOW BASE OF RAIL FOR UNCASED NATURAL GAS PIPELINES. CASING PIPES 5'1/2" (1.68 m) BELOW BOR AND 3' (0.91 m) BNG	** STEEL CASING CAN BE OMITTED IF XING IS 15' (4.57 m) OR MORE BELOW BASE OF RAIL AND INSTALLED BY HDD METHOD	-	

*UTILITIES SHALL NOT BE PLACED WITHIN CULVERTS OR UNDER RAILROAD BRIDGE ABUTMENTS, BUILDINGS, OR OTHER IMPORTANT STRUCTURE NOR ATTACHED TO BRIDGES

** CARRIER PIPE MUST BE STEEL AND THE WALL THICKNESS MUST CONFORM TO E-80 LOADING FOR CASING PIPE SHOWN IN THE TABLES AS INCLUDED IN THE AREMA MANUAL CHAPTER 1, PART 5 FOR PIPELINE CROSSINGS

Table A.5: Kansas City Southern Engineering Review Matrix [18]

STANDARD REQUIREMENTS		**UNDERGROUND**	**CASING**	**OFFSET FROM TRACK**	**PROXIMITY TO STRUCTURES**
UTILITY CROSSING	WATER LINE XING	10 ' (3.05 m) BNG AND 10' (3.05 m) BELOW BASE OF RAIL FOR STEEL. PLASTIC MUST BE 15' (4.57 m) BELOW FOR ENTIRE ROW	ENCASEMENT SHALL BE STEEL WHERE APPLICABLE. THE CASING SHALL EXTEND THE FULL WIDTH OF THE ROW AND MUST MEET AREMA STANDARDS FOR E80 CASING W&W/O COATING AND CATHODIC PROTECTION	-	UTILITY CROSSING SHALL NOT BE PLACED WITHIN 100' (30.5 m) OF THE END OF ANY RAILROAD BRIDGE, CENTERLINE OF ANY CULVERT OR SWITCH AREA
	CRUDE OIL XING			-	
	SEWER LINE XING			MANHOLES 25' (7.62 m) MINIMUM FROM MAINLINE	
	ELEC LINE XING			-	
	HV ELEC LINE XING (> 6 kV)			-	
	COMM LINE XING			-	
	FIB OPT LINE XING			-	
	GAS LINE XING	10' (3.05 m) BNG AND 10 (3.05 m) BELOW BASE OF RAIL	** STEEL CASING CAN BE OMITTED IF XING IS 15' (4.57 m) OR MORE BELOW BASE OF RAIL	VENTS FOR STEEL CASING SHUT OFF VALVES SHALL BE OUTSIDE OF ROW	

*UTILITIES SHALL NOT BE PLACED WITHIN CULVERTS OR UNDER RAILROAD BRIDGE ABUTMENTS, BUILDINGS, OR OTHER IMPORTANT STRUCTURE NOR ATTACHED TO BRIDGES
** CARRIER PIPE MUST BE STEEL AND THE WALL THICKNESS MUST CONFORM TO E-80 LOADING FOR CASING PIPE SHOWN IN THE TABLES AS INCLUDED IN THE AREMA MANUAL CHAPTER 1, PART 5 FOR PIPELINE CROSSINGS

Table A.6: Norfolk Southern Engineering Review Matrix [19] [20]

STANDARD REQUIREMENTS		UNDERGROUND	CASING	OFFSET FROM TRACK	PROXIMITY TO STRUCTURES
UTILITY CROSSING	WATER LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5	ENCASEMENT SHALL BE STEEL WHERE APPLICABLE. THE CASING SHALL EXTEND THE FULL WIDTH OF THE ROW AND MUST MEET AREMA STANDARDS FOR E80 CASING W&W/O COATING AND CATHODIC PROTECTION	-	UTILITY CROSSING SHALL NOT BE PLACED WITHIN 50' (15.24 m) OF THE END OF ANY RAILROAD BRIDGE, CENTERLINE OF ANY CULVERT OR SWITCH AREA
	CRUDE OIL XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5. 6' (1.83 m) BNG AND 10' (3.05 m) BELOW BASE OF RAIL FOR UNCASED.		-	
	SEWER LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5		MANHOLES LOCATED OUTSIDE OF RAILROAD ROW WHERE POSSIBLE	
	ELEC LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5		-	
	HV ELEC LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5		-	
	COMM LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5		-	
	FIB OPT LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5		-	
	GAS LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5. 6' (1.83 m) BNG AND 10' (3.05 m) BELOW BASE OF RAIL FOR UNCASED.	** STEEL CASING CAN BE OMITTED If THE CARRIER PIPE MEETS THE REQUIREMENTS OF AREMA MANUAL CHAPTER 1, PART 5 SECTION 5.2.3.	-	

*UTILITIES SHALL NOT BE PLACED WITHIN CULVERTS OR UNDER RAILROAD BRIDGE ABUTMENTS, BUILDINGS, OR OTHER IMPORTANT STRUCTURE NOR ATTACHED TO BRIDGES

** CARRIER PIPE MUST BE STEEL AND THE WALL THICKNESS MUST CONFORM TO E-80 LOADING FOR CASING PIPE SHOWN IN THE TABLES AS INCLUDED IN THE AREMA MANUAL CHAPTER 1, PART 5 FOR PIPELINE CROSSINGS

Table A.7: Union Pacific Engineering Review Matrix [21]

STANDARD REQUIREMENTS		**UNDERGROUND**	**CASING**	**OFFSET FROM TRACK**	**PROXIMITY TO STRUCTURES**
UTILITY CROSSING	WATER LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5	THE CASING SHALL EXTEND 30' (9.1 m) FROM TRACK CENTERLINE AND MUST MEET AREMA STANDARDS FOR E80 CASING W&W/O COATING AND CATHODIC PROTECTION. PVC CASING WILL BE CONSIDERED IF BURIAL DEPTH IS MINIMUM 15' (4.57 m)	-	UTILITY CROSSING SHALL NOT BE PLACED WITHIN 50' (15.2 m) OF THE END OF ANY RAILROAD BRIDGE, CENTERLINE OF ANY CULVERT OR SWITCH AREA
	CRUDE OIL XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5		-	
	SEWER LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5		-	
	ELEC LINE XING	4'1/2" (1.38 m) BELOW BOR AND 3' (0.91 m) BNG. 15' (4.57 m) BELOW BASE OF RAIL FOR HDD INSTALLATION.		-	
	HV ELEC LINE XING (> 450 kV)	4'1/2" (1.38 m) BELOW BOR AND 4' (1.2 m) BNG. 15' (4.57 m) BELOW BASE OF RAIL FOR HDD INSTALLATION.		-	
	COMM LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5		-	
	FIB OPT LINE XING	5' (1.52 m) BELOW BOR AND BNG		-	
	GAS LINE XING	FOLLOW AREMA MANUAL CHAPTER 1, PART 5	FOLLOW AREMA MANUAL CHAPTER 1, PART 5	-	

*UTILITIES SHALL NOT BE PLACED WITHIN CULVERTS OR UNDER RAILROAD BRIDGE ABUTMENTS, BUILDINGS, OR OTHER IMPORTANT STRUCTURE NOR ATTACHED TO BRIDGES

** CARRIER PIPE MUST BE STEEL AND THE WALL THICKNESS MUST CONFORM TO E-80 LOADING FOR CASING PIPE SHOWN IN THE TABLES AS INCLUDED IN THE AREMA MANUAL CHAPTER 1, PART 5 FOR PIPELINE CROSSINGS

APPENDIX B: Measurand SAAX Specification Sheet

MEASURAND

SAAX

Model 002

ShapeArray is patented technology.

Purpose-built for heavy duty horizontal measurement: soil settlement, rail-line deformation, and pipeline monitoring. SAAX1000's watertight construction combines twist-resistant joints and thick-walled stainless steel segment tubes. The construction contains a compact array of triaxial MEMS accelerometers.

SAAX1000 delivers superior cost-benefit returns to project budgets. All ShapeArray installations are fast and low-cost, requiring far fewer people than traditional in-place inclinometers. SAAX1000 is rolled off a reel and set into user-installed conduit.

SAAX1000's segment length is 1000 mm.

SPECIFICATIONS

PHYSICAL PROPERTIES

SEGMENT LENGTH	1000 mm (Joint centre to joint centre)
STANDARD LENGTH OF SAAX	Up to 150 m
CUSTOM LENGTH OF SAAX	Over standard length, contact Measurand for details
MAXIMUM DIAMETER	23 mm
LENGTH OF UNSENSORIZED NEAR CABLE END SEGMENT	500 mm standard (includes: 260 mm Cable Terminator Segment and 300 mm PEX, less 60 mm overlap)
LENGTH OF COMMUNICATION CABLE	15 m standard, (14.7 m extending past the PEX tubing)
LENGTH OF FAR TIP EYEBOLT	32 mm
WEIGHT	1.0 kg/m
MAXIMUM TENSILE RESISTANCE	550 kgf
MAXIMUM JOINT BEND ANGLES	70°
STORAGE TEMPERATURE	-40°C to 60°C
OPERATING TEMPERATURE	-40°C to 60°C
WATERPROOF TO	2000 kPa (200 m Water)
POWER REQUIREMENTS	12 VDC at 1.8 mA/segment

ELASTIC TWIST TOLERANCE

MAXIMUM TORQUE FOR ELASTIC RETURN[3]	2.0 N-m per joint
TWIST TOLERANCE	0.5° per joint
ACCURACY OF RETURN FOR ELASTIC TWIST[3]	±0.01° per joint

STATIC SHAPE MEASUREMENTS

RANGE OF 2D MODE (HORIZONTAL)	± 30° with respect to horizontal
ACCURACY OF DEFORMATION RELATIVE TO STARTING SHAPE[1,2,3]	± 1.5 mm for 32 m SAAX
RESOLUTION[1,2,3]	± 0.5 mm for 32 m SAAX
RESOLUTION OF SINGLE SEGMENT	± 1 arcsecond
ACCURACY OF TILT/SEGMENT WITHIN 20° OF HORIZONTAL[1,2,3]	± 0.0005 rad = 0.029°

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MEASURAND

NOTES

[1] One-sigma value, based on field measurements of horizontal arrays > 1 year of operation. Accuracy value is a function of the square root of length.

[2] Value based on AIA (Average in Array) setting of 1000 samples.

[3] RMS calculated from published noise figure of sensor (verified by Measurand) and bandwidth of system using highest AIA setting of 25,600 samples.

PATENT INFORMATION

ShapeArray is patented technology.

Measurand's patents include, but are not limited to:

Shape-Acceleration Measurement Device and Method, Canadian Patent 2,472,421& 2,747,236

Shape-Acceleration Measurement Device and Apparatus, US Patent 7,296,363

Cyclical Sensor Array, Canadian Application 2,815,199 & 2,911,178

Bipartite Sensor Array, Canadian Application 2,815,195 & 2,911,175

ShapeArray patents include coverage in: United States, Canada, France, United Kingdom, Italy, Japan and Germany.

Installation patents include coverage in United States, Canada, France, Untied Kingdom, Italy, Germany, China, Hong Kong, and Korea.

Patent families are sufficiently broad to capture most or all usage of ShapeArray in longer lists of countries.

NOTES

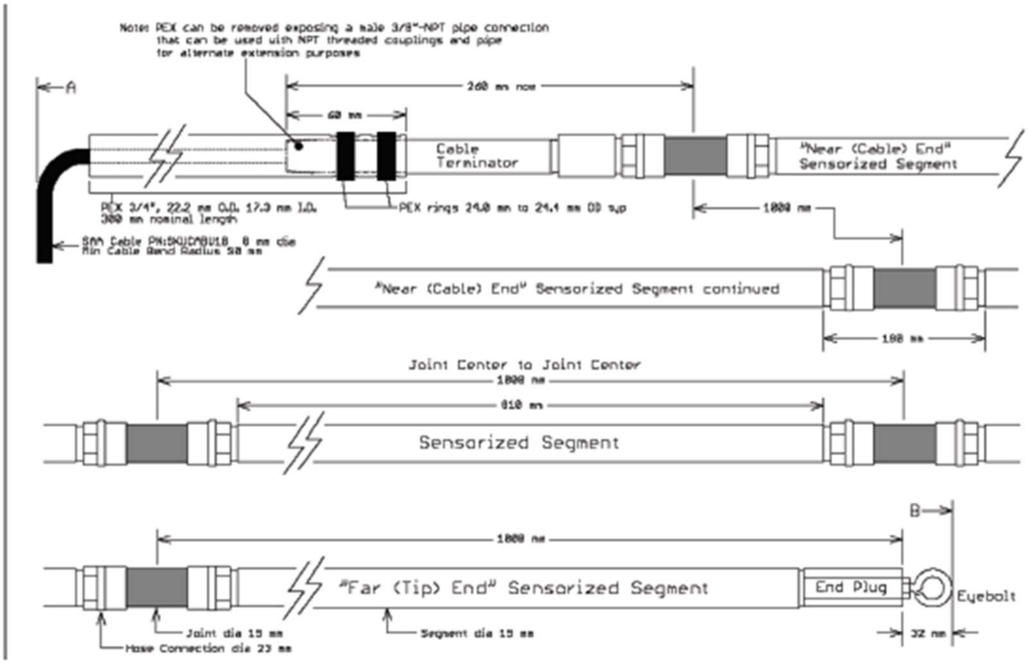
Minimum Capped ShapeArray Length (A to B) = Min Cable Bend Radius + Unsensorized Length + Sensorized Length + Eyebolt

Standard Unsensorized Length = 500 mm

Sensorized Length = "Near (Cable) End" Sensorized Segment through "Far (Tip) End" Sensorized Segment

PVC conduit End Cap and Install Kit Top Stack require additional depth.

Sensorized length tolerance within 1.5 % of total specified sensorized length.



APPENDIX C: Settlement Troughs

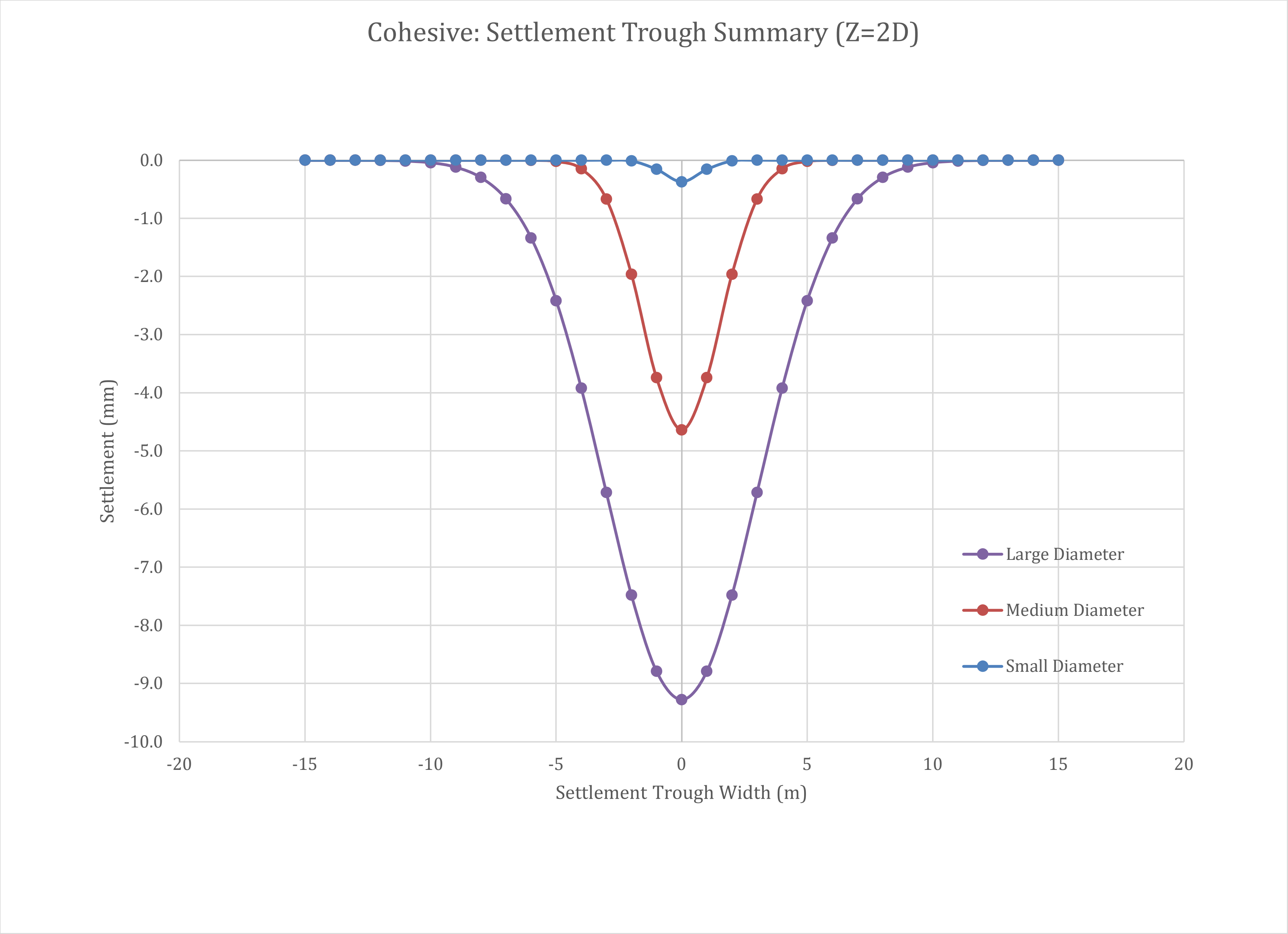


Figure C.1: Cohesive Settlement Trough Summary (Z=2D)

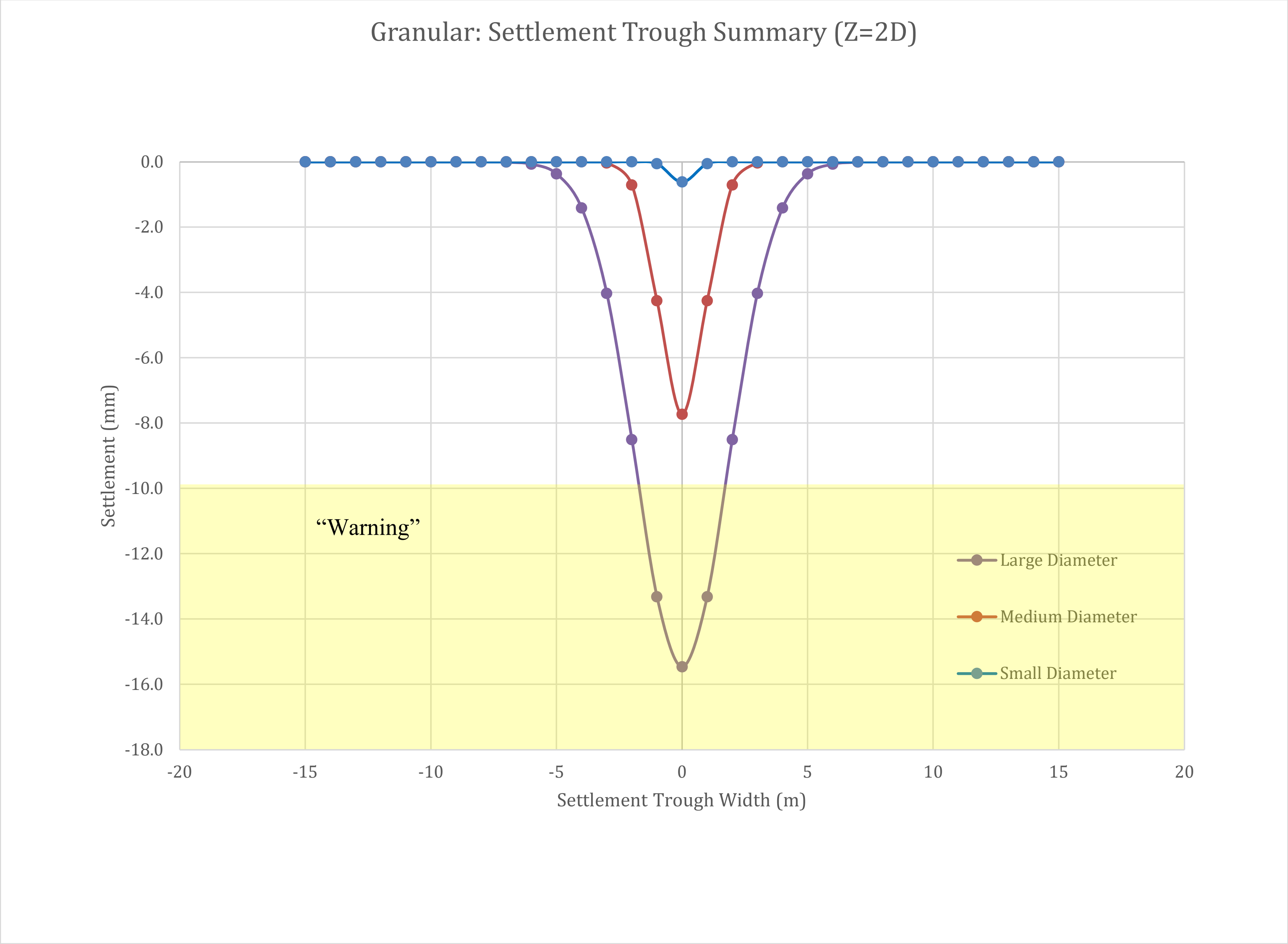


Figure C.2: Granular Settlement Trough Summary (Z=2D)

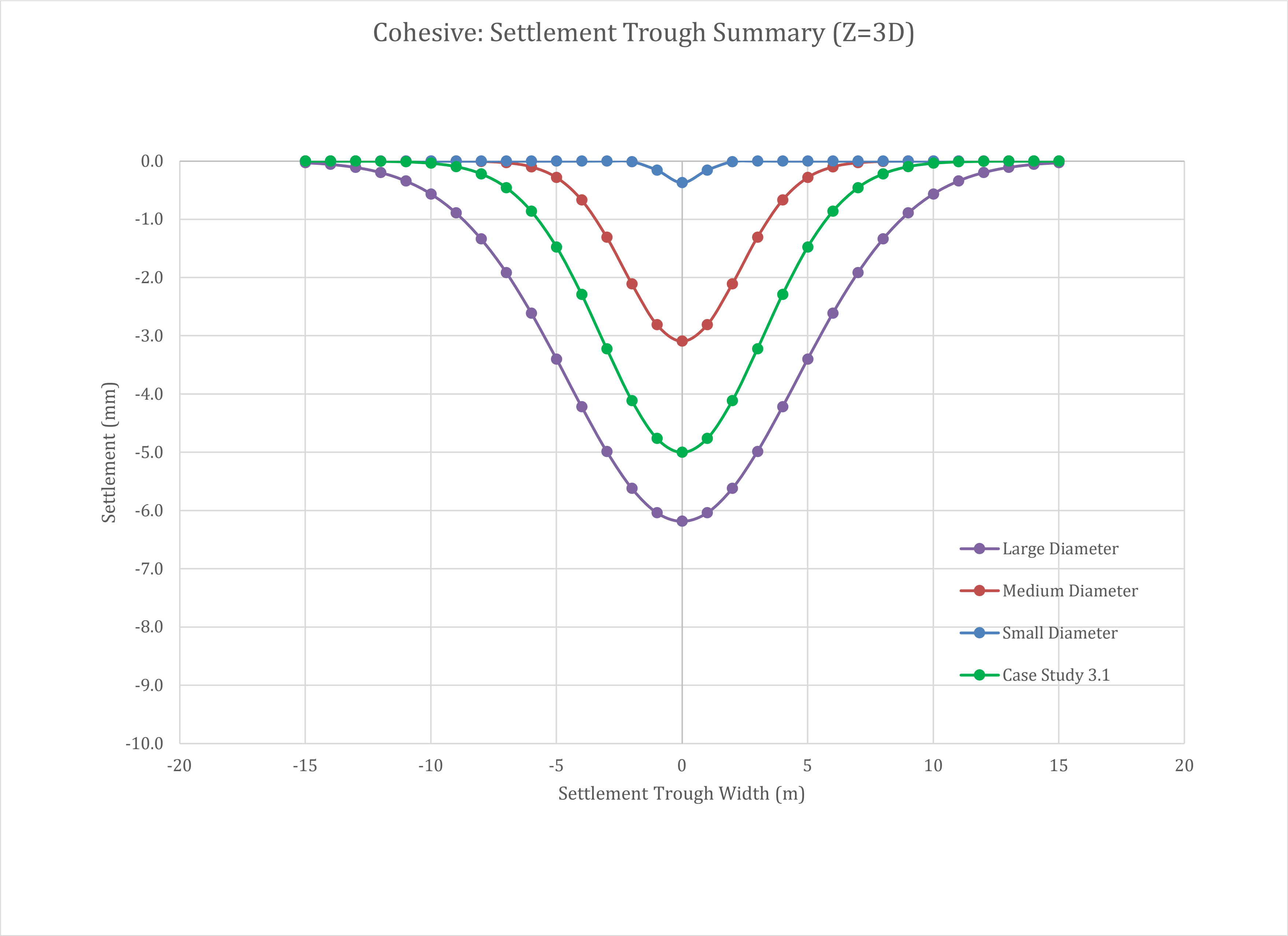


Figure C.3: Cohesive Settlement Trough Summary (Z=3D)

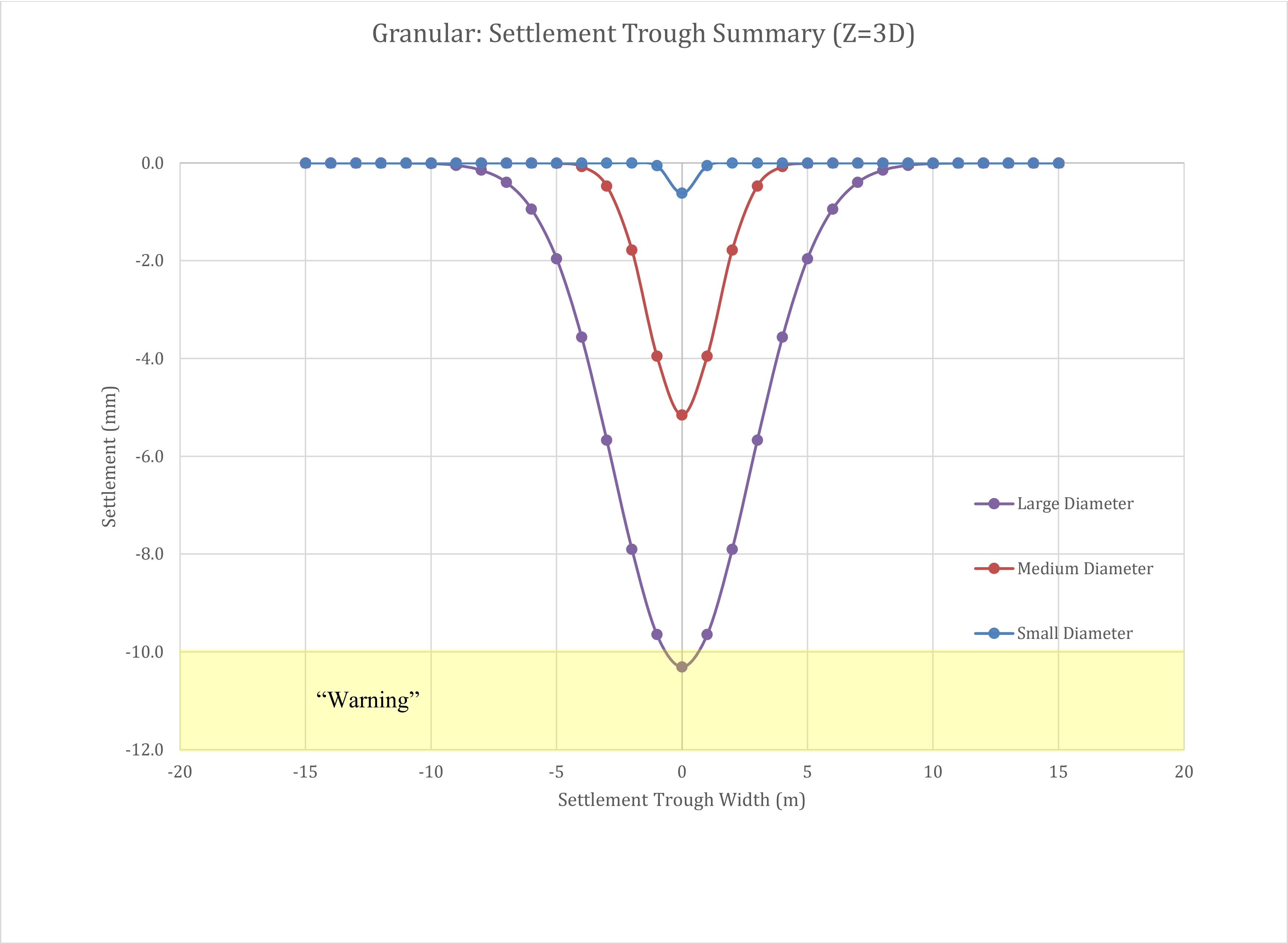


Figure C.4: Granular Settlement Trough Summary (Z=3D)