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2017 TECHNICAL REPORT

Resource on Unmitigated Loads over Buried Pipe

Resource on Unmitigated Loads over Buried Pipe

3002010598

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EPRI Project Manager
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All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product.

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ABSTRACT

The placement or passage of a heavy load in the yard of a nuclear power plant is well planned, analyzed, and, if necessary, mitigated to avoid damage to buried commodities. However, more common intermediate loads, on the order of 100,000 lbf (100 kips) or less (such as a dump truck, a concrete mixer, a small crane, or an office trailer), might not receive the same level of planning and engineering analysis. Past Electric Power Research Institute Underground Piping and Tank Integrity state-of-the-fleet self-assessments have pointed to cases where such intermediate loads caused damage to buried piping. This report provides practical engineering data, methods, and criteria to assess the conditions under which an intermediate load can be placed over or traverse over a buried pipe, without damaging the pipe. The assessment methods follow a three-tiered approach: a conservative Level 1 screening approach, a Level 2 analytical approach, and a Level 3 numerical finite element analysis approach. Alternatively, mitigation options are provided to reduce the effect of the surface load on the buried pipe.

Keywords

Buried pipe
Civil engineering
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PRIMARY AUDIENCE: Buried pipe program owner and design engineering—civil-structural or mechanical department

SECONDARY AUDIENCE: Work control, project engineering, and project engineers

KEY RESEARCH QUESTION

- When intermediate surface loads (in the order of 100,000 lbf [100 kips] or less, such as dump trucks, concrete mixers, and small cranes) are traversing the yard of a nuclear power plant, have such loads been evaluated to not pose a threat to underground commodities, such as buried and underground pipe?
- Is the buried pipe program manager contacted prior to intermediate loads being allowed to traverse the yard?
- Does the design engineer know the methods and criteria to evaluate the effect of the surface load on buried pipe?
- Does the design engineer have the input necessary to assess the effect of the surface load on the buried pipe, including pipe size and material, depth of burial, type of pipe lining or coating, types of joints, current pipe condition (corrosion, damage), trench fill and compaction, and current differential ground settlement?

RESEARCH OVERVIEW

This report was created to assist the buried pipe program owner and the design engineer in avoiding damage to buried pipe caused by the placement or traffic of an intermediate load (in the order of 100,000 lbf [100 kips] or less) on the ground surface. This resource offers a three-tiered approach to the assessment, a conservative Level 1 screening approach, a Level 2 analytical approach, and guidance for a Level 3 numerical analysis. Alternatively, mitigation options are provided to reduce the effect of the surface load on the buried pipe.

KEY FINDINGS

- This resource report applies to flexible pipe. Rigid pipe—that is, pipe that cannot accommodate 0.1% ovalization without structural distress (such as cast iron or concrete)—represents a challenge recognized in this report. Concrete pressure pipe, with or without a steel cylinder, and prestressed cylindrical concrete piping are also considered to be rigid pipe and represent a challenge recognized in this report.
- Industry and regulatory experience are addressed in Section 2.
- It is possible, using a conservative approach and certain limits of applicability, to assess the technical adequacy of surface loads up to 120,000 lbf (120 kips) using screening charts provided in Section 3.1 of this report.
- If the conservative Level 1 does not screen out the surface load, analytical equations are provided for a more detailed evaluation, in Section 3.2.
- If necessary, because Levels 1 and 2 do not qualify or if the pipe is subjected to settlement caused by the surface load, guidance is provided for a Level 3 detailed analysis, in Section 3.3.

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EXECUTIVE SUMMARY

WHY THIS MATTERS

As described in this report, there have been instances where surface traffic has damaged buried pipes. This report was developed to provide the buried pipe program owner and the civil-structural or mechanical design engineer a single reference to perform the assessment of buried piping due to surface loads. American Society of Mechanical Engineers (ASME) Code B31 and ASME Section III do not address this load. Only recently did ASME XI publish Code Case N-806 for corroded buried pipe, but the Code Case, which focused on wall thinning corrosion, does not provide sufficient guidance for the surface loads. The data to assess surface loads are dispersed among American Water Works Association standards, technical journals, an American Lifelines Alliance guide, an American Petroleum Institute (API) standard for high-pressure oil and gas pipeline at railroad and highway crossings (API 1102), and textbooks. As a result, the assessment of surface loads was not conducted, or not conducted in sufficient detail, and surface loading caused damage to buried pipe.

To resolve these difficulties, this report merges into a single document the dispersed sources of engineering data, methods, and criteria and provides a practical three-tiered assessment approach to evaluate the adequacy of surface loads on buried pipes and, where necessary, actions to prevent damage.

HOW TO APPLY RESULTS

For a given traffic surface load, determine the characteristics of the load, the load path, and the characteristics of the buried pipe (see Section 3.1). Select the Level 1 chart applicable to the pipe material, and enter the surface load and burial depth. Read on the chart whether the load is acceptable. If the surface load is not acceptable when applying the Level 1 charts, assemble the input for the Level 2 assessment (see Section 3.2.1). Calculate the soil and surface loads (see Section 3.2.2), and perform the demand-capacity checks using the equation in Section 3.2.3 (for metallic piping) or Section 3.2.4 (for high-density polyethylene.) If the surface load is not acceptable when applying the Level 2 equations, determine whether to proceed with a Level 3 beam on elastic foundation analysis or a finite element analysis (see guidance provided in Section 3.3). If mitigation is required, Section 4 provides a case study and general guidance.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- This report is of importance to the buried pipe program owner and the design engineers (civil-structural or mechanical) who are responsible for the planning and decisions regarding the effects of surface loads on buried pipe.
- This resource may be of interest to industries that rely on buried pipes in congested areas, such as waterworks, pipelines, and chemical plants.

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PROGRAM: Nuclear Power, P41 and Plant Engineering, P41.05.02

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NOMENCLATURE

List of Variables

A	cross-sectional area of pipe, square inches
B	width over which a surface point load is distributed, inches
B'	coefficient of elastic support of piping by surrounding soil, unitless
b_W	length over which the surface load is distributed, inches
b_L	width over which the surface load is distributed, inches
D_L	deflection lag factor, unitless
D_O	pipe outside diameter, inches
DR	dimension ratio, unitless
d	offset of point load to vertical center line of pipe, inches
E'	modulus of soil reaction, pounds per square inch
E_{pipe}	elastic modulus of pipe, pounds per square inch
F	friction force per unit length between the soil and the buried pipe, pound-force/inches
F'	impact factor, unitless
F'_{occ}	impact factor for occasional loads, unitless
F'_{sust}	impact factor for sustained loads, unitless
F_S	soil support factor, unitless
F_{surf}	vertical force at the ground surface, pound-force
F_{surf_sust}	sustained loading at ground surface, pound-force
F_{surf_occ}	occasional or transient loading at ground surface, pound-force
f	coefficient of friction between the soil and the pipe, unitless
H_{BD}	pipe burial depth (soil cover) from top of pipe to the ground surface, inches
h_W	height of water above top of pipe, inches
I	moment of inertia of the pipe cross section, $inches^4$

I_{TWP}	through-wall bending moment of inertia per unit length, cubic inches
K	bedding constant, unitless
k	spring constant of soil perpendicular to the buried pipe, pound force/square inch
P_{gw}	hydrostatic pressure due to groundwater, pounds per square inch
P_{neg}	negative internal pressure, pounds per square inch
P_P	vertical pressure on buried pipe due to a point load, pounds per square inch
P_{soil}	vertical pressure on buried pipe due to soil loading, psi
P'_{SS}	total vertical pressure on buried pipe due to all loading, pounds per square inch
P_{SS}	vertical pressure on buried pipe due to soil plus surface loading, pounds per square inch
P_{surf}	vertical pressure on buried pipe due to surface loading, pounds per square inch
P_{surf_1}	vertical pressure on buried pipe due to one axle of Alternate Military Load, pounds per square inch
P_{surf_2}	vertical pressure on buried pipe due to one axle of Alternate Military Load, pounds per square inch
P_{surf_occ}	occasional pressure due to loading at the surface, pounds per square inch
P_{surf_sust}	sustained pressure due to loading at the surface, pounds per square inch
R	pipe mean radius, inches
R_C	radius of curvature of bent pipe, inches
R_W	buoyancy factor, unitless
S_{comp}	high-density polyethylene material allowable sidewall compression stress, pounds per square inch
S_h	material allowable stress at hot condition, pounds per square inch
t	pipe wall thickness, inches
V	distance between axle loads for HS-20 truck, varies between 14 and 30 ft
V_{AF}	vertical arching factor, unitless
X	normalized length parameter in P_{surf} calculation due to distributed load, unitless
Y	normalized length parameter in P_{surf} calculation due to distributed load, unitless
Z	normalized length parameter in P_{surf} calculation due to distributed load, unitless
Z_1	normalized length parameter in P_{surf} calculation due to distributed load, unitless
Δx	imposed axial movement, inches

Δy	imposed downward vertical movement, inches
Φ_H	hoop stiffness parameter, unitless
Φ_{soil}	angle of soil internal friction, degrees
γ_S	density of dry soil or trench fill, pound force/cubic inches
γ_W	water density, pound force/cubic inches
λ	beam on elastic foundation parameter, unitless
Θ	total bedding angle, degrees
s_a	axial stress due to soil settlement, pounds per square inch
s_{SW}	compressive stress in the pipe sidewalls, pounds per square inch
Ω	ovalization of pipe cross section, percent
Ω_{max}	maximum acceptable ovalization, percent

List of Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
AWWA	American Water Works Association
BPIG	Buried Pipe Integrity Group
CFR	Code of Federal Regulations
CL	inorganic clays of low to medium plasticity
CLSM	controlled low strength material
CPP	concrete pressure pipe
EPRI	Electric Power Research Institute
FEA	finite element analysis
FLEX	Diverse and Flexible Coping Strategies
FSAR	final safety analysis report
HDPE	high-density polyethylene
ISFSI	independent spent-fuel storage installation
ML	inorganic silts and very fine sand, or silty or clayey fine sands
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission

NUREG	Nuclear Regulatory Commission Regulation
OE	operating experience
OSHA	Occupational Safety and Health Administration
PCCP	prestressed cylindrical concrete piping
PVC	polyvinylchloride
RCP	reinforced concrete pipe

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1
INTRODUCTION

Surface loading has the potential to damage buried piping and cause pressure boundary failures. Typical surface loading at nuclear power plants can be occasional or live loads. These terms are used interchangeably, and the loads may be due to highway transports, heavy (construction) equipment, heavy haulers, railroads, and cranes driving over the ground surface, or dead loads such as the soil cover, equipment laydown, and placement of temporary structures. This report is intended to be a resource to the buried pipe program owner when identifying the impact of surface loads on buried piping.

1.1 Objective

The objective of this report is to provide a resource for the buried pipe program owner to help identify, assess, and manage challenges to buried piping that are posed by unmitigated surface loads and differential soil settlement. This report will support this objective by providing the following:

- Identification of the types of loads traversing the yard of a nuclear power plant that need to be evaluated to ensure that they do not pose a threat to buried pipe
- Screening processes to allow the buried piping program owner to identify and prioritize piping materials that may be the most susceptible
- Guidance on screening loads during project or maintenance activities
- Situations in which the buried piping program owner and design engineer should be involved in intermediate load movements through the yard
- Guidance for addressing uncertainty in location of buried piping
- Evaluation of site-specific live/deadweight loads and differential ground settlement loads
- Providing a tiered approach to simplify application of the soil-to-piping interaction, as follows:
  - Level 1: simplified acceptance criteria
  - Level 2: equations for performing site-specific evaluations
  - Level 3: guidance for performing detailed evaluations

The analysis results in Section 3 are divided into three levels with increasing complexity. The Level 1 analysis provides figures for screening which loads have the potential to impact buried piping based on the pipe material and burial depth. The Level 1 screening identifies applicability criteria and makes conservative assumptions in developing the screening tools. For sites that are either outside of the applicability criteria or that do not pass the Level 1 screening, Level 2 provides the equations for use in site-specific analysis. For each material type, the required inputs, equations to be used, and acceptance criteria are defined. Although site-specific, the Level 2 approach is still considered to be a conservative analysis. If the Level 2 approach does not show acceptance, users can find guidance for detailed analyses in Level 3.

It is not required that the user start with the Level 1 screening. Instead, the user is free to enter any of the levels without evaluating the previous level. However, the amount of resources required for each level increases significantly from the previous level.

In some cases, the surface loading may be significant enough to damage buried piping. In these cases, guidance is provided for mitigation of the surface load. Section 4 provides typical mitigation options as well as relevant industry operating experience (OE).

1.2 Scope

This report addresses and aims to prevent damage that can occur to buried pipe from traffic or other temporary surface loads. It does not address damage from other loads, such as internal pressure, external hydrostatic pressure, ground or building settlement, constrained thermal expansion or contraction, seismic wave passage or anchor motion, or flood-induced flotation of the buried pipe. These loads should have been addressed as part of the piping design. Further, the report does not address damage from corrosion; however, the Level 1 screening criteria include a general corrosion allowance.

1.2.1 Pipe Materials

The scope of this report covers buried pipe of the following materials:

- Carbon steel
- Carbon steel cement lined
- Stainless steel
- Ductile iron
- Ductile iron cement lined
- High-density polyethylene (HDPE)

The following materials are specifically excluded from the scope of this report:

- Fiberglass
- Polyvinylchloride (PVC)
- Cast iron
- Asbestos-cement or transite
- Concrete pressure pipe (CPP), with or without a steel cylinder
- Prestressed cylindrical concrete piping (PCCP)

It is recognized that many of these materials are commonly used in nuclear power plant applications. Rigid pipes and their mechanical joints may not accommodate the same level of ovalization as do flexible pipes that are within the scope of this report. Design of rigid piping is based on three-edge bearing tests established through ASTM International. Section 3.2.5 of this report provides additional resources for evaluation of cement piping. To develop Level 1 screening and Level 2 equations, additional research is required to define acceptance criteria due to soil and surface loading. Such work is recommended as future research in Section 5.3. Although PVC and Fiberglass are not considered rigid pipe, they are excluded from the scope of this report because these materials require additional investigation to understand their structural limits and failure modes.

Corrugated metal pipe and corrugated HDPE are not explicitly excluded from the scope. However, the stiffness of the corrugation is not included in the scope of this report. Section 3 provides instructions for the evaluation of corrugated piping.

1.2.2 Pipe Joints

This report applies to base material and welded or fused joints. It does not apply to mechanical joints, which are prone to leakage by relative movement, rotation, or translation, across the joint.

1.2.3 Corrosion Damage

This report applies to nondegraded pipe. However, the Level 1 screening for carbon steel and ductile iron includes a small amount of wall loss. If the pipe is expected to experience more corrosion than is allowed by the Level 1 screening, the Level 2 guidance could be applied. This approach assumes that the pipe is corroded by uniform metal loss around the circumference. If the actual wall loss is localized corrosion, it is preferable to apply Code Case N-806-1 [1] within its limits of applicability. The finite element guidance in Level 3 can potentially be applied to evaluation of wall thinning corrosion. This report does not apply to pipe with cracklike flaws. Evaluation of stress corrosion cracking, for example, may require finite element analysis (FEA) to develop the appropriate stress field, as well as fracture mechanics analysis. Because of the complexity and variety of evaluation approaches, the scope of this report is limited to nondegraded piping.

1.2.4 Flexible Pipe

A flexible pipe is one whose cross-sectional shape can be deflected by more than 3% without structural distress. This deflection allows the soil to provide structural support on the sides of the pipe. Flexible pipe includes steel, stainless steel, ductile iron, PVC, HDPE, fiberglass-reinforced polymer, and corrugated steel pipes.

1.2.5 Rigid Pipe

A rigid pipe is one that experiences structural distress when deflected by more than 0.1%. This level of deflection does not allow the soil to provide the same level of structural support as the flexible pipe. Rigid pipes include concrete, clay, cast iron asbestos cement, and cast-in-place pipes.

1.3 User Guidance

This report is intended to provide background information and analysis guidance to determine whether a surface load requires additional evaluation or mitigating actions by the site. Section 2 provides background information on industry OE, parameters that impact buried piping loads, and a description of the equations used in Level 1 and Level 2. Section 3 provides the results of the Level 1 screening, briefly presents the inputs and equations for a Level 2 analysis, and offers guidance for a Level 3 evaluation. Experienced users may go directly to Section 3. Should mitigation of surface loads be required, Section 4 provides industry experience and guidance. Section 5 provides conclusions and additional options for evaluation of degraded piping.

For end users who do not implement American Society of Mechanical Engineers (ASME) standards, this report presents sound engineering methodologies that may be used for reference and generic guidelines. In all cases, the applicable governing standards in place for design and evaluation of buried piping should be consulted.

References to specific revisions or editions of guidance documents are not meant to limit applicability of newer versions of these documents. Although it is not anticipated that newer versions of these documents would invalidate the analysis approach herein, it is the responsibility of the user to confirm that guidance documents published after this report are appropriate for use. Alternatively, the user may evaluate the impact of occasional live loading in accordance with the specific edition and revision of guidance documents cited in this report.

1.4 Conversion Factors

Table 1-1 provides conversion factors for units of measure used in this report.

Table 1-1
Conversion factors

Parameter	Conversions
Pressure	1 psi = 6.89 x 10^{-3} MPa 1 ksi = 6.89 MPa
Force	1 lbf = 4.448 x 10^{-3} kN 1 lbf/ft = 1.459 x 10^{-5} kN/mm 1 kip = 1000 lbf 1 kip = 4.448 kN 1 ton = 2000 lbf
Length	1 in. = 25.4 mm 1 ft = 304.8 mm
Area	1 in^2 = 654 mm^2
Density	1 lbm/ft^3 = 5.2 x 10^{-8} N/mm^3 1 lbm/in^3 = 9.05 x 10^{-5} N/mm^3
Moment of inertia	1 in^3 = 1.639 x 10^4 mm^3
Through-Wall Bending Moment of Inertia	1 in^4 = 4.16 x 10^5 mm^4
Spring constant	1 lbf/in^2 = 6.8 x 10^{-6} kN/mm^2
Temperature	1°F = (°C x 9/5) + 32

2
BACKGROUND

The section provides background information on industry OE, parameters that impact the stress due to surface loads in buried piping, and more details on the equations used to determine the pressure on buried pipe resulting from surface loads.

2.1 Load Definitions

Buried piping is subjected to loading that is significantly different from in-building piping. In addition to resisting the weight of the soil directly above the pipe, the weight of objects at the ground surface is also transmitted to the buried line. Figure 2-1 illustrates these loads.

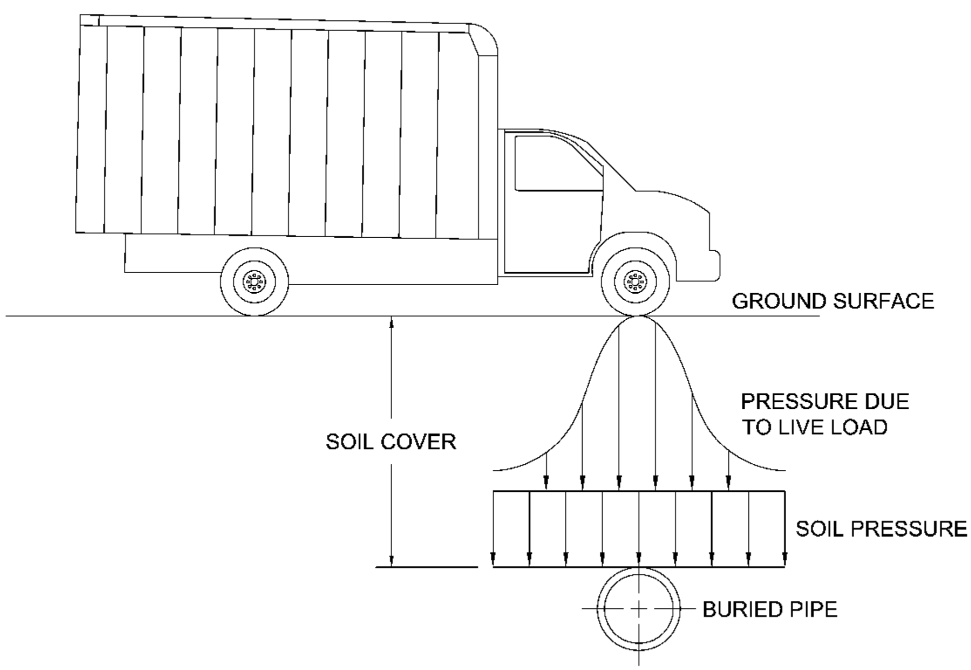

Figure 2-1
Buried pipe soil and surface loading

Pressure due to soil loading is a sustained load. As burial depth increases, the loading due to soil increases because the soil cover increases. Live loading, such as vehicle traffic, is a transient or occasional load. Live loading is distributed over an increasing area as depth increases, which results in less loading on the pipe as the burial depth increases.

In some cases, only the general routing of buried piping is known. It is conservative to assume that the occasional live load at the ground surface acts directly over the buried pipe. The Level 1 screening adopts this approach and assumes that all live loads act directly over the buried pipe.

2.2 Industry OE

Industry experience on buried piping damaged by surface loading has been captured in a Buried Pipe Integrity Group (BPIG) member survey. This section also explores guidance documents that may prove helpful in preventing such damage.

2.2.1 BPIG Survey 2014-011

A BPIG member survey initiated in 2014 [2] revealed cases of damage related to surface loading, as well as potentially insufficient procedures for screening or controlling surface loading.

Ten of 23 respondents reported damage or leaks resulting from heavy surface loads. In some cases, the damaged lines were relatively inconsequential, such as a compressed air line that was abandoned in place. However, several sites reported damage to fire protection lines. Much of the damage reported was attributed to occasional surface loading due to heavy equipment driving over or near the lines. In one instance, the damage was attributed to sustained loading from temporary water tanks.

Only nine of the 23 survey respondents reported provisions to control heavy hauls or mobile crane activities. In some cases, the survey respondents were unclear as to when or how an evaluation surface loading was initiated or conducted, even whether their sites had provisions to control heavy hauls. The Electric Power Research Institute (EPRI) 2014 state-of-the-fleet self-assessments report [3] identified a weakness at Station C due to the lack of a process for notifying the buried pipe program owner of heavy loads in the yard. The Level 1 screening in Section 3.1 of this report is designed to help the buried pipe program owner determine the need for processes or procedures to control surface loading by defining thresholds beyond which damage to buried piping may occur.

2.2.2 Heavy Lift Guidance Documents

The documents discussed in this section address heavy loads and heavy lifts. These documents present recommended actions and limits for heavy lifts but do not address the impact of surface loading on buried piping. These documents are covered in this section in order to emphasize that implementation of the documents’ recommended actions does not create a comprehensive process to address all of the potential impacts of a heavy lift.

2.2.2.1 NUREG-0612, Control of Heavy Loads at Nuclear Power Plants

Nuclear Regulatory Commission Regulation 0612 (NUREG-0612) [4] was developed to control the risk associated with heavy lifts. Although the wording of NUREG-0612 specifies that it is applicable to heavy loads and damage to redundant safe shutdown paths, NUREG-0612 does not provide guidance on how surface loads may impact the structural integrity of buried piping.

2.2.2.2 NEI 08-05, Industry Initiative on Controls of Heavy Loads

Nuclear Energy Institute Standard (NEI 08-05) [5] continues the work of NUREG-0612 and requires a final safety analysis report (FSAR) change to include a summary description of the site heavy load process. As with NUREG-0612, NEI 08-05 focuses on heavy lifts within the reactor building and, specifically, on cranes and the impact of potential load drop on safety equipment. The document also states that most sites consider a load of 1000 lb or more a heavy load. A 1000-lb load is significantly less than trucks and cranes operating in the yard. Because of this relatively small threshold and the FSAR revision commitment, the buried pipe program owner could reasonably expect that all loading is evaluated through existing site controls. However, NEI 08-05 does not address the impact of surface loading on buried piping.

2.2.2.3 29CFR Part 1926.1402*,* Ground Conditions

Unlike the previous documents, 29 Code of Federal Regulations (CFR) Part 1926.1402 [6] provides explicit requirements for crane operation in the yard. The focus of 1926.1402 is the safe operation of cranes and derricks, specifically on the surface conditions (that is, firm and drained soil) during operation. The document requires the controlling entity to notify the crane operator of known underground hazards “such as voids, tanks, utilities.” Buried pipe does not necessarily fit within the underground hazard category because failure of the piping does not typically pose an immediate threat to the personnel involved in the lifting operation. However, the site may elect to define buried piping as an underground hazard because piping failure can create a void or impact the surface conditions. BPIG survey 2014-011 identifies one case in which a heavy load damaged a domestic water line that resulted in an underground void. Also identified in the survey, water was observed flowing out from under a road during independent spent-fuel storage installation (ISFSI) transportation. Both of these situations are defined as hazards under 1926.1402.

2.2.2.4 EPRI 3002005356, *Handling and Maintenance Guide for Spent Nuclear Fuel Dry Storage Systems and Facilities*

The guidance for the ISFSI haul path in EPRI report 3002005356 [7] is limited to a discussion of fire and explosion hazard removal. The report does identify that one site used a multiwheeled vehicle for spent-fuel cask transportation. The site was able to avoid ISFSI haul path upgrades because of the additional load distribution, but the report does not indicate whether the buried pipe or the haul path surface was the component overloaded prior to selecting a multiwheeled vehicle. The report does not provide specific guidance to address the impact of surface loading on buried piping.

2.3 Parameters Impacting Buried Pipe Loading

Soil and surface loads for flexible piping are evaluated against the following three failure modes:

- Ovalization of the cross section
- Crushing of the pipe sidewalls
- Ring buckling

The magnitude of the load, or demand, is an obvious parameter in the evaluation of these failure modes, along with the strength of the pipe, or capacity. Parameters that may not be intuitive are the type and quality of bedding, haunching, and backfill (see Figure 2-2). Excavations for long runs of piping in which no particular care is given to the bedding and haunching experience much higher stresses. This is because the undisturbed native soil that forms the bedding and the as-dumped, uncompacted soil that is returned to the trench settle over time and do not fully support the pipe cross section. The reduction in the pipe constraint, both in the vertical and horizontal directions, allows the cross section to more easily ovalize. Additionally, piping that is not fully supported along its length begins to act as simply supported pipe but with significantly more deadweight loading due to the soil above.

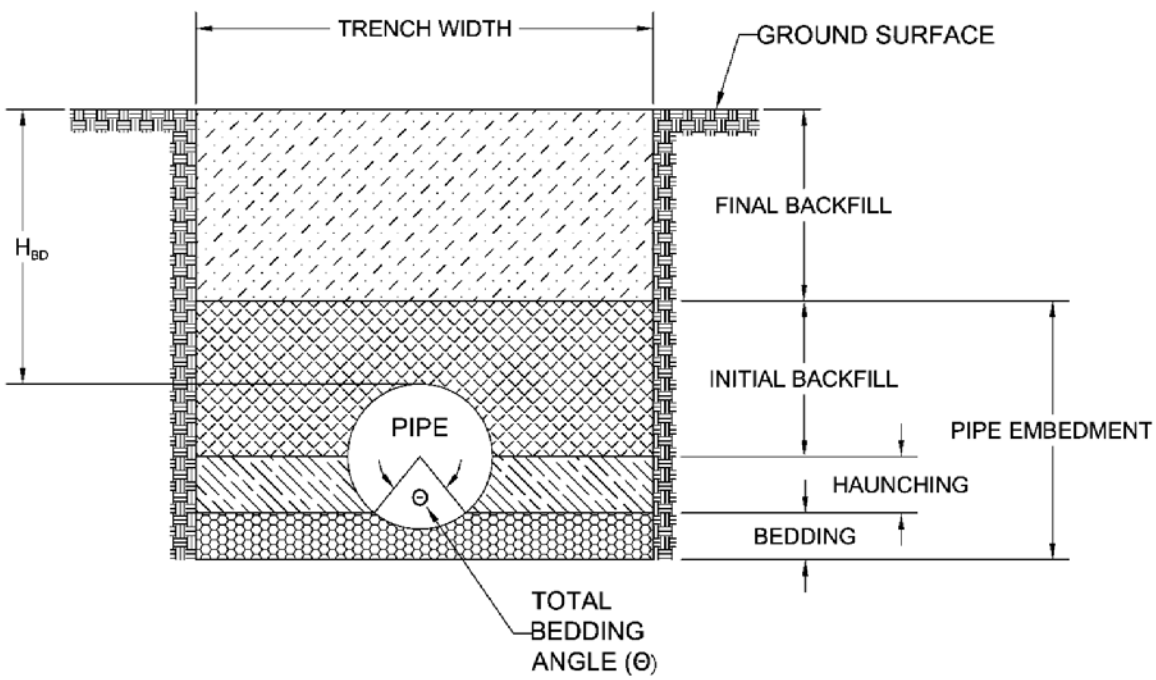

Figure 2-2
Buried pipe cross section

When properly designed and installed in accordance with recognized buried pipe standards, the soil type and minimum compaction of the bedding, haunching, and backfill are typically specified during original construction. Native soils often contain relatively high amounts of clay and silt, which do not provide the constraint and subsequent resistance to ovalization that engineered fill provides. Bedding, haunching, and backfill are typically specified as engineered fill consisting of coarse-grained gravel and sand. In addition to soil type, minimum compaction is also specified. Soil compaction is a mechanical process that increases the density and resistance to ovalization. Engineered fill and compaction requirements can generally be found in original pipe yard drawings, civil backfill specifications, yard piping specification, and/or system specifications for safety related systems. Original construction typically required compaction of greater than 85% standard or modified proctor according to ASTM D698 and D1557, respectively. Note that a proctor test is a measurement of relative density from compaction efforts during pipe installation or excavation backfill. Fill and compaction requirements should be verified for safety-related and balance-of-plant piping.

From a practical standpoint, the soil type and compaction influence the selection of the modulus of soil reaction, E'. The modulus of soil reaction is a measurement of the soil's resistance to ovalization and influences the capacity of the piping to resist soil and surface loads. Low E' values have little resistance to ovalization, and high E' soils increase the capacity.

Controlled low strength material (CLSM) is low-strength cementitious material used as backfill and is sometimes called *flowable fill*. The material is poured into the trench in lifts (that is, multiple pours over time) around the pipe and allowed to cure, which helps ensure good pipe-to-soil contact and support from the springline down. To facilitate future excavation, CLSM should have a long-term compressive strength not exceeding 300 psi. CLSM has a high modulus of soil reaction, and the high pH provides additional corrosion protection. However, after the material is set, it may be difficult to excavate in order to access the surface of the pipe.

Backfill procedures for operating nuclear plants should include controls on the type of soil and minimum compaction requirements. Compaction by any means other than mechanical should be avoided. Examples of nonmechanical means that should be avoided are jetting and flooding, which involve fluid action to perform the necessary compaction.

Differential settlement within the pipe embedment can result in an overstress condition. This type of settlement could occur from settlement of the bedding or haunching or from settlement of a building at a piping wall penetration. The FSAR may contain information on the local geology and predicted building settlement.

Erosion of the bedding and backfill resulting from groundwater movement can cause an overstress condition in buried piping. In these cases, the pipe supports the entire column of soil above the pipe, in addition to any additional loading at the ground surface. A Level 3 evaluation may be needed for this type of situation, even if mitigating actions are taken to minimize the effect of surface loading.

It is assumed that all piping is below the frost line. Therefore, seasonal effects such a ground freezing are not applicable. Piping that is above the frost line is subject to additional loading and should be evaluated using a Level 3 approach.

Ground cover can influence the loads transferred to buried piping. Steel plates and reinforced concrete act to distribute the load over a larger area, as covered in Section 4.2 of this report. The effect of ground cover can be conservatively ignored when using the Level 1 screening and Level 2 analysis. Alternatively, a Level 3 evaluation may be performed to take credit for the ground cover.

2.4 Buried Pipe Loading Equations

Surface and soil loading is the focus of this report. It is assumed that the buried piping was designed and installed in accordance with a recognized buried pipe standard and that the design considered all normal operation, such as the pressure due to soil overburden, internal pressure, and thermal expansion. The following sections provide a discussion of the types of surface loads that can impact buried piping, as well as a discussion of piping loads that are assumed to be addressed in the design basis evaluation.

2.4.1 Surface Loads

Surface load in this report is defined as a force exerted on the ground surface over an area. The weight of a truck load, for example, is transferred to the soil through the contact area of each tire. The weight of small structures and tanks are similarly distributed. The force at the ground surface results in a pressure over an increasing area as the depth increases. Because the area that is influenced by the surface loading increases with depth, the resulting pressure due to the surface load decreases. As a simplification, the loading may be assumed to act at a point. This approach conservatively increases the vertical pressure on the pipe. See Figure 2-3 for a general comparison of distributed loading and point loading.

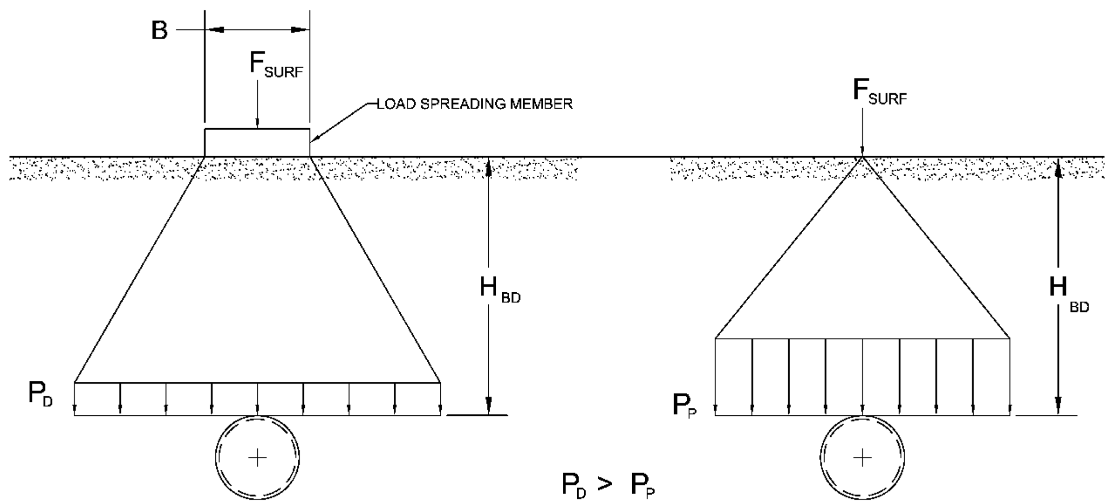

Figure 2-3
Distributed and point surface loading

Surface and soil loading both produce vertical pressure on buried piping, but their maximums are at opposite depths. Pressure on the buried pipe due to surface loading, P_{surf}, is highest at the ground surface and dissipates rapidly with increasing depth. Conversely, pressure on the buried pipe due to soil loading, P_{soil}, is zero at the ground surface and increases linearly with increasing depth. The total pressure due to surface and soil loads, P_{SS}, is the sum of P_{surf} and P_{soil}. A plot of the relationship between the pressure terms is shown as a function of burial depth in Figure 2-4, which shows surface loading of 20,000 lbf and 80,000 lbf.

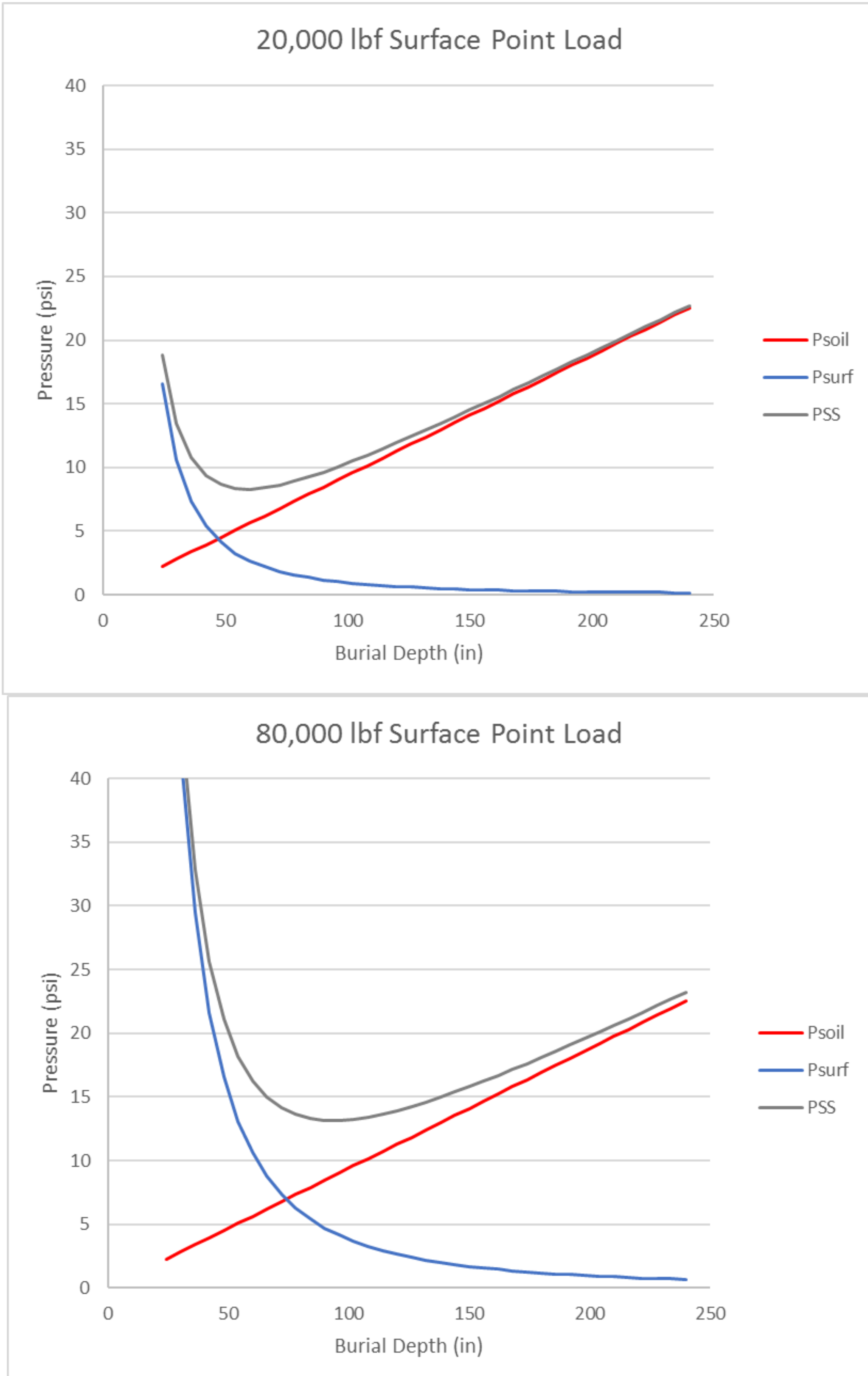

Figure 2-4
Pressure due to surface and soil loads

The pressure due to soil loading is a function of the backfill type, burial depth, and height of the water table. The formula for soil pressure assumes that the column of soil is supported entirely by the pipe. It follows that increasing the backfill density or burial depth results in an increase in the soil pressure. The height of the water table above the top of the buried pipe also influences the vertical pressure at the pipe depth. Similar to the pressure due to soil, the water above the pipe is assumed to be supported by the pipe. The inclusion of both soil and water somewhat complicates the calculation. It would be overly conservative to take the sum of the pressure due to the column of water and the pressure due to the column of soil. Instead, a factor is applied to the calculation of the pressure due to the column of soil to account for the change in density of the water and soil column. The pressure due to soil loading, P_{soil}, is taken from Code Case N-806-1 as [1, Equation A-9]:

$$P_{soil} = \gamma_W h_W + R_W \gamma_S H_{BD}$$

$$R_W = 1 - \frac{h_W}{3H_{BD}}$$

where:

γ_W = water density, lbm/in^3

h_W = height of water above top of pipe, in.

R_W = buoyancy factor, unitless

γ_S = density of dry soil or trench fill, lbm/in^3

H_{BD} = pipe burial depth from top of pipe to the ground surface, in.

The Level 1 screening in Section 3.1 assumes that the ground water level is at the ground surface. This increases the calculated value of P_{soil}, provided that the density of dry backfill is not more than three times the density of water.

In Figure 2-4, and more generally in this report, the pressure caused by the column of soil on top of the pipe is calculated based on the prism load—that is, the weight of the whole prism of soil above the pipe bears down on the pipe. This causes the soil-induced pressure in Figure 2-4 to increase linearly with the pipe depth. This approach conservatively neglects the arching effect that occurs as the pipe depth increases. The arching effect transmits part of the soil load to the sides of the trench and reduces the downward pressure on the pipe.

Code Case N-806-1 also provides equations for the soil pressure if the ground water level is below the pipe [1, Equation A-6]:

$$P_{soil} = V_{AF} \gamma_S H_{BD}$$

$$V_{AF} = 0.76 - 0.71\left(\frac{\Phi_H - 0.7}{\Phi_H + 1.75}\right)$$

$$\Phi_H = \frac{E'R}{\pi E_{pipe} D_O}$$

where:

V_{AF} = vertical arching factor, unitless

Φ_H = hoop stiffness parameter, unitless

E' = modulus of soil reaction, psi

R = pipe mean radius, in.

E_{pipe} = elastic modulus of pipe, psi

D_O = pipe outside diameter, in.

The vertical arching factor is dependent upon the ratio of E'/E_{pipe}. For all materials evaluated in this report, this ratio approaches zero and results in vertical arching factor of approximately 1. As stated in Code Case N-806-1, V_{AF} may be set to 1.0, which slightly simplifies the calculation of P_{soil}. However, the use of Code Case N-806-1 Equation A-6 requires justification that the water table is below the top of the pipe.

The vertical pressure produced by surface loading, P_{surf}, can be defined by Boussinesq's equation provided that the following occur [8, Section 40.1]:

- The width over which the load is distributed, B, is small relative to the burial depth, H_{BD}.
- A semi-infinite domain is valid.
- The soil is elastic, isotropic, and homogeneous.

For point loading, the assumption that B/H_{BD} is small is appropriate. Piping in the yard can be approximated as a semi-infinite solid if there are no large discontinuities, such as building foundations or vaults, in the area of influence. Engineered backfill is designed to be isotropic and homogeneous, as well as to remain in the elastic regime. In cases with different cover and backfill material, the lowest E' value of the two materials may be used in the analysis. Code Case N-806-1 defines P_{surf} due to point loading based on Boussinesq's equation [1, Equation A-11]:

$$P_{surf} = \frac{3F_{surf}F'}{2\pi H_{BD}^2\left[1+\left(\frac{d}{H_{BD}}\right)^2\right]^{2.5}}$$

where:

F_{surf} = point load at ground surface, lbf

F' = impact factor, unitless

d = offset of point load to vertical center line of pipe, in.

The vertical pressure produced by distributed surface loading is also defined by Code Case N-806-1 [1, Equation A-12]:

$$P_{surf} = \frac{1}{4\pi} \frac{F_{surf} F'}{b_W b_L} \left[\left(\frac{2XY\sqrt{Z}}{Z + Z_1} \right) \left(\frac{Z+1}{Z} \right) + \tan^{-1} \left(\frac{2XY\sqrt{Z}}{Z - Z_1} \right) \right]$$

$$X = \frac{b_W}{H_{BD}}$$

$$Y = \frac{b_L}{H_{BD}}$$

$$Z = X^2 + Y^2 + 1$$

$$Z_1 = (XY)^2$$

where:

b_W = length over which the surface load is distributed, in.

b_L = width over which the surface load is distributed, in.

The variables X, Y, Z, and Z_1 are normalized length parameters based on the area of the surface load and the burial depth. The equation for distributed loading is particularly useful for crane outriggers where the general location of the loading is known and will not be traversing the yard. Figure 2-5 shows a schematic of a yard crane. Note that load spreading members are shown, but may not be required in all situations. See Section 4.2 for additional discussion of mitigation options.

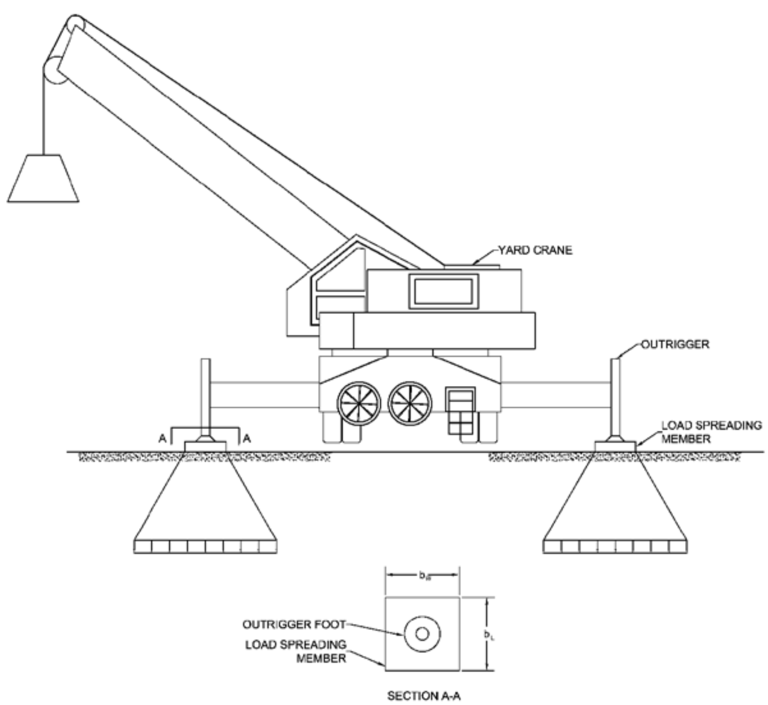

Figure 2-5
Yard crane

For point and distributed loading, the impact factor, F', is used to account for the dynamic nature of transient surface loading, such as vehicle traffic. Sustained loading, such as the weight of a temporary structure or the force at crane outriggers during lifting, should use an impact factor of 1.0. The two main sources of occasional live loading applicable to buried pipe in nuclear plants are highway and railway. This report assumes that the burial depth of all piping is at least 2 ft. The American Lifelines Alliance [9, Table 4.1-2] provides values of F' as a function of cover height for highway and railway surfaces and shows a maximum value at 2 ft of 1.5. Although the value of F' decreases to 1.0 over 3 ft, it is not readily apparent that 1.0 can be used for evaluation of buried yard piping. The ground surface condition in most plants is likely not equivalent to that of a highway, which would suggest that F' should be increased. However, it is also reasonable to assume that vehicle traffic in the yard is well below highway speeds. Therefore, it is reasonable to set F' equal to 1.5 for all traffic loads. The Level 1 screening in Section 3.1 uses an impact factor of 1.5 and is independent of the loading source.

Typical surface loads that require evaluation are trucks, railway, yard cranes (both as traffic loads and static loads during lifts), and other heavy equipment, such as ISFSI or FLEX equipment. Standard truck loading for bridge design is defined by the American Association of State Highway and Transportation Officials (AASHTO) as H-20 and HS-20 loads [10, Topic 5.1]. For evaluation of buried piping structural integrity, the maximum axle load may be used. Figure 2-6 [10] shows that the maximum axle load in both cases is 32,000 lbf. Note that the axle spacing for the HS-20 load, V, ranges from 14 ft to 30 ft. HS-25 loading could be identified in more recent design requirements, but the HS-25 classification does not officially exist within the AASHTO specifications. HS-25 is typically considered to be axle loading of 40,000 lbf.

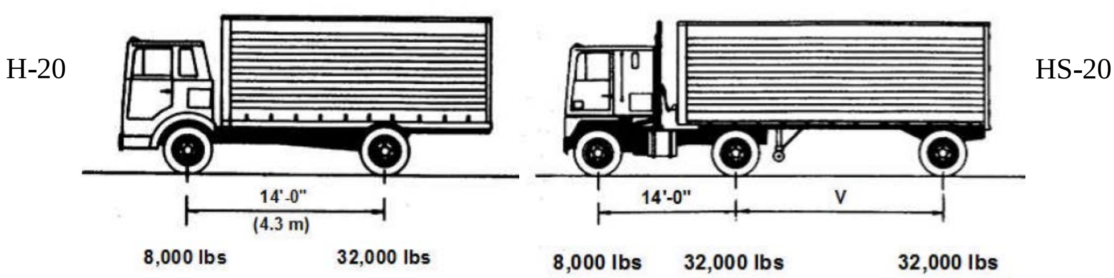

Figure 2-6
H-20 and HS-20 truck loading
Government document used with permission from U.S. Department of Transportation

Recent AASHTO specifications have introduced HL-93 loading, which is specific to bridge design using the load and resistance factor design approach [10, Topic 5.1]. HL-93 loading is identical to HS-20 loading for the purpose of evaluating buried structures.

In addition to the HS-20 loading, the Alternate Military Loading is also considered in bridge design. The load, shown in Figure 2-7, consists of two axles 4 ft apart, each loaded at 24,000 lbf [10, Topic 5.1]. For evaluation of buried piping, analysis of the Alternate Military Loading is not required. Although the loading is spaced significantly closer (4 ft) than the HS-20 loading (14 ft minimum), the 24,000-lbf axle loads do not interact significantly. Figure 2-8 is generated using Equation A-11 from Code Case N-806-1 [1] and shows that the pressure is significantly lower when the pipe is centered between the wheels. P_{surf_1} and P_{surf_2} represent the pressure from Axle 1 and Axle 2, respectively, with P_{surf} being the sum of the two pressures. Note that P_{surf_1} is not visible in Figure 2-8 (b) because it is equivalent to P_{surf_2}. Based on Figure 2-8, HS-20 loading is the only significant truck load for evaluation of buried piping.

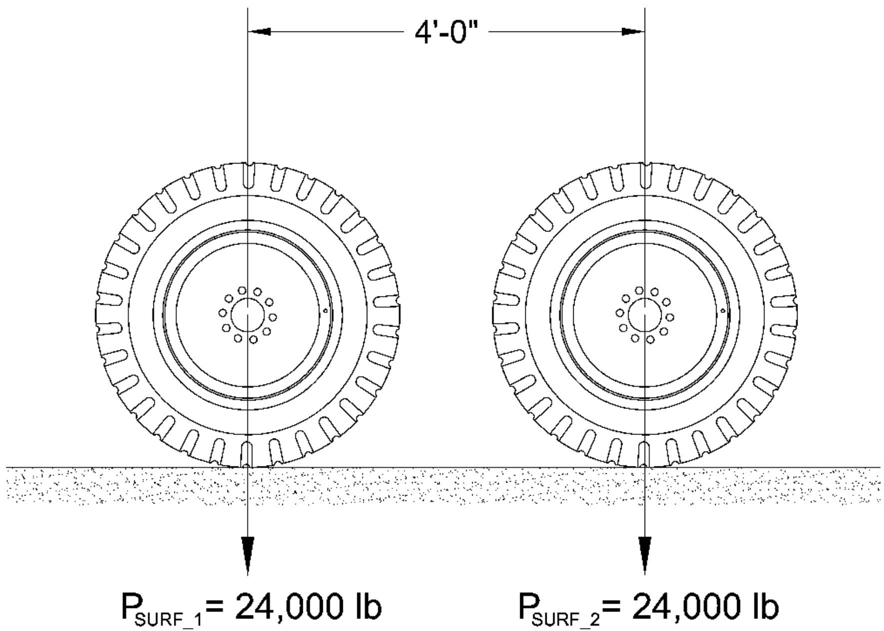

Figure 2-7
Alternate Military Loading

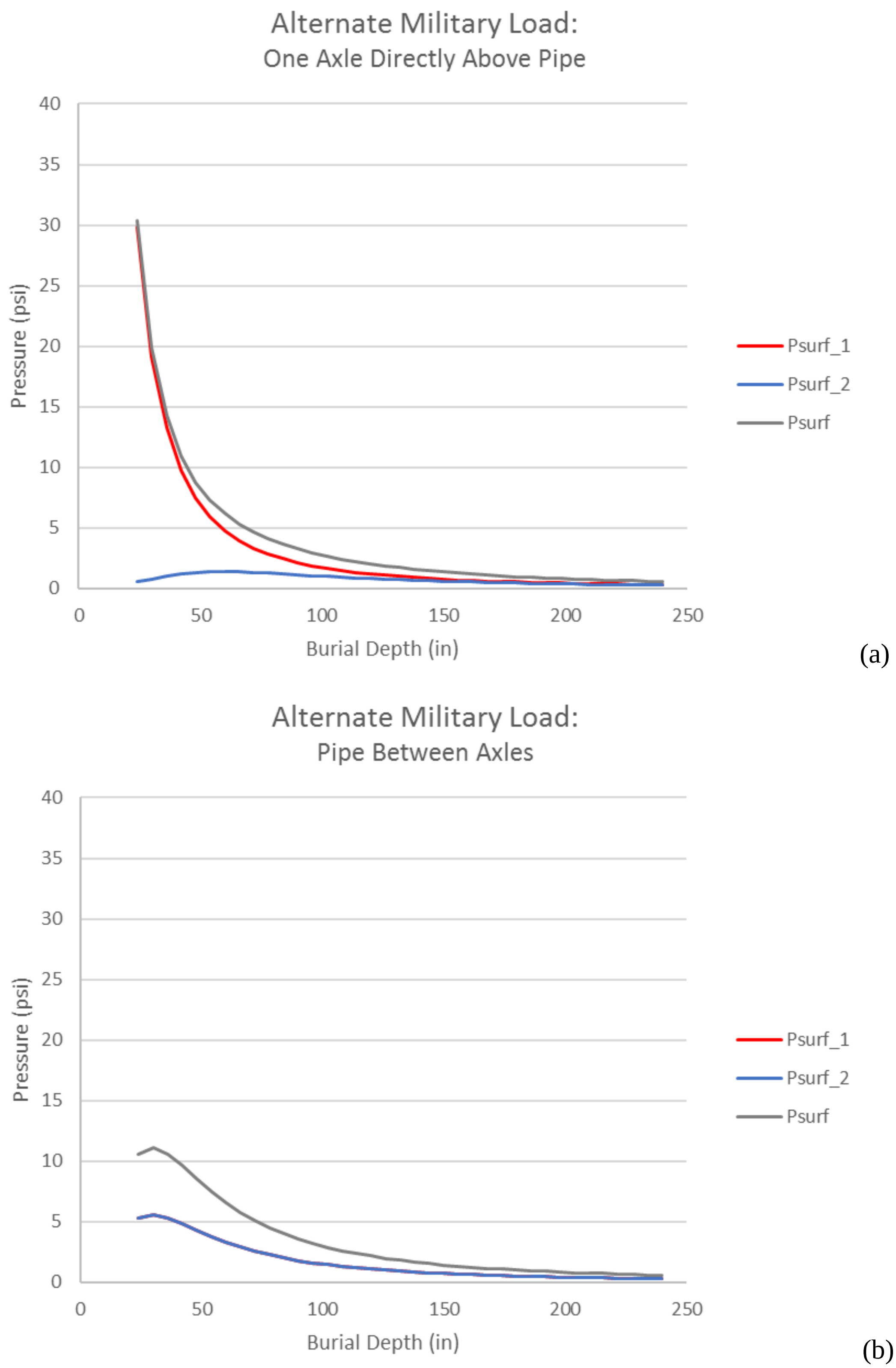

Figure 2-8
Axle interaction of Alternate Military Loading

Pressure due to railway loading is given by the American Lifelines Alliance [9, Table 4.1-1] for various burial depths. The table is generated based on an 80,000 lbf/ft load and includes the effect of the impact factor. If railway loading is applicable, the use of Table 4.1-1 in “Guidelines for the Design of Buried Steel Pipe” [9] in a Level 2 evaluation is recommended.

Mobile cranes operate in the yard at most nuclear power plants, which presents two potential loading scenarios relevant to buried piping: evaluation of loading during the lift and evaluation of loading during transportation. Evaluation of the surface loading during the lift is the most likely situation to be considered and can result in the highest vertical pressure on buried piping if the load acts directly over the line. However, as covered in Section 2.2.2 of this report, 29CFR Part 1926.1402 requires that the ground surface be suitable for crane operation but does not address protection of buried piping. The range of potential loading during the lift is significant, with some sites operating mobile cranes with a 300-ton capacity (Note: 1 North American ton = 2,000 lbf). The surface loading at the outriggers for a 300-ton lift, even without consideration of the weight of the crane, is significantly higher than that of the HS-20 truck loading. Therefore, a site-specific analysis is required to use the Level 1 screening. The user should confirm that the outriggers are sufficiently far from each other so that the pressures due to loading at each outrigger do not interact significantly. The user may then apply the maximum outrigger loading to the Level 1 screening as a point load to determine whether additional analysis is required. Evaluation of loading during crane transportation must also be performed. As with the lift analysis, a site-specific evaluation is required. As a conservative approximation, the entire weight of the crane may be considered as a point load in the Level 1 screening. If the results show that the buried piping is overloaded, the force at each axle may be obtained and considered to be a point load for the Level 1 screening. In the event that the buried piping is still overloaded, a Level 2 or Level 3 analysis may be required. Alternatively, mitigation of the surface loading may be considered as covered in Section 4. For equipment with crawler tracks, a Level 2 evaluation is required. The distributed load equation may be used to determine the vertical pressure at the piping. Consistent with the preceding recommendation, an impact factor of 1.5 should be used.

FLEX and ISFSI equipment follow the same approach as the crane transportation evaluation. The weight of the specific piece of equipment or the axle load may be considered as a point load in the Level 1 screening. Evaluation of the ISFSI roadway has likely been performed, but that evaluation may not have included the impact on buried piping. As covered in Section 2.2.2, damage to buried piping has been reported during ISFSI transportation. Information about the axle loading of ISFSI equipment may need to be obtained from the manufacturer to perform the Level 1 screening.

2.4.2 Ground Settlement from Surface Loads

Damage to buried pipes from surface traffic or other temporary surface loads may be caused by two effects: the pressure imparted by the surface load onto the pipe or ground settlement or ground failure that is caused by the surface load.

The first effect, the pressure imparted by the surface load, is evaluated in this report, using a three-level approach. The effect of settlement or ground failure caused by surface loads is addressed in this section.

2.4.2.1 Design Settlement

Natural ground or building settlement can cause severe damage to buried pipes. The design of structures, systems, and components for ground or building settlement was typically addressed at the design stage and documented in Chapter 2 of the plant safety analysis report. The structures, systems, and components were originally designed to accommodate the original estimates of the design settlements. The settlements are then monitored periodically through a sitewide settlement monitoring program, using monitoring techniques such as settlement markers with optical surveys, and multiple position extensometers.

2.4.2.2 Surface Load Settlement

To prevent settlement or compressive and shear failure of the ground in the vicinity of the buried pipe, the planning for surface traffic or temporary surface loads must ensure that the surface load will not exceed the bearing capacity of the soil, with safety factors. This requires up-to-date knowledge of the geotechnical condition of the ground, including the review of any post-construction boring logs to determine the ground bearing pressure capacity. In some cases of heavy loads or when soil instability or sinkholes are suspected, it may be necessary to perform additional borings or new ground-penetrating radar surveys.

Occupational Safety and Health Administration (OSHA) Standard 1926.1402, Ground Conditions [6] requires that “[t]he equipment must not be assembled or used unless ground conditions are firm, drained, and graded to a sufficient extent so that, in conjunction (if necessary) with the use of supporting materials, the equipment manufacturer’s specifications for adequate support and degree of level of the equipment are met. The requirement for the ground to be drained does not apply to marshes/wetlands” where “[g]round conditions means the ability of the ground to support the equipment (including slope, compaction, and firmness).”

Although there are no national standards that address OSHA 1926-1402 ground condition safety factors to apply when calculating the demand (the surface bearing load) and the ground bearing capacity, the responsible engineer may consult a local geotechnical firm for local or state regulations, insights, practices, and guidelines specific to the area. The responsible engineer may refer to Chapter 22 of *Soil Engineering* by M. S. Spangler and R. L. Handy for bearing capacity and site investigation options [11].

If ground settlement from surface loads is predicted and conservatively estimated, the capacity of the pipe to absorb the ground settlement without damage can be analyzed using a Level 3 technique, such as described in this report: beam on elastic foundation or FEA. However, it is typically difficult to qualify buried pipes for ground settlement, unless they have been originally designed for this effect, with flexible joints that are purposely designed to absorb shear and rotation.

2.4.3 Buried Pipe Loads Not Required to Be Evaluated

It is assumed that the buried piping was designed and installed in accordance with a recognized buried pipe standard, such as American Water Works Association (AWWA) Manual M11 “Steel Pipe—A Guideline for Design and Installation” [12] or Bechtel Topical Report BC-TOP-4-A, “Seismic Analyses of Structures and Equipment for Nuclear Power Plants” [13]. This assumption is applicable to safety-related and balance-of-plant piping.

Design codes for buried piping typically include wall thickness requirements due to internal pressure and mechanical axial loads. Internal pressure produces circumferential and axial tensile stress, which do not align with the stress produced by surface loading. Constrained thermal expansion, seismic wave passage, and seismic anchor movement all produce axial stress and moment loading which do not align with the surface loading stresses. Therefore, internal pressure, constrained thermal expansion, seismic wave passage, and seismic anchor movements are not required to be evaluated when assessing surface loads.

Buried pipe codes, including ASME Code Case N-806-1, provide rules to prevent flotation of the pipe due to groundwater. Buoyancy checks are performed to determine whether the piping requires anchoring during the design phase. Surface loading produces a vertical pressure down on the piping, which acts in the opposite direction of the buoyant force. Therefore, buoyancy is not required to be evaluated when assessing surface loads.

Postulated loading required to be evaluated in the design basis could include flooding. Water accumulation at the ground surface increases the vertical pressure on buried piping and is additive to the type of surface loading evaluated in this report. However, site flooding is typically considered a Service Level D (faulted) event and may be evaluated using alternative acceptance criteria, such as ASME Section III, Appendix F, Rules for Evaluation of Service Loadings with Level D Service Limits. Such evaluations use a lower factor of safety because the events have lower probabilities of occurrence. It is also unlikely that the largest surface loads, such as a heavy lift, would occur concurrently with a flooding event. Therefore, flooding is not required to be evaluated when assessing surface loads.

3
RESULTS

This section provides three levels to evaluate the impact of surface loads on the structural integrity of buried piping. The user may start with the Level 1 screening and progress through each level sequentially. Alternatively, the user may wish to begin with the Level 2 analysis or the Level 3 guidance.

The Level 1 screening in Section 3.1 may be used as a conservative estimate of the impact of surface loading. Little site-specific input is required for the Level 1 screening. If the piping under evaluation is above the curve for the appropriate material, the impact of surface loading is acceptable. If the piping does not meet the Level 1 screening or does not fall within the bounds of the screening limits or if Level 1 screening is not provided, a Level 2 evaluation may be performed.

The Level 2 analysis in Section 3.2 provides the user with the equations to determine the applied loading, or demand, and the pipe's ability to resist the applied loading, which is the capacity. If the capacity exceeds the demand, including the appropriate factors of safety, the line meets the acceptance criteria. If the line fails the Level 2 analysis, if equations are not provided for the specific pipe material and loading combination, or if additional margin is required, a Level 3 evaluation may be performed.

The Level 3 guidance in Section 3.3 provides the user with guidance to perform or review a more sophisticated evaluation. Recommended approaches and best practices are specifically provided for beam on an elastic foundation and FEA. Due to the complexity and variety of potential analyses for buried piping, detailed instructions for a Level 3 analysis are not provided.

Corrugated product forms provide additional stiffness relative to cylindrical piping, meaning that a smaller wall thickness is required to resist soil and surface loads in corrugated products. However, corrugation does not provide additional resistance to internal pressure loading. As a result, corrugated piping is commonly used in storm drains and other low-pressure applications. This report does not explicitly include corrugated products. However, for soil and surface loads, the user may conservatively evaluate corrugated piping as cylindrical piping. For steel piping, it is likely that the Level 1 screening will require a wall thickness that exceeds the wall thickness of the corrugated product. In this case, a Level 2 analysis may be performed.

Double-walled piping may be conservatively evaluated in this report by taking credit for only one of the pressure boundaries. Only the outer pressure boundary should be used in the Level 1 screening or the Level 2 analysis. A Level 3 evaluation may be performed to accurately quantify the double-walled piping capacity to resist surface loading.

Regarding HDPE piping, there are two common fusion joining methods. The first directly joins two pipe segments and is similar to butt welded metallic pipe. The other is electrofusion, which joins the pipe to a fitting. When properly performed, both joining methods are stronger than the base material. Therefore, the type of fusion joining method does not impact the Level 1 screening or the Level 2 analysis.

3.1 Level 1 Screening

The Level 1 screening is based on point loading at the ground surface. Figures are developed for buried piping based on the material type. Buried piping that falls above the line meets the Level 1 screening criteria and is acceptable without further evaluation. Buried piping that is below the line does not meet the screening criteria. In this case, a Level 2 (see Section 3.2) or Level 3 (see Section 3.3) evaluation is recommended. The information in Table 3-1 should be collected to prepare for the Level 1 screening. Note that the diameter and thickness specified in Table 3-1 do not include coatings or linings, because these are not considered structural members of the piping.

Table 3-1
Level 1 screening inputs

Input	Carbon Steel (with or Without Lining)	Stainless Steel	Ductile Iron (with or Without Lining)	HDPE
Pipe material	X	X	X	X
Pipe size	X	X	X	X
Pipe schedule/wall thickness if corrosion is expected	X	X	X	
Material allowable stress	X	X	X	X
Material allowable sidewall compression stress				X
Material elastic modulus				X
Internal lining	X		X	
Depth of soil cover	X	X	X	X
Surface live load	X	X	X	X
Surface dead load (if applicable)	X	X	X	X
Embedment compaction	X	X	X	X
Soil type	X	X	X	X
Trench width				X
Subject to negative pressure	X	X	X	
Design temperature				X

3.1.1 Level 1 Modeling Simplifications

Several assumptions and modeling simplifications are required in order to generate the Level 1 screening figures. In many cases, a Level 2 analysis can be used to decrease conservatism and more accurately account for the actual pipe loading. If these simplifications are not applicable, a Level 2 analysis may be performed.

Level 1 modeling simplifications are as follows:

1. Backfill compaction is assumed to be 85% standard or modified proctor or higher. In addition, the soil or backfill type is assumed to not be fine grain soils CL or ML (silts and clays with less than 50% liquid) with less than 30% sand and gravel. These assumptions are typical for engineered fill used in nuclear power plants. Based on Code Case N-806-1 [1, Table A-1], the minimum modulus of soil reaction is 1000 psi. Use of the minimum value of E' conservatively increases the calculated ovalization and decreases the allowable buckling stress.
2. The offset of surface loads to the vertical pipe center line, d, is taken as zero. This maximizes the vertical pressure at the pipe due to surface loads.
3. The total bedding angle, θ, is taken as zero. This conservatively increases the bedding constant, K, to be 0.110, which increases the calculated ovalization.
4. The impact factor, F', is taken as 1.5 for all burial depths. This is considered conservative based on the discussion in Section 2.4.1.
5. The density of dry soil or trench fill, γ_S, is assumed to be 150 lbm/ft^3. This density conservatively bounds the types of fill commonly used in nuclear power plant applications.
6. The density of groundwater, γ_W, is assumed to be 62.4 lbm/ft^3, which is typical of fresh water at standard temperature and pressure.
7. The water table is assumed to be at the ground surface ($h_W = H_{BD}$). This conservatively increases the vertical pressure on the pipe, provided that the backfill density is not more than three times the groundwater density. For the Level 1 evaluation, this assumption meets this criterion. See Modeling Simplifications 5 and 6.
8. Negative pressure is not evaluated in the Level 1 evaluation. If negative pressure is applicable, a Level 2 evaluation is required.
9. The elastic modulus for carbon steel is assumed to be 27.7 x 10^6 psi, which is typical of carbon steel piping with less than 0.3% C.
10. The allowable stress for carbon steel is assumed to be 15 ksi, which is typical of carbon steel piping with less than 0.3% C.
11. The elastic modulus for stainless steel is assumed to be 27.1 x 10^6 psi, which is typical of austenitic stainless steel piping at 300°F.
12. The allowable stress for stainless steel is assumed to 14 ksi, which is less than typical stainless steel piping with an operating temperature that does not exceed 300°F.
13. The elastic modulus for ductile iron piping is taken as 20.5 x 10^6 psi, which is the minimum reported value in “Ductile Iron Data for Design Engineers” [14]. Use of the minimum value conservatively decreases the resistance to ovalization (that is, a reduction in capacity).

14. The allowable stress for ductile iron piping is assumed to 9.6 ksi, which is the lower bound value in B31.1 for operating temperatures that do not exceed 600°F.
15. The elastic modulus for HDPE is taken as 12,500 psi from Code Case N-755-3 [15, Table -3210-3(a)] at 140°F for a 50-year design life. This assumption conservatively increases the calculated ovalization and decreases the allowable buckling pressure.
16. The trench width for HDPE piping is assumed to be a minimum of three times the diameter of the piping to facilitate installation. This assumption influences the selection of the soil support factor, F_S. The soil support factor is taken as 0.80 from Code Case N-755-3 [15, Table -3210-2(a)], which is the minimum value for trench to pipe diameter ratio of 3.0.
17. The design temperature and maximum operating temperature for HDPE piping is limited not greater than 140°F. The strength of HDPE material decreases significantly with increasing temperature. It is possible to evaluate HDPE piping with transient operation exceeding 140°F (but such evaluations are beyond the scope of this report.
18. The allowable sidewall compressive stress for HDPE piping is taken as 520 psi from Code Case N-755-3 [15, Table -3220(a)] at 140°F. This temperature is the highest HDPE temperature for which this report is applicable.

3.1.2 Level 1 Screening Figures

Level 1 screening figures are provided in the following sections for a variety of materials. The capacity of each material is strongly dependent upon the material's allowable stress and the modulus of elasticity. HDPE, for example, has low allowable stress and modulus of elasticity. The result is that the impact of surface loading is more pronounced for HDPE relative to a material such as carbon steel. Figure 3-1 shows each material evaluated for a 16-in. line.

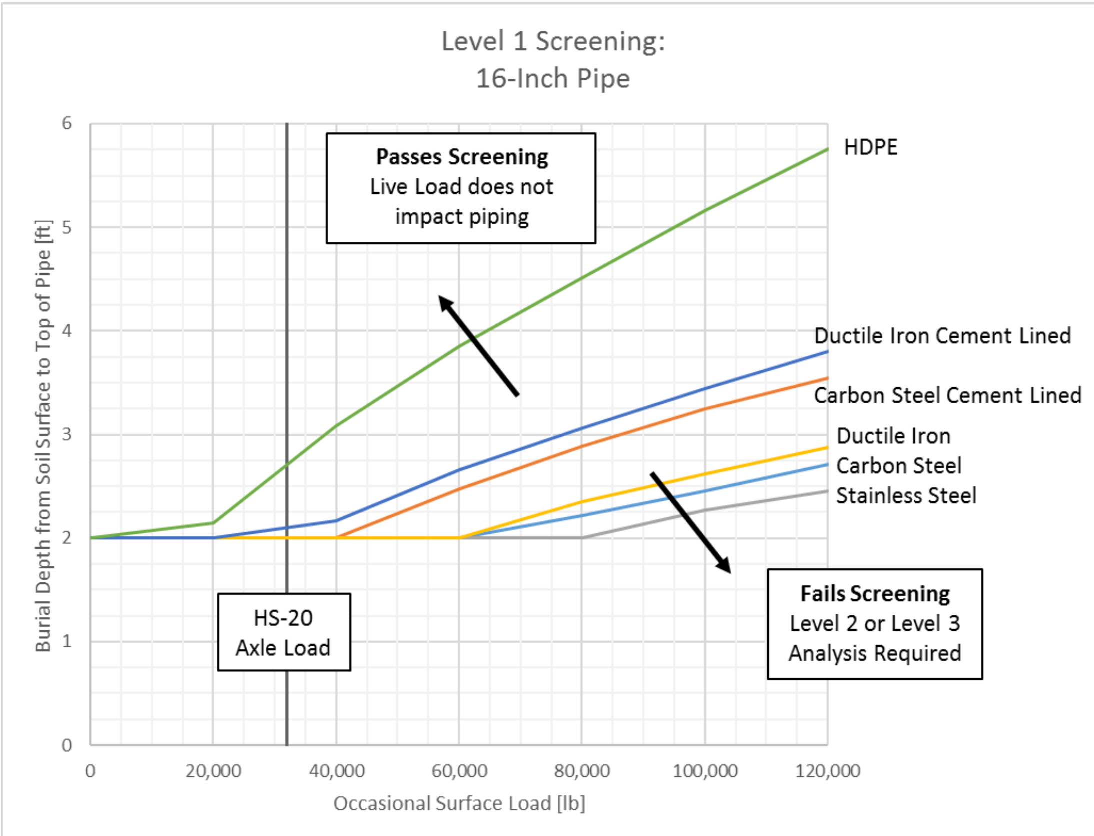

Figure 3-1
Level 1 screening, 16-in. pipe

For all materials except HDPE and ductile iron cement-lined piping, a burial depth of 2 ft reduces the loading from an HS-20 truck to a point where the piping is unaffected by the surface load. Ductile iron cement-lined piping requires 2 1/4 ft to achieve the same result, and HDPE requires approximately 2 3/4 ft.

The concrete lining in carbon steel and ductile iron pipe reduces the allowable ovalization relative to unlined pipe. A limit of 3% is applied to prevent cracking of the lining, whereas the unlined pipe may ovalize to 5%.

3.1.2.1 Level 1 Example

The Level 1 screening figures may be used to evaluate, among other loads, the impact of crane loading. A 60-ton mobile crane is to be used during outage related activities. Although the lifting location is remote from buried piping, the crane will drive over several 16-in. buried lines during staging. The 60-ton crane has a total weight of approximately 100,000 lbf. Using Figure 3-1, and applying the crane as a point load over the piping, the required cover height for each material is as follows:

- HDPE: 5 3/4 ft
- Ductile iron cement lined: 4 ft
- Carbon steel cement lined: 3 3/4 ft
- Ductile iron: 3 ft
- Carbon steel: 2 3/4 ft
- Stainless steel: 2 1/2 ft

If one of the carbon steel lines has a cover depth of only 2 ft, the surface load due to the crane would fail the Level 1 screening. Rather than perform a Level 2 analysis, the axle loads for the crane are obtained. In this case, the rear axle loads are the bounding (or highest) loading at approximately 55,000 lbf. Again referring to Figure 3-1, the Level 1 required burial depth for a 16-in. carbon steel line subjected to a 55,000 lbf point load at the surface is 2 ft. Therefore, the 16-in. line passes the Level 1 screening.

The Level 1 screening figures may also be used by the buried pipe program owner to develop or modify the site process applicability review. The process applicability review determines which plant licensing basis documents and processes are affected by a proposed activity. If a proposed activity involves bringing construction equipment to the owner-controlled area or staging replacement components, a screening value can be added to the process applicability review. Using the previous example and referring to Figure 3-1, any equipment heavier than 60,000 lbf would require engineering review.

3.1.2.2 Carbon Steel

The Level 1 screening for carbon steel is based on the following assumptions, **which require verification by the user**:

1. Embedment compaction ≥85% proctor (see Level 1 Modeling Simplification 1).
2. Soil type may not be CL or ML with less than 30% sand and gravel (see Level 1 Modeling Simplification 1).
3. Wall thickness meets the criteria that are presented in Table 3-2.
4. Negative pressure is not applicable (see Level 1 Modeling Simplification 8).
5. Allowable stress is not less than 15,000 psi (see Level 1 Modeling Simplification 10).
6. Piping is not internally lined with concrete or other brittle material.

The Level 1 screening for carbon steel piping is given in Figure 3-2.

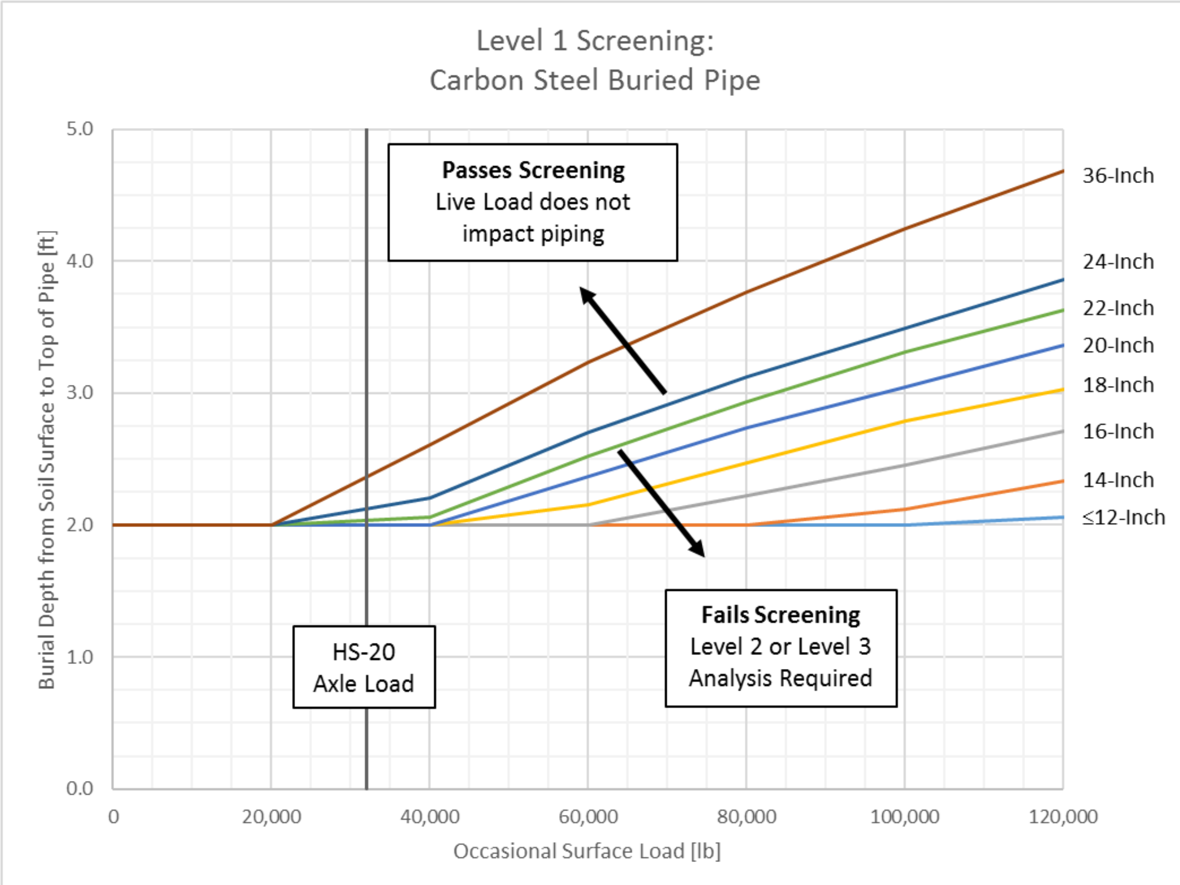

Figure 3-2
Level 1 screening, carbon steel

(See the preceding assumptions requiring user verification.)

The following modeling simplifications are conservative or actual (These do not require user verification and are listed here for completeness.):

1. Modulus of soil reaction is 1000 psi (see Level 1 Modeling Simplification 1).
2. Surface loading lateral offset is zero (see Level 1 Modeling Simplification 2).
3. Total bedding angle is zero degrees (see Level 1 Modeling Simplification 3).
4. Impact factor is 1.5 (see Level 1 Modeling Simplification 4).
5. Backfill density is 150 lbm/ft^3 (see Level 1 Modeling Simplification 5).
6. Groundwater density is 62.4 lbm/ft^3 (see Level 1 Modeling Simplification 6).
7. Water table height is at the ground surface (see Level 1 Modeling Simplification 7).
8. Elastic modulus is 27.7 x 10^6 psi (see Level 1 Modeling Simplification 9).
9. Sustained surface loading, F_{surf_sust}, is zero. Sustained loading may be conservatively evaluated as occasional surface loading, F_{surf_occ}.

For each nominal pipe size in Table 3-2, standard schedule wall thickness with a certain amount of general wall thinning is evaluated. The user must determine whether the wall thickness evaluated is appropriate for the line under consideration. If pitting or wall loss is expected to produce wall thicknesses less than those used in the Level 1 screening, a Level 2 or Level 3 analysis may be performed. The wall thickness requirements for carbon steel pipe are given in Table 3-2. Note that pipe sizes less than 12 in. are not shown in Figure 3-2. Pipe sizes less than 12 in. may conservatively use the ≤12-in. curve.

Table 3-2
Level 1 screening, carbon steel, wall thickness requirements

<table>
<tr><th>Nominal Pipe Size (in.)</th><th>Wall Thickness (in.) [1]</th><th>Nominal Pipe Size (in.)</th><th>Wall Thickness (in.) [1]</th></tr>
<tr><td>1</td><td rowspan="6">0.100</td><td>14</td><td rowspan="12">0.300</td></tr>
<tr><td>1.5</td><td>16</td></tr>
<tr><td>2</td><td>18</td></tr>
<tr><td>2.5</td><td>20</td></tr>
<tr><td>3</td><td>22</td></tr>
<tr><td>3.5</td><td>24</td></tr>
<tr><td>4</td><td rowspan="3">0.200</td><td>26</td></tr>
<tr><td>5</td><td>28</td></tr>
<tr><td>6</td><td>30</td></tr>
<tr><td>8</td><td>0.250</td><td>32</td></tr>
<tr><td>10</td><td rowspan="2">0.300</td><td>34</td></tr>
<tr><td>12</td><td>36</td></tr>
</table>

[1] The Level 1 assessment applies to pipes with a wall thickness equal to or larger than the tabulated values. This allows for a small amount of corrosion. If the wall thickness is expected to be less than these values, a Level 2 or Level 3 evaluation may be performed.

3.1.2.3 Carbon Steel Cement Lined

The Level 1 screening for carbon steel cement-lined pipe is based on the following assumptions, **which require verification by the user**:

1. Embedment compaction is 85% proctor or higher (see Level 1 Modeling Simplification 1).
2. Soil type may not be CL or ML with less than 30% sand and gravel (see Level 1 Modeling Simplification 1).
3. Wall thickness meets the criteria that are presented in Table 3-3.
4. Negative pressure is not applicable (see Level 1 Modeling Simplification 8).
5. Allowable stress is not less than 15,000 psi (see Level 1 Modeling Simplification 10).
6. Piping has internal cement lining.

The Level 1 screening for carbon steel cement-lined piping is given in Figure 3-3.

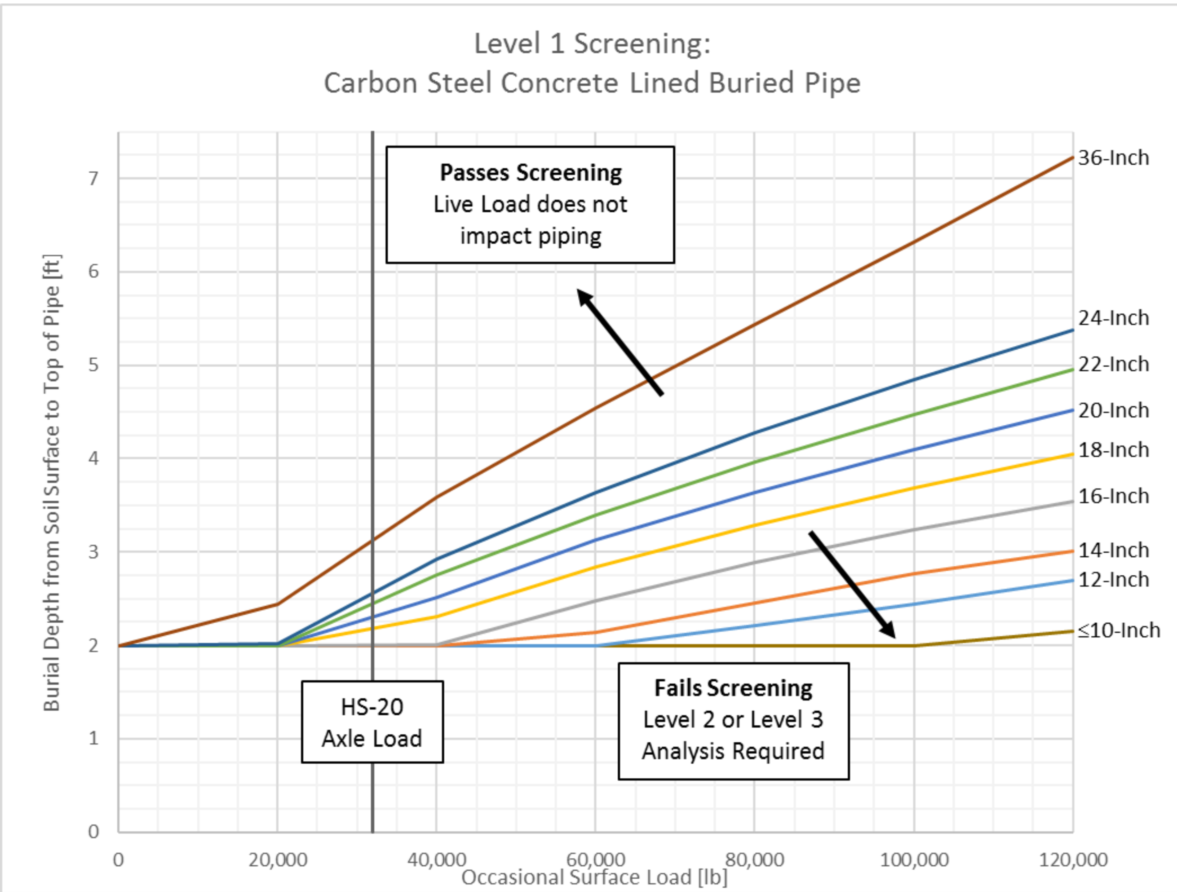

Figure 3-3
Level 1 screening, carbon steel cement lined

(See the preceding assumptions requiring user verification.)

The following modeling simplifications are conservative or actual (These do not require user verification and are listed here for completeness.):

1. Modulus of soil reaction is 1000 psi (see Level 1 Modeling Simplification 1).
2. Surface loading lateral offset is zero (see Level 1 Modeling Simplification 2).
3. Total bedding angle is zero degrees (see Level 1 Modeling Simplification 3).
4. Impact factor is 1.5 (see Level 1 Modeling Simplification 4).
5. Backfill density is 150 lbm/ft^3 (see Level 1 Modeling Simplification 5).
6. Groundwater density is 62.4 lbm/ft^3 (see Level 1 Modeling Simplification 6).
7. Water table height is at the ground surface (see Level 1 Modeling Simplification 7).
8. Elastic modulus is 27.7 x 10^6 psi (see Level 1 Modeling Simplification 9).
9. Sustained surface loading, F_{surf_sust}, is zero. Sustained loading may be conservatively evaluated as occasional surface loading, F_{surf_occ}.

For each nominal pipe size in Table 3-3, standard schedule wall thickness with a certain amount of general wall thinning is evaluated. The user must determine whether the wall thickness evaluated is appropriate for the line under consideration. If pitting or wall loss is expected to produce wall thicknesses less than those used in the Level 1 screening, a Level 2 or Level 3 analysis may be performed. The wall thickness requirements for carbon steel cement-lined pipe are given in Table 3-3. Note that pipe sizes less than 10 in. are not shown in Figure 3-3. Pipe sizes less than 10 in. may conservatively use the ≤10-in. curve.

Table 3-3
Level 1 screening, carbon steel cement-lined, wall thickness requirements

<table>
<tr><th>Nominal Pipe Size (in.)</th><th>Wall Thickness (in.) [1]</th><th>Nominal Pipe Size (in.)</th><th>Wall Thickness (in.) [1]</th></tr>
<tr><td>1</td><td rowspan="6">0.100</td><td>14</td><td rowspan="12">0.300</td></tr>
<tr><td>1.5</td><td>16</td></tr>
<tr><td>2</td><td>18</td></tr>
<tr><td>2.5</td><td>20</td></tr>
<tr><td>3</td><td>22</td></tr>
<tr><td>3.5</td><td>24</td></tr>
<tr><td>4</td><td rowspan="3">0.200</td><td>26</td></tr>
<tr><td>5</td><td>28</td></tr>
<tr><td>6</td><td>30</td></tr>
<tr><td>8</td><td>0.250</td><td>32</td></tr>
<tr><td>10</td><td rowspan="2">0.300</td><td>34</td></tr>
<tr><td>12</td><td>36</td></tr>
</table>

[1] The Level 1 assessment applies to pipes with a wall thickness equal to or larger than the tabulated values. This allows for a small amount of corrosion. If the wall thickness is expected to be less than these values, a Level 2 or Level 3 evaluation may be performed.

3.1.2.4 Stainless Steel

The Level 1 screening for stainless steel is based on the following assumptions, **which require verification by the user**:

1. Embedment compaction is 85% proctor or higher (see Level 1 Modeling Simplification 1).
2. Soil type may not be CL or ML with less than 30% sand and gravel (see Level 1 Modeling Simplification 1).
3. Wall thickness meets the criteria that are presented in Table 3-4.
4. Negative pressure is not applicable (see Level 1 Modeling Simplification 8).
5. Allowable stress is not less than 14,000 psi (see Level 1 Modeling Simplification 12).

The Level 1 screening for stainless steel piping is given in Figure 3-4.

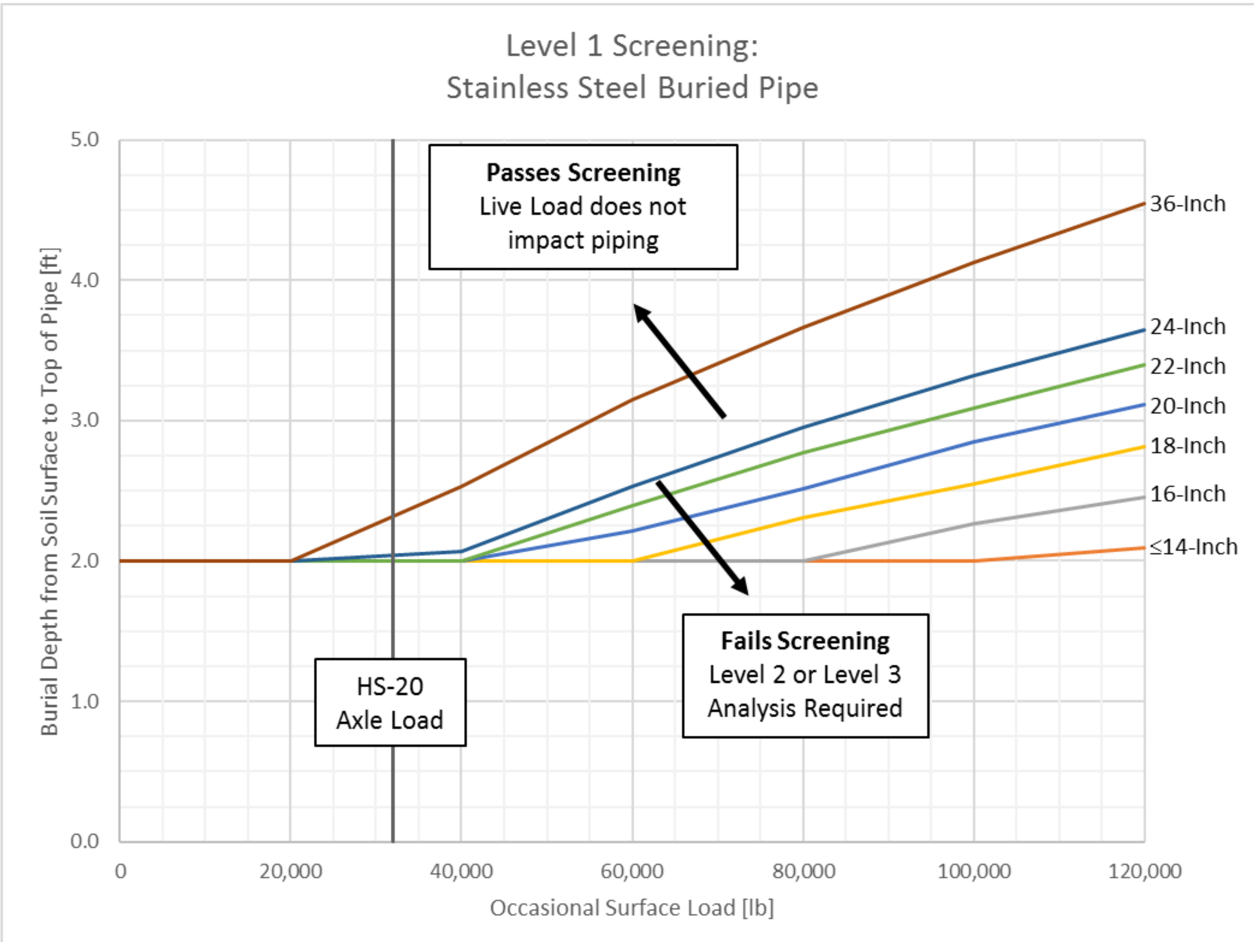

Figure 3-4
Level 1 screening, stainless steel

(See the preceding assumptions requiring user verification.)

The following modeling simplifications are conservative or actual (These do not require user verification and are listed here for completeness.):

1. Modulus of soil reaction is 1000 psi (see Level 1 Modeling Simplification 1).
2. Surface loading lateral offset is zero (see Level 1 Modeling Simplification 2).
3. Total bedding angle is zero degrees (see Level 1 Modeling Simplification 3).
4. Impact factor is 1.5 (see Level 1 Modeling Simplification 4).
5. Backfill density is 150 lbm/ft^3 (see Level 1 Modeling Simplification 5).
6. Groundwater density is 62.4 lbm/ft^3 (see Level 1 Modeling Simplification 6).
7. Water table height is at the ground surface (see Level 1 Modeling Simplification 7).
8. Elastic modulus is 27.1 x 10^6 psi (see Level 1 Modeling Simplification 11).
9. Sustained surface loading, F_{surf_sust}, is zero. Sustained loading may be conservatively evaluated as occasional surface loading, F_{surf_occ}.

For each nominal pipe size in Table 3-4, standard schedule wall thickness is evaluated and includes the manufacturing tolerance of -12.5%. The user must determine whether the wall thickness evaluated is appropriate. If the expected wall thickness is less than those used in the Level 1 screening, a Level 2 or Level 3 analysis may be performed. The wall thickness requirements are given in Table 3-4. Note that pipe sizes less than 14 in. are not shown in Figure 3-4. Pipe sizes less than 14 in. may conservatively use the ≤14-in. curve.

Table 3-4
Level 1 screening, stainless steel, wall thickness requirements

<table>
<tr><th>Nominal Pipe Size (in.)</th><th>Wall Thickness (in.) [1]</th><th>Nominal Pipe Size (in.)</th><th>Wall Thickness (in.) [1]</th></tr>
<tr><td>1</td><td>0.116</td><td>14</td><td rowspan="12">0.328</td></tr>
<tr><td>1.5</td><td>0.127</td><td>16</td></tr>
<tr><td>2</td><td>0.135</td><td>18</td></tr>
<tr><td>2.5</td><td>0.178</td><td>20</td></tr>
<tr><td>3</td><td>0.189</td><td>22</td></tr>
<tr><td>3.5</td><td>0.198</td><td>24</td></tr>
<tr><td>4</td><td>0.207</td><td>26</td></tr>
<tr><td>5</td><td>0.226</td><td>28</td></tr>
<tr><td>6</td><td>0.245</td><td>30</td></tr>
<tr><td>8</td><td>0.282</td><td>32</td></tr>
<tr><td>10</td><td>0.319</td><td>34</td></tr>
<tr><td>12</td><td>0.328</td><td>36</td></tr>
</table>

[1] The Level 1 assessment applies to pipes with a wall thickness equal to or larger than the tabulated values. This allows for the manufacturing tolerance. If the wall thickness is expected to be less than these values, a Level 2 or Level 3 evaluation may be performed.

3.1.2.5 Ductile Iron

The Level 1 screening for ductile iron piping is based on the following assumptions, **which require verification by the user**:

1. Embedment compaction is 85% proctor or higher (see Level 1 Modeling Simplification 1).
2. Soil type may not be CL or ML with less than 30% sand and gravel (see Level 1 Modeling Simplification 1).
3. Wall thickness meets the criteria that are presented in Table 3-5.
4. Negative pressure is not applicable (see Level 1 Modeling Simplification 8).
5. Allowable stress is not less than 9600 psi (see Level 1 Modeling Simplification 14).
6. Piping is not internally lined with concrete or other brittle material.

The Level 1 screening for ductile iron piping without internal lining is given in Figure 3-5.

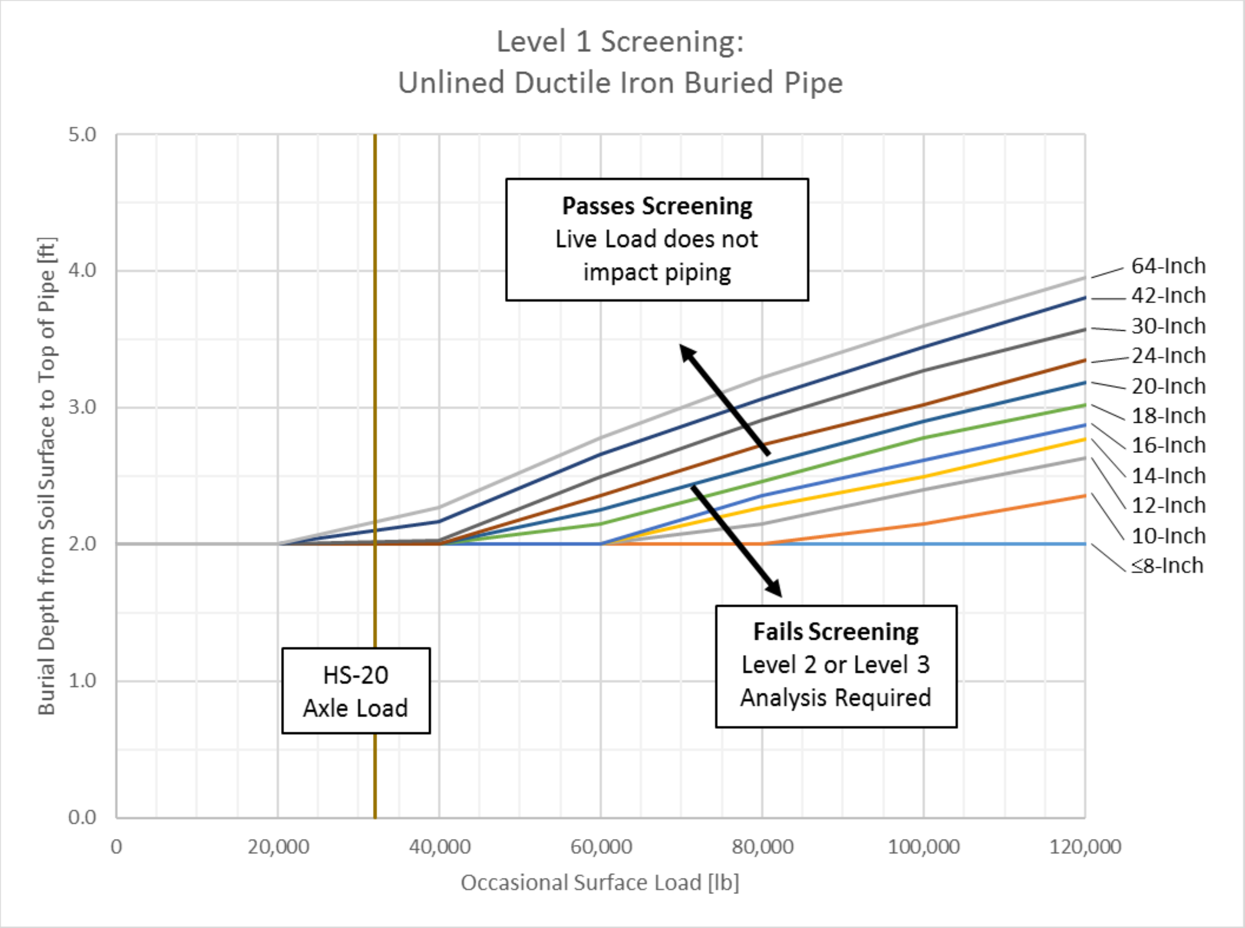

Figure 3-5
Level 1 screening, ductile iron unlined

(See the preceding assumptions requiring user verification.)

The following modeling simplifications are conservative or actual (These do not require user verification and are listed here for completeness.):

1. Modulus of soil reaction is 1000 psi (see Level 1 Modeling Simplification 1).
2. Surface loading lateral offset is zero (see Level 1 Modeling Simplification 2).
3. Total bedding angle is zero degrees (see Level 1 Modeling Simplification 3).
4. Impact factor is 1.5 (see Level 1 Modeling Simplification 4).
5. Backfill density is 150 lbm/ft^3 (see Level 1 Modeling Simplification 5).
6. Groundwater density is 62.4 lbm/ft^3 (see Level 1 Modeling Simplification 6).
7. Water table height is at the ground surface (see Level 1 Modeling Simplification 7).
8. Elastic modulus is 20.5 x 10^6 psi (see Level 1 Modeling Simplification 13).
9. Sustained surface loading, F_{surf_sust}, is zero. Sustained loading may be conservatively evaluated as occasional surface loading, F_{surf_occ}.

For each nominal pipe size in Table 3-5, Class 350 wall thickness is evaluated and includes the service allowance and casting tolerance. The user must determine whether the wall thickness evaluated is appropriate. If the expected wall thickness is less than those used in the Level 1 screening, a Level 2 or Level 3 analysis may be performed. The wall thickness requirements are given in Table 3-5. Note that pipe sizes less than 8 in. are not shown in Figure 3-5. Pipe sizes less than 8 in. may conservatively use the ≤8-in. curve. The 26-in. piping may use the curve for 30-in. piping; and 48-in., 54-in., and 60-in. piping may use the curve for 64-in. piping.

Table 3-5
Level 1 screening, ductile iron unlined, wall thickness requirements

Nominal Pipe Size (in.)	Wall Thickness (in.) [1]	Nominal Pipe Size (in.)	Wall Thickness (in.) [1]
3	0.25	20	0.38
4		24	0.43
6		30	0.49
8		36	0.56
10	0.26	42	0.63
12	0.28	48	0.70
14	0.31	54	0.79
16	0.34	60	0.83
18	0.36	64	0.87

[1] The Level 1 assessment applies to pipes with a wall thickness equal to or larger than the tabulated values. This allows for casting tolerance and a small amount of corrosion. If the wall thickness is expected to be less than these values, a Level 2 or Level 3 evaluation may be performed.

3.1.2.6 Ductile Iron Cement Lined

The Level 1 screening for ductile iron cement-lined piping is based on the following assumptions, **which require verification by the user**:

1. Embedment compaction is 85% proctor or higher (see Level 1 Modeling Simplification 1).
2. Soil type may not be CL or ML with less than 30% sand and gravel (see Level 1 Modeling Simplification 1).
3. Wall thickness meets the criteria that are presented in Table 3-6.
4. Negative pressure is not applicable (see Level 1 Modeling Simplification 8).
5. Allowable stress is not less than 9600 psi (see Level 1 Modeling Simplification 14).
6. Piping has internal cement lining.

The Level 1 screening for ductile iron cement-lined piping is given in Figure 3-6.

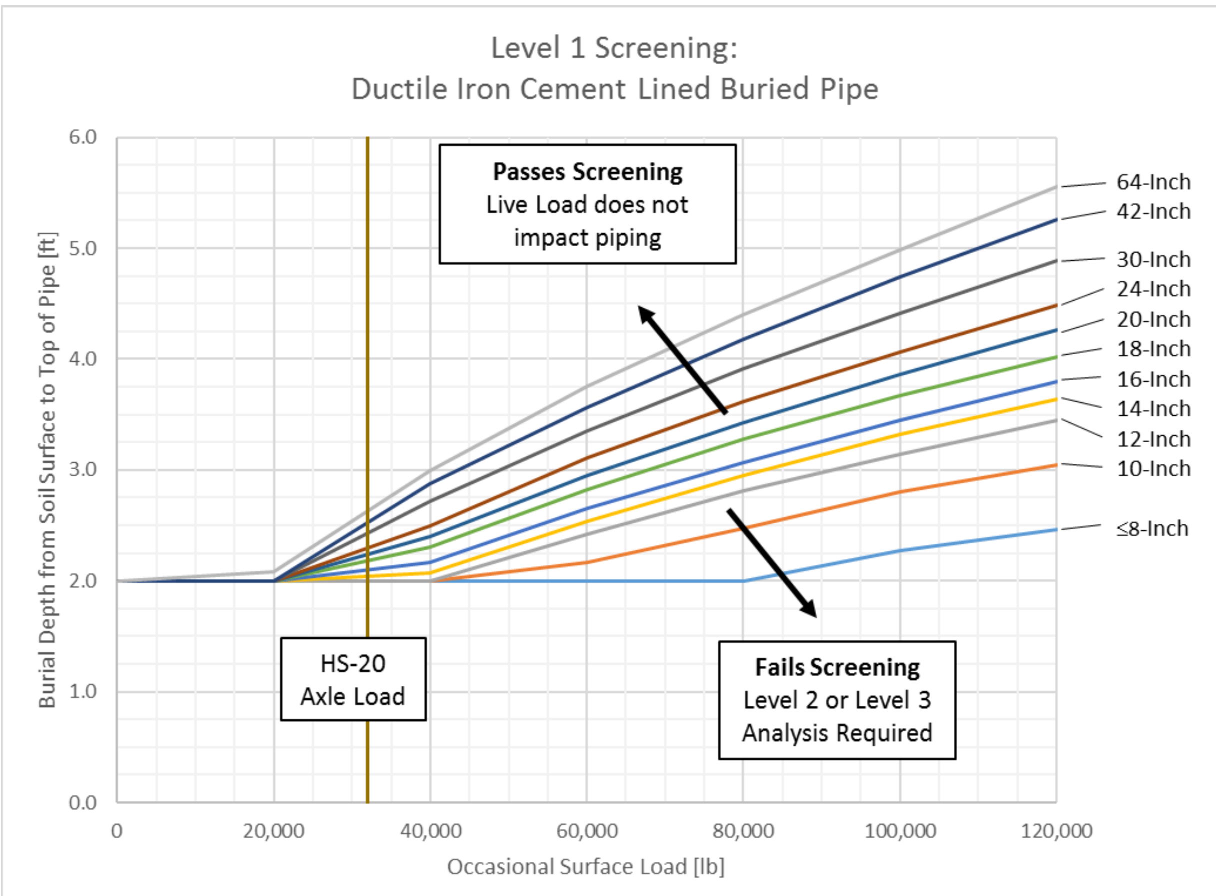

Figure 3-6
Level 1 screening, ductile iron cement lined

(See the preceding assumptions requiring user verification.)

The following modeling simplifications are conservative or actual (These do not require user verification and are listed here for completeness.):

1. Modulus of soil reaction is 1000 psi (see Level 1 Modeling Simplification 1).
2. Surface loading lateral offset is zero (see Level 1 Modeling Simplification 2).
3. Total bedding angle is zero degrees (see Level 1 Modeling Simplification 3).
4. Impact factor is 1.5 (see Level 1 Modeling Simplification 4).
5. Backfill density is 150 lbm/ft^3 (see Level 1 Modeling Simplification 5).
6. Groundwater density is 62.4 lbm/ft^3 (see Level 1 Modeling Simplification 6).
7. Water table height is at the ground surface (see Level 1 Modeling Simplification 7).
8. Elastic modulus is 20.5 x 10^6 psi (see Level 1 Modeling Simplification 13).
9. Sustained surface loading, F_{surf_sust}, is zero. Sustained loading may be conservatively evaluated as occasional surface loading, F_{surf_occ}.

For each nominal pipe size in Table 3-6, Class 350 wall thickness is evaluated and includes the service allowance and casting tolerance. The user must determine whether the wall thickness evaluated is appropriate. If the expected wall thickness is less than those used in the Level 1 screening, a Level 2 or Level 3 analysis may be performed. The wall thickness requirements are given in Table 3-6. Note that pipe sizes less than 8 in. are not shown in Figure 3-6. Pipe sizes less than 8 in. may conservatively use the ≤8-in. curve. The 26-in. piping may use the curve for 30-in. piping, and 48-in., 54-in., and 60-in. piping may use the curve for 64-in. piping.

Table 3-6
Level 1 screening, ductile iron cement lined, wall thickness requirements

<table>
<tr><th>Nominal Pipe Size (in.)</th><th>Wall Thickness (in.) [1]</th></tr>
<tr><td>3</td><td rowspan="4">0.25</td></tr>
<tr><td>4</td></tr>
<tr><td>6</td></tr>
<tr><td>8</td></tr>
<tr><td>10</td><td>0.26</td></tr>
<tr><td>12</td><td>0.28</td></tr>
<tr><td>14</td><td>0.31</td></tr>
<tr><td>16</td><td>0.34</td></tr>
<tr><td>18</td><td>0.36</td></tr>
</table>

Nominal Pipe Size (in.)	Wall Thickness (in.) [1]
20	0.38
24	0.43
30	0.49
36	0.56
42	0.63
48	0.70
54	0.79
60	0.83
64	0.87

[1] The Level 1 assessment applies to pipes with a wall thickness equal to or larger than the tabulated values. This allows for casting tolerance and a small amount of corrosion. If the wall thickness is expected to be less than these values, a Level 2 or Level 3 evaluation may be performed.

3.1.2.7 HDPE

The Level 1 screening for HDPE piping is based on the following assumptions, **which require verification by the user**:

1. Embedment compaction is 85% proctor or higher (see Level 1 Modeling Simplification 1).
2. Soil type may not be CL or ML with less than 30% sand and gravel (see Level 1 Modeling Simplification 1).
3. Dimension ratio (DR) is limited to those that are presented in Table 3-7.
4. Elastic modulus is not less than 12,500 psi (see Level 1 Modeling Simplification 15).
5. Trench width is not less than three diameters (see Level 1 Modeling Simplification 16).
6. Design temperature does not exceed 140°F (see Level 1 Modeling Simplification 17).
7. Allowable sidewall compression stress is not less than 520 psi (see Level 1 Modeling Simplification 18).

The Level 1 screening for HDPE piping is given in Figure 3-7. Note that because the ovalization acceptance criteria change with DR, all values of DR fall roughly at the same location. Therefore, a bounding curve is shown in Figure 3-7 for clarity.

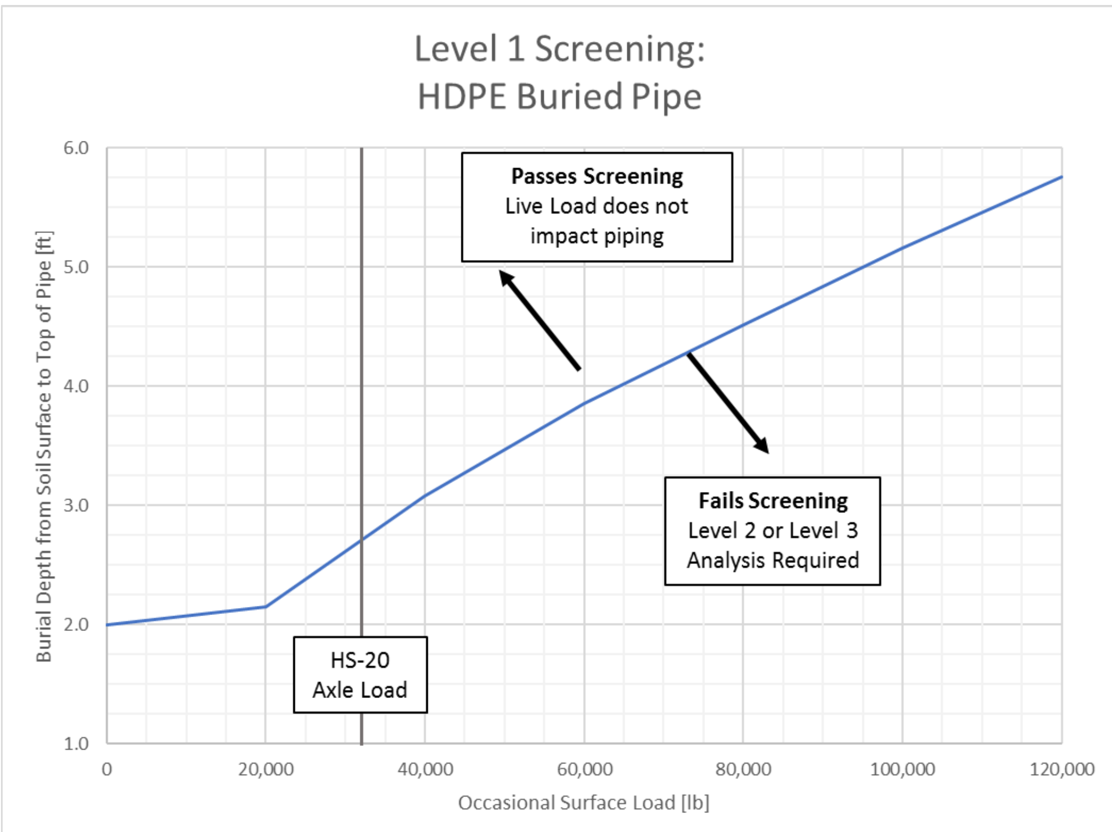

Figure 3-7
Level 1 screening, HDPE

(See the preceding assumptions requiring user verification.)

The following modeling simplifications are conservative or actual (These do not require user verification and are listed here for completeness.):

1. Modulus of soil reaction is 1000 psi (see Level 1 Modeling Simplification 1).
2. Surface loading lateral offset is zero (see Level 1 Modeling Simplification 2).
3. Impact factor is 1.5 (see Level 1 Modeling Simplification 4).
4. Backfill density is 150 lbm/ft^3 (see Level 1 Modeling Simplification 5).
5. Groundwater density is 62.4 lbm/ft^3 (see Level 1 Modeling Simplification 6).
6. Water table height is at the ground surface (see Level 1 Modeling Simplification 7).
7. Soil support factor is 0.80 (see Level 1 Modeling Simplification 16).
8. Sustained surface loading, F_{surf_sust}, is zero. Sustained loading may be conservatively evaluated as occasional surface loading, F_{surf_occ}.

The DR sizes for which the Level 1 screening is valid are given in Table 3-7.

Table 3-7
Level 1 screening, applicable HDPE DR values

DR
13.5
11
9
7.3

3.2 Level 2 Evaluation

Level 2 provides the equations required to perform site-specific evaluations for live or deadweight loading at the ground surface. Use of the equations in this section requires additional inputs to be collected by the user. Tables are provided to facilitate this task based on the specific material type. Some of the required inputs, such as the modulus of soil reaction E', are derived values. For metallic piping, Code Case N-806-1 [1] is an excellent reference for determining these values. Similarly, Code Case N-755-3 [15] may be used for HDPE. The Level 1 screening values may be used if inputs are not available. However, selection of the appropriate inputs is the responsibility of the user. In some cases, specialized skills, such as those provided by geotechnical engineers, may be required.

After collecting the required inputs, the total pressure acting on the piping, P_{SS}, is calculated using the equations in Section 3.2.2, Applicable Loadings. This is the demand loading on the buried piping. The capacity of the piping to resist the demand is then calculated in Sections 3.2.3, 3.2.4, and 3.2.5 for the applicable piping material.

Piping that meets the acceptance criteria of Level 2 is demonstrated to retain structural integrity under the evaluated loading. If the Level 2 acceptance criteria are not met, the specific loading is not addressed in this section, or the material type is not applicable, the user may perform a more detailed Level 3 evaluation (see Section 3.3). Alternatively, the user may elect to perform mitigative actions, as described in Section 4.

A qualitative discussion of acceptance criteria for cement piping and brittle materials, including piping joints, is given in Sections 3.2.5 and 3.2.6.

3.2.1 Required Inputs

3.2.1.1 Carbon Steel

The following inputs are required for a Level 2 evaluation of carbon steel piping. Level 1 screening values may be used if inputs are not available, but selection of the appropriate inputs is the responsibility of the user. Specialized skills may be required for some inputs.

Variable	Value (units)
1. Compaction of pipe embedment	(% proctor)
2. Pipe burial depth, H_{BD}	(in.)
3. Sustained point load at ground surface, F_{surf_sust}	(lbf)
4. Occasional point load at ground surface, F_{surf_occ}	(lbf)
5. Elastic modulus of pipe, E_{pipe}	(psi)
6. Pipe mean radius, R	(in.)
7. Pipe wall thickness, t	(in.)
8. Negative internal pressure, P_{neg} (if applicable)	(psi)
9. Pipe outside diameter, D_O	(in.)
10. Material allowable stress at hot condition, S_h	(psi)
11. Internal lining type a. None b. Cement	(unitless)
12. Modulus of soil reaction, E' (see Level 1 Modeling Simplification 1 if unknown)	(psi)
13. Offset of point load to vertical center line of pipe, d (see Level 1 Modeling Simplification 2 if unknown)	(in.)
14. Total bedding angle, θ (See Level 1 Modeling Simplification 3 if unknown)	(deg)
15. Dry soil or trench fill density, γ_S (see Level 1 Modeling Simplification 5 if unknown)	(lbm/in^3)
16. Groundwater density, γ_W (see Level 1 Modeling Simplification 6 if unknown)	(lbm/in^3)
17. Height of groundwater above top of pipe, h_W (see Level 1 Modeling Simplification 7 if unknown)	(in.)

3.2.1.2 Stainless Steel

The following inputs are required for a Level 2 evaluation of stainless steel piping. Level 1 screening values may be used if inputs are not available, but selection of the appropriate inputs is the responsibility of the user. Specialized skills may be required for some inputs.

Variable	Value (units)
1. Compaction of pipe embedment	(% proctor)
2. Pipe burial depth, H_{BD}	(in.)
3. Sustained point load at ground surface, F_{surf_sust}	(lbf)
4. Occasional point load at ground surface, F_{surf_occ}	(lbf)
5. Elastic modulus of pipe, E_{pipe}	(psi)
6. Pipe mean radius, R	(in.)
7. Pipe wall thickness, t	(in.)
8. Negative internal pressure, P_{neg} (if applicable)	(psi)
9. Pipe outside diameter, D_O	(in.)
10. Material allowable stress at hot condition, S_h	(psi)
11. Modulus of soil reaction, E' (see Level 1 Modeling Simplification 1 if unknown)	(psi)
12. Offset of point load to vertical center line of pipe, d (see Level 1 Modeling Simplification 2 if unknown)	(in.)
13. Total bedding angle, θ (See Level 1 Modeling Simplification 3 if unknown)	(deg)
14. Dry soil or trench fill density, γ_S (see Level 1 Modeling Simplification 5 if unknown)	(lbm/in^3)
15. Groundwater density, γ_W (see Level 1 Modeling Simplification 6 if unknown)	(lbm/in^3)
16. Height of groundwater above top of pipe, h_W (see Level 1 Modeling Simplification 7 if unknown)	(in.)

3.2.1.3 Ductile Iron

The following inputs are required for a Level 2 evaluation of ductile iron piping. Level 1 screening values may be used if inputs are not available, but selection of the appropriate inputs is the responsibility of the user. Specialized skills may be required for some inputs.

Variable	Value (units)
1. Compaction of pipe embedment	(% proctor)
2. Pipe burial depth, H_{BD}	(in.)
3. Sustained point load at ground surface, F_{surf_sust}	(lbf)
4. Occasional point load at ground surface, F_{surf_occ}	(lbf)
5. Elastic modulus of pipe, E_{pipe}	(psi)
6. Pipe mean radius, R	(in.)
7. Pipe wall thickness, t	(in.)
8. Negative internal pressure, P_{neg} (if applicable)	(psi)
9. Pipe outside diameter, D_O	(in.)
10. Material allowable stress at hot condition, S_h	(psi)
11. Internal lining type a. None b. Cement	(unitless)
12. Modulus of soil reaction, E' (see Level 1 Modeling Simplification 1 if unknown)	(psi)
13. Offset of point load to vertical center line of pipe, d (see Level 1 Modeling Simplification 2 if unknown)	(in.)
14. Total bedding angle, θ (see Level 1 Modeling Simplification 3 if unknown)	(deg)
15. Dry soil or trench fill density, γ_S (see Level 1 Modeling Simplification 5 if unknown)	(lbm/in^3)
16. Groundwater density, γ_W (see Level 1 Modeling Simplification 6 if unknown)	(lbm/in^3)
17. Height of groundwater above top of pipe, h_W (see Level 1 Modeling Simplification 7 if unknown)	(in.)

3.2.1.4 HDPE

The following inputs are required for a Level 2 evaluation of HDPE piping. Level 1 screening values may be used if inputs are not available, but selection of the appropriate inputs is the responsibility of the user. Specialized skills may be required for some inputs.

Variable	Value (units)
1. Compaction of pipe embedment	(% proctor)
2. Pipe burial depth, H_{BD}	(in.)
3. Sustained point load at ground surface, F_{surf_sust}	(lbf)
4. Occasional point load at ground surface, F_{surf_occ}	(lbf)
5. Elastic modulus of pipe, E_{pipe}	(psi)
6. DR	(unitless)
7. Material allowable sidewall compression stress, S_{comp}	(psi)
8. Modulus of soil reaction, E' (see Level 1 Modeling Simplification 1 if unknown)	(psi)
9. Offset of point load to vertical center line of pipe, d (see Level 1 Modeling Simplification 2 if unknown)	(in.)
10. Dry soil or trench fill density, γ_S (see Level 1 Modeling Simplification 5 if unknown)	(lbm/in^3)
11. Groundwater density, γ_W (see Level 1 Modeling Simplification 6 if unknown)	(lbm/in^3)
12. Height of groundwater above top of pipe, h_W (see Level 1 Modeling Simplification 7 if unknown)	(in.)
13. Soil Support Factor, F_S (see Level 1 Modeling Simplification 16 if unknown)	(unitless)
14. Design temperature (see Level 1 Modeling Simplification 17)	(°F)

3.2.2 Applicable Loadings

Vertical pressure downward on the piping is the only loading evaluated in this report. Other design basis loads may produce different loading, such as bending due to thermal expansion, but such loading is assumed to be accounted for in the design basis stress report (see Section 2.4.3).

The focus of the structural evaluation in this report is on the impact of occasional loading, but it also includes sustained loading that produces vertical pressure downward. Sustained loads can be due to trench fill as well as sustained loads acting at the surface. Occasional loads are associated with vehicle traffic or heavy lifts over the piping. The total pressure on the piping is:

$$P_{SS} = D_L \left(P_{soil} + P_{surf\_sust} \right) + P_{surf\_occ}$$

where:

P_{SS} = total vertical pressure on piping, psi

D_L = deflection lag factor, unitless

P_{soil} = sustained pressure due to trench fill, psi

P_{surf_sust} = sustained pressure due to loading at the surface, psi

P_{surf_occ} = occasional pressure due to loading at the surface, psi

The deflection lag factor, D_L, accounts for differential settlement of the bedding over the life of the piping. Level 1 Modeling Simplification 1 states that compaction of pipe embedment is 85% standard or modified proctor (85% P) or higher, which is typical of engineered fill used in nuclear power plant environments. The deflection lag factor is defined by N-806-1 as [1, A-3(d)]:

- Compaction ≥85% P, $D_L = 1.0$
- Compaction <85% P, $D_L = 1.5$

When the top of the pipe is below the water table or assumed to be below the water table, P_{soil} is given in Code Case N-806-1 as [1, Equation A-9]:

$$P_{soil} = \gamma_W h_W + R_W \gamma_S H_{BD}$$

$$R_W = 1 - \frac{h_W}{3H_{BD}}$$

where:

γ_W = water density, lbm/in^3

h_W = height of water above top of pipe, in.

R_W = buoyancy factor, unitless

γ_S = density of dry soil or trench fill, lbm/in^3

H_{BD} = pipe burial depth from top of pipe to the ground surface, in.

Code Case N-806-1 also provides guidance for calculation of P_{soil} when the top of the pipe is above the water table [1, Equation A-6]:

$$P_{soil} = V_{AF} \gamma_S H_{BD}$$

$$V_{AF} = 0.76 - 0.71\left(\frac{\Phi_H - 0.7}{\Phi_H + 1.75}\right)$$

$$\Phi_H = \frac{E'R}{\pi E_{pipe} D_O}$$

where:

V_{AF} = vertical arching factor, unitless

Φ_H = hoop stiffness parameter, unitless

E' = modulus of soil reaction, psi

R = pipe mean radius, in.

E_{pipe} = elastic modulus of pipe, psi

D_O = pipe outside diameter, in.

As covered in Section 2.4.1, pressure at the top of the pipe due to ground surface loading may be modeled as a point load using Boussinesq's equation. This is true of both sustained and occasional loading. The pressure due to sustained surface loading, P_{surf_sust}, modeled as point loading is given in Code Case N-806-1 as [1, Equation A-11]:

$$P_{surf\_sust} = \frac{3F_{surf\_sust}F'_{sust}}{2\pi H_{BD}^2\left[1+\left(\frac{d}{H_{BD}}\right)^2\right]^{2.5}}$$

where:

F_{surf_sust} = sustained point load at ground surface, lbf

F'_{sust} = impact factor for sustained loads, unitless

d = offset of point load to vertical center line of pipe, in.

The impact factor accounts for the dynamic nature of surface loading. For sustained loads, F'_{sust} is equal to 1.0.

The vertical pressure produced by sustained surface loading, P_{surf_sust}, modeled as distributed loading, is defined by Code Case N-806-1 [1, Equation A-12]:

$$P_{surf\_sust} = \frac{1}{4\pi}\frac{F_{surf\_sust}F'_{sust}}{b_W b_L}\left[\left(\frac{2XY\sqrt{Z}}{Z+Z_1}\right)\left(\frac{Z+1}{Z}\right)+\tan^{-1}\left(\frac{2XY\sqrt{Z}}{Z-Z_1}\right)\right]$$

$$X = \frac{b_W}{H_{BD}}$$

$$Y = \frac{b_L}{H_{BD}}$$

$$Z = X^2 + Y^2 + 1$$

$$Z_1 = (XY)^2$$

where:

b_W = length over which the surface load is distributed, in.

b_L = width over which the surface load is distributed, in.

Pressure at the top of the pipe due to occasional or live loading at the ground surface, P_{surf_occ}, may be conservatively modeled as a point load. For point loading, or distributed loading conservatively modeled as point loading, P_{surf_occ} is given in Code Case N-806-1 as [1, Equation A-11]:

$$P_{surf\_occ} = \frac{3F_{surf\_occ}F'_{occ}}{2\pi H_{BD}^2\left[1+\left(\frac{d}{H_{BD}}\right)^2\right]^{2.5}}$$

where:

F_{surf_occ} = occasional or live load at ground surface, lbf

F'_{occ} = impact factor for occasional loads, unitless

d = offset of point load to vertical center line of pipe, in.

The impact factor due to occasional loads accounts for the dynamic nature of live loads and is a strong function of the type of loading, surface condition, and depth of burial. A factor of 1.5 is judged to be conservative for live loads in nuclear plant applications (see discussion of impact factor in Section 2.4.1).

The vertical pressure produced by occasional or live loading at the ground surface, P_{surf_occ}, modeled as distributed loading is defined by Code Case N-806-1 [1, Equation A-12]:

$$P_{surf\_occ} = \frac{1}{4\pi}\frac{F_{surf\_occ}F'_{occ}}{b_W b_L}\left[\left(\frac{2XY\sqrt{Z}}{Z+Z_1}\right)\left(\frac{Z+1}{Z}\right)+\tan^{-1}\left(\frac{2XY\sqrt{Z}}{Z-Z_1}\right)\right]$$

$$X = \frac{b_W}{H_{BD}}$$

$$Y = \frac{b_L}{H_{BD}}$$

$$Z = X^2 + Y^2 + 1$$

$$Z_1 = (XY)^2$$

where:

b_W = length over which the surface load is distributed, in.

b_L = width over which the surface load is distributed, in.

3.2.3 Acceptance Criteria of Metallic Piping

The following three failure mechanisms are evaluated:

- Ovalization of the pipe ring
- Crushing of pipe sidewalls
- Ring buckling

Piping shown to be acceptable must meet the acceptance criteria for all three failure mechanisms.

3.2.3.1 Ovalization

Ovalization of the pipe cross section is calculated using the Iowa formula in Code Case N-806-1 [1, Equation A-2]:

$$\Omega = \frac{P_{SS}K}{\frac{E_{pipe}I_{TWP}}{R^3}+0.061E'}$$

where:

P_{SS} = total vertical pressure on piping, psi

K = bedding constant [1, Table A-2], unitless

E_{pipe} = elastic modulus of pipe, psi

I_{TWP} = through-wall bending moment of inertia per unit length, in^3

R = pipe mean radius, in.

E' = modulus of soil reaction, psi

I_{TWP} is calculated as [1, Equation A-3]:

$$I_{TWP} = \frac{t^3}{12}$$

where:

t = pipe wall thickness, in.

The maximum acceptable ovalization, Ω_{max}, for carbon steel without cement lining, stainless steel, and ductile iron piping without cement lining is 0.05 (5%) [1, A-3(a)]. The maximum acceptable ovalization for carbon steel pipe with cement lining and ductile iron pipe with cement lining is 0.03 (3%) [16, Section 4.3.5]. The acceptance criterion for pipe ovalization is written as follows:

$$\Omega \leq \Omega_{max}$$

3.2.3.2 Sidewall Crushing

The compressive stress in the pipe sidewalls, σ_{SW}, is calculated as [1, Equation A-17]:

$$\sigma_{SW} = \frac{\left(P_{SS} - P_{neg}\right) D_O}{2t}$$

where:

P_{SS} = total vertical pressure on piping, psi

P_{neg} = negative internal pressure, psi

D_O = pipe outside diameter, in.

t = pipe wall thickness, in.

The negative internal pressure is input into the preceding equation as a negative value, which results in an increase in the applied pressure load. The allowable stress at operating conditions, S_h, is taken as the allowable sidewall crushing stress limit [1, A-4.1]:

$$\sigma_{SW} \leq S_h$$

3.2.3.3 Ring Buckling

The total pressure from all loading, P_{SS}', is calculated as [1, Equation A-19]:

$$P_{SS}' = P_{SS} + P_{gw} - P_{neg}$$

where:

P_{SS} = total vertical pressure on piping, psi

P_{gw} = hydrostatic pressure due to groundwater, psi

P_{neg} = negative internal pressure, psi

The hydrostatic pressure due to groundwater, P_{gw}, is included in the preceding equation P_{soil}. Therefore, the total pressure from all loading is reduced to:

$$P'_{SS} = P_{SS} - P_{neg}$$

The critical buckling pressure is calculated as [1, Equation A-20]:

$$P_{cr} = \left[32 R_W B' E' \frac{E_{pipe} I_{TWP}}{D_O^3} \right]^{1/2}$$

where:

- R_W = buoyancy factor, unitless
- B' = coefficient of elastic support of piping by surrounding soil, unitless
- E' = modulus of soil reaction, psi
- E_{pipe} = elastic modulus of pipe, psi
- I_{TWP} = through-wall bending moment of inertia per unit length, in^3
- D_O = pipe outside diameter, in.

The coefficient of elastic support may be obtained from AWWA M11 [12] or as [1, Equation A-21]:

(U.S. customary units)

$$B' = \frac{1}{1 + 4\exp\left[-0.065\left(\frac{H_{BD}}{12}\right)\right]}$$

where:

- H_{BD} = pipe burial depth from top of pipe to the ground surface, in

(SI units)

$$B' = \frac{1}{1 + 4\exp\left[-0.213\left(\frac{H_{BD}}{1,000}\right)\right]}$$

where:

- H_{BD} = pipe burial depth from top of pipe to the ground surface, mm

The buckling acceptance criterion is as follows [1, Equation A-18]:

$$P'_{SS} \le \frac{P_{cr}}{2}$$

3.2.4 Acceptance Criteria of HDPE Piping

The following three different failure mechanisms are evaluated:

- Ovalization of the pipe ring
- Crushing of pipe sidewalls
- Ring buckling

Piping shown to be acceptable must meet the acceptance criteria for all three failure mechanisms. The acceptance criteria for HDPE piping are taken from Code Case N-755-3 [15], with some equations rewritten to be consistent with the equations for metallic piping. Code Case N-755 is listed in Nuclear Regulatory Commission (NRC) Regulatory Guide 1.193, Revision 4, as not acceptable for use [17]. Use of N-755-3 guidance herein is considered acceptable for the following reasons:

- N-755 is required for installation of safety-related HDPE, but the majority of HDPE piping is not safety-related.
- The two sites with safety-related buried HDPE piping (Callaway and Catawba) used early versions of N-755 as the governing Code requirements.
- The NRC objections to N-755 are based on lack of material property testing, the joining process, and nondestructive evaluation of HDPE. The equations for structural evaluation and the associated acceptance criteria have not been challenged by the NRC.
- The third revision (N-755-3) represents the industry best approach for analysis of buried HDPE piping.

Based on these reasons, use of N-755-3 is considered appropriate for the structural evaluation of buried HDPE piping.

3.2.4.1 Ovalization

Ovalization of the pipe cross section is based on [15, -3210]:

$$\Omega = \frac{P_{SS}K}{\frac{2E_{pipe}}{3}\left(\frac{1}{DR-1}\right)^3 + 0.061F_S E'}$$

where:

P_{SS} = total vertical pressure on piping, psi

K = bedding constant, unitless

E_{pipe} = elastic modulus of pipe, psi

DR = dimension ratio, unitless

F_S = soil support factor, unitless

E' = modulus of soil reaction, psi

The bedding constant, K, is taken as 0.1 [15, -3210]. The elastic modulus is a function of both design life and temperature and may be taken from Code Case N-755-3 [15, Table -3210-3(a)].

The maximum acceptable ovalization, Ω_{max}, for HDPE piping is a function of pipe geometry [15, Table -3210-1]:

- DR = 13.5, $\Omega_{max} = 0.06$
- DR = 11, $\Omega_{max} = 0.05$
- DR = 9, $\Omega_{max} = 0.04$
- DR = 7.3, $\Omega_{max} = 0.03$

The acceptance criterion for pipe ovalization is written as:

$$\Omega \leq \Omega_{max}$$

3.2.4.2 Sidewall Crushing

The compressive stress in the pipe sidewalls, σ_{SW}, is calculated as [15, -3220]:

$$\sigma_{SW} = \frac{P_{SS} DR}{2}$$

where:

P_{SS} = total vertical pressure on piping, psi

DR = dimension ratio, unitless

The allowable sidewall compressive stress, S_{comp}, may be obtained from Code Case N-755-3 [15, Table -3220(a)]. The sidewall crushing limit is [15, -3220]:

$$\sigma_{SW} \leq S_{comp}$$

Unlike metallic pipe, negative internal pressure is not evaluated in the sidewall crushing limit in Code Case N-755-3. Instead, the effect of negative pressure is evaluated separately [15, -3221.2]. Because surface loading and negative pressure are not evaluated in the same equation, the effect of negative pressure in HDPE piping systems is not evaluated in this report. This is consistent with the treatment of other design loadings for all pipe materials (see Section 2.4.3).

3.2.4.3 Ring Buckling

The total pressure from all loading, P_{SS}', is calculated as [15, -3221.1]:

$$P_{SS}' = P_{SS} + P_{gw}$$

where:

P_{SS} = total vertical pressure on piping, psi

P_{gw} = hydrostatic pressure due to groundwater, psi

The hydrostatic pressure due to groundwater, P_{gw}, is included in the preceding P_{soil} equation. Therefore, the total pressure from all loading is reduced to the following:

$$P'_{SS} = P_{SS}$$

The allowable buckling pressure is calculated as [15, -3221.1]:

$$P_B = 2.8\sqrt{\frac{R_W \times B' \times E' \times E_{pipe}}{12\left(DR-1\right)^3}}$$

where:

R_W = buoyancy factor, unitless

B' = coefficient of elastic support of piping by surrounding soil, unitless

E' = modulus of soil reaction, psi

E_{pipe} = elastic modulus of pipe, psi

DR = dimension ratio, unitless

The coefficient of elastic support is given in Code Case N-755-3 [15, -3221.1] (Note that H_{BD} is converted from inches to feet in the calculation.):

(U.S. customary units)

$$B' = \frac{1}{1 + 4\exp\left[-0.065\left(\frac{H_{BD}}{12}\right)\right]}$$

where:

H_{BD} = pipe burial depth from top of pipe to the ground surface, in.

(SI units)

$$B' = \frac{1}{1 + 4\exp\left[-0.213\left(\frac{H_{BD}}{1,000}\right)\right]}$$

where:

H_{BD} = pipe burial depth from top of pipe to the ground surface, mm

The buckling acceptance criterion is [15, -3221.1]:

$$P'_{SS} \le P_B$$

3.2.5 Acceptance Criteria of Cement Piping

In buried pipe engineering, cement pipes are considered rigid pipes, which are defined as pipes that "do not deflect enough for deflection to affect soil pressure against the pipe" [18]. Unlike the flexible pipes covered previously, concrete pipes are typically not designed to an ovality or stress limit. Instead, reinforced concrete pipes (RCPs) are designed on the basis of their supporting strength under three-edge bearing test conditions, established through ASTM tests on an RCP cylinder. For the methods and criteria for the evaluation of the demand versus capacity of buried RCP subject to soil and surface loads, see "Concrete Pipe Design Manual" by the American Concrete Pipe Association [19], as well as "Recommendations for Design of Reinforced Concrete Pipe" by E. Erdogmus, B. N. Skourup, and M. Tadros in J*ournal of Pipeline Systems Engineering and Practice* [20].

3.2.6 Brittle Materials and Joints

The passage of heavy traffic loads over brittle materials, such as gray cast iron, can lead to the fracture of the pipe or its joints. The purpose of this section is to point out the difficulties of assessing the integrity of such pipes and joints. Buried pipes made of brittle materials, such as cast iron, cement or concrete, are typically joined by mechanical joints such as bell-and-spigot (with or without gasket or stuffing), grooved coupling (such as Victaulic[1]), or bolted couplings (such as Dresser). Mechanical joints may have also been used with ductile materials, such as buried ductile iron fire protection mains. In this case, a large surface load that exceeds the ground bearing capacity would cause the pipe to deflect downward, which in turn could cause the joint to fail in one of two ways: direct compressive bearing pressure on the coupling or joint separation due to shear and tensile or by rotation of the coupling.

These failure modes at the joints are in addition to the pipe itself fracturing in a brittle manner. More than in the case of welded or fused joints the behavior of mechanical joints is dependent on the method of joining and bedding. For example, the protrusion of a bell in a bell-and-spigot joint required that the sand bed beneath the pipe be contoured to provide even support to the protruding bell.

The capacity of mechanical joints to sustain large compressive bearing pressures and separation or rotations loads is joint-dependent, as the following examples show:

- For bell-and-spigot joints with lead caulking in cast iron pipes, the designer is referred to the work by the Cast Iron Pipe Research Association [21] and the more recent experimental and analysis work sponsored by the National Research Council in Canada [22].
- For bell-and-spigot joints in concrete pipes, the designer is referred to several ASTM C-series standards on joint capacity tests and alignment requirements [23, 24].
- For grooved couplings, the designer is referred to tests sponsored by the U.S. Department of Energy to determine the moment-rotation capacity of fire protection joints under large deflections [25].

[1] *Victaulic* is a registered trademark of Victaulic Company.

Because the analysis of brittle buried pipes joined by mechanical means under surface loads is dependent on the type of joint, pipe material, and installation procedure, it calls for the knowledge of the fabrication and burial data, and for joint-specific experimental data on the joint capacity to absorb bearing compression, and separation and rotation. Therefore, intermediate or heavy traffic above brittle and mechanically joined pipes is preferably mitigated using techniques such as those described in Section 4.2, instead of being analyzed.

3.3 Level 3 Analysis Guidance

In the event that the capacity of a specific line is unable to support the demand or if specific loading is not covered in the Level 1 or Level 2 approach is required to be evaluated, a Level 3 analysis may be performed. Due to the complexity and variety of potential analyses for buried piping, detailed instructions for a Level 3 analysis are not provided. Instead, general guidance for best practices is provided for a beam on elastic foundation approach and for FEA.

3.3.1 Beam on Elastic Foundation

The engineering planning for heavy surface traffic over buried pipe should eliminate the possibility of the surface load causing ground settlement. This would be achieved by spreading the surface load as described in Sections 2.4.1 and 4.2. However, should ground settlement occur, it is possible to evaluate the resulting stresses in the buried pipe, as described in this section of the report.

If ground settlement causes axial or vertical downward movement, the buried pipe will act as a beam on elastic foundation, and the resulting axial, bending, and shear stresses can be calculated using either conservative analytical solutions or a more realistic finite element model of the pipe surrounded by soil springs. The axial, bending, and shear stresses caused by this beam effect are superimposed to the ring effect caused by the soil and surface load. The analytical, closed-form, stress equations for the beam effects are reported in this section, based on "Structural Analysis and Design of Nuclear Plant Facilities" [26].

If soil settlement causes an axial movement Δx along the pipe axis, the resulting axial stress in the pipe, σ_a, is:

$$\sigma_a = \sqrt{\frac{2E_{pipe}F\Delta x}{A}}$$

$$F = \pi D_O \gamma_S H_{BD} f$$

$$f = \tan \Phi_{soil}$$

where:

E_{pipe} = elastic modulus of pipe, psi

F = friction force per unit length between the soil and the buried pipe, lbf/in.

Δx = imposed axial movement, in.

A = cross-sectional area of pipe, in^2

D_O = pipe outside diameter, in.

γ_S = density of dry soil or trench fill, lbm/in^3

H_{BD} = pipe burial depth from top of pipe to the ground surface, in.

f = coefficient of friction between the soil and the pipe, unitless

Φ_{soil} = angle of soil internal friction, degree

If soil settlement causes a downward vertical movement Δy perpendicular to the pipe axis, the resulting maximum bending stress in the pipe wall, σ_b, is:

$$\sigma_b = \frac{kD_O}{4\lambda^2 I}\Delta y$$

$$\lambda = \sqrt[4]{\frac{k}{4E_{pipe}I}}$$

where:

k = spring constant of soil perpendicular to the buried pipe, lbf/in^2

I = moment of inertia of the pipe cross-section, in^4

Δy = imposed downward vertical movement, in.

λ = beam on elastic foundation parameter, unitless

If soil settlement causes a downward vertical movement Δy perpendicular to the pipe axis, the resulting maximum shear stress in the pipe wall, τ, is:

$$\tau = \frac{2k}{\lambda A}\Delta y$$

Note that the preceding equation [26] was corrected by errata and is correct as written.

In addition to the axial, bending, and shear stresses caused by settlement, the curvature imposed on the pipe by the ground settlement will cause the pipe as a beam to ovalize. This ovalization should be added to that caused by the soil and surface loads. The settlement-induced ovalization of the pipe as a beam is addressed by Moser and Folkman [27, Equation 2.12], and has the form:

$$\Omega = \frac{1}{16}\left(\frac{D_O}{t}\right)^2\left(\frac{D_O}{R_C}\right)^2$$

where:

t = pipe wall thickness, in.

R_C = radius of curvature of bent pipe, in.

3.3.2 Guidance for FEA

The effect of a large surface load on buried pipe can be evaluated by FEA. In this case, the soil can be modeled using solid brick elements, and the pipe can be modeled using shell or solid brick elements, as illustrated in Figure 3-8. If the pipe and soil are uniform in the area of interest, a two-dimensional model is sufficient. If the pipe or the soil varies along the pipe, a three-dimensional model is necessary.

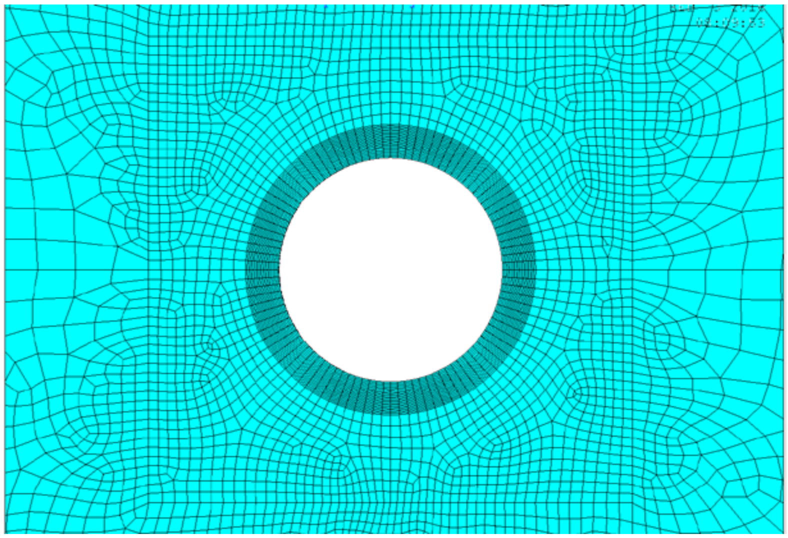

Figure 3-8
FEA model of pipe soil for surface load analysis

In most cases, where the ovalization is limited to 5% for steel pipe, there will be no separation between the pipe and the soil, either by shear or tensile strains in the soil or by failure of the soil. If tensile or shear strains develop that exceed the soil capacity, contact interface elements need to be incorporated between the soil and the pipe.

A good benchmark of the adequacy of the FEA model for the analysis of soil and surface loads is to compare the FEA ovalization of the pipe to the prediction using the Level 2 formula (see Section 3.2.2). The ovality is measured as the difference in vertical and horizontal diameters divided by the nominal diameter. With a good FEA model, it is possible to achieve a match of approximately 10% between the FEA results and the Level 2 formula.

FEA analysis can also be used to evaluate adequacy of the bearing capacity of the ground surface and the settlement under a large footprint load. For example, Figure 3-9 represents a soil model, with, on top, two steel plate mats that are used to spread the bearing pressure from crane tracks. Figure 3-10 plots the ground pressures beneath the mat, which are then compared with the permissible soil bearing pressure.

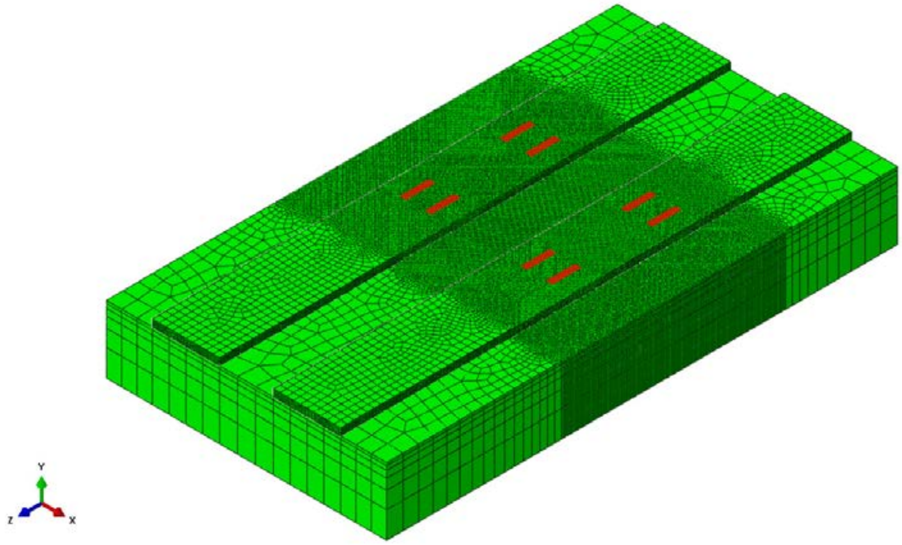

Figure 3-9
FEA model of soil, steel plate mats, and track bearing loads

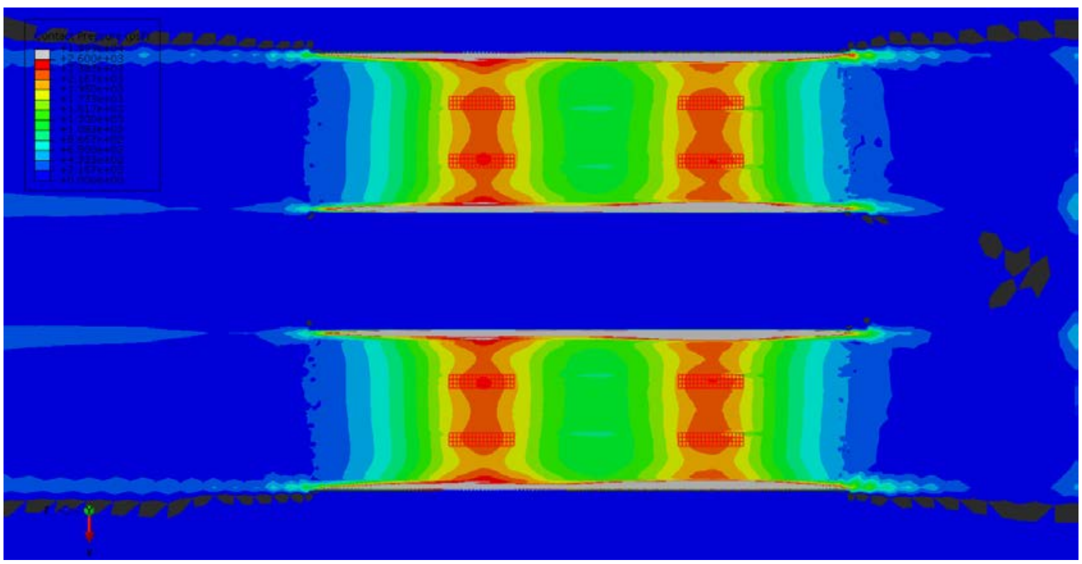

Figure 3-10
Soil bearing pressures from a crane placed on top of two steel plates

4
MITIGATION OPTIONS

This section presents plant OE and guidance for mitigating the impact of surface loading.

4.1 Nuclear Plant OE: ISFSI Haul Path

A nuclear plant evaluated the impact of a cask transporter on the haul route from the reactor building access door to the ISFSI.

A calculation was prepared based on manufacturer recommendations to document the evaluation of the existing roadway for the loads imposed by the cask transporter. The evaluation included an assessment of the pavement and subgrade utilities located beneath the heavy haul roadway that is used for the transportation of the fuel casks. The pavement must maintain its integrity to properly convey the transported load. The underground utilities must be able to withstand the pressure at depth resulting from the surface loading imposed by the transporter carrying a fully loaded cask. The roadway is categorized as non-safety-related. Some of the underground utilities are safety related. Therefore, the calculation report is designated as safety related.

A composite listing of the underground commodities was prepared based on a review of the existing site drawings and a subsurface survey. The transporter to be used for cask movement employs a combination of component redundancy and increased factors of safety, consistent with the cask licensing basis, to prevent cask drop during transport. As an added conservatism, a drop analysis was performed. The analysis of the haul route pavement and underlying soil materials is performed based on the methodologies outlined by Huang [28]. The analysis of the underground utilities is based on methodologies previously used in design documents and evaluations. In lieu of evaluating each individual underground commodity, the items were grouped by category, diameter, and depth. A review of these category groupings enables selection of only the controlling group for evaluation. The choice of items selected as controlling was clearly stated with justifications provided.

The loads imposed on utilities buried in the soil depend upon the stiffness properties of both the conduit structure and the surrounding soil. This results in a statically indeterminate problem in which the pressure of the soil on the structure produces deflections that, in turn, affect the soil pressure. The evaluation of underground utilities was performed in a two-step process. The first step is to determine the soil pressures at the depth of the utility. The soil pressure at the depth of the commodity is usually influenced by the flexibility of the commodity. The pressures imposed on an underground utility include the dead weight of the overburdened soil and the live load pressure imposed by the cask transporter. The effect of the dead load on the buried component will increase with depth. The effect of the live load on the buried component decreases with depth. The second step involves evaluation of the utility based on specific properties of the commodity. The method of this evaluation is dependent upon the configuration of the utility—its dimensions, how it was installed, location of adjacent structures, and so forth. Allowable pressures, loads, or stresses were found in the literature for most conduit sizes and materials.

The calculation assumes that the pavement and subgrade materials are linear elastic half spaces that may be evaluated for point or distributed surface loadings using classical Boussinesq theory. This is a simplifying assumption that has been shown to produce reasonable and accurate results.

Based on this example, the buried pipe program owner should perform the following:

- Cask transporter
  - Obtain the characteristics of the cask transporter gross weight and footprint (wheels plan). Note that the gross weight of a vehicle is the maximum operating weight of the vehicle as specified by the manufacturer, including the vehicle's chassis, body, engine, engine fluids, fuel, accessories, driver, passenger, and cargo.
  - Determine that the cask transporter is designed to prevent the drop of the carried load. As additional conservatism, if credible, the drop may be assumed to occur and becomes a postulated surface impact load.
- Route
  - Map the planned route and possible alternatives.
  - Based on the route map, identify road pavements, overpasses, tunnels, bridges, parking or turning platforms, and so forth that will be used.
  - Based on the route map, identify the buried commodities.
  - Confirm the structural condition of the route by walkdown, and document with photographs.
  - Determine whether a subsurface survey is necessary to assess the condition of the ground (that is, are voids or sinkholes present?).
  - Determine whether a subsurface survey is necessary to confirm the routing and cover height of buried commodities.
- Evaluations
  - Evaluate the demand and capacity of the route (road pavements, overpasses, tunnels, bridges, parking or turning platforms, and so forth) and the ground bearing and shear capacity. For heavy traffic it may be necessary to increase the pavement thickness or to add steel plates to prevent pavement damage.
  - Evaluate the integrity of the buried pipes using the three-level criteria in this report.
  - Evaluate the integrity of buried commodities other than cylindrical conduits and pipes. Note: refer to the ASCE manual, "Structural Analysis and Design of Nuclear Plant Facilities" [26].

The site evaluation drew the following conclusions:

- Bituminous asphaltic concrete pavement has been shown to have insufficient thickness to meet the acceptance criteria when considering loads imposed by the cask transporter vehicle. Therefore, pavement modifications are required. An overall pavement thickness of 6.5 in. would be sufficient to ensure that all acceptance criteria are met. However, in order to provide greater design margin, an overall pavement thickness of 7 in. is recommended.
- All of the commodities located beneath the load path of the cask transporter have been shown to be adequate to withstand the imposed load. The cask transporter turning pad has the same thickness, reinforcement details, and concrete strength as the cask support pad and cask fabrication pad. Therefore, the turning pad is acceptable to withstand the loaded transporter load by comparison.

Note that the analysis did not consider the steel plates shown in Figure 4-1. They were added later to prevent chewing up the asphalt.

Figure 4-1
ISFSI haul path

4.2 Load Spreading Members

Concentrated loads on the ground surface may have to be spread by use of purpose-designed structural members, such as bearing pads, cribs, dunnage, timbers, or mats [6, (a)(2)]. Typical load spreading members for crane outriggers are shown in Figure 4-2. Load spreading members may be necessary to reduce the bearing pressure for the following two reasons: to stay below the ground bearing capacity, with safety margin, to prevent sinking of the structure or vehicle at the surface, and failure or cave-in of the ground and to reduce the pressure on buried commodities, if necessary to satisfy Level 1 or Level 2 criteria.

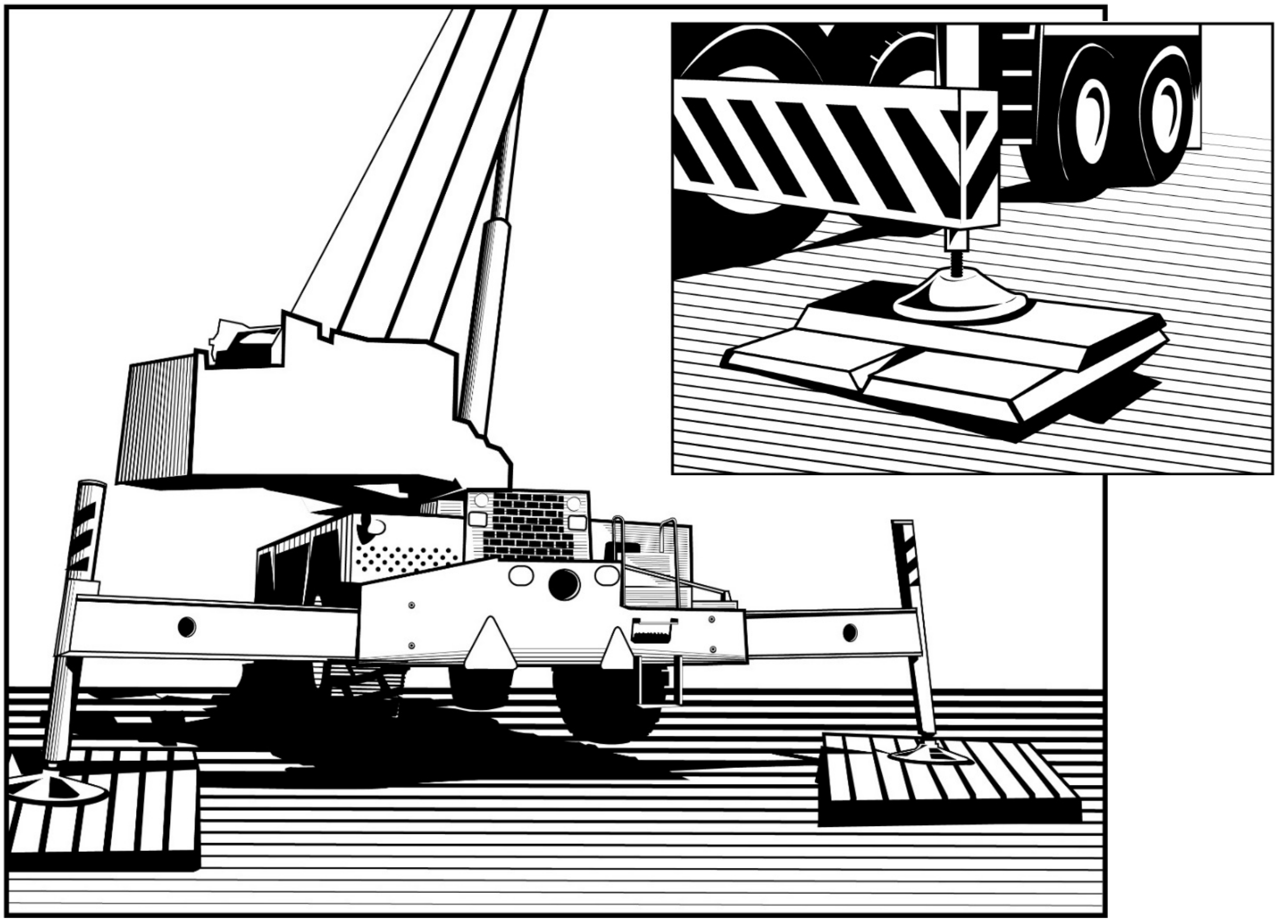

Figure 4-2
Crane outrigger load spreading members

The width and length of the load spreading plates should be calculated to achieve the required reduction in bearing pressure. The design may be straightforward, as in the case of a fixed static load, or complex, as in the case of a crane with a moving load.

In addition to the width and length of the load spreading member, other considerations apply. They are as follows:

- The material and thickness (that is, the strength of the plate)
- The fixity to the ground
- The joining of multiple plates
- The antiskid resistance of the plate top surface
- For heavy traffic the tapering, ramps, or feathering with asphalt wedges around the perimeter
- The visibility of the plate edges
- The flatness of the plate and its uniform bearing against the ground surface
- The design life of the plate
- Periodic inspections that may be required

5 CONCLUSIONS

Unmitigated surface loading has the potential to damage buried piping and cause pressure boundary failures. A BPIG survey revealed a number of failures in which surface loading is either confirmed or suspected to be the cause of failure [2]. There are several industry guidance documents that could lead the buried piping program owner to conclude that actions have been taken to mitigate the threat that surface loading poses to buried piping. However, none of the documents reviewed specifically addresses the threat to buried piping. This report provides guidance for the evaluation of surface loading through a tiered approach. Level 1 is the most conservative approach and provides easy to use screening figures. Level 2 provides a more accurate determination of the demand and capacity by requiring the user to solve the appropriate equations. Level 3 provides general guidance for the performance of accurate evaluations. In addition, mitigation options are presented in Section 4.

Use of the screening requires the user to confirm that the piping under investigation is within the scope of the Level 1 screening. A summary of these requirements is given in Section 5.1. Degraded piping may not meet the Level 1 screening. Section 5.2 summarizes the options for evaluation of known or suspected degraded piping.

This report provides guidance for the majority of the buried piping in the U.S. nuclear fleet, but there are some piping materials that were excluded due to their brittle nature and lack of available destructive testing. Inclusion of these materials would increase the usefulness of this report, and Section 5.3 provides a list of materials that could be added to the next revision of this report. That section also includes other future work intended to increase the usefulness and scope of the report.

5.1 Limitations of Applicability

Use of the Level 1 screening criteria requires confirmation by the user that the limits of applicability are maintained. These limits are specified in Section 3.1.2 and are dependent on the pipe embedment and material type.

The pipe embedment is required to have a compaction not less than 85% standard or modified proctor with soil type other than CL or ML with less than 30% sand and gravel. This ensures that the soil provides sufficient and uniform support to resist ovalization.

For metallic piping, negative pressure is not included in the Level 1 screening. If the piping may experience negative pressure concurrently with surface loading, a Level 2 evaluation is recommended. Negative pressure in HDPE piping is evaluated separately from other loading and is, therefore, not required to be evaluated concurrently with surface loading.

The material allowable stress (for metallic piping) or the allowable sidewall compressive side (for HDPE) must not be less than that used in the Level 1 screening. For metallic piping, the vast majority of piping should meet or exceed the allowable stress used in the screening. A similar statement cannot be made for HDPE due to the variability in resin. In addition to the sidewall compressive stress, the elastic modulus for HDPE piping may not be less than that used in Level 1. If the material properties are beyond those used in the screening, a Level 2 evaluation is recommended.

Pipe internal lining impacts the ovalization acceptance criteria. Although concrete lining may increase the resistance to ovalization, no structural credit is taken for such lining. Instead, the allowable ovalization is limited to prevent damage to the concrete lining. Carbon steel and ductile iron piping with concrete lining must use the Level 1 screening specific to either concrete lined carbon steel or concrete lined ductile iron. If the piping has other linings that are known to be flexible, the material screening without a lining may be used. If the piping has lining that may crack or fail in a brittle manner, the Level 2 evaluation may be used with modified ovalization limits specified by the manufacturer.

Each of the metallic screening figures contains multiple curves based on the pipe size. For example, Figure 3-2 contains curves for carbon steel nominal pipe sizes between ≤12 in. and 36 in. Pipe sizes less than 12 in. may conservatively use the ≤12-in. curve. Similarly, Figure 3-5 shows curves for ductile iron pipe sizes between ≤8 in. and 64 in. In order to ensure that the figure is legible, pipe sizes 26 in., 48 in., 54 in., and 60 in. are not included in the figure. Pipe sizes less than 8 in. may conservatively use the ≤8-in. curve. The 26-in. piping may use the curve for 30-in. piping, and 48-in., 54-in., and 60-in. piping may use the curve for 64-in. piping.

The wall thickness for metallic pipe is a significant variable in determining the capacity of the piping. The Level 1 screening is based on typical wall thicknesses for carbon steel, stainless steel, and ductile iron piping. Ductile iron and stainless steel pipe include allowances for manufacturing tolerance. Carbon steel pipe includes allowances for manufacturing tolerance plus some level of general or local corrosion. If the wall thickness is known or expected to be thinner than that evaluated in the screening, a Level 2 evaluation is recommended. Section 5.2 provides options for degraded buried piping.

HDPE requires several additional values to be confirmed beyond what is required for metallic piping. HDPE uses a DR instead of pipe size and thickness. *DR* is defined as the outside diameter divided by the wall thickness. DRs of 13.5, 11, 9, and 7.3 are applicable to the Level 1 screening. The trench width is also an important parameter in screening. The HDPE Level 1 screening assumes a width of at least three diameters. Finally, HDPE material properties are very sensitive to temperature, and the screening is limited to not more than 140°F. If the DR is not applicable, the trench width is smaller than three diameters, or the piping experiences temperatures above 140°F, a Level 2 evaluation may need to be performed.

5.2 Options for Degraded Piping

Degraded piping, or piping that is suspected to be degraded, may not meet the wall thickness requirements of the Level 1 screening. Alternatively, the piping may meet the Level 1 requirements but not meet the acceptance criteria. In either case, there are three basic options: a Level 2 evaluation, a Level 3 analysis, or decreasing the applied loading.

A Level 2 evaluation may be performed based on the smallest known or suspected wall thickness. This conservatively ignores the load-carrying capacity of wall thickness surrounding the corrosion that is larger than the small evaluated thickness.

Determination of the capacity of the piping may be accomplished through the use of detailed FEA. Known or suspected degradation may be modeled to more appropriately determine the capacity of the piping. This approach is a Level 3 analysis. Although not specific to degraded piping, guidance for a Level 3 evaluation is given in Section 3.

The final approach involves decreasing the demand or loading. This may be accomplished through the use of load spreading members. This approach reduces the pressure applied to the pipe by increasing the area at the ground surface over which the force is applied. Section 4.2 covers load spreading members. The Level 2 equations in Section 3.2.2 may be used to calculate the pressure based on the distributed loading.

5.3 Future Work

Future work should be considered to expand the applicability of this report to additional loading cases and materials. The following topics may be considered for inclusion in a potential subsequent revision to this report or as supplemental guidance:

- **Additional mitigation strategies based on industry OE**. This will give the user a better understanding of what options are available and, potentially, what options have not worked well at other sites.
- **Level 1 screening expanded to include distributed loads such as a crane outrigger with load distribution block**. This will expand the Level 1 applicability to common loading.
- **Level 1 and Level 2 expanded to include guidance for cast iron**. This will expand the applicability of the report to additional common materials.
- **Level 1 and Level 2 expanded to include guidance for CPP and PCCP**. This will expand the applicability of the report to additional common materials.
- **Expansion of Level 1 and Level 2 guidance to more DR sizes for HDPE**. This will expand the applicability of the report to include additional sizes that may be common in nuclear plants.
- **A new section should be added for detailed Level 1 and Level 2 example problems**. This would increase usability of the report.

The technical bases in this report are focused on U.S. and/or ASME standards. Inclusion of international standards would expand applicability to other EPRI-member utilities.

6
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A
TABULAR DATA FOR LEVEL 1 SCREENING FIGURES

Tables A-1 through A-6 represent a Level 1 screening value for minimum safe burial depth (in feet) based on occasional surface loading and nominal pipe size. See to the text associated with each figure for the assumptions used within the calculations to create the tabular data and respective figures.

Table A-1
Numerical data for Figure 3-2, Level 1 Screening: carbon steel

Pipe Size (nominal pipe size)⇒ / Occasional Surface Load (lbf) ⇓	12-in.	14-in.	16 -in.	18-in.	20-in.	22-in.	24-in.	36-in.
0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
20,000	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
40,000	2.0	2.0	2.0	2.0	2.0	2.1	2.2	2.6
60,000	2.0	2.0	2.0	2.2	2.4	2.5	2.7	3.2
80,000	2.0	2.0	2.2	2.5	2.7	2.9	3.1	3.8
100,000	2.0	2.1	2.5	2.8	3.0	3.3	3.5	4.2
120,000	2.1	2.3	2.7	3.0	3.4	3.6	3.9	4.7

Table A-2
Numerical data for Figure 3-3, Level 1 Screening: carbon steel cement lined

Pipe Size (nominal pipe size)⇒ / Occasional Surface Load (lbf) ⇓	12 -in.	14-in.	16-in.	18-in.	20-in.	22-in.	24-in.	36-in.
0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
20,000	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.4
40,000	2.0	2.0	2.0	2.3	2.5	2.8	2.9	3.6
60,000	2.0	2.1	2.5	2.8	3.1	3.4	3.6	4.5
80,000	2.2	2.5	2.9	3.3	3.6	4.0	4.3	5.4
100,000	2.4	2.8	3.2	3.7	4.1	4.5	4.8	6.3
120,000	2.7	3.0	3.5	4.0	4.5	5.0	5.4	7.2

Table A-3
Numerical data for Figure 3-4, Level 1 Screening: stainless steel

Pipe Size (nominal pipe size)⇒ / Occasional Surface Load (lbf) ⇓	12 -in.	14-in.	16-in.	18-in.	20-in.	22-in.	24-in.	36-in.
0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
20,000	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
40,000	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.5
60,000	2.0	2.0	2.0	2.0	2.2	2.4	2.5	3.1
80,000	2.0	2.0	2.0	2.3	2.5	2.8	2.9	3.7
100,000	2.0	2.0	2.3	2.5	2.8	3.1	3.3	4.1
120,000	2.0	2.1	2.5	2.8	3.1	3.4	3.6	4.5

Table A-4
Numerical data for Figure 3-5, Level 1 Screening: ductile iron unlined

Pipe Size (nominal pipe size)⇒ / Occasional Surface Load (lbf) ⇓	≤8-in.	12-in.	16-in.	18-in.	20-in.	24-in.	30-in.	42-in.	64-in.
0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
20,000	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
40,000	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.2	2.3
60,000	2.0	2.0	2.0	2.1	2.3	2.4	2.5	2.7	2.8
80,000	2.0	2.2	2.4	2.5	2.6	2.7	2.9	3.1	3.2
100,000	2.0	2.4	2.6	2.8	2.9	3.0	3.3	3.4	3.6
120,000	2.0	2.6	2.9	3.0	3.2	3.3	3.6	3.8	4.0

Table A-5
Numerical data for Figure 3-6, Level 1 Screening: ductile iron cement lined

Pipe Size (nominal pipe size)⇒ / Occasional Surface Load (lbf) ⇓	≤8-in.	12-in.	16-in.	18-in.	20-in.	24-in.	30-in.	42-in.	64-in.
0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
20,000	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.1
40,000	2.0	2.0	2.2	2.3	2.4	2.5	2.7	2.9	3.0
60,000	2.0	2.4	2.7	2.8	2.9	3.1	3.4	3.6	3.8
80,000	2.0	2.8	3.1	3.3	3.4	3.6	3.9	4.2	4.4
100,000	2.3	3.1	3.4	3.7	3.9	4.1	4.4	4.7	5.0
120,000	2.5	3.4	3.8	4.0	4.3	4.5	4.9	5.3	5.6

Table A-6
Numerical data for Figure 3-7, Level 1 Screening: HDPE

DR⇒ / Occasional Surface Load (lbf) ⇓	13.5	11.0	9.0	7.3	Limit
0	2.0	2.0	2.0	2.0	2.0
20,000	2.1	2.0	2.1	2.1	2.1
40,000	3.0	2.8	3.0	3.1	3.1
60,000	3.7	3.5	3.7	3.9	3.9
80,000	4.3	4.1	4.4	4.5	4.5
100,000	4.9	4.6	4.9	5.2	5.2
120,000	5.3	5.1	5.5	5.8	5.8

Figure 3-7 shows only the curve for limit; this table offers additional data for specific DRs.

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