

PVC Pipe— Design and Installation

Third Edition



American Water Works
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PVC Pipe—Design and Installation

Third Edition

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**American Water Works
Association**

Manual of Water Supply Practices—M23, Third Edition

PVC Pipe—Design and Installation

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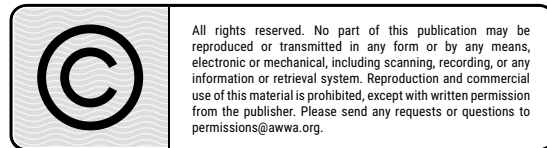
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Preface



This is the third edition of AWWA M23, *PVC Pipe—Design and Installation*. This manual provides the user with both general and technical information to aid in design, procurement, installation, and maintenance of PVC pipe and fittings.

This manual presents a discussion of recommended practices. It is not intended to be a technical commentary on AWWA standards that apply to PVC pipe, fittings, and related appurtenances.

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Chapter **1**

General Properties of Polyvinyl Chloride Pipe

Polyvinyl chloride (PVC)* was discovered in the late nineteenth century. Scientists at that time found the new plastic material unusual in that it appeared nearly inert to most chemicals. However, it was soon discovered that the material was resistant to change, and it was concluded that the material could not be easily formed or processed into usable applications.

In the 1920s, scientific curiosity again brought PVC to public attention. In Europe and America, extended efforts eventually brought PVC plastics to the modern world. Technology, worldwide and particularly in Germany, slowly evolved for the use of PVC in its unplasticized, rigid form, which today is used in the production of a great many extruded and molded products. In the mid-1930s, German scientists and engineers developed and produced limited quantities of PVC pipe. Some PVC pipe installed at that time continues to provide satisfactory service today. Molecularly oriented polyvinyl chloride (PVCO) pressure pipe has been installed in Europe since the early 1970s and in North America since 1991. Fusible PVC pipe has been installed in North America since 2004.

MATERIAL PROPERTIES OF PVC PIPE COMPOUNDS

Polyvinyl chloride pipe and fabricated fittings derive properties and characteristics from the properties of their raw material components. Essentially, PVC pipe and fabricated

* Unless otherwise noted in this manual, “polyvinyl chloride pipe” or “PVC” refers to PVC bell-and-spigot pipe and PVC fusible pipe; “PVCO” refers to molecularly oriented PVC pipe.

fittings are manufactured from PVC extrusion compounds. Injection molded fittings use slightly different molding compounds. PVCO is manufactured from conventional PVC extrusion compounds. The following summary of the material properties for these compounds provides a solid foundation for an understanding and appreciation of PVC pipe properties.

Polyvinyl chloride resin, the basic building block of PVC pipe, is a polymer derived from air, salt water, and natural gas. PVC resin, produced by any of the common manufacturing processes (bulk, suspension, or emulsion), is combined with heat stabilizers, lubricants, and other ingredients to make PVC compound that can be extruded into pipe or molded into fittings.

Chemical and taste-and-odor evaluations of PVC compounds for potable water conveyance are conducted in accordance with procedures established by NSF International.* The extracted water must not exceed the maximum contaminant levels established by the US Environmental Protection Agency's (USEPA's) National Interim Primary Drinking Water Regulations (1975) and by the NSF limits of acceptance for residual vinyl chloride monomer and for taste and odor as shown in Table 1-1 of NSF Standard 61. Monitoring is conducted by NSF International or approved laboratories.

PVC pipe extrusion compounds must provide acceptable design stress properties as determined by long-term testing under hydrostatic pressure. Hydrostatic design stress ratings for pipe compounds are established after 10,000 hr of hydrostatic testing. Long-term performance of injection molded PVC fittings compounds are subject to at least 2,000 hr of hydrostatic testing.

AWWA's[†] PVC pipe and fittings standards define the basic properties of PVC compound using the American Society for Testing and Materials[‡] (ASTM) Specification D1784, Standard Specification for Rigid Poly(Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds. The specification includes a five-digit cell class designation system by which PVC compounds are classified according to their physical properties.

As shown in Table 1-1, the five properties designated are (1) base resin, (2) impact strength, (3) tensile strength, (4) elastic modulus in tension, and (5) deflection temperature under loading. Figure 1-1 shows how the classification system establishes minimum properties for the compound 12454, which is used in PVC pressure pipe manufactured in accordance with ANSI/AWWA C900, Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 In. Through 60 In. (100 mm Through 1500 mm) and ANSI/AWWA C909, Molecularly Oriented Polyvinyl Chloride (PVCO) Pressure Pipe, 4 In. Through 24 In. (100 mm Through 600 mm) for Water, Wastewater, and Reclaimed Water Service. The material classification can be found on the pipe as part of its identification marking. Cell class is not part of the required marking in C900 and C909.

Many of the important properties of PVC pipe are predetermined by the characteristics of the PVC compound from which the pipe is extruded. PVC pressure pipe manufactured in accordance with ANSI/AWWA C900 or C909 must be extruded from PVC compound with cell classification 12454 or better. Those compounds must also qualify for a hydrostatic design basis of 4,000 psi (27.58 MPa) for water at 73.4°F (23°C) per the requirements of PPI[§] TR-3, Policies and Procedures for Developing Hydrostatic Design Basis (HDB), Pressure Design Basis (PDB), Strength Design Basis (SDB), and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe.

* NSF International, P.O. Box 130140, 789 N. Dixboro Rd., Ann Arbor, MI 48105.

† AWWA, 6666 W. Quincy Ave., Denver, CO 80235.

‡ ASTM, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428.

§ Plastics Pipe Institute, 105 Decker Court, Suite 825, Irving, TX 75062.

Table 1-1 Cell class requirements for rigid poly(vinyl chloride) compounds*

Order No.	Designation Property and Unit	Cell Limits							
		0	1	2	3	4	5	6	7 8
1	Base resin	Unspecified	Poly(vinyl chloride) homopolymer	Chlorinated poly(vinyl chloride)	Ethylene vinyl chloride copolymer	Propylene vinyl chloride copolymer	Vinyl acetate-vinyl chloride copolymer	Alkyl vinyl ether-vinyl chloride copolymer	
2	Impact strength (Izod), min. J/m of notch ft-lb/in. of notch	Unspecified	<34.7 <0.65	34.7 0.65	80.1 1.5	266.9 5.0	533.8 10.0	800.7 15.0	
3	Tensile strength, min. MPa psi	Unspecified	<34.5 <5,000	34.5 5,000	41.4 6,000	48.3 7,000	55.2 8,000		
4	Modulus of elasticity in tension, min. MPa psi	Unspecified	<1,930 <280,000	1,930 280,000	2,206 320,000	2,482 360,000	2,758 400,000	3,034 440,000	
5	Deflection temperature under load, min. 1.82 MPa (264 psi): deg C deg F	Unspecified	<55 <131	55 131	60 140	70 158	80 176	90 194	100 110 212 230

Source: ASTM D1784, ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959.

* The minimum (min.) property value will determine the cell number, although the maximum expected value may fall within a higher cell.

Note: Flammability. All compounds covered by this specification, when tested in accordance with method D635, shall yield the following results: average extent of burning of <25 mm; average time of burning of <10 s.

Class	1	2	4	5	4
<i>Identification:</i>					
Poly (vinyl chloride) homopolymer					
<i>Property and Minimum Value:</i>					
Impact strength (Izod) (34.7 J/m [0.65 ft-lb/in.])					
Tensile strength (48.3 MPa [7,000 psi])					
Modulus of elasticity in tension (2,758 MPa [400,000 psi])					
Deflection temperature under load (70°C [158°F])					

Source: ASTM D1784, ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959.

Note: The cell-type format provides the means for identification and close characterization and specification of material properties, alone or in combination, for a broad range of materials. This type format, however, is subject to possible misapplication since unobtainable property combinations can be selected if the user is not familiar with commercially available materials. The manufacturer should be consulted.

Figure 1-1 Class 12454 requirements

The manner in which selected materials are identified by this classification system is illustrated by a Class 12454 rigid PVC compound having the requirements shown in Table 1-1 and Figure 1-1.

CORROSION, PERMEATION, AND CHEMICAL RESISTANCE

PVC and PVCO pipes are resistant to almost all types of corrosion—both chemical and electrochemical—that are experienced in underground piping systems. Because PVC is a nonconductor, galvanic and electrochemical effects are nonexistent in PVC piping systems. PVC pipe cannot be damaged by aggressive waters or corrosive soils. Consequently, no lining, coating, cathodic protection, or plastic encasement is required when PVC and PVCO pipes are used.

Permeation

The selection of materials is critical for water service and distribution piping in locations where the pipe may be exposed to significant concentrations of pollutants comprised of low molecular weight petroleum products or organic solvents or their vapors. If a water pipe must pass through an area subject to contamination, the manufacturer should be consulted regarding permeation of pipe walls, jointing materials, etc., *before* selecting materials for use in that area.

When the contaminant of concern is commercial gasoline, the Water Research Foundation project, “Impact of Hydrocarbons on PE/PVC Pipes and Pipe Gaskets,” offers considerable design guidance. One of the key findings of the report is that the PVC pipe wall is impervious to gasoline, either the free product, the vapor, or when it has contaminated the groundwater (p. 174 of the report). The most commonly used gasket (SBR) for the

gasket PVC pipe joint was also studied. The report states that SBR gaskets can be used safely in water mains in contact with groundwater contaminated with any level of gasoline (p. 173). The report also states that SBR gaskets may be used (without any contaminant exceeding its maximum contaminant level) for water mains in all conditions of gasoline contamination provided there is at least a minimal flow in the main (e.g., the velocity is 2 ft/s or greater).

Chemical Resistance

Pipe. Response of PVC pipe under normal conditions to commonly anticipated chemical exposures is shown in Table 3.1 of the *Uni-Bell Handbook of PVC Pipe—Design and Construction*. Resistance of PVC pipe to reaction with or attack by the chemical substances listed has been determined by research and investigation. The information is primarily based on the immersion of unstressed strips into the chemicals and, to a lesser degree, on field experience. In most cases, the detailed test conditions, such as stress, exposure time, change in weight, change in volume, and change in strength, were not reported. Because of the complexity of some organochemical reactions, additional long-term testing should be performed for critical applications. Data provided are intended only as a guide and should not necessarily be regarded as applicable to all exposure durations, concentrations, or working conditions. The chemical resistance data are similar for PVC pipe.

Gaskets. A check of the chemical resistance of the gasket should be completed independently of that for the pipe. Because gasket and pipe materials are different, so too are their abilities to resist chemical attack. Similarly, charts for resistance of gasket materials to chemical attack are based on manufacturers' testing and experience. The use of these charts is complicated by the fact that more than one elastomer may be present in a rubber compound. Chemical resistance information for commonly used gasket materials is provided in Table 3-2 and 3.3 of the *Uni-Bell Handbook of PVC Pipe—Design and Construction*.

Tables 3.2 and 3.3 provide general guidelines regarding the suitability of various elastomers currently used in these chemicals and services. The ratings are primarily based on literature published by various polymer suppliers and rubber manufacturers, as well as the opinions of experienced compounders. Several factors must be considered in using a rubber or polymer part. The most important of these factors include the following:

- Temperature of service. Higher temperatures increase the effect of all chemicals on polymers. The increase varies with the polymer and the chemical. A compound quite suitable at room temperature may perform poorly at elevated temperatures.
- Conditions of service. A compound that swells considerably might still function well as a static seal yet fail in any dynamic application.
- Grade of the polymer. Many types of polymers are available in different grades that vary greatly in chemical resistance.
- The compound itself. Compounds designed for other outstanding properties may be poorer in performance in a chemical than one designed especially for fluid resistance.
- Availability. Consult the elastomer manufacturers for availability of a compound for use as a PVC pipe gasket material.

If it is anticipated that gasket elastomers will be exposed to aggressive chemicals, it is advisable to test the elastomers.

ENVIRONMENTAL EFFECTS

The following paragraphs discuss the effects of environmental factors on PVC pipe, including temperature, biological attack, weather, abrasion, and tuberculation.

Thermal Effects

The performance of PVC pipe is significantly related to its operating temperature. Because it is a thermoplastic material, PVC will display variations in its physical properties as temperature changes (Figure 1-2). PVC pipe can be installed properly over the ambient temperature range in which construction crews can work. PVC pipe is rated for performance properties at a temperature of 73.4°F (23°C); however, it is recognized that operating temperatures of 33–90°F (1–32°C) do exist in water systems. As the operating temperature decreases, the pipe's stiffness and tensile strength increase, thereby increasing the pipe's pressure capacity and its ability to resist earth-loading deflection. At the same time, PVC pipe loses impact strength and becomes less ductile as temperature decreases, necessitating greater handling care in sub-freezing weather. As the operating temperature

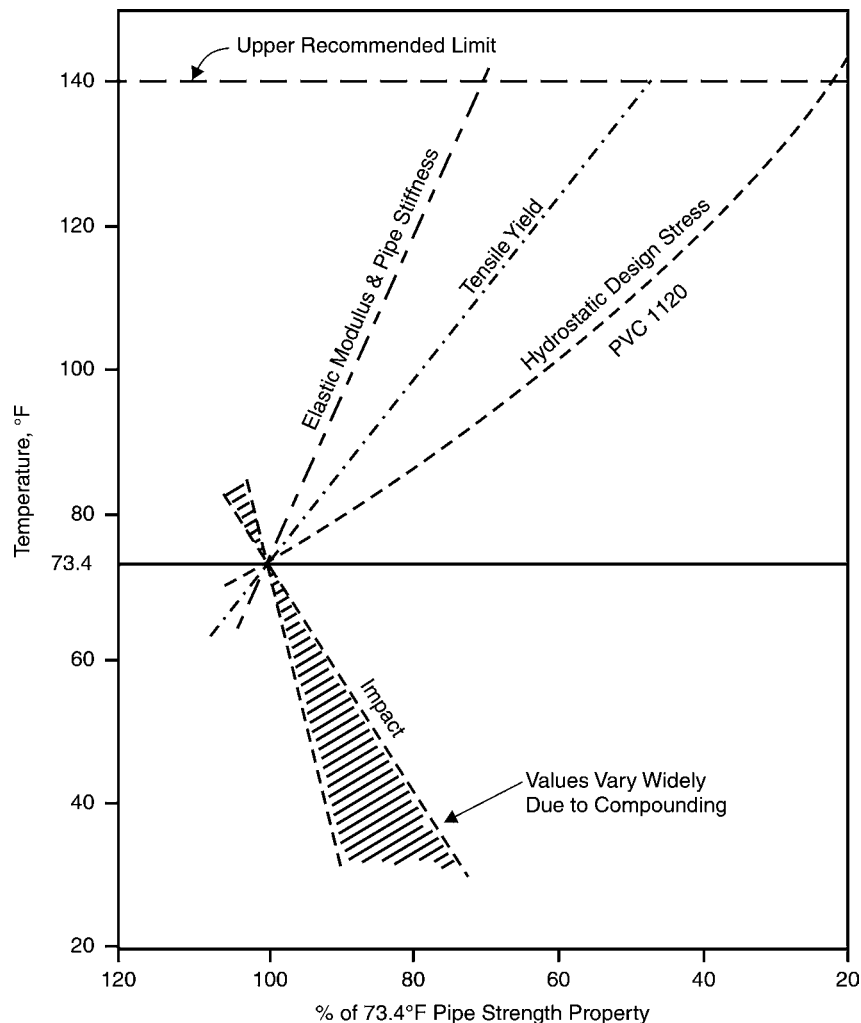


Figure 1-2 Approximate relationship for 12454 PVC for PVC pipe strength properties versus temperature

increases, the impact strength and flexibility of PVC pipe increases. However, with the increase in temperature, PVC pipe loses tensile strength and stiffness; consequently, the pressure capacity of the pipe will be reduced, and more care will be needed during installation to avoid excessive deflection.

Most municipal water systems operate at temperatures at or below 73.4°F (23°C). In these applications, the actual pressure capacity of PVC pipe will be equal to or greater than the product's rated pressure. Intermittent water system temperatures above 73.4°F (23°C) do not warrant de-rating of pipe or fitting pressure designations.

New users and installers of PVC pipe should be aware of the pipe's capacity to expand and contract in response to changes in temperature. The PVC coefficient of thermal expansion is roughly five times the normal value for cast iron or steel. Provisions must be made in design and installation to accommodate expansion and contraction if the pipeline is to provide service over a broad range of operating temperatures. In general, allowance must be made for $\frac{3}{8}$ in. (5.4 mm) of expansion or contraction for every 100 ft (30.5 m) of pipe for each 10°F (5.6°C) change in temperature. Gasket joints provide excellent allowance for thermal expansion and contraction of PVC pipelines. The coefficient of thermal expansion for PVCO is the same as for PVC.

Resistance to Biological Attack

PVC pipe is nearly totally resistant to biological attack. Biological attack can be described as degradation or deterioration caused by the action of living microorganisms or macroorganisms. Microorganisms that attack organic materials are normally listed as fungi and bacteria. Macroorganisms that can affect organic materials located underground include an extremely broad category of living organisms; for example, grass roots, termites, and rodents. The performance of PVC pipe in environments providing severe exposure to biological attack in its various anticipated forms has been studied and evaluated since the 1930s.

PVC pipe will not deteriorate or break down under attack from bacteria or other microorganisms, nor will it serve as a nutrient to microorganisms, macroorganisms, or fungi. *The interior walls of PVC pipe or construction debris left in the pipe can support internal growth of biofilms.* No cases have been documented where buried PVC pipe products have degraded or deteriorated because of biological action. As a result, no special engineering or installation procedures are presently required to protect PVC or PVCO pipe from any known form of biological attack.

Elastomeric seals are manufactured from organochemical materials, which can be formulated to produce a variety of properties. Some elastomers are susceptible to biological attack, whereas others provide resistance comparable to those inherent in polyvinyl chloride. PVC pipe manufacturers select gaskets produced from elastomeric compounds that provide high resistance. A material that will not support bacterial growth is a requirement, particularly in potable water systems.

In normal practice, when installing PVC pipe with gasketed joints, assembly of joints is facilitated using a lubricant applied in accordance with the manufacturer's instructions. Care must be exercised in the selection of this lubricant to ensure compatibility with the elastomeric seal and the PVC pipe and to ensure that the lubricant will not support the growth of fungi or bacteria. Care must also be taken to ensure that only the amount of lubricant required to facilitate assembly is used. Excess lubricant can adversely affect water quality and ultimately delay commissioning of a water system. Only the lubricant recommended by the pipe manufacturer should be used. These lubricants must also satisfy all NSF 61 requirements.

Weathering Resistance

PVC pipe can incur surface damage when subjected to long-term exposure to ultraviolet (UV) radiation from sunlight, an effect called ultraviolet degradation. Unless specifically formulated to provide substantial protection from UV radiation, or unless a limited service life is acceptable, PVC pipe is not recommended for applications where it will be continuously exposed to direct sunlight without some form of physical protection (such as paint or wrapping).

Ultraviolet degradation in PVC occurs when energy from the UV radiation causes excitation of the molecular bonds in the plastic. The resulting reaction occurs only on the exposed surface of PVC pipe to a depth of only 0.001–0.003 in. (0.025–0.075 mm). Within the affected zone of reaction, the structure of the PVC molecule is permanently altered with the molecules being converted into a complex structure typified by polyene formations. The polyene molecule causes a light-yellow coloration on the PVC pipe and slightly increases its tensile strength.

Regarding the organochemical reactions that characterize UV deterioration of PVC, the following should be noted:

- Chalking or frosting should not be confused with UV degradation. Chalking is a powdery residue on the surface of a material resulting from degradation and/or migration of an ingredient. Chalking (also known as frosting, haze, or bloom) is a light-scattering surface resembling fine crystals. In these cases, the color change is an aesthetic issue but does not denote UV degradation.
- UV degradation has occurred when the color has changed to yellow, tan, brown, or black.
- UV degradation results in a slight increase in tensile strength, slight increase in the modulus of tensile elasticity, and decrease in impact strength in PVC pipe.
- UV degradation does not continue when exposure to UV radiation is terminated.
- UV degradation occurs only in the plastic material directly exposed to UV radiation and to an extremely shallow penetration depth (the first 0.001–0.003 in. of exposed surface.)
- UV degradation of PVC pipe formulated for buried use will not have significant adverse effect with up to two full years of outdoor weathering and direct exposure to sunlight.

The above is also true regarding PVCO pipe.

Abrasion

After years of investigation and observation, it has been established that the combination of PVC resin, extenders, and various additives in PVC compounds, plus the methods of extrusion for PVC pipe, produce a resilient product with good resistance to abrasive conditions.

Many investigations and tests have been conducted, both in North America and Europe, by manufacturers, independent laboratories, and universities seeking to define PVC pipe's response to abrasion. Although the approaches to the various tests and investigations have varied substantially, the data developed have been consistent in defining the extent of PVC pipe resistance to abrasion. The nature and resiliency of PVC pipe cause it to gradually erode over a broad area when exposed to extreme abrasion rather than to develop the characteristic localized pitting and more rapid failure observed in pipe products with lower abrasion resistance.

PVC pipe is well suited to applications where abrasive conditions are anticipated. In extremely abrasive exposures, wear must be anticipated; however, in many conditions PVC pipe can significantly reduce maintenance costs incurred because of extreme abrasion. It should be noted that potable water, regardless of its makeup, is not considered abrasive to PVC pipe.

In trenchless applications, PVC has continued to exhibit its resistance to external abrasion. As a real-world example, a 10-in. DR 14 PVC pipe was installed under the Beaufort River in South Carolina as part of a 5,120 linear foot horizontal directional drilling installation. The soil conditions included silty sands and some areas of shell deposits. The scratch depths measured in the pipe exterior behind the pull head were $\leq 2.5\%$ of the pipe wall thickness—after being pulled nearly a mile underground.

Tuberculation

Soluble encrustants (such as calcium carbonate) in some water supplies do not precipitate onto the smooth walls of PVC or PVCO pipe. Because these materials do not corrode, there is no tuberculation caused by corrosion by-products.

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Chapter **2**

Testing and Inspection

PVC pipe manufacturing has continuously evolved and improved since it began in the 1930s. Today's PVC compounding operations are highly automated and controlled. PVC pipe extrusion, molding, and fabrication operations are technologically sophisticated and closely monitored. This chapter covers testing and inspection as it applies to the manufacturing of PVC and PVCO pipe and their related products.

TESTING AND INSPECTION

Testing and inspection in PVC pipe manufacturing may be divided into three categories: (1) qualification testing, (2) quality control testing, and (3) assurance testing.

Qualification Testing

Qualification testing is performed on piping products and on the materials from which they are produced to ensure that the finished products meet the requirements of applicable specifications. Qualification testing must demonstrate that the materials, process equipment, and manufacturing technology consistently yield, through proper production procedures and controls, finished products that comply with applicable standards.

Material Qualification Requirements

Early in the evolution of the PVC pipe industry, it was recognized that the sustained strength capacity of a PVC compound is significantly influenced by duration of loading. For a more complete discussion of PVC and PVCO pipes' behavior under sustained pressure, please see Chapter 5.

It was also recognized that a PVC compound's long-term capacity to handle sustained stress is not only determined by the base PVC polymer but is also influenced by the nature and quantity of ingredients (such as extrusion processing aids, heat stabilizers, impact modifiers, UV inhibitors, and colorants) that are used to enhance performance, facilitate processing, and provide product identification. Consequently, testing requirements and rules have been developed to ensure that the PVC compounds used to manufacture PVCO and PVC pressure pipe and PVC fittings are capable of providing minimum required stress capacity, over both the short and long term.

The formulation of each PVC compound for pressure pipe is fixed and specific, with the amount and identity of each ingredient spelled out. The ingredient identification includes its chemical and physical properties. When more effective and cost competitive ingredients are incorporated, companies are required to qualify alternative suppliers and products. Early on, a company had to generate extensive long-term stress-rupture data that demonstrated the proposed ingredient supplier change would not compromise the compound's long-term strength. The knowledge gained from qualifying countless substitutions of the basic PVC compound ingredients over the span of several decades led to policies whereby an ingredient can qualify for substitution provided that its physical and chemical properties comply with requirements established for that class of ingredient.

In 1985, a generic and public "PVC range formulation," along with related policies, was adopted. Since that time, many new ingredient suppliers and alternative ingredients have been qualified for use in the PVC range formulation.

The strength qualification requirements for PVC compounds used to manufacture PVC and PVCO pressure pipe and PVC pressure fittings are included in Appendix A. In addition, PVCO and PVC pressure pipe and PVC fittings are required to be made from PVC resin that has been compounded to provide physical and chemical properties that equal or exceed cell class 12454 as defined in ASTM D1784.

Pipe Qualification Requirements

PVC compounds and products to be used for potable water shall be certified by an accredited testing agency for compliance with NSF/ANSI 61.

The following qualification tests are required in the manufacture of ANSI/AWWA C900 PVC and C909 PVCO pipe to evaluate the design properties noted.

Gasket joint design testing. One option for testing joint design is to perform pressure tests to verify that joint assemblies qualify for a hydrostatic design basis category of 4,000 psi (27.6 MPa) for PVC pipe or 7,100 psi (49.0 MPa) for PVCO pipe.

Joint performance testing. All joints must be designed to provide a water tight seal. A representative size of each assembled joint design must meet the requirements of ASTM D3139. Fusion joints shall also provide axial strength for trenchless installation and operational loading. A full wall thickness coupon sample (cut across a joint that has been thermally butt-fused using commercially available equipment in accordance with the manufacturer's recommended procedures and parameters) must withstand a minimum axial stress of 6,400 psi following test procedures set forth in ASTM D638.

Lap-shear test. This test is used to verify that fabricated-fitting solvent cementing procedures result in minimum average lap-strengths of 900 psi (6.2 MPa). Lap-shear test samples are produced by solvent-cementing of component pipe segments identical to those that are used to fabricate fittings.

Quality Control Testing

Quality control testing is routinely performed on specimens of PVC piping products as they are manufactured to ensure that the products comply with applicable standards.

Quality control testing includes, but is not limited to, inspection and testing to verify proper dimensional, physical, and mechanical properties. Frequently, quality control tests are required that may not define a desired finished product property but that do verify the use of proper procedures and controls in the manufacturing process. Quality control tests and inspection required in the manufacture of ANSI/AWWA C900 PVC and C909 PVCO products are as follows.

Workmanship inspection. Inspection is conducted to ensure that the PVC or PVCO pipe product is homogeneous throughout—free from voids, cracks, inclusions, and other defects—and reasonably uniform in color, density, and other physical properties. Surfaces are inspected to ensure that they are free from nicks, gouges, severe scratches, and other such blemishes. Joining surfaces are inspected to ensure freedom from damage and imperfections.

Marking inspection. Inspection verifies proper marking of the pipe as required in the applicable product standard. Marking of ANSI/AWWA C900 PVC and C909 PVCO pipe includes the following:

- PVC or PVCO
- Manufacturer's name or trademark and production-record code
- Nominal pipe size
- Outside diameter (C900 only)
- Dimension ratio (DR; e.g., DR 25)
- AWWA pressure class (e.g., PC 100)
- AWWA standard designation (e.g., ANSI/AWWA C900)
- Seal of the testing agency that verified the suitability of the pipe material for potable-water service
- In compliance with NSF/ANSI 61 or, if not intended for potable water, the words "NOT FOR POTABLE USE"
- For deflectable joints, the maximum allowable axial joint deflection in degrees (e.g., joint $D \leq 1^\circ$)

Markings of machined couplings and fabricated fitting include the following:

- Nominal size and deflection angle (if applicable)
- AWWA pressure class
- AWWA standard designation
- Manufacturer's name or trademark
- Seal of the testing agency that verified the suitability of the pipe material for potable-water service in compliance with NSF/ANSI 61 or, if not intended for potable water, the words "NOT FOR POTABLE USE"
- For deflectable joints, the maximum allowable axial joint deflection in degrees (e.g., joint $D \leq 1^\circ$)

Dimension measurement. Measurement of dimensions on a regular and systematic basis is essential. Failure to meet dimensional requirements may render the product unsatisfactory regardless of success in other inspections and tests. All dimensional measurements are made in accordance with ASTM D2122 and include the following:

- Product diameter
- Product wall thickness
- Bell joint dimensions
- Fabricated-fitting configurations
- Length

Some dimensional requirements are defined in the manufacturer's product specifications.

Product packaging inspection. The finished package of PVC pipe prepared for shipment to the customer is inspected to ensure correct pipe quantity and adequate protection of the pipe.

Quick-burst test. The PVC pipe sample is pressurized to burst within the test time period of 60–70 s. Burst pressure measured must not be less than the minimum burst pressure requirements defined in ANSI/AWWA C900 or C909. Quick-burst testing is conducted in accordance with ASTM D1599. ASTM D2290 may be used in place of quick-burst testing of pipe. This test is also performed on machined couplings.

Flattening test. The PVC pipe specimen is partially flattened between moving parallel plates. When the pipe is flattened 60 percent (the distance between the parallel plates equals 40 percent of the original outside diameter), the specimen must display no evidence of splitting, cracking, or breaking.

Extrusion quality test. The PVC pipe specimen is immersed in anhydrous (dry) acetone for 20 min. When removed from the acetone bath, the pipe specimen must pass the failure criteria in ASTM D2152. Extrusion quality testing is conducted in accordance with ASTM D2152 and distinguishes only between unfused and properly fused PVC pipe.

Quality control inspection and testing must not be confused with field acceptance testing. Quality control testing is appropriate only during or immediately following the manufacturing process.

Arc test for fabricated fittings. The arc test is required for butt-fused or thermally welded joints in fabricated fittings. Any discontinuity in a segment joint is indicated by the presence of an arc (spark) from a probe tip and is cause for rejection of the fitting.

Fabricated-fitting pressure test. In this test, the fabricated fitting must not fail, balloon, burst, or weep when subjected to an internal pressure test. For ANSI/AWWA C900 fabricated fittings, the internal pressure test is equal to two times its designated pressure class for a minimum of two hours.

Assurance Testing

Assurance testing is performed at the completion of the manufacturing process to assure the finished products consistently and reliably satisfy the requirements of applicable standards. Quality assurance tests required in the manufacture of ANSI/AWWA C900 PVC and C909 PVCO products are as follows.

Sustained pressure test. ANSI/AWWA C909 pipe and C900 pipe or fabricated fittings shall not fail, balloon, burst, or weep as defined in ASTM D1598 at the applicable sustained pressure when tested for 1,000 hr.

Hydrostatic proof test. The hydrostatic proof test is required in the manufacture of PVC and PVCO pipe as well as machined PVC couplings in accordance with ANSI/AWWA C900 and C909. In the test, every PVC coupling and every standard length of PVC or PVCO pipe is proof-tested for a minimum dwell time of 5 s. The standards require that the hydrostatic proof test pressure be a minimum of two times the pressure class of the pipe (i.e., $2 \times 235 \text{ psi} = 470 \text{ psi}$ for PC235 pipe).

The hydrostatic proof-test frequency for nonstandard lengths of pipe is every 24 hrs. The hydrostatic proof-test frequency may also be modified by agreement between manufacturer and producer/supplier.

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Chapter **3**

Hydraulics

Many empirical formulas and equations have been developed to provide a solution to the problem of flow in pipes and are used daily by water utility engineers. Relatively few specific problems in pipe hydraulics, such as laminar flow, can be solved entirely by rational mathematical means. Solutions to the majority of flow problems depend on experimentally determined coefficients and relationships. Commonly used flow formulas have been developed through research by Darcy, Chezy, Kutter, Scobey, Manning, Weisbach, Hazen, and Williams.

FLOW FORMULAS

Hydraulic flow research and analysis have established that the Hazen–Williams equation can be used for PVC pressure piping system design. Flow conditions may also be analyzed more precisely and with more detail using the Darcy–Weisbach equation.

Darcy–Weisbach Equation

The Darcy–Weisbach equation provides the hydraulic design of PVC pressure water pipe. Relative pipe roughness (ε/D) and Reynolds number ($R_e = VD/\nu$) are also defined. The commonly used form of the Darcy–Weisbach formula is shown in Eq 3-1.

$$h_f = f \frac{LV_f^2}{D2g} \quad (\text{Eq 3-1})$$

where:

- h_f = head loss, ft of H₂O
- f = friction factor
- L = pipe length, ft
- D = pipe inside diameter, ft
- V_f = mean flow velocity, ft/s
- g = acceleration of gravity, 32.2 ft/s²

Investigation and analysis by Neale and Price have established that the friction factor f for a hydraulically smooth flow in PVC pipe may be defined by the following equation:

$$\frac{1}{\sqrt{f}} = 2 \log_{10} (R_e \sqrt{f}) - 0.8 \quad (\text{Eq 3-2})$$

where:

f = friction factor
 R_e = Reynolds number

The calculations for the friction factor (f) may be tedious. In common practice, the factor is established by using the Moody diagram shown in Figure 3-1. Relative roughness (ϵ/D) is related to friction factor (f) as shown in Eq 3-3. Figure 3-2 provides values for relative roughness (ϵ/D) for various pipe products.

$$\frac{1}{\sqrt{f}} = 1.14 - 2 \log_{10} \left(\frac{\epsilon}{D} + \frac{9.35}{R_e \sqrt{f}} \right) \quad (\text{Eq 3-3})$$

where:

f = friction factor
 ϵ = 0.000005 ft, PVC pipe
 D = pipe inside diameter, ft
 R_e = Reynolds Number

Hazen–Williams Equation

The Hazen–Williams flow equation is the most widely accepted and used for calculating pressure pipe flow conditions. The equation can be expressed in the following ways depending on the solution needed. Flow velocity in a pipeline can be calculated using Eq 3-4.

$$V = 1.318C(R_H)^{0.63}(S)^{0.54} \quad (\text{Eq 3-4})$$

where:

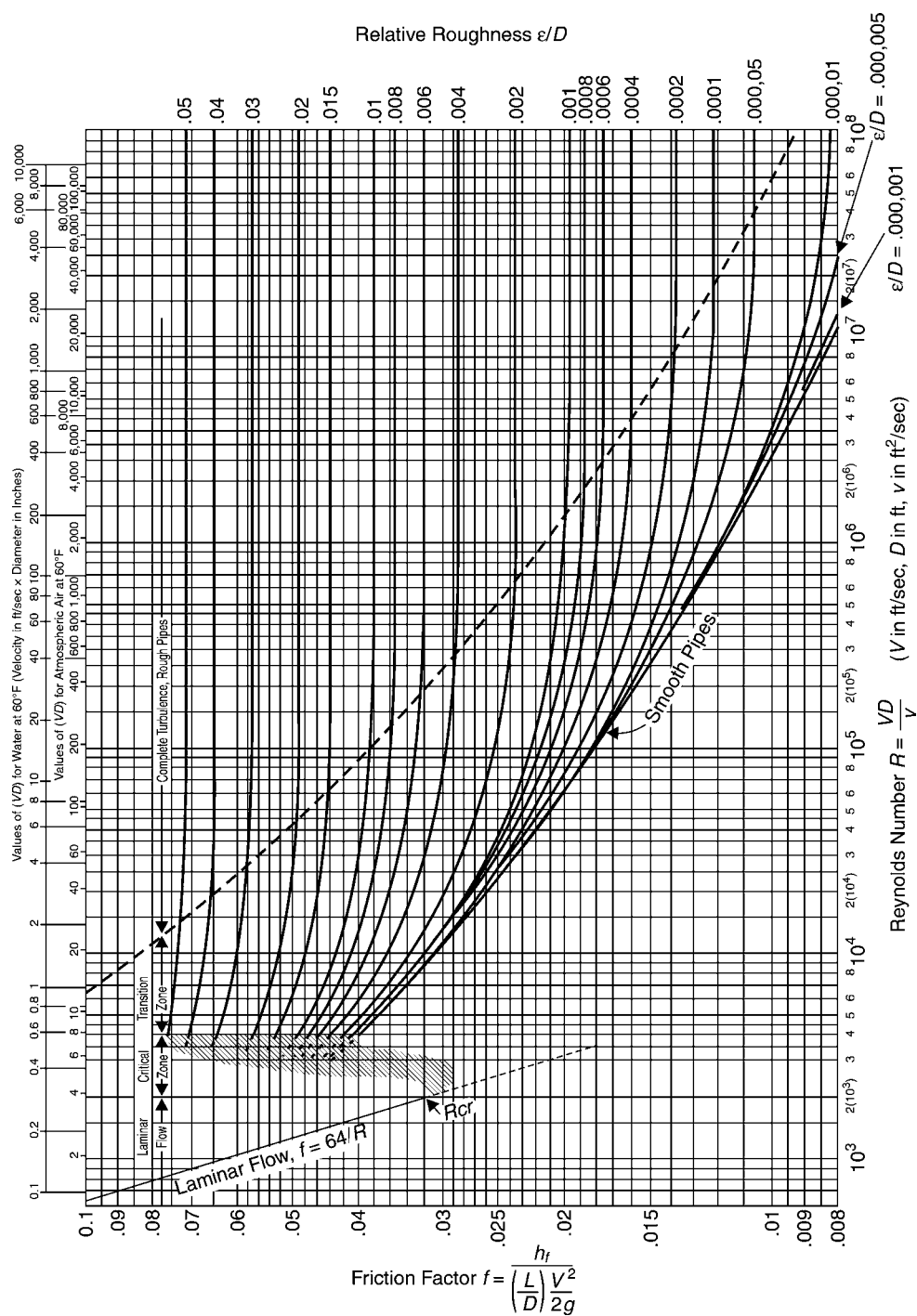
V = flow velocity, ft/s
 C = flow coefficient
 R_H = hydraulic radius, ft
 Note: $R_H = 1/4(D)$ for pipe flowing full
 S = hydraulic slope, ft/ft

Flow rate in gpm, given pressure drop in psi, can be calculated using Eq 3-5.

$$Q = 0.442 d_i^{2.63} C \left(\frac{P_1 - P_2}{L} \right)^{0.54} \quad (\text{Eq 3-5})$$

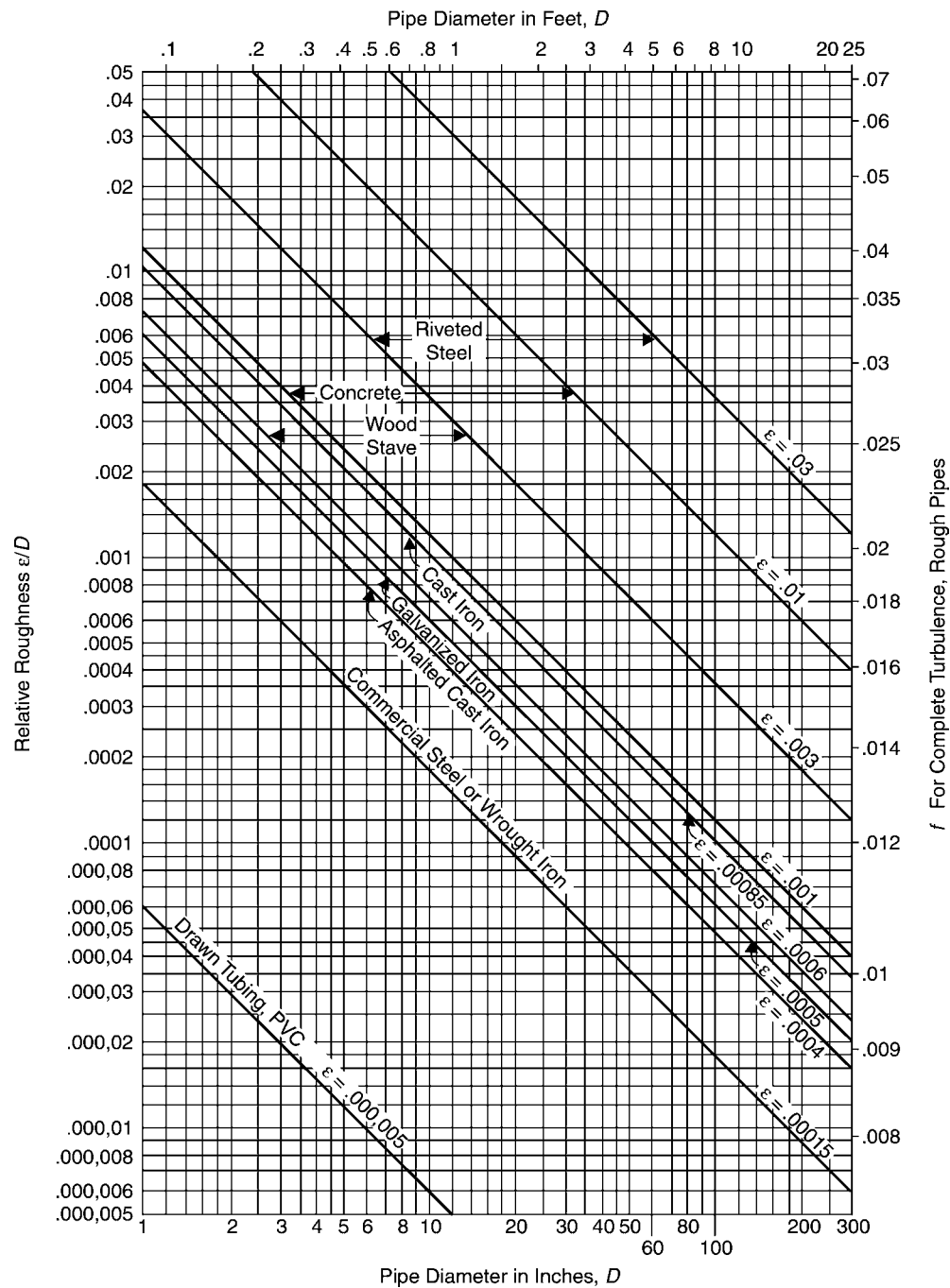
where:

Q = flow rate, gpm (All gallons are US gallons unless otherwise noted.)
 d_i = pipe inside diameter, in.
 C = flow coefficient
 P_1, P_2 = gauge pressures, psi
 L = pipe length, ft



Source: American Society of Mechanical Engineers, New York, Transactions, ASME, Vol. 66 (1944) L.F. Moody.

Figure 3-1 Moody diagram—friction factor



Source: American Society of Mechanical Engineers, New York, Transactions, ASME, Vol. 66 (1944) L.F. Moody.

Figure 3-2 Moody diagram—relative roughness, where ε is in ft

Using Eq 3-6, flow rate can be derived from pressure drop expressed in terms of feet per 1,000 ft.

$$Q = 0.006756 C d_i^{2.63} H^{0.54} \quad (\text{Eq 3-6})$$

where:

Q = flow rate, gpm
 C = flow coefficient

d_i = pipe inside diameter, in.

H = head loss, ft/1,000 ft

Friction loss in hydraulic flow can be derived from Eq 3-7.

$$f = 0.2083 \left(\frac{100}{C} \right)^{1.852} \frac{Q^{1.852}}{d_i^{4.8655}} \quad (\text{Eq 3-7})$$

where:

f = friction loss, ft of water/100 ft

C = flow coefficient

Q = flowrate, gpm

d_i = pipe inside diameter, in.

Flow coefficients for PVC pipe have been derived through research and analysis by various researchers, including Neale, Price, Bishop, and Jeppson. Research has established that the Hazen–Williams flow coefficient C can range in value from 155 to 165 for both new and previously used PVC pipe. Therefore, a flow coefficient of $C = 150$ is generally used as a conservative value for determining the headloss through PVC pipe. The roughness value may decrease after the pipeline is in service if there is scale or biofilm buildup. While a Hazen–Williams flow coefficient of 150 is considered conservative for calculating steady-state hydraulics on new PVC pipe, a lower coefficient should be considered to account for minor losses if not otherwise specifically accounted for (valves, bends, etc.).

Using $C = 150$ for PVC pipe, Eq 3-4 through 3-7 can be simplified as follows:

$$V = 197.7 R_H^{0.63} (S)^{0.54} \quad (\text{Eq 3-8})$$

$$Q = 66.3 d_i^{2.63} \left(\frac{P_1 - P_2}{L} \right)^{0.54} \quad (\text{Eq 3-9})$$

$$Q = 1.0134 d_i^{2.63} H^{0.54} \quad (\text{Eq 3-10})$$

$$f = 0.0984 \frac{Q^{1.85}}{D_i^{4.86}} \quad (\text{Eq 3-11})$$

where:

V = flow velocity, ft/s

R_H = hydraulic radius, ft

S = hydraulic slope, ft/ft

Q = flowrate, gpm

d_i = pipe inside diameter, in.

P_1, P_2 = gauge pressures, psi

L = pipe length, ft

H = head loss, ft/1,000 ft

f = friction loss, ft of water/100 ft

For convenience in design, Tables B-1, B-2, and B-3 in Appendix B have been developed based on the Hazen–Williams formula with $C = 150$ to provide flow capacity (gpm), friction loss (feet per 100 ft), and flow velocity (ft/s) for ANSI/AWWA C900, ASTM D2241, and C909 PVC pressure pipe products. Nomographs for solving head loss characteristics are provided in Figures 3-3 and 3-4.

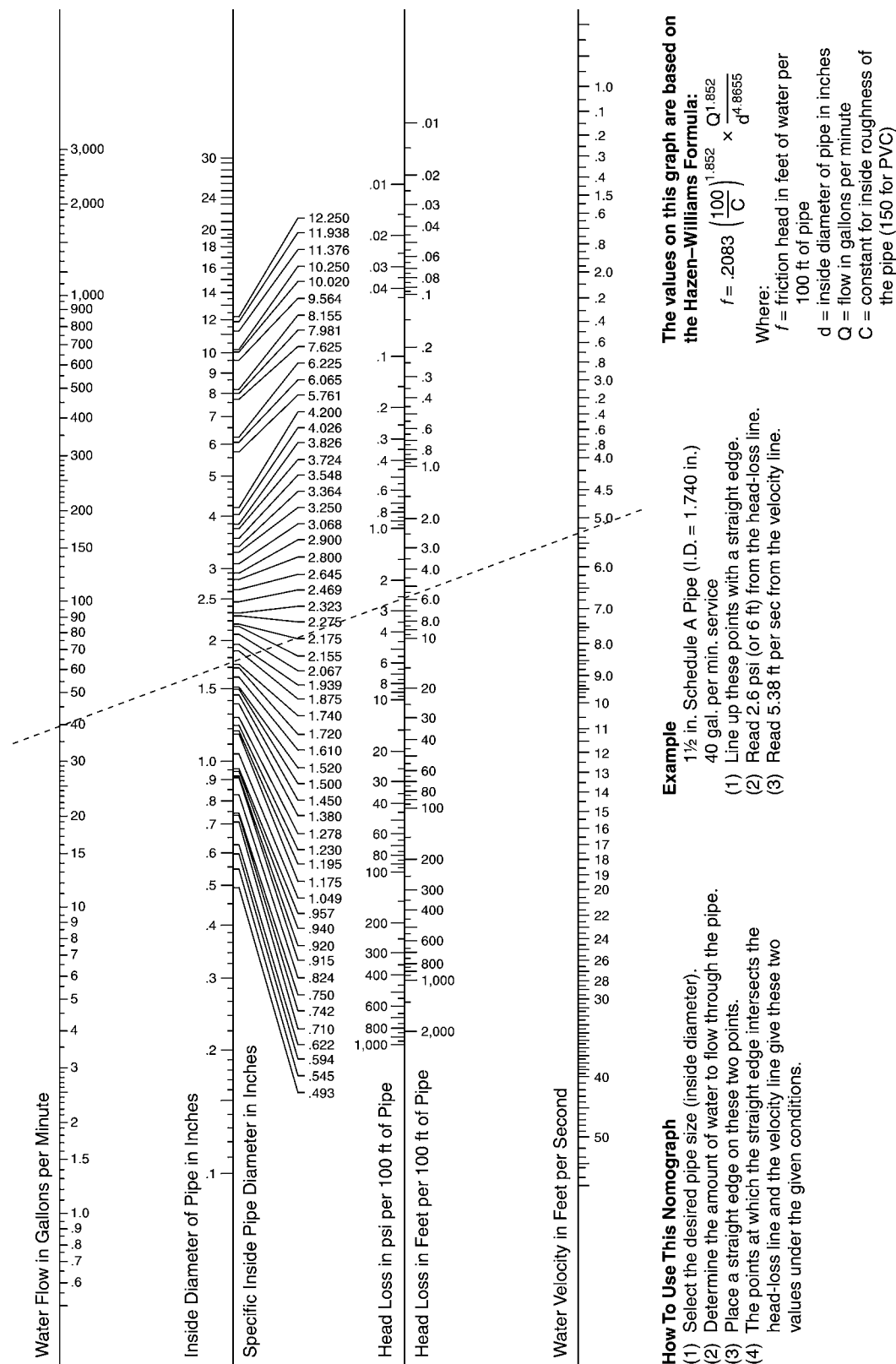
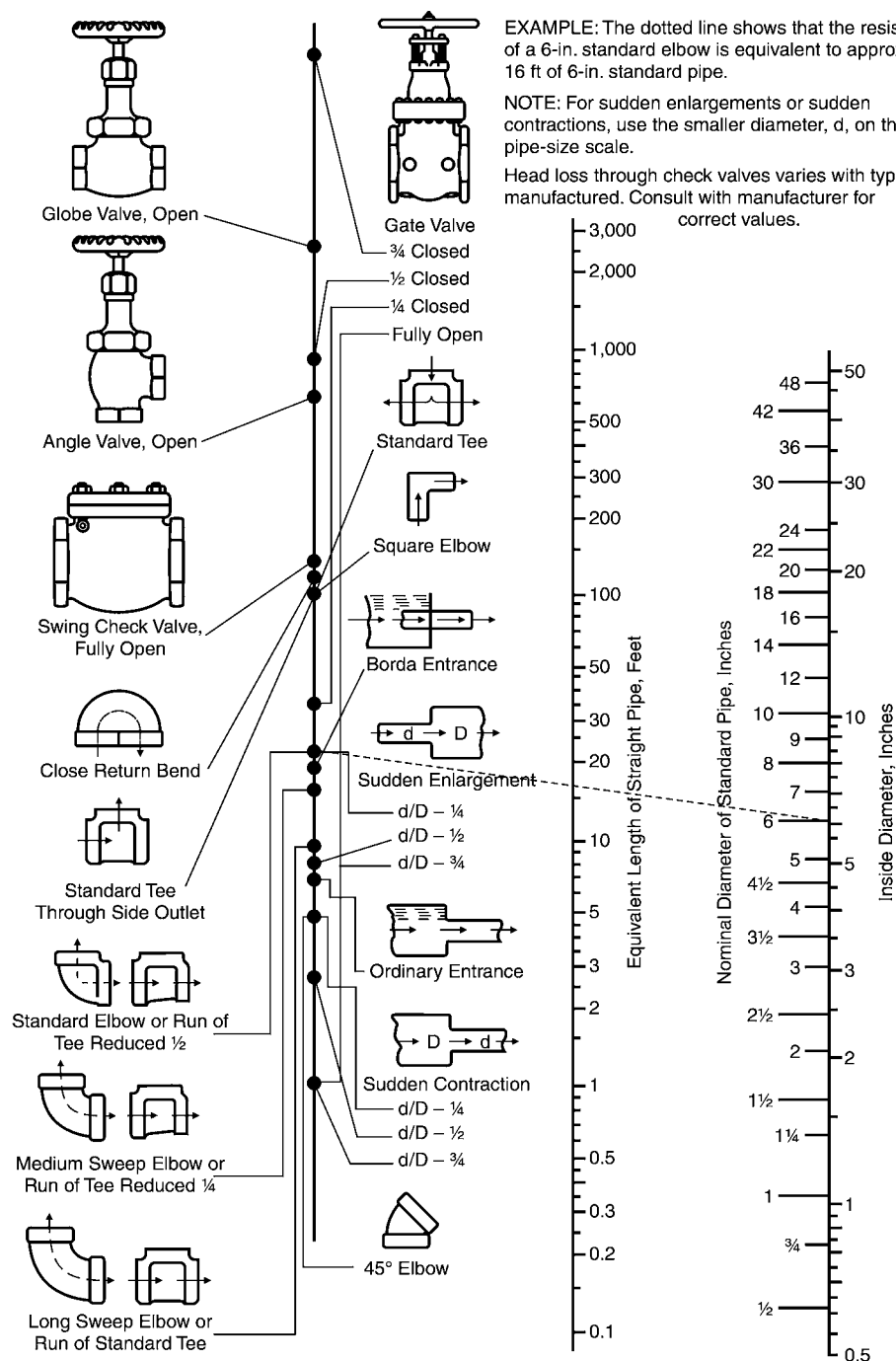


Figure 3-3 Friction loss characteristics of water flow through PVC pipe



Source: Flow of Fluids through Valves, Fittings, and Pipe. Copyright 1942 by Crane Company.

Figure 3-4 Resistance of valves and fitting to flow of fluids

Impact of Internal Bead on Flow in Fused PVC

The resulting joint of fused PVC contains an internal ridge. This ridge or internal bead has negligible effect on flow or head loss in pressure applications. Using a C value of 150 is recommended for fused PVC, as it is for bell-and-spigot joint PVC and covers the effect of the internal bead as it does for the bell-and-spigot joint. As a result, there is no need to remove the bead in pressure applications.

It should be noted in gravity flow applications that the internal bead can be removed to eliminate a place where a biological buildup could occur.

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Chapter 4

External Load Design for Trench Installation

This chapter presents design considerations for selecting the pipe stiffness, soil properties, and installation requirements to support the earth loads, live loads, and surcharge loads. These parameters may be adjusted to determine an optimum design.

This discussion is for pipe in a trench installation. Trenchless applications, such as pipe bursting and sliplining, where the original host pipe is in place, can use this analysis as well. Horizontal directional drilling (HDD) may also use this method but may require an arched or bridged analysis due to depth in undisturbed soils. As not all soils bridge or arch, specific geotechnical expertise may be required for trenchless HDD installations.

FLEXIBLE PIPE DESIGN

As illustrated in Figure 4-1, PVC and PVCO pipe can deflect due to load, thereby developing passive soil support at the sides of the pipe. At the same time, soil arching over the pipe due to the deflection transfers a portion of the vertical soil load to the soil at the side of the pipe. When designed and installed correctly, the pipe-soil system can effectively support the load on the pipe.

The deflection of the pipe is the change in vertical diameter divided by the original pipe diameter, most often stated as a percentage. Conceptually and without regard for any internal pressure, the relationship between load and deflection may be expressed as shown in Eq 4-1.

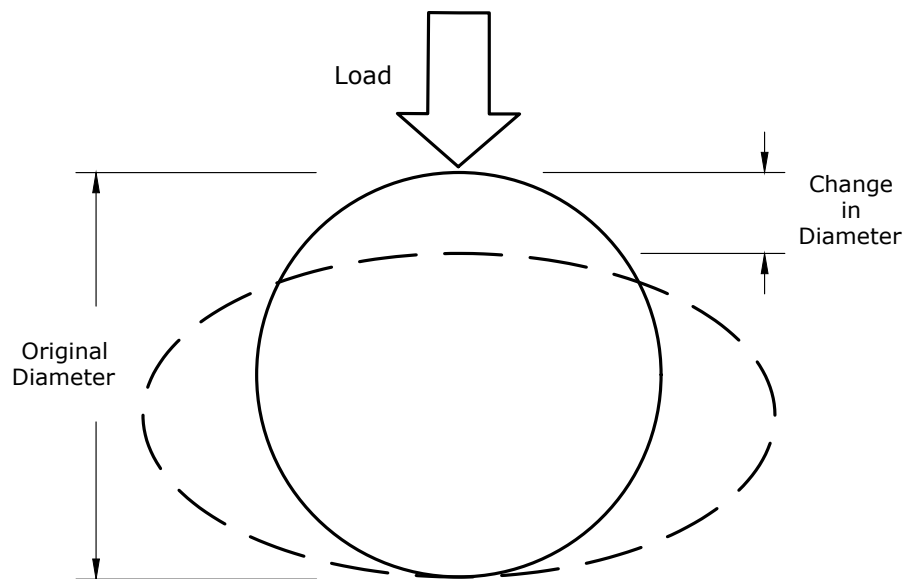


Figure 4-1 Flexible pipe deflection

$$\text{Deflection} = \frac{\text{Load}}{\text{Pipe stiffness} + \text{Soil stiffness}} \quad (\text{Eq 4-1})$$

The soil stiffness depends on the soil classification and compaction. Because internal pressure usually determines the wall thickness required, PVC and PVCO pressure pipes experience minimal deflection under most soil conditions. The horizontal and vertical deflections may be considered equal in the range of deflections allowed in the AWWA PVC and PVCO pipe standards.

The design methods in this chapter will use specific terminology for the trench construction, soil classification, and soil compaction.

TRENCH TERMINOLOGY

Embedment and backfill materials that surround a buried pipe are defined by their function and location. Figure 4-2 represents the trench terms based on ASTM D2774. This chapter provides information to aid selection of the appropriate embedment soil and the percent compaction required. The methods for proper compaction and subsequent testing are discussed in Chapter 7, “Installation in Trenches and Embankments.”

Foundation: The foundation is the native soil at the bottom of the excavation. If the foundation is unsuitable, remediation will be required to provide a stable trench bottom.

Bedding: The bedding is the soil placed at the bottom of the trench on top of the foundation. The bedding serves as a cushion for the pipe.

Haunch Zone: The haunch zone is from the bottom of the pipe up to the springline. The haunch zone and the initial backfill provide side support for flexible pipe that limits deflection. (The springline is the horizontal centerline.)

Initial Backfill: The initial backfill extends from the top of the haunch zone to 12 in. above the top of the pipe. The lower portions of initial backfill (i.e., below the pipe crown), combined with the haunch zone, provide lateral support for flexible pipe.

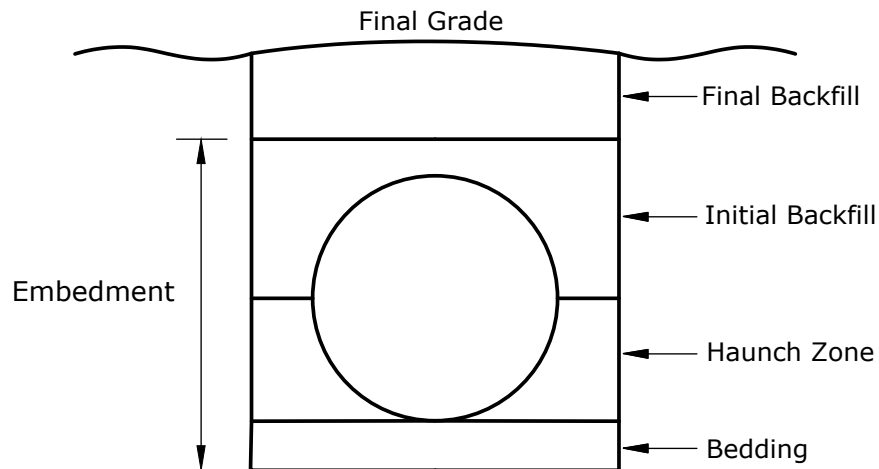


Figure 4-2 Trench construction and terminology

Embedment: The embedment includes the bedding, haunch zone, and initial backfill.

Final Backfill: The final backfill extends from the top of the initial backfill to the final grade.

The haunch zone and initial backfill, from the bottom of the pipe to 75 percent of the outside diameter of the pipe, provide support that limits pipe deflection. The initial backfill above that level serves as a padding over the top of the pipe and reduces the impact of the final backfill when it is dumped into the trench. The maximum particle size in the initial backfill should be specified to avoid pipe damage.

As discussed in Chapter 7 for a wide trench or a trench with sloped walls, the initial backfill padding need not extend across the entire width of the trench and can be about 12 in. thick over the top of the pipe. This reduces the amount of imported soil, if needed, for the initial backfill.

SOIL CLASSES

Table 4-1 gives the soil classes used in ASTM D 2774 to describe the allowable materials for each area around the pipe. The soil classes, Class I to Class V as defined by the Unified Soil Classification System (USCS), are in descending order of stiffness when the soil is compacted. Class I and Class II soils are usually considered cohesionless and are best compacted using vibration. Class III and Class IV are usually considered cohesive and are best compacted with pressure, impact, or kneading. Class V soils are considered cohesive and are not recommended to use as embedment for pipe with low stiffness (high dimension ratio) values.

As discussed in Chapter 7, there is a maximum particle size limit associated with the soil that applies within each of the soil classes.

SOIL COMPACTION

The soil support for the pipe is dependent on the degree of compaction, referred to as *percent compaction*. Percent compaction is defined by ASTM D653 as the ratio of the field compaction to the laboratory maximum density, expressed as a percentage. The field

Table 4-1 Soil classes for pipe installation

Soil Class	Description	USCS Symbol		
Class I	Crushed rock 100% passing $1\frac{1}{2}$ -in. sieve, $\leq 25\%$ passing $\frac{3}{8}$ -in. sieve, $\leq 15\%$ passing #4 sieve, $\leq 12\%$ fines			
Class II	Clean, coarse-grained soils or any soil beginning with one of these symbols (can contain up to 12% fines) (Note 1)	GW	GP	
		SW	SP	
Class III	Coarse-grained soils with fines	GM	GC	
		SM	SC	
	Sandy or gravelly fine-grained soils with $\geq 30\%$ retained on #200 sieve	ML	CL	
Class IV	Fine-grained soils with $< 30\%$ retained on #200 sieve	ML	CL	
Class V	Fine-grained soils, organic soils, high compressibility silts and clays, organic soil	MH	CH,	
		OL	OH	Pt

Notes:

1. Uniform fine sands (SP) (SP-SC) (SP-SM) with more than 50 percent passing a #100 sieve should be treated as Class III material.
2. Soil classification in accordance with ASTM D2487 or ASTM D2488.
3. *Fines* are soil particles that pass a #200 sieve.
4. Class I: crushed rock particles should have all fractured faces.
5. Recycled concrete, slag, and shells should be considered Class II.

compaction is measured by in-place density tests such as sand cone or nuclear gauge. For soil Classes III, IV, or V, the laboratory maximum density is determined using the standard Proctor compaction test ASTM D698. For soil Classes I or II, the laboratory maximum density is determined using a vibratory compaction test ASTM D7382 or D4253. ASTM D7382 is a new procedure using a vibratory hammer to obtain a maximum density and is considered more reliable than D4253.

References to the percent compaction of soils in this manual will be as recommended in ASTM D653. The percent of the maximum density of the soil is followed by the ASTM test procedure used to determine the maximum density. For example, 95 percent (D698) means that the in-place density should be equal to or higher than 95 percent of the maximum density obtained using D698. The references to soil stiffness in this manual are based on standard Proctor density, which is ASTM D698. Therefore, plans and specifications should reference D698.

Chapter 7 discusses the various methods of compacting soils, measuring densities, and evaluating the percent compaction. In some situations, installing the pipe with the proper soil and compaction may be critical to establishing the correct support for the pipe. Inspection during construction will ensure that the installation meets the design criteria.

In many cases, flowable fill can be substituted for the bedding and embedment. Chapter 7 discusses the proper use of flowable fill for buried pipe.

BASIC AND ENGINEERED INSTALLATIONS

For flexible pipe, there are some combinations of pipe selection, external loads, and soil stiffness that may not need design verification for deflection. Accordingly, the design and construction may be divided into *basic installations* and *engineered installations*.

Basic Installation

Some pressure pipe will have adequate stiffness to withstand the external loads and will not be reliant on the embedment for additional support. Such pipe does not require deflection calculations and may be installed with minimum soil support. The embedment

material can be the soil excavated from the trench. The pipe can be laid directly on the trench bottom, and minimal testing and inspection are required.

A basic installation can be used when all of the following conditions are met:

- Nominal pipe size of 24 in. or less.
- DRs equal to or less than 25.
- Depths of cover 15 ft or less.
- Natural ground water below pipe.
- For depths of cover with less than 6 ft, no live load or surcharge load.
- Final backfill compaction is not required.
- Embedment soil E' will be at least 200 psi (as discussed later).
- Trench foundation and trench walls are stable and have a minimum unconfined compressive strength of 5 psi, an N value of at least 5 from the standard penetration test, or an E' of at least 400 psi (as discussed later).
- The foundation does not consist of expansive clays, collapsing soils, or landfill.
- The soils in the foundation and used for the embedment do not contain rock particles larger than the maximum particle size discussed in Chapter 7.

An engineered installation should be used when these conditions are not met. In some cases where live or surcharge loads may occasionally occur, such as road crossings, the pipeline system may consist of both basic installations and engineered installations.

Class I, II, III, or IV soils, whether native or imported, can provide an embedment $E' \geq 200$ psi when dumped in place beside the pipe without any compaction. Class V soil may not be a suitable embedment for pipes with low stiffness (high DR) values.

Engineered Installation

When the basic installation is deemed to be not adequate, the pipe design will warrant estimating deflection, as outlined in this chapter. An engineered installation design will need to consider the trench wall support, the effects of ground water, selection of embedment material, increased percent compaction, time before pipeline is pressurized, live load, and surcharge load. Construction may require imported embedment material, placing a bedding for the pipe, soil testing requirements, and more stringent inspection. Where the pipeline crosses under another pipeline, a heavily travelled roadway, or a large waterway, an engineered installation design should be used.

PIPE DEFLECTION

For PVC and PVCO pressure pipe, deflection is usually not a critical design parameter because pipe stiffness values are relatively high and operating internal pressures are usually sufficient to induce re-rounding of the pipe. However, for the *engineered installation*, the deflection should be estimated for those instances when the pipe is not pressurized. A 7.5 percent deflection limit (which is based on a 4 to 1 safety factor over the empirically tested maximum of 30 percent) has been established as a long-term deflection design limit. For the initial deflection, a 5 percent limit should be used.

Deflection Calculation

Pipe deflection will depend upon the pipe's stiffness, the external load(s), and the stiffness of the embedment soil along the sides of the pipe. Deflection can be estimated using Eq 4-2.

$$\% \frac{\Delta Y}{D} = \frac{k(T_L W_E + W_L + W_S)}{0149PS + 0.061E'} (100) \quad (\text{Eq 4-2})$$

where:

$\% \frac{\Delta Y}{D_o}$	=	vertical deflection, %	
ΔY	=	vertical deflection or change in diameter, in.	
D	=	diameter, in.	
k	=	bedding constant, use 0.1	
T_L	=	time-lag factor, use 1.0, 1.5, or 2.0	See Discussion
W_E	=	earth load pressure, psi	See Eq 4-5
W_L	=	live load pressure, psi	See Eq 4-7
W_S	=	surcharge pressure, psi	See Eq 4-6
PS	=	pipe stiffness, lbf/in./in.	See Table 4-3
E'	=	modulus of soil reaction, psi	See Eq 4-14

LOAD ON PIPE

The load on the pipe is the earth load, W_E , plus the live load, W_L , and surcharge load, W_S , if any.

Earth Load

For simplicity, the earth load on the pipe is considered to be a prism load. As indicated in Eq 4-3, the prism load is the weight of the full column height of soil directly over the pipe. Equation 4-4 results in soil pressure in psi for the prism load.

$$\text{Prism Load:} \quad W_p = HwD \text{ (lb/lin ft)} \quad (\text{Eq 4-3})$$

Prism load may also be expressed in terms of soil pressure as follows:

$$\text{Soil Pressure:} \quad P = wH \text{ (lb/ft}^2\text{)} \quad (\text{Eq 4-4})$$

where:

P	=	pressure caused by soil weight at depth H , lb/ft ²
w	=	unit weight of soil, lb/ft ³
H	=	depth at which soil pressure is desired, ft
D	=	pipe diameter

The prism load can be converted to lb/in² for W_E as follows:

$$\text{Earth Load Pressure:} \quad W_E = \frac{W_p}{144} \quad (\text{Eq 4-5})$$

Surcharge Load

Building foundations, other structure foundations, or other static, long-term loads above the pipe must be considered and are treated as surcharge loads. These loads may be present at the time that the pipe is installed or may be superimposed on the pipe at some point in time subsequent to the pipe installation. These loads increase soil pressure onto the buried pipe and can generally be categorized into two types: (1) loads that have confined footprints or areas of influence, or (2) loads that have wide areas of influence, normally

parallel the pipe. Type 1 loads are usually analyzed as point source loads, while type 2 loads are analyzed as uniformly distributed loads.

The basis for analysis of both types of static loads is the Boussinesq theory, which is mathematically stated as

$$W_s = P_A = \frac{WZ^3}{96\pi R^5} \quad (\text{Eq 4-6})$$

where:

P_A = soil pressure at point A, psi

W = superimposed load, lb

Z = vertical distance from the point of the load to the top of the pipe, ft

$R = \sqrt{X^2 + Y^2 + Z^2}$, straight line distance from the point where the load is applied to point A on the top of the pipe; X and Y are measured horizontally at 90 degrees to each other. (Note: Y is usually measured along the horizontal axis of the pipe, and X is usually measured perpendicular to the horizontal axis of the pipe.)

Live Loads

The following calculations can be used to compute the live load on the pipe for surface traffic (see Figure 4-3). The procedure is based on the AASHTO LRFD (American Association of State Highway and Transportation Officials load-and-resistance factor design philosophy) Bridge Design Specification, 6th ed., 2012. These calculations are for a single-axle truck traveling perpendicular to the pipe on an unpaved surface or a road with flexible pavement. With the inclusion of the multiple presence factor (M_p), they will generally yield acceptably conservative load estimates. The M_p accounts for the probability relationship between the number of loaded lanes and the weight as any single vehicle. M_p is typically taken as 1.2 for single passing vehicle.

$$W_L = \frac{M_p P I_F}{(L_1)(L_2)} \quad (\text{Eq 4-7})$$

where:

W_L = live load on pipe, psi

M_p = multiple presence factor = 1.2

P = wheel load magnitude

= 16,000 lb for AASHTO HS20 truck

= 20,000 lb for AASHTO HS25 truck

I_F = impact factor

L_1 = load width parallel to direction of travel, in.

L_2 = load width perpendicular to direction of travel, in.

$$I_F = 1 + 0.33 \frac{(96 - h)}{96} \geq 1.0 I_F \quad (\text{Eq 4-8})$$

where:

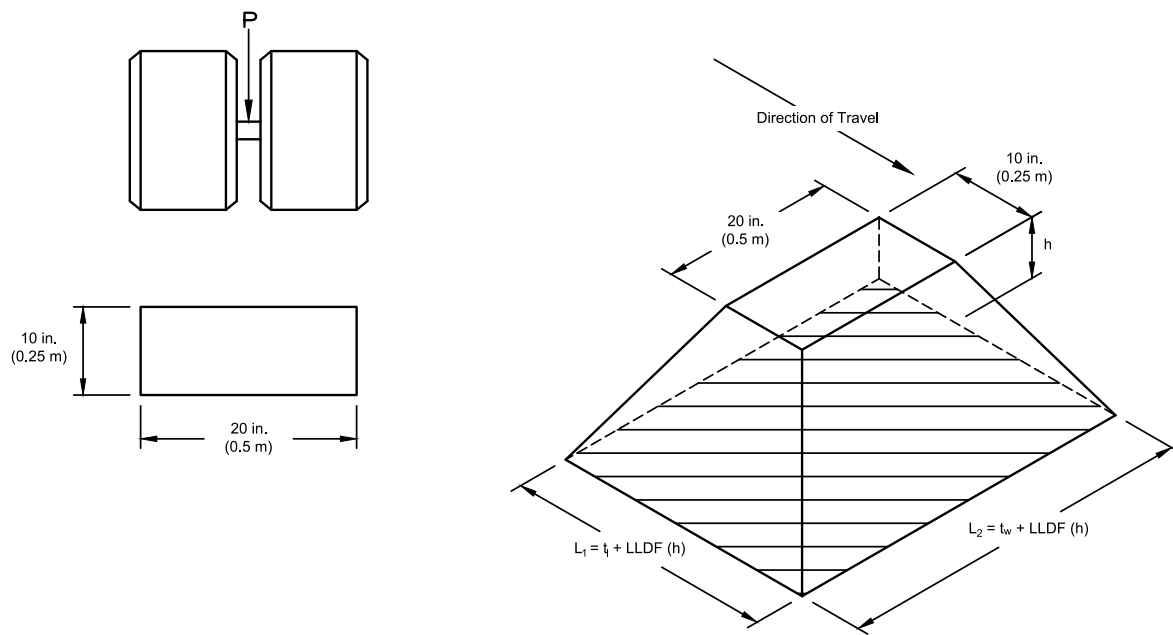
h = burial depth to top of pipe, in.

$$L_1 = t_\ell + \text{LLDF}(h) \quad (\text{Eq 4-9})$$

where:

t_ℓ = length of tire footprint = 10 in.

LLDF = factor to account for live load distribution with depth of fill



Source: Adapted from AASHTO

Note: For $H > 45$ in. (1.14 m), see part 2 of the L_2 formula. (Change accounts for overlapping influence areas from adjacent wheel loads.)

Figure 4-3 Distribution of AASHTO HS20 or HS25 live load through granular fill for $h \leq 45$ in. (3.75 ft)

- = 1.15 for Class I and Class II backfills
- = 1.0 for all other backfills

$$\text{If } h \leq h_{\text{int}} \quad L_2 = t_w + \text{LLDF}(h) \quad (\text{Eq 4-10})$$

where:

t_w = width of tire footprint = 20 in.

$$\text{If } h > h_{\text{int}} \quad (\text{Eq 4-11})$$

$$L_2 = \frac{t_w + 72 \text{ in.} + \text{LLDF}(h)}{2}$$

where:

h_{int} = depth at which load from wheels interacts

$$h_{\text{int}} = \frac{72 \text{ in.} - t_w}{\text{LLDF}} \quad (\text{Eq 4-12})$$

Calculation notes:

- Equations as shown are for h in inches.
- AASHTO also specifies a surface lane load of 640 lb/ft over a 10-ft lane width. This lane load is ignored in these calculations as it has only a small effect on the total live load and may be added by the engineer if deemed appropriate.
- The above calculation method assumes that the live load extends over the full diameter of the pipe. This may be conservative for a large-diameter pipe under low fills. To account for this, the calculated live load pressure on the pipe may be reduced by the ratio L_1/OD if the truck is moving across the pipe and $L_1 < \text{OD}$ or by L_2/OD if the truck is moving parallel to the pipe and $L_2 < \text{OD}$. OD is the outside diameter of the pipe in inches.

4. For depths of fill less than 2 ft, or for live load magnitudes greater than HS-25, it may be necessary to consider the local live load effects at the crown of the pipe. Such an analysis is beyond the scope of this manual.
5. The previous calculation is for single-axle trucks. Design for tandem-axle trucks may use the same procedures; however, the following substitutions for L_1 should be used if both axles load the pipe at the same time.

$$L_1 = \frac{\text{axle spacing} + t_w + \text{LLDF} (h)}{2} \quad (\text{Eq 4-13})$$

Tandem-axle wheel loads are usually lighter than HS20 or HS25 trucks; for example, the AASHTO LRFD Design Tandem has a 12,500-lb wheel load.

6. Rigid pavements dramatically reduce live load effects on pipe. The Portland Cement Association developed a calculation method to consider loads transmitted through concrete pavements (*Vertical Pressure on Concrete Culverts Under Wheel Loads on Concrete Pavement Slabs*, Portland Cement Assoc. Publication ST-65, 1951) that is still in use today and is suitable for computing live loads on PVC pipe under rigid pavements. The same method is also presented in the *Concrete Pipe Design Handbook* published by the American Concrete Pipe Association.

Table 4-2 presents computed live loads for AASHTO HS20 and HS25 single-axle trucks based on an LLDF of 1.15 (for granular fills). The loads shown assume that the load extends over the full diameter of the pipe. This assumption will not be true for large-diameter pipes with shallow covers. Loads for this condition may be lower. See calculation note #3 below Eq 4-12 for guidance on appropriate adjustments.

Also included in Table 4-2 are live loads from Cooper's E80 railroad loading (taken from the *Concrete Pipe Design Manual*).

Figures 4-4 to 4-6 depict graphically the AASHTO truck and Cooper's E80 railroad live loads shown in Table 4-2.

PIPE STIFFNESS

The inherent strength, regarding external load-carrying capacity, of flexible pipe is quantified as pipe stiffness. Pipe stiffness is measured, according to ASTM D 2412, Standard Test Method for External Loading Properties of Plastic Pipe by Parallel-Plate Loading, at a uniform datum of 5 percent deflection.

Pipe stiffness is defined as follows:

$$PS = F / (\Delta Y) \geq \frac{EI}{0.149r^3} = \frac{6.7EI}{r^3} = \frac{6.7Et^3}{12r^3} = 0.559E \left(\frac{t}{r} \right)^3 \quad (\text{Eq 4-14})$$

where:

PS = pipe stiffness, lbf/in./in.

F = force, lb/lin in.

ΔY = vertical deflection, in.

E = modulus of elasticity, psi

I = moment of inertia of the wall cross-section per unit length of pipe

$\left(\frac{t^3}{12} \times 1 \right)$, in.⁴/lin in. = in.³

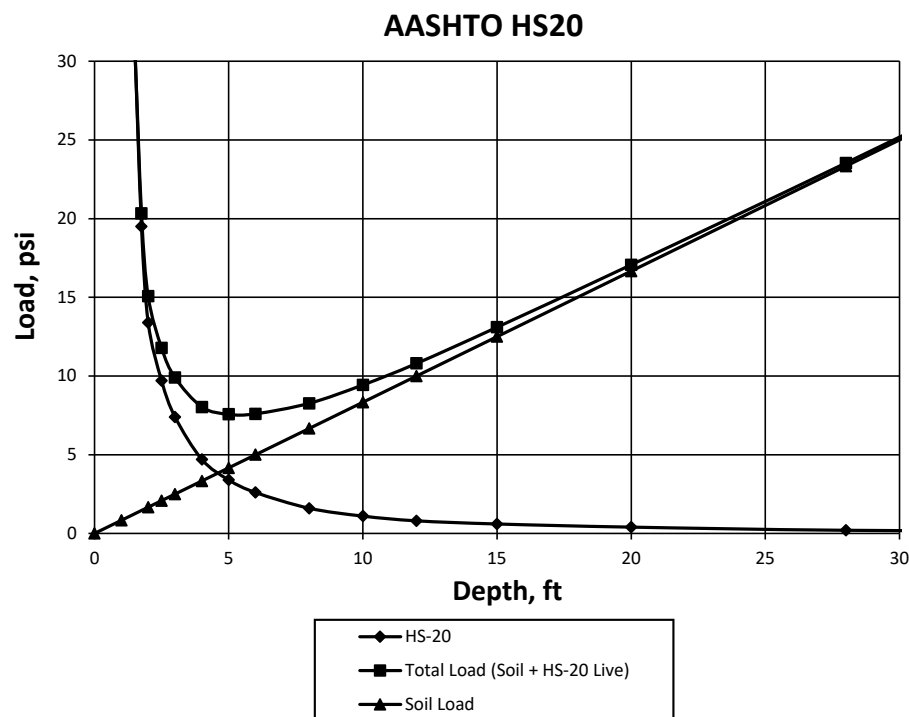
r = mean radius of pipe, in.

t = wall thickness, in.

Table 4-2 AASHTO HS20, HS25, and Cooper E80 live loads (psi)

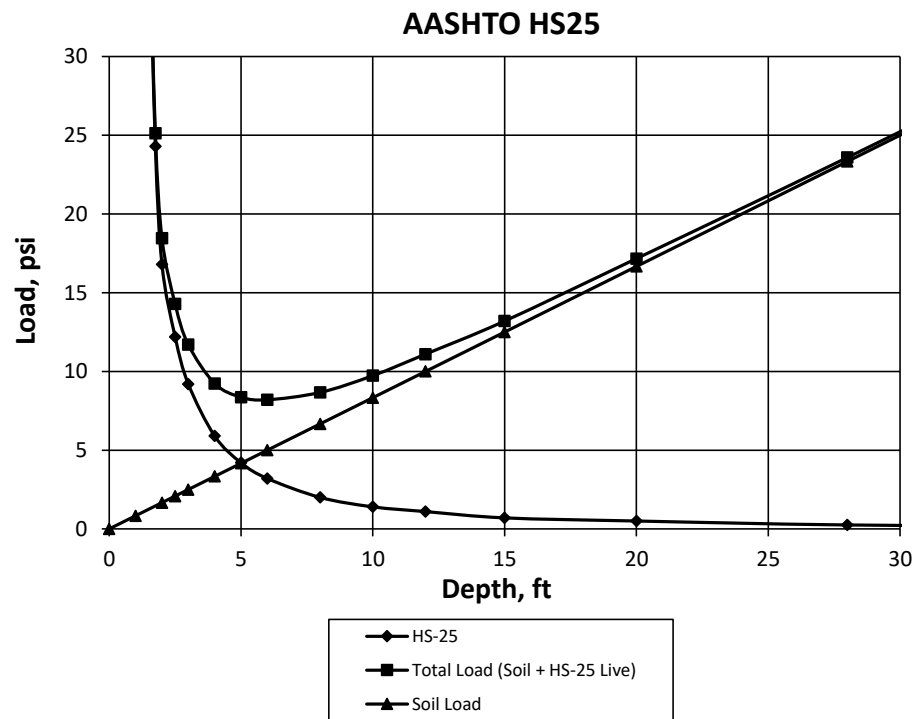
AASHTO Live Loads		HS20		HS25		Cooper E80 Live Loads			
Depth		W_L		W_L		Depth		W_L	
<i>ft</i>	<i>m</i>	<i>psi</i>	<i>kPa</i>	<i>psi</i>	<i>kPa</i>	<i>ft</i>	<i>m</i>	<i>psi</i>	<i>kPa</i>
2	0.6	13.4	92	16.8	116	3	0.9	16	110
2.5	0.8	9.7	67	12.2	84	4	1.2	14.1	97
3	0.9	7.4	51	9.2	63	5	1.5	12.2	84
4	1.2	4.7	32	5.9	41	6	1.8	10.5	72
5	1.5	3.4	23	4.2	29	7	2.1	9	62
6	1.8	2.6	18	3.2	22	8	2.4	7.7	53
8	2.4	1.6	11	2	14	10	3.0	5.7	39
10	3.0	1.1	7.6	1.4	10	12	3.7	4.6	32
12	3.7	0.8	5.5	1.1	7.6	15	4.6	3.4	23
15	4.6	0.6	4.1	0.7	4.8	20	6.1	2.2	15
20	6.1	0.4	2.8	0.5	3.4	25	7.6	1.5	10
28	8.5	0.2	1.4	0.25	1.8	30	9.1	1.1	7.6
40	12.2	0.1	0.7	0.1	0.7	40	12.2	0.6	4.1

Note: Cooper E80 as defined by AREMA (American Railway Engineering and Maintenance-of-Way Association) in its Manual of Railway Engineering.



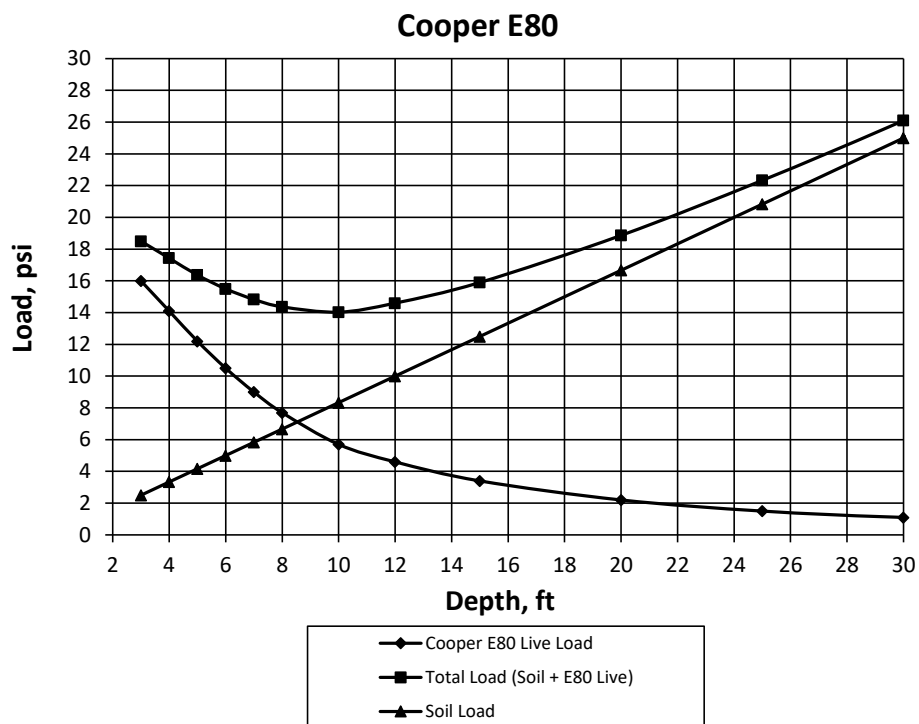
Source: US Bureau of Reclamation

Figure 4-4 AASHTO HS20 live load, soil load (120 pcf), and total load graph



Source: US Bureau of Reclamation

Figure 4-5 AASHTO HS25 live load, soil load (120 pcf), and total load graph



Source: US Bureau of Reclamation

Figure 4-6 Cooper E80 live load, soil load (120 pcf), and total load graph

For PVC pipe with outside diameter controlled dimensions, Eq 4-14 can be simplified further:

$$PS = 4.47 \frac{E}{(DR - 1)^3} \quad (\text{Eq 4-15})$$

where:

$$DR = \text{dimension ratio, } \frac{D_o}{t}$$

$$D_o = \text{outside diameter, in.}$$

The resulting PS values for various dimension ratios of ANSI/AWWA C900 PVC and pressure classes for ANSI/AWWA C909 PVCO pipe are shown in Table 4-3.

For pipe with outside diameter controlled dimensions (i.e., DR classifications), Eq 4-2 can be simplified further:

$$\% \frac{\Delta Y}{D} = \frac{k(T_L W_E + W_L + W_S)}{\frac{2E}{3(DR - 1)^3} + 0.061E'} \quad (\text{Eq 4-16})$$

Time Lag

Buried flexible pipe continues to deflect after the pipe has been initially backfilled. The time lag factor, T_L , relates the immediate deflection of the pipe to the deflection of the pipe after many years. The primary cause of increasing pipe deflection with time is the increase in overburden load. The full load is not realized until 3–12 months after completion of backfilling (or longer). A secondary cause of increasing pipe deflection is the time-related consolidation of the embedment. The soil consolidation is generally of much less significance than the increasing load.

When the operating internal pipe pressure equals or exceeds the external load, the pipe will tend to re-round. For pipes that are pressurized within 3 months of installation, a time-lag factor of 1.0 can be used. Otherwise, a time-lag factor of 1.5 should be used to estimate the deflection that may occur while the pipe is not pressurized. If the pipe will not be pressurized for several years, a time-lag factor of 2.0 should be used to estimate the deflection until pressurized.

Table 4-3 PVC and PVCO pipe stiffness

PVC Stiffness Min. $E = 400,000$ psi		PVCO Stiffness Min. $E = 500,000$ psi	
<i>DR</i>	<i>lb/in./in.</i>	<i>Pressure Class</i>	<i>lb/in./in.</i>
51	14	PR160, IPS	24
41	28	PR200, IPS	48
32.5	57	PR250, IPS	98
27.5	96	PR150, CIOD	21
26	115	PR200, CIOD	48
25	129	PR250, CIOD	98
21	224	PC165, CIOD	28
18	364	PC235, CIOD	81
14	815	PC305, CIOD	178