United States Department of Agriculture

Soil Conservation Service

P.O. Box 2890
Washington, D.C.
20013

August 21, 1990

TECHNICAL RELEASE NO. 77
210-VI

SUBJECT: ENG - DESIGN AND INSTALLATION OF FLEXIBLE CONDUITS

Purpose. To transmit Technical Release (TR) No. 77, Design and Installation of Flexible Conduits--Plastic Pipe.

Expiration Date. This technical release is effective upon receipt.

TR-77 is the final product of a draft prepared by Oscar Perez and distributed for comment in 1985. Based on the comments received and other factors considered, the TR was finalized limiting the design analysis to a single procedure, the modified Iowa method of estimating the deflection of a flexible conduit. Also, strain limit considerations are included due to their significance for the analysis of plastic pipe vs. pipe made of materials that have elastic properties.

Even though the TR is written for plastic pipe materials, many of the procedures can be applied to other flexible conduits by using the respective pipe material properties.

The TR has been finalized by Rodney S. White, Jr., Drainage Engineer, at the South National Technical Center (SNTC) (formerly a design engineer at the SNTC) and the final text form and format have been prepared and edited by the Cartographic Unit in the SNTC.

TR-75 and TR-76 are in preparation and have not been distributed.

Filing Instruction. File with other technical releases.

Distribution. The distribution is shown on the reverse side and is based on the number of copies needed to provide one copy to each practicing professional engineer in each state and NTC. Additional copies may be obtained from the Consolidated Forms and Publications Distribution Center by ordering TR-77.

Robert R. Shaw

ROBERT R. SHAW
Deputy Chief for Technology

DIST: TR-77

U.S. DEPARTMENT OF AGRICULTURE
Soil Conservation Service

TR-77

NHQ-ADS-012
3-90

DESIGN and INSTALLATION of FLEXIBLE CONDUITS

DISTRIBUTION LIST

STATES	NO. COPIES	NATIONAL HEADQUARTERS	NO. COPIES
Alabama	30	**OFFICE OF THE CHIEF**	
Alaska	5	Associate Chief	
Arizona	30	Congressional and Public Liaison Staff	
Arkansas	40	Strategic Planning and Budget Analysis	
California	70	Assistant Chief - Midwest	
Colorado	35	Assistant Chief - South	
Connecticut	10	Assistant Chief - Northwest	
Delaware	10	Assistant Chief - West	
Florida	20	**ADMINISTRATION**	
Georgia	40	Deputy Chief	
Guam	5	Associate Deputy Chief	
Hawaii	10	Administrative Services	
Idaho	20	Financial Management	
Illinois	40	Human Resources and Equal Opportunity	
Indiana	25	Information Resources Management	1
Iowa	40	Public Information	
Kansas	45	NHQ Administrative Support Staff	
Kentucky	25	**PROGRAMS**	
Louisiana	30	Deputy Chief	
Maine	15	Associate Deputy Chief	
Maryland	15	Basin and Area Planning	
Massachusetts	15	Civil Rights	
Michigan	20	Conservation Planning	
Minnesota	30	Land Treatment Program	
Mississippi	40	Operations Management	
Missouri	30	Project Development and Maintenance	
Montana	35	**TECHNOLOGY**	
Nebraska	30	Deputy Chief	
Nevada	10	Associate Deputy Chief	
New Hampshire	10	Cartography & Geographic Inf. Systems	
New Jersey	15	Ecological Sciences	
New Mexico	40	Economics and Social Sciences	
New York	33	Engineering	20
North Carolina	30	International Conservation	
North Dakota	20	Resources Inventory	
Ohio	40	Soil Survey	
Oklahoma	50	**TOTAL** →	1509
Oregon	20	**OTHERS:**	
Pennsylvania	35	Helen Gilbert	1
Puerto Rico	5	Engineering (Cotton Annex)	10
Rhode Island	5	Central Supply	800
South Carolina	25		
South Dakota	20		
Tennessee	30		
Texas	100		
Utah	15		
Vermont	10		
Virginia	25		
Washington	35		
West Virginia	35		
Wisconsin	20		
Wyoming	20		
NTC'S		**TOTALS** →	2320
Lincoln, Neb.	25	SIGNATURE *(Official requesting distribution)*	DATE
Portland, Ore.	25	[signature]	8/14/90
Chester, Pa.	25		
Ft. Worth, Tex.	25		

United States Department of Agriculture

Soil Conservation Service

Engineering Division

Technical Release No. 77

Design and Installation of Flexible Conduits

Plastic Pipe

Design and Installation of Flexible Conduits

Plastic Pipe

Technical Release 77

S. Rodney White, Jr., Design Engineer
South National Technical Center
U.S. Department of Agriculture
Soil Conservation Service
Fort Worth, Texas

U.S. Department of Agriculture
Soil Conservation Service
Engineering Division
Washington, DC

August 1990

Contents

Symbols

Figures

Tables

Symbols

ABS = acrylonitrile-butadiene-styrene

B' = empirical coefficient of elastic support

C = pipe friction coefficient

C_a = buckling coefficient for hydrostatic pressure loading on the pipe

$\overline{CF}$ = creep factor

C_m = moment coefficient

C_w = reduction of earth load for buoyancy

d = average inside diameter, inches

D = average outside diameter, inches

D_m = mean diameter, inches

D_L = deflection lag factor

E = modulus of elasticity of the pipe material, psi

E' = modulus of soil reaction of embedment material, psi

E_0 = initial modulus of elasticity of the pipe material, psi

E_{10} = apparent modulus of elasticity of the pipe material after 10 years under constant stress or strain

f = design stress, psi

F = force, lb

g = acceleration due to gravity, ft/sec/sec

h = height of soil above the top of the pipe, ft

HDB = hydrostatic design basis

h_w = height of groundwater above the top of the pipe, ft

I = moment of inertia, in^4

$\overline{IF}$ = impact factor

K = bulk modulus of the liquid, psi

K_b = bedding constant

L = length of the pipeline, feet

$\overline{LF}$ = load factor

LL = liquid limit

M = bending moment, Force x Length (FL), lb-in

$\overline{MF}$ = moment factor

n = Manning's roughness coefficient

n_w = capacity reduction factor for modulus of soil reaction for wheel loads

P = working pressure, psi

P'_{cr} = critical buckling pressure on the pipe under hydrostatic loading,

P'_{su} = minimum factored pressure due to the soil load, psi

P'_{wu} = minimum factored pressure due to the wheel load, psi

P_{bu} = ultimate factored pressure on the pipe bottom, psi

P_{cr} = critical buckling pressure on the pipe, psi

PE = polyethylene

P_f = internal pressure, psi

$\overline{PF}$ = strain concentration factor at the perforations

P_{fu} = ultimate factored internal pressure, psi

P_{gu} = ultimate factored groundwater pressure, psi

P_r = pressure rating of the pipe

P_s = soil pressure, psi

$\overline{PS_0}$ = initial pipe stiffness, psi

$\overline{PS_{10}}$ = pipe stiffness after 10 years, psi

PVC = polyvinyl chloride

P_{vu} = ultimate factored vacuum pressure, psi

P_w = pressure due to wheel loading excluding load factors, psi

P_{wh} = pressure due to wheel loading including load factors, psi

P_{wu} = ultimate factored pressure due to wheel loading, psi

Q = flow, cfs

Q_g = rate of flow, gpm

r = hydraulic radius

$\overline{RF}$ = rerounding factor

R_i = average inside radius, inches

R_m = mean radius, inches

R_o = average outside radius, inches

S = slope, ft/ft

SDR = standard dimension ratio as defined in ASTM F 412

t = minimum wall thickness, inches

T = time, seconds

V = velocity, ft/sec

V_w = velocity of the pressure wave, ft/sec

y = maximum deflection at the end of a cantilever beam, inches

Z = section modulus, in^3

ΔP = change in pressure, psi

ΔP_{100} = friction pressure loss in psi per 100 feet of pipe

ΔV = change in velocity, ft/sec

σ_L = longitudinal tensile stress, psi

μ = Poisson's ratio

γ = unit weight, lb/ft^3

γ_s = unit weight of soil, lb/ft^3

γ_w = unit weight of water, lb/ft^3

Δ = total deflection, inches

Δ_i = deflection that occurs during installation, inches

Δ_s = average deflection due to the soil pressure, inches

Δ_w = average deflection due to the wheel loading, inches

ϕ = capacity reduction factor for pipe strength

ϕ'' = capacity reduction factor for long term pipe stiffness for buckling

ϕ' = capacity reduction factor for embedment material modulus of soil reaction

ε = strain

ε'_{csu} = minimum factored ring compression due to the soil load

ε'_{csu} = ring compression strain due to earth loading with the minimum load factor applied

ε'_{cwu} = minimum factored ring compression due to the wheel loading

ε'_{cwu} = ring compression strain due to surface wheel loads with minimum load factor applied

ε_{biu} = factored ring bending strain that occurs during installation

ε_{bsu} = factored ring bending strain due to soil loads

ε_{bu} = sum of factored ring bending strains

ε_{bwu} = factored ring bending strain due to wheel loads

ε_{C} = ultimate strain in creep

ε_{cgu} = factored ring compression due to groundwater

ε_{csu} = maximum factored ring compression strain due to the earth load

ε_{Cu} = initial reduced ultimate strain in creep

ε_{cvu} = factored ring compression strain due to a vacuum

ε_{cwu} = maximum factored ring compression strain due to the wheel load

ε_{R} = strength in relaxation

ε_{Ru} = initial reduced ultimate strain in relaxation

ε_{tu} = maximum ring tensile strain due to internal pressure in the pipe

θ = angle from pipe invert to the perforations

Introduction

Plastic pipe is used in a broad range of applications for soil and water conservation including irrigation, drainage, well casing, pipelines, waste management, and erosion control. Several physical properties of plastic make it acceptable and desirable for use as an engineering material. Some of these properties are abrasion resistance, low friction, toughness, light weight, and good strength. However, plastic has some physical properties that are undesirable. Some of these are combustibility, plastic deformation over time (creep), degradable with time under certain exposure to heat and light, and high coefficient of thermal expansion or contraction.

Polymer chemists have created families of synthetic chemical materials such as polyvinyl chloride (PVC), polyethylene (PE), acrylonitrile - butadiene - styrene (ABS), and polybutylene (PB). Each has a range of characteristics and, depending upon the compound formulated, can have some structural properties as great as and even greater than traditional piping materials.

Plastic materials are divided into two basic groups—thermoset and thermoplastic—both of which are used in the manufacture of plastic pipe. Thermosets are permanently set by either chemical action or heat. By contrast, thermoplastics, as the name implies, soften upon application of heat and harden upon cooling; they can be formed and reformed repeatedly by applying and removing heat. Thermoplastics are used in about 90 percent of the total tonnage of plastic pipe currently produced.

Thermoset Plastics

The thermoset plastics that are used to make pipe and fittings are usually reinforced with some material, such as asbestos, cotton, or glass fibers.

The principal thermoset plastic piping materials are polyester and epoxy plastics that are reinforced with fiberglass and crosslinked polyethylene. The crosslinked polyethylene contains at least 40 percent of carbon black. No figures are available on the production of thermoset plastic pipe but, the total quantity produced is much less than that made of thermoplastics.

Pipes made of these plastics have much higher hydrostatic strengths than thermoplastics and are suitable for use at higher temperatures. Their properties vary widely depending on the base resin and on the type, kind, amount, and orientation of the reinforcement.

Thermoplastics

This technical release, for brevity, will concentrate on the three most widely used types of thermoplastic pipe, namely:

PVC—Polyvinyl Chloride

Available in smooth-wall pipe, corrugated or combinations of these; and is commonly tinted white, green, or blue. Burning PVC gives off highly toxic chlorine gases that may extinguish flames unless a supply of oxygen is available. When tinted, PVC is tolerant to ultraviolet light and is highly susceptible to stress-corrosion.

PE—Polyethylene

Available in smooth-wall pipe and corrugated tubing; and is tinted black, white, gray, red, or yellow. PE is neither fire resistant nor tolerant to ultraviolet light, and is highly susceptible to stress-corrosion.

ABS—Acrylonitrile Butadiene Styrene

Available in smooth-wall pipe and is black. ABS is neither fire resistant nor tolerant to ultraviolet light and is highly susceptible to stress corrosion. An advantageous combination of toughness, good strength, and stiffness largely accounts for the major use of ABS pipe.

Some uses of plastic pipe in installations include irrigation, drainage, erosion control structures, spring development, surface mine reclamation, terraces, waste management systems, water and sediment control basins, wells, and road crossings.

Identification Codes

Plastic piping materials are identified by alpha-numeric codes. These are especially important for materials and pipes having pressure ratings. Although details are given in relevant ASTM Standards, a few examples are included here for convenience.

Typical pipe materials include:

ABS	5-2-2	(Formerly known as Type I Grade 2)	(ASTM D 1788)
PE	11CDP23	(Formerly known as P23, Class C)	(ASTM D 1248)
PVC	12454	(Formerly known as Type I Grade 1)	(ASTM D 1784)

For nonpressure uses, these classifications are based on short-term tests. When used in pressure applications, the long-term properties are also important:

ABS	1210 means an ABS 5-2-2 that has an RHDS* of 1000 psi
PE	2306 means a PE Type II Grade P23 with an RHDS of 630 psi
PVC	1120 means a PVC 12454 that has an RHDS of 2000 psi

* Recommended Hydrostatic Design Stress for water at 73 °F. For higher operating temperatures, design stresses must be reduced.

Summary

In summary, the plastics used for piping have properties that vary between one and another as widely as those between different metals. Consequently, each plastic should be considered as a separate material from other plastics, and when designing the details of a piping system, each one should be evaluated on its own merits and site requirments.

Design of Flexible Conduits Plastic Pipe

Definitions and Terminology

Users of plastic pipe must understand and use the unique terminology correctly. Some of the references and terms are detailed in the following discussion. A glossary of terms is in the appendix. The ASTM D 883–866, Plastics, and ASTM F 412–85, Plastic Piping Systems, define most of the terms used in the industry.

Some terms relating to plastics and plastic pipe:

Rigid plastic

A plastic that has a modulus of elasticity, either in flexure or in tension, greater than 700 MPa (100,000 psi) at 23 °C and 50 percent relative humidity when tested in accordance with ASTM Method D 747, ASTM D 790, ASTM D 638, or ASTM D 882.

Semirigid plastic

A plastic that has a modulus of elasticity, either in flexure or in tension, of between 70 and 700 MPa (10,000 and 100,000 psi) at 23 °C and 50 percent relative humidity when tested in accordance with ASTM D 747, ASTM D 790, ASTM D 638, or ASTM D 882.

Nonrigid plastic

A plastic that has a modulus of elasticity, either in flexure or in tension, of not over 70 MPa (10,000 psi) at 23 °C and 50 percent relative humidity when tested in accordance with ASTM D 790, ASTM D 747, ASTM D 638, or ASTM D 882.

Flexible pipe

A pipe that can deflect at least 2 percent without any structural distress such as rupture or cracking.

Rigid pipe

A pipe that cannot deflect more than 0.10 percent without causing injurious cracks or distress in the pipe.

Elongation
The increase in the vertical diameter of the pipe caused by the bedding soil being placed and compacted beside the pipe.

General Discussion

The design of plastic pipe is a straightforward repetitive procedure that requires attention to detail and exercise of some judgment. Every application is different, and the type of design constraints is diverse. To achieve acceptable perforance of the installed piping system, the design must be analyzed for site specific conditions encountered during and after installation.

Regardless of design criteria, the design process is essentially the selection of a pipe that has the proper size and wall thickness to safely carry the required flow, all external loads, and the system internal pressure for many years within the operating ranges.

The following guidelines are suggested by the plastic pipe industry for the design of plastic pipes:

1. Consider service life requirements.
2. Determine pipe inside diameter needed to meet flow requirements.
3. Determine the pipe size and wall thickness that will meet steady state internal pressure requirements.
4. Consider influence of longitudinal stress and transients.
5. Consider effects of thermal expansion and contraction.
6. Consider the external loads on the pipe.
7. Adjust wall thickness as required for expanded combinations of external loadings.

The step by step procedure in designing a plastic pipe system follows:

System life requirements
Pipe materials must be characterized for their strength under long-term stress and strain. The standard method for determining ultimate long-term strength for plastic pressure pipe under sustained stress is defined in ASTM D 2837 as the Hydrostatic Design Basis (HDB). The following equations are used for the relation between hoop stress in the wall and pressure:

$$P_f = \frac{2f(t)}{(D-t)} \quad \text{(for } \textit{outside diameter controlled pipe}\text{)} \qquad (1)$$

$$P_f = \frac{2f(t)}{(d+t)} \quad \text{(for } \textit{inside diameter controlled pipe}\text{)} \qquad (2)$$

P_r = working pressure
f = design stress
D = average outside diameter
d = average inside diameter
t = minimum wall thickness

The Hydrostatic Design Stress (HDS) is determined by using a factor of safety against the long-term hoop stress Hydrostatic Design Basis. The hydrostatic design basis is determined by first evaluating (1) The hydrostatic strength at 100,000 hours (2) The hydrostatic strength at 50 years (3) The stress that will give 5% expansion at 100,000 hours and then using the results, follow the procedure outlined in paragraph 5.4 of ASTM D 2837. A factor of safety of 2.0 is commonly used for all pipe except AWWA C900 PVC, which has a safety factor of 2.5 (See AWWA C900, Appendix A, paragraph A3.6).

Table 1 provides recommended HDS (wall hoop stress) values for the most common thermoplastic pipe compounds.

Table 1. ***Recommended hydrostatic design stresses for use with water at 23 °C (73.4 °F)***

ASTM Material Designation	HDB, psi	HDS, psi
D 1788		
ABS 1208	1600	800
ABS 1210	2000	1000
ABS 1316	3200	1600
ABS 2112	2500	1250
D 1248		
PE 1404	800	400
PE 2305	1000	500
PE 2306	1260	630
PE 3306	1260	630
PE 3406	1260	630
PE 3408	1600	800
D 1784		
PVC 1120	4000	2000
PVC 1220	4000	2000
PVC 2110	2000	1000
PVC 2112	2500	1250
PVC 2116	3200	1600
CPVC* 2120	4000	2000
CPVC* 4116	3200	1600
CPVC* 4120	4000	2000

* Chlorinated polyvinyl chloride

System flow requirements

In designing any plastic pipe system, pressure losses caused by fittings, pipe friction, changes in alignment and elevation, or similar problems, are all considered when the system is expected to operate under pressure.

Selection based on pressurized flow

The pipe selection process may need to be repeated to find a pipe that has the right combination of diameter, flow capacity and velocity, and an acceptable pressure drop. The Hazen and Williams formula may be used to determine the pressure loss caused by friction.

The Hazen and Williams formula

$$\Delta P_{100} = \frac{452 Q_g^{1.85}}{C^{1.85} d^{4.86}} \qquad (3)$$

Where:

ΔP_{100} = Friction pressure loss, in pounds per square inch per 100 feet of pipe
Q_g = Rate of flow, U.S. gallons per minute
C = Pipe coefficient (Chezy)
d = Pipe internal diameter, inches

The coefficient C is essentially a friction factor. "C" values vary for plastic pipe from 150 for ABS and PVC to 155 for PE.

Fitting pressure drop

Listed below in Table 2 are various common piping system components and the associated pressure loss through the fitting expressed as an equivalent length of straight pipe in terms of diameters. The inside diameter (in inches) multiplied by the equivalent length diameters gives the equivalent length (in feet) of pipe. This equivalent length of pipe is added to the total footage of the piping system when calculating the total system pressure drop.

These equivalent lengths were developed from an average of published data and thus should be considered an approximation suitable for most installations.

Table 2. ***Equivalent length of fittings***

Fabricated Fitting	Equivalent Length in Feet
Running Tee	1.667 d *
Branch Tee	4.167 d
90° Fab, Ell	2.500 d
60° Fab, Ell	2.083 d
45° Fab, Ell	1.500 d
45° Fab, Wye	5.000 d
Conventional Globe Valve (Full Open)	29.167 d
Conventional Angle Valve (Full Open)	15.000 d
Conventional Wedge Gate Valve (Full Open)	1.250 d
Butterfly Valve (Full Open)	3.333 d
Conventional Swing Check Valve	8.333 d

*d = inside diameter in inches

Design precautions

After appropriate pipe sizes, based upon flow requirements, have been selected the designer should consider the following before proceeding with the remaining design steps:

The system pressure drop (including fittings and transients) should not exceed the pressure rating of the pipe selected.

The pump pressure should exceed the system pressure drop, but should not exceed the pressure rating or pressure class of the pipe selected.

Pipe flow

Pipe flow systems are typified by irrigation pipelines, as well as water and slurry pipelines. Some may operate with full flow and some may operate partially full.

Full flow. Four things are required to select and size a pipe for a full flow system: (1) flow-rate requirements, (2) the elevation change of the pipeline, (3) the pipe roughness, and (4) a selection of an appropriate pipe inside diameter.

Based upon a full flow situation, the flow rate can be calculated from the Manning's equation as follows:

$$Q = \frac{1.486}{n} A r^{2/3} S^{1/2} \tag{4}$$

Where:

Q = Flow in CFS
r = Hydraulic radius, ft
S = Friction slope, ft/ft
A = Cross sectional area of pipe I.D., ft^2
n = Roughness coefficient

Partial flow. A gravity pipeline at the same energy slope will carry more liquid when flowing 85 percent to 95 percent full than when 100 percent full. This is recognized as the effect of reduced friction because of the liquid's contact with less pipe wall surface. The discharge rate of partial flow pipelines can be calculated by using Manning's equation. Table 3 illustrates the changes in velocity and flow capacity when compared to full flow.

Table 3. ***Carrying capacity of partially full pipes***

Percent Full	Velocity (percent of Full)	Flow Capacity (percent of Full)
100	100	100
95	111	106.3
90	115	107.3
80	116	98
70	114	84
60	108	67
50	88	33
30	72	19
25	65	14
20	56	9
10	36	3

Standard dimension ratio and internal pressure rating

SDR is the abbreviation for the "Standard Dimension Ratio." *DR* is used when a nonstandard dimension ratio is referenced. *SDR* or *DR* is the ratio of the pipe outside diameter to the minimum thickness of the wall of the pipe. The ratio can be expressed mathematically as:

$$SDR \text{ or } DR = \frac{D}{t} \quad (\text{for OD controlled pipe}) \tag{5}$$

or

$$DR = \frac{d}{t} \quad (\text{for ID controlled pipe}) \tag{6}$$

SDR = Standard Dimension Ratio as defined by ASTM F 412
D = Average pipe outside diameter in inches
d = Average pipe inside diameter in inches
t = Pipe minimum wall thickness in inches

For a given SDR, the ratio of the D to the minimum wall thickness remains constant. An SDR 11 means the D of the pipe is eleven times the thickness of the wall. This remains true regardless of diameter. For example, a 14-inch diameter pipe with a wall thickness of 1.273 inches is an SDR 11 pipe. A 18-inch diameter pipe with a wall thickness of 1.637 inches is also an SDR 11 pipe. Common SDR ratios are SDR 13.5, SDR 17, SDR 21, SDR 26, and SDR 32.5. *For high SDR ratios, the pipe wall is thin in comparison to the pipe D. For low SDR ratios, the pipe wall is thick in comparison to the pipe D.* By definition most references consider SDR ≤ 20 to be thick wall cylinders. However, all literature to date has treated PVC pipe, regardless of SDR, as thin walled cylinders. Given two pipes of the same D, the pipe with the thicker wall will be stronger than the one with the thinner wall. (However wall strength is not the sole criterion of design. Strain limitations sometimes control design, at which time the thicker wall is not always the best alternative.) *Thus, high SDR's have low pressure ratings and low SDR's correspond to high pressure ratings because of the relative wall thickness.*

The pressure rating of thermoplastic pipe is mathematically calculated from the SDR and an allowable hoop stress. The allowable hoop stress is commonly known as the long-term hydrostatic design stress. It is the stress level (laboratory tested and field proven) which can exist in the pipe wall continually with a high degree of confidence that the pipe will operate under pressure with safety. The formula relating SDR and hydrostatic design stress has been adopted as the standard for the industry by ISO (International Standards Organization), ASTM (American Society for Testing Materials), and PPI (Plastic Pipe Institute) (See ASTM D 1785, ASTM D 2241, ISO R161–1960, Unibel Handbook of PVC pipe).

The formula for use with outside diameter controlled pipe is:

$$P_r = \frac{2f\,(t)}{(D-t)} \quad or \quad P_r = \frac{2f}{SDR-1} \qquad (1)$$

Where:

P_r = *Pressure rating, psi*
f = *Hydrostatic Design Stress*
D = *Average pipe outside diameter, in*
t = *Minimum wall thickness, in*
$SDR = \frac{D}{t}$

For inside diameter controlled pipe, the equation becomes $P_r = \frac{2f}{SDR+1}$ (2)

Both may be derived from the equation for wall hoop–stress in hollow cylinders,

$$f = \frac{P_r\,D_m}{2\,t} \qquad (6)$$

From the formula it can be shown that all pipes of the same SDR (regardless of diameter) will have the same pressure rating for a given design stress. Thus, a 36-inch diameter SDR 32.5 pipe has the same pressure rating as a 14-inch SDR 32.5.

Other system pressure requirements

Most pipeline systems are designed for one of two types of service: (a) pressure flow; or (b) non-pressure flow.

When designing a pressurized pipe system, the pipe selected must withstand the internal pressure safely and continuously for many years.

Water hammer/pressure surge

Any moving object has mass and velocity. Hence, any flowing liquid has momentum and inertia. When flow is suddenly stopped, the mass inertia of the flowing stream is converted into a shock wave or high static head on the pressure side of the pipeline. Some of the more common causes of hydraulic transients are (a) the opening and closing (full or partial) of valves; (b) starting and stopping of pumps; and (c) entrapped air (usually accumulates at high points in the line and is the result of pipeline filling or release of dissolved air in the liquid).

Instantaneous surge pressures are shock waves known as "water hammer." The pressure wave caused by water hammer races back and forth in the pipe getting progressively weaker with each hammer. The magnitude of the pressure change caused by a water hammer shock wave depends upon the elastic properties of the pipe and liquid as well as upon the magnitude and rapidity of the shock wave's velocity change. The maximum surge pressure results when the time required to change a flowstream velocity a given amount is equal to or less than $2L/V_w$ such that:

$$T \le \frac{2L}{V_w} \tag{7}$$

Where:

$$V_w = 12\sqrt{\frac{KE}{\frac{\gamma}{g}\left[E + K\left(\frac{d}{t}\right)\right]}} \tag{8}$$

Where:

K = Bulk modulus of the liquid, psi
= 300,000 psi for water
E = Modulus of elasticity of pipe material, psi
γ = Unit weight of fluid, lb/ft^3
g = Acceleration due to gravity
= 32.2 ft/sec/sec

The pressure change caused by water hammer is:

(9)

Where:

ΔP = Change in pressure, psi
ΔV = Change in velocity, ft/sec occurring within critical time $2L/V_w$.
γ, g and V_w are as above.

The following example illustrates the use of these equations.

Example:
Water is flowing in a 6 inch PE pipeline with an *SDR* of 21 at a velocity of 10 ft/sec. Determine the maximum pressure increase when a valve is closed in a time equal to or less than $2L/V_w$.

Where:

$SDR = 21$ $\quad K = 300{,}000\,psi$ $\quad E = 100{,}000\,psi$ $\quad d=5.972$

$$V_w = 12\sqrt{\frac{(300{,}000)\ (100{,}000)}{\frac{62.4}{32.2}\left[100{,}000 + 300{,}000\left(\frac{5.972}{0.315}\right)\right]}} = 620.622\ ft/\sec \qquad (8)$$

$$V = 10 - 0 = 10\,ft/sec$$

$$\Delta P = [(62.4/32.2)(620.622)(10)] \div 144 = 83.52\ psi$$

The use of 100,000 psi for the modulus of elasticity for PE pipe is justified by the short-term duration of the pressure surges and the rapidity with which the surges are dampened. Because the long-term modulus on which allowable operating pressures are based is only a fraction of the short-term modulus, occasional total overpressure caused by pressure surges up to 2.5 times rated pressure can be tolerated safely. The changes in pressure can be minimized by using a valve closure time greater than $2L/V_w$. Because the magnitude of the surge is basically a function of the rate of velocity change, particular attention should be given to the final portion of valve closure. This is the time during maximum change in velocity of the flowing liquid. The actual increase in pressure caused by valve closure is difficult to determine. A closure time of 10 times $2L/V_w$ for a gate valve that has linear closure characteristics should reduce the pressure surge to the range of 10 to 20 percent of the surge caused by closure in a time equal to or less than $2L/V_w$.

In general, good system design will eliminate quick opening/closing valves on anything but very small or very short lines. The design engineer should use judgement with regard to the addition of surge pressures to operating pressures when selecting pipe SDR's. The following rules of thumb may help:

> Occasional shock pressures can be accommodated within the design safety factor. Because of the short time duration of the surge pressure, occasional shock wave surge pressures to 2.5 times the SDR pressure rating at 73.4 °F are usually allowable.
>
> If surge pressure or water hammer is expected, maximize the time required to shut off a valve or reduce flow. A valve shutting period 6-10 times longer than the time period $2L/V_w$ is suggested to minimize surge pressures by gradually slowing the fluid flowstream.

Any system with a velocity in excess of 2 ft/sec should be examined for overpressurization caused by water hammer.

If constant and repetitive surge pressure are present, the excess pressure should be added to nominal operating pressure when selecting the pipe SDR.

Longitudinal stress from internal pressure

When a fully restrained pipeline such as a buried or well anchored pipeline is pressurized, longitudinal stresses develop in the pipe wall. The longitudinal stress is calculated as follows:

$$\delta_L = \frac{\mu P_f (D - t)}{2t} \qquad (10)$$

Where:

δ_L = Longitudinal tensile stress, psi
μ = Poisson's ratio. Varies from 0.30 to 0.45 for all thermoplastics.
P_f = Internal operating pressure, psi
D = Average pipe outside diameter, inches
t = Pipe wall thickness, inches

Because most pressurized pipe systems are buried, they operate under a dual state of stress; hoop stress and longitudinal stress. The longitudinal stress factor is already included in the pipe's pressure rating at normal temperature.

Thermal considerations

All thermoplastics respond to changes in temperature in a predictable manner. Tests have been conducted on various types of pipe to define its response to temperature within a practical range from below freezing to +180 °F. The results of such testing allow the pipeline designer to design an installation to match design criteria while minimizing compensations required for thermal expansion and contraction.

The following is a discussion on thermal expansion and contraction by the Plastic Pipe Institute in its Plastic Piping Manual, First Edition, 1976, Chapter 3, Design Parameters.

Thermal movement

Expansion and contraction of piping systems because of temperature changes are not unique to plastics. All materials undergo dimensional changes, to some degree,due to temperature variations. The amount of change depends on the material characteristic (coefficient of linear thermal expansion) and the magnitude of the temperature change. Everyone is familiar with the typical expansion loops put in long steel pipelines (such as steam lines) where large temperature changes are expected.

Because plastics have substantially larger coefficients of thermal expansion than metals, there is considerable concern about this property. However, laboratory testing and installation experience have demonstrated that the problems are not as great as the coefficients would suggest. The interplay of other properties such as modulus, stress relaxation, and thermal conductivity effectively reduce the magnitude of the problem. The stresses developed in plastic pipe are generally much smaller than those developed in metal pipe for equal temperature changes because of the differences in the elastic moduli.

These various aspects of thermal expansion and contraction are discussed in detail below, together with established methods of compensating for dimensional changes.

Coefficients of linear thermal expansion

Coefficients of thermal expansion (and contraction) for a number of materials commonly used for pipe are given in Appendix "E". It should be noted that these are only typical values, and actual values for specific compounds may be larger or smaller. These coefficients are determined in accordance with ASTM D 696 and are based on completely unrestrained specimens.

Underground piping

The detailed techniques used when installing pipe vary, and are partially dependent on whether the pipe is classified as continuous or jointed. These terms are relative, and are dependent on the pipe diameter, its wall thickness, the flexural modulus of the material, and the pipe temperature. Continuous refers to pipe that can be readily coiled and uncoiled, and which is usually provided in coils or on reels. Jointed pipe is usually supplied in straight lengths, and although snaking is practical in some cases, expansion loops or other designs are typically required to cope with thermal movement for jointed piping.

Expansion-contraction problems in underground installations are relatively easy to solve because temperature changes are usually less drastic. Piping is not exposed to direct heating from solar radiation and the insulating nature of the soil prevents rapid temperature changes. The temperature of the transported medium often has a stabilizing effect on the pipe temperature, and, in addition, the earth cover generally imposes a restraint on the system.

Contraction of continuous pipe can readily be accommodated by snaking the pipe in the ditch. An approximate sine wave configuration will accommodate most situations.

The installation should be brought to the service temperature before to backfilling.

If expansion of the pipe is expected, the pipe should be installed straight, brought to the service temperature, and take up the increased length by snaking. The trench may then be backfilled in the normal manner.

Jointed pipe with solvent cemented joints or other couplings, up to 3 in. nominal size, can be handled by snaking in the same manner as for coiled pipe, provided the joint has cured sufficiently. For runs less than 30 feet, 90 degree changes in direction will readily take up any expansion or contraction that may occur.

For larger sizes of pipe, snaking is not practical, or possible, in most cases. When snaking is not possible the line should be completely installed except that it is left free at one end. The pipe is then brought to within 15 °F of the service temperature and the final connection made. This can be accomplished by shading backfilling, allowing the pipe to cool at night and then connecting early in the morning, or cooling with water. The stresses produced by the final 15 °F temperature change will be absorbed by the piping.

Pipe coupled with slip joints having elastomeric seals that have sufficient latitude for movement does not require any special precautions to handle thermal expansion and contraction because these dimensional changes are taken up by movement in each joint.

Aboveground piping

Aboveground piping generally undergoes larger and more frequent temperature changes than underground piping because of atmospheric temperature changes and the greater temperature differentials of the materials being conveyed. Pipe supports should permit longitudinal movement of the pipe.

If runs in excess of 20 ft are required, flexural offsets or loops should be provided. To not exceed the maximum allowable strain in the piping, the developed length that should be provided in the offset or loop can be calculated from the equation.

$$y = \frac{F\,L^3}{3\,E\,I} \qquad (11)$$

Where:

y = maximum deflection at the end of a cantilever beam, in
F = force at end, lb
L = length of pipe subjected to flexural stress, in
E = flexural modulus of elasticity, psi
I = moment of inertia, in^4

The following symbols are also used in this section:

D = average outside diameter, in
R_o = outside radius, in
R_i = inside radius, in
t = wall thickness, in
M = bending moment = FL, lb-in
ε = strain
f = fiber stress $\frac{M}{Z}$, psi
Z = section modulus, in^3

Note, also, that y is the maximum expansion or contraction to be accommodated (in).

For pipes in which the wall thickness is large with respect to the outside diameter, (SDR≤ 20)

$$I = \frac{\pi}{4}\left(R_o^4 - R_i^4\right) \qquad (12)$$

$$Z = \frac{\pi}{4}\left(\frac{R_o^4 - R_i^4}{R_o}\right) \qquad (13)$$

When the wall thickness is not large with respect to the outside diameter (which is the case for most plastic pipes) these equations can be expressed as:

$$I = \pi\,R_o^3\,t \qquad (12a)$$

$$Z = \pi\,R_o^2\,t \qquad (13a)$$

Therefore, for most plastic piping

$$I = \frac{\pi D^3 t}{8} \qquad (12b)$$

$$Z = \frac{\pi D^2 t}{4} \qquad (13b)$$

$$f = \frac{4F \ L}{\pi D^2 t} \qquad (14)$$

$$F = \frac{\pi D^2 f \ (t)}{4L} \qquad (15)$$

Substituting in equation (11)

$$y = \frac{2f \ L^2}{3E \ D} \qquad (11a)$$

(11b)

(11c)

Equation (11b) is used when the maximum allowable stress is fixed and equation (11c) when the maximum allowable strain is fixed. When equation (11b) is used, the flexural modulus of elasticity must be known. In cases where the modulus of the specific compound is not available, the following approximate average values are usually adequate:

Compound	Flexural modulus (psi)
PVC 1120	400,000
PVC 2110	320,000
ABS 1210	240,000
ABS 1316	340,000
PE 2306	90,000
PE 3306	120,000

Using the above values, equation (11b) reduces to

Compound	Equation (11b) L, in.
PVC 1120	$17.3\,(Dy)^{1/2}$
PVC 2110	$22.8\,(Dy)^{1/2}$
ABS 1210	$19.0\,(Dy)^{1/2}$
ABS 1316	$17.9\,(Dy)^{1/2}$
PE 2306	$14.6\,(Dy)^{1/2}$
PE 3306	$16.9\,(Dy)^{1/2}$

Apparently an approximate value of 18 $(Dy)^{1/2}$ in. is sufficiently precise in most cases for use with most thermoplastic pipe covered by current ASTM standards.

Alternately, using a *maximum allowable strain of 0.01*, equation (11c) reduces to

$$L = 12.2(Dy)^{1/2}\ in. \tag{11d}$$

Superimposed loads

Previous design steps analyzed pipeline stresses developed by internal flow and pressure. This section deals with the stresses imposed on a pipeline by external forces, namely earth load and live loads on buried pipe.

When pipelines are buried, they are subjected to external loads. The effect of external pressure on flexible pipe is more complex than the effect of internal pressure only. For design purposes, a distinction is usually made between rigid and flexible pipes. A rigid pipeline (such as concrete) is considered to be the total structure and must be designed to sustain all external loads as well as internal pressure. But, a flexible pipe is considered to be only one component of the "pipe-soil" system.

Thus, in a buried situation, the SDR of the pipe and the strength of the soil envelope must be specified to keep the three burial design parameters (wall crushing, wall buckling, and ring deflection) within acceptable limits. The pipe and soil envelope become one system. The mutual interaction and strength contributions of the pipe to the soil and the soil to the pipe results in a highly successful integral structure. Correct design centers around two points:

1. Matching the proper wall thickness to the external soil pressure, and

2. The analysis of how the pipe and the soil surrounding it accept the earthloading and transfer it to the undisturbed walls of the ditch or trench such that the pipeline will deflect slightly into static equilibrium with the soil.

Structural design of flexible conduits

Design of flexible conduits is a relatively new design theory. Test data is limited and design parameters and coefficients are based on past experiences with rigid pipelines (concrete, asbestos-cement, cast iron, and/or steel). Published research and design analysis to date has been for thin-walled pipe [dimension ratio (DR) > 20]. Therefore this TR will be developed assuming all pipe acts as thin-walled pipe.

The design analysis chosen for use in SCS work is the procedure developed by R. E. Chambers, T. J. McGrath, and F. J. Heger (National Cooperative Highway Research Program Report 225 "Plastic Pipe for Subsurface Drainage of Transportation Facilities)." This analysis has been expanded and updated by ASCE Manuals and Reports on Engineering Practice No. 63, "Structural Plastics Design Manual." Minor variations of equations presented in this TR from those in the ASCE Manual No. 63 are the result of more recent developments or assumptions of the SNTC staff when deriving the equations from basic, long-recognized hollow-cylinder equations.

Service limits. To design a flexible conduit the designer tries several pipes in the site-specific conditions that exist and selects the pipe that meets the design criteria. The designer must check the pipe-soil system for the deflection, strain, and buckling resistance for the service limitations. Currently the service limits recommended are:

Deflection limits.

long term 5%
short term 3%

Strain limits. Strains caused by bending and axial stresses are combined in interaction equations. These strains are the result of all the loads, both internal and external, to which the pipe cross section will be subjected. This assures that bending strains, when compared to allowable relaxation strains (constant strain), combined with axial strains, when compared to allowable creep strains (constant stress), do not exceed unity. Corrections are made for the influence of both perforations (where appropriate) and rerounding of the pipe.

Buckling resistance. Buckling is checked by comparing combined external loads plus an internal vacuum to the load obtained from the Modified AWWA formula. This formula considers the influence of the pipe deflection, pipe cross sectional properties, and soil embedment properties. An additional check is made that compares the combined influence of external hydrostatic and internal vacuum loads to an allowable load which is a function of the pipe stiffness and the embedment soils.

Flexible pipe is dependent on the soil-pipe interaction for its strength in service. Flexible pipe derives its load carrying ability from the deflection of the pipe that is sufficient to develop passive soil support at the sides of the pipe. This lateral support prevents a properly designed pipe from developing large deflections, thus allowing the pipe cross section to carry much of the load in ring compression while ring deflection permits much of the vertical load to be carried by the surrounding soil through arching over the pipe. The designer must specify the correct pipe, soil, embedment, soil densification, bedding, and haunching so that the necessary soil-pipe interaction can develop.

Strength relationships for pipe materials are in the appropriate ASTM specification. The ASCE Manual No. 63 contains a detailed discussion of strength parameters to be used in plastic pipe design. Some of the factors are:

1. Hydrostatic Design Basis (HDB) = Hydrostatic Design Stress x Service Factor (Safety Factor)

2. Creep Factor

$$\overline{CF} = \frac{E_o}{E_{10}} \tag{16}$$

3. Strength in Creep (constant stress)

$$\varepsilon_C = \frac{HDB}{E_o} \ ,\% \tag{17}$$

4. Strength in Relaxation (constant strain)

$$\varepsilon_R = \frac{HDB}{E_o}\overline{CF} \ ,\% \tag{18}$$

Safety factors. As with all designs, safety factors are included to account for variations from assumed conditions. These factors are in the form of capacity reduction factors and load factors.

Capacity reduction factors account for variations in materials, ultraviolet exposure, scratches, variation of cross section, and other strength-reducing problems. Capacity reduction factors currently recommended are:

For pipe stiffness for buckling, ϕ''	= 0.75
For pipe strength, ϕ	= 0.80
For soil modulus of soil reaction	= 0.50

Load factors are used to account for overloads, surges, impacts, and other load variations that cannot be predicted accurately. Load factors, $\overline{LF}$, currently recommended for use in SCS work are:

Vehicle load factor = 1.8 maximum, 0.0 minimum

Earth load factor = 1.5 maximum, 0.80 minimum

Groundwater load factor = 1.0 (in most SCS designs, the designer should be able to estimate maximum groundwater accurately)

Installation load factor = 1.0

Vacuum load factor = 1.2

Internal pressure load factor = 2.0

Loads. The prism load theory is used to determine the soil load above the pipe. This will yield a conservative soil load because, as the flexible pipe deflects with any load increase, some of the prism load is transferred into the sidewalls of the trench, thus reducing the load transmitted to the pipe. The soil load in this analysis is the total weight of soil above the outside diameter of the pipe per unit of length. The earth pressure without a load factor is represented by

$$P_s = \frac{\gamma_s\ h}{144},\ lbs/in^2 \tag{21}$$

When groundwater is above the top of the pipe, the earth pressure, P_s, may be reduced for buoyancy by the factor C_w.

$$Cw = 1 - \frac{h_w}{3h} \tag{19}$$

Where h = height of the soil above the top of the pipe and h_w=height of water above the top of the pipe. When adjusted for load factors

$$P_{su} = P_s\ \overline{LF}\ \text{(maximum)} \tag{22}$$

$$P'_{su} = P_s\ \overline{LF}\ \text{(minimum)} \tag{23}$$

The effect of wheel loads varies with depth. The Boussinesq theory was used to verify the equations given in SCS West Technical Note Number 1, "External Loads on Rigid Pipe Conduits," September 1982. The equations for wheel loads, excluding impact factor and load factors are:

$$if\ D-t < 2.67h\,(12)$$

$$P_{wh} = \frac{0.48\,P_{wL}\left(\dfrac{D-t}{12}\right)^2}{2.67\,h^3\,(D-\ t)\,12}\left[\frac{2.67\,h}{\dfrac{D-t}{12}} - 0.5\right] \tag{24}$$

$$if\ D-t \geq 2.67h\,(12)$$

$$P_{wh} = \frac{0.64\,P_{wL}}{h(D-t)\ 12} \tag{25}$$

Wheel loads multiplied by an impact factor accounts for the reduction of the effect of wheel loads with depth.

$$\text{Impact factor, } \overline{IF} = \frac{\text{wheel load}}{\text{wheel load + soil load}} + 1 \tag{20}$$

Including impact factor the equations become:

$$P_w = P_{wh}\left(\overline{IF}\right) \tag{26}$$

and adjusted for load factors

$$P_{wu} = P_w\left(\overline{LF}\right) \text{ maximum} \tag{27}$$

$$P'_{wu} = 0 \text{ minimum (No wheel load)} \tag{28}$$

Deflection. One of the limiting criteria of design is deflection expressed in percent or inches of vertical deflection divided by the mean diameter in inches. The average deflection may be calculated and an installation deflection is added to obtain the maximum deflection. For SCS work, acceptable limits are 3% for short-term deflection and 5% for long-term deflection. Short-term deflection is that deflection that occurs during construction. The deflection limits were established primarily to prevent joint leakage and to permit cleanout by pulling a plug through the pipe rather than for reasons of structural distress.

The Modified Iowa Formula is the basis for determination of the average deflection created by the earth load.

$$\frac{\Delta_s}{2R_m} = \frac{K_b P_s D_L}{0.149\,\overline{PS_o} + 0.061\,E'} \tag{29}$$

K_b is the bedding constant and varies from 0.083 for pipe bedded to the springline to 0.110 for pipe that has zero bedding angle. Unless otherwise known, a value of $K_b = 0.10$ may be used.

P_s is the earth load in psi above the pipe.

D_L is the deflection lag factor. A value of 1.0 is recommended for initial or short term deflections and 1.5 for the long term deflections. The deflection lag factor was recommended by Spangler to account for the increase in load caused by the consolidation of the soil at the sides of the pipe, which is a function of time.

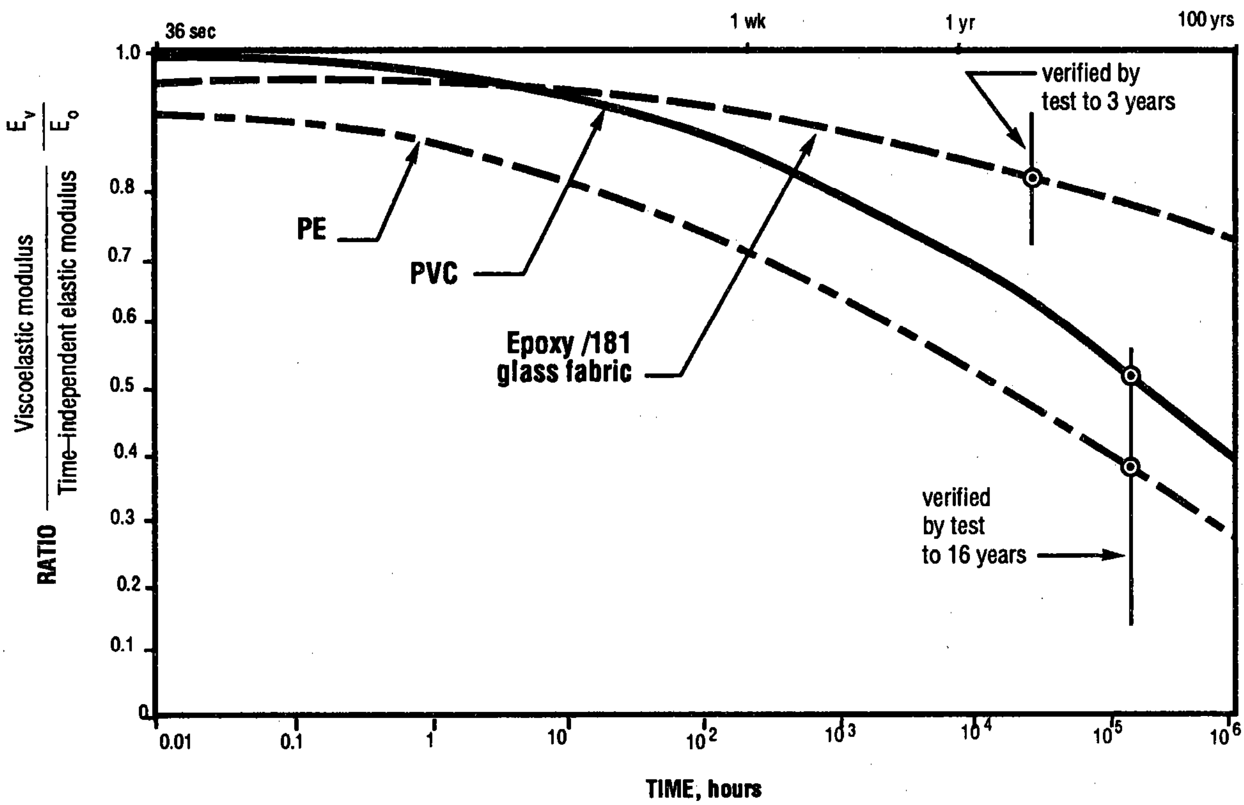
$\overline{PS_o}$ is the pipe stiffness computed from the equation

$$\overline{PS_o} = 4.47\frac{E_o}{(DR-1)^3} \tag{30}$$

for OD-controlled pipe.

E_0 is used for all computations of deflection, no matter whether the short- term or long-term deflection value is desired. For the purposes of this discussion, long-term is defined as 10 years in the United States and 50 years in Europe. Figure 1 shows the ratio of the decrease of the E_0 value with time for the thermoplastics polyethylene and polyvinyl chloride.

Figure 1. ***Variation in viscoelastic modulus with time***



The question arises "Why not use a different E value when comparing deflection for a 10-year-old pipe than the value used for a new pipe?" The following discussion is this author's rationale for using only E_0 to calculate deflection.

Many technical articles were studied in the preparation of this Technical Release(TR). Most articles report that properly installed thermoplastic pipe did not deflect any significant amount after completion of loading or at least by the end of the first year following installation. The E_1 is approximately 0.70 E_0. In the Iowa equation the E value has a small effect on deflection, therefore a 30% reduction of E would be insignificant in the deflection computation.

Another consideration is the effects of the pipe-soil relationship and the value of the pipe E. In other words, at what point in the aging of the pipe does the sidewall support and arching effect of the soil become the major factor in the computation of deflection? Currently the Iowa equation assumes the pipe-soil relationship is fully developed upon completion of fill for granular and low plastic soils. There is no data available for use with highly plastic soils that may creep when a load is applied or shrink significantly when dried. One could write an equation for the variation of E with time and

substitute that equation into the Iowa equation. However, if that degree of accuracy is needed, one must also account for the effects of temperature change and environment, as both affect the aging E value. Structural design of thermoplastic pipe has not evolved to this precision.

E' is the modulus of soil reaction of the embedment material and is defined in the following table.

Table 4. ***Average values of modulus of soil reaction***

Embedment material per Unified Soil Classification System ASTM D 2487	Average E' for degree of compaction of bedding (lb / in²) [1,3]			
	Dumped	Lass than 85% of maximum density	85 to 95% of maximum density	Greater than 95% of maximum density
Crushed rock	1,000	3,000	3,000	3,000
Coarse grained soil with little or no fines GW, GP, SW, SP contains less than 5 percent fines.	200	1,000	2,000	3,000
Coarse–grained soils with fines GW, G< SM, SC contains more than 12 percent fines	100	400	1,000	2,000
Fine–grained soils (LL<50)[2] soils with medium to no plasticity CL, ML, ML–CL, with more than 25 percent coarse–grained particles	50	200	400	1,000
Fine–grained soils (LL<50)[2] Soils with medium to no plasticity CL, ML, ML–CL, with less than 25 percent coarse–grained particles	50	200	400	1,000
Fine–grained soils (LL>50)[2] Soils with medium to high plasticity CH, MH, CH–MH		No data Availavble		

Notes:
1. Source ASTM D 3839–79
2. LL= Liquid limit.
3. Maximum density determined in accordance with ASTM D 698
4. $1 lb / in^2 = 1 psi = 6.9 kPa$

The average deflection caused by wheel loads may be calculated in essentially the same manner. The D_L = 1.0 and E' is reduced by "n_w", a multiplier, to account for the rapid loading and unloading before soil support can develop. Currently n_w = 0.5 is recommended.

$$\frac{\Delta_w}{2\,R_m} = \frac{K_b P_w D_L}{0.149\,\overline{PS_o} + 0.061\,E' n_w} \tag{29a}$$

An installation deflection is recommended that should be added to the calculated average deflection. The installation deflection is based upon the measurements of many installed flexible pipe systems and accounts for the deflection that may occur because of installation quality. The installation deflection currently used by the industry is shown in the following table.

Table 5. ***Tentative design installation deflection***

	Installation deflection ($\Delta_i/2R_m$) (%) [1]		
Pipe stiffness $\overline{PS}_o$ (lb/in/in) [4]	Embedment Less than 85% pf Max. dry density [2] or dumped [3]	Embedment 85 to 95% of Max. dry density [2]	Embedment greater than 95% of Max. dry density [2]
Less than 40	6+	4	3
40 to 100	4+	3	2
Greater than 100	2+	2	1

Notes: [1] Deflections of unhaunched pipe are significantly larger.
[2] Maximum dry density determined in accordance with ASTM D 698
[3] Dumped materials and materials with less than 85 percent maximum dry density are not recommended for embedment. Deflection values are provided for information only.
[4] 1 lb/in/in = 6.9 kPa

Strains. Research published to date indicates a wide variation of opinion on strain and its importance as a structural limitation in plastic pipe design. The recommended strain consideration is presented in the following analysis. The strains considered are ring bending, resulting from nonuniform external loads, and tensile and compressive strains resulting from internal or external radial loads (or loads that otherwise create axial stresses) with the appropriate load factor adjustment.

The equations for the various strain components are as follows:

(1) Ring bending strain

Due to soil loads:

$$\varepsilon_{bsu} = 2.5 \frac{t}{R_m} \overline{MF} \frac{\Delta_s}{2 R_m} \overline{LF} \tag{31a}$$

Use maximum load factor

Due to wheel loads:

$$\varepsilon_{bwu} = 2.5 \frac{t}{R_m} \overline{MF} \frac{\Delta_w}{2 R_m} \overline{LF} \tag{32a}$$

Use maximum load factor

Due to installation:

$$\varepsilon_{biu} = 2.14 \frac{t}{R_m} \overline{MF} \frac{\Delta_i}{2 R_m} \overline{LF} \tag{33a}$$

Total factored ring bending strain

$$\varepsilon_{bu} = \varepsilon_{bsu} + \varepsilon_{bwu} + \varepsilon_{biu} \tag{34a}$$

(2) Ring tension strain from internal pressure

$$\varepsilon_{tu} = \frac{P_{fu} R_i}{t E_o} \tag{35}$$

(3) Ring compression from internal and external loads

Earth maximum $\varepsilon_{csu} = \left| \frac{R_o}{t E_o} \right| x \; P_{su}$ (36)

minimum $\varepsilon'_{csu} = \left| \frac{R_o}{t E_o} \right| x \; P'_{su'}$ (36a)

Vehicle maximum $\varepsilon_{cwu} = \left| \frac{R_o}{t E_o} \right| x \; P_{wu}$ (37)

minimum $\varepsilon'_{cwu} = \left| \frac{R_o}{t E_o} \right| x \; P'_{wu} = 0$ (37a)

Groundwater $\varepsilon_{cgu} = \frac{R_o}{tE_o} \times P_{gu}$ (38)

Vacuum $\varepsilon_{cvu} = \frac{R_i}{tE_o} \times P_{vu}$ (39)

The symbol, $\overline{MF}$, is a factor that accounts for the effects of bedding and haunching on bending moments and bending strains. Based on limited field observations and tests, a value of 1.5 is recommended for unhaunched pipe, 0.75 for carefully bedded and haunched pipe, and 1.0 for some intermediate range of installation conditions.

The points of maximum ring bending strain are the crown, springline, and invert. The equations for ring bending strain shown above are for determining the ring bending strain at the maximum points only. For most designs ring bending strain at the crown, springline, or invert is a critical design element of strain, but in some instances checking the ring bending strain may be necessary at some other point. An example is perforated pipe which requires consideration of strain concentrations. When perforated pipe is used, a perforation factor, $\overline{PF}$, is introduced. See table 7. A moment coefficient is used in the above ring-bending strain equations to account for the perforation location and is based on the angle θ as measured from the invert to the perforation. The moment coefficients are shown in the following table.

Table 6. ***Moment coefficient for use with perforated pipe, C_m***

θ	Coefficient	θ	Coefficient
0	0.2500	50	0.0434
10	0.2349	60	0.1250
20	0.1915	70	0.1915
30	0.1250	80	0.2349
40	0.0434	90	0.2500
45	0.0000		

Table 7. ***Perforation factors for strain concentrations***

Condition	Perforation factor ($\overline{PF}$)
Circular hole in smooth-wall pipe in bending	2.3
Circular hole, uniform tension (e.g, one shell of ABS Composite, or in flanges of corrugated tubing)	3.0
Circumferential slot, rounded ends, assume aspect ratio = 8x1 (e.g., 1 inch circumferential slot, 1/8 inch width; factor varies with actual aspect ratio)	1.3

The equations for ring bending strains at the perforations become:

$$\overline{PF}\,\varepsilon_{bsu} = 10\frac{t}{R_m} C_m \overline{MF} \frac{\Delta_s}{2\,R_m} \overline{LF}\,\overline{PF} \quad (31)$$

$$\overline{PF}\,\varepsilon_{bwu} = 10\frac{t}{R_m} C_m \overline{MF} \frac{\Delta_w}{2\,R_m} \overline{LF}\,\overline{PF} \quad (32)$$

$$\overline{PF}\,\varepsilon_{biu} = 8.56\frac{t}{R_m} C_m \overline{MF} \frac{\Delta_i}{2\,R_m} \overline{LF}\,\overline{PF} \quad (33)$$

The total ring bending strain at the perforations is the sum of the ring bending strains at the perforations.

$$\overline{PF}\,\varepsilon_{bu} = \overline{PF}\,\varepsilon_{bsu} + \overline{PF}\,\varepsilon_{bwu} + \overline{PF}\,\varepsilon_{biu} \quad (34)$$

The factored ring tensile strain caused by internal pressure is calculated using the equation for ε_{tu}. The ring compressive strains are calculated from the appropriate ring compression strain equations shown above.

Load factors determine the maximum and minimum ring compressive strains from the earth and wheel loads. The *maximum* ring compressive strain added to the ring bending strain determines the *maximum* compressive strain in the wall. The *minimum* ring compressive strain is used with the maximum ring bending strain and any direct tensile strain to determine the *maximum* tensile strain.

The capacity reduction factor for pipe strength is used with the ultimate strength in creep, ε_C, and ultimate strength in relaxation, ε_R to determine the reduced ultimate strength in creep, ε_{Cu}, and reduced ultimate strength in relaxation, ε_{Ru}.

$$\varepsilon_{Cu} = \varepsilon_C\,\phi \quad (18a)$$

$$\varepsilon_{Ru} = \varepsilon_R\,\phi \quad (19a)$$

The following interaction equations have been developed to evaluate the ability of the designed system to resist the various combinations of the strain components:

Maximum compressive strain

$$\frac{\varepsilon_{bu}}{\varepsilon_{Ru}} + \frac{\varepsilon_{csu} + \varepsilon_{cwu} + \varepsilon_{cgu} + \varepsilon_{cvu}}{\varepsilon_{Cu}} \leq 1 \quad (40)$$

Tension at perforations, nonpressure pipe

$$\frac{\overline{PF}\,\varepsilon_{bu}}{\varepsilon_{Ru}} - \frac{\varepsilon'_{csu} + \varepsilon'_{cwu} + \varepsilon_{cgu}}{\varepsilon_{Cu}} \leq 1 \qquad (41)$$

$\overline{PF}$ = strain concentration factor at the perforations

ε'_{csu} = ring compressive strain from earth loading with the minimum load factor applied

$\varepsilon'_{cwu} = 0$

Tension in pressure pipe

$$\frac{\overline{RF}\,\varepsilon_{bu}}{\varepsilon_{Ru}} + \frac{\varepsilon_{tu}}{\varepsilon_{Cu}} - \frac{\varepsilon'_{csu} + \varepsilon'_{cwu}}{\varepsilon_{Cu}} \leq 1 \qquad (42)$$

$\overline{RF}$ = rerounding factor

Use minimum factored compressive strain and $\overline{RF} = 1$ for nonpressure pipe

For pressure pipe $\overline{RF}$ is:

$$\overline{RF} = \left[1 + \frac{2\,P_f\,R_i}{(P_s + P_w)\,R_o}\left(\frac{\Delta}{2\,R_m}\right)\right]^{-1} \qquad (43)$$

Redesign is required if any combination of the strain components results with a ratio greater than 1.

Buckling. Buckling is generally not a problem with pipe but it must be checked. Buckling does present a problem with low modulus of elasticity materials or pipe that has a high dimension ratio (DR). For buckling strength the factored compressive stress must be less than the buckling resistance times the capacity reduction factor. Current buckling resistance equations are still being reviewed by the industry. The following two analyses are recommended.

Buckling resistance reduces with time, therefore the pipe stiffness at 10 years is used for computations. The $\overline{PS}_{10}$ is calculated from the equation:

$$\overline{PS}_{10} = \frac{\overline{PS}_o}{\overline{CF}} \qquad (44)$$

$$\overline{PS}_0 = 4.47\,\frac{E_o}{(DR-1)^3} \qquad (30)$$

$$\overline{CF} = \frac{E_0}{E_{10}} \tag{16}$$

For all thermoplastic pipe $\overline{CF} \cong 2.0$

The modified AWWA formula for buckling is:

$$P_{cr} = 0.77\sqrt[3]{\left(\frac{\left(1-\frac{\Delta}{2R_m}\right)}{\left(1+\frac{\Delta}{2R_m}\right)^2}\right) C_w B' E' \phi' \overline{PS_{10}}\ \phi''} \tag{45}$$

$$C_w = 1 - \frac{h_w}{3h} \tag{19}$$

Where:

for $O < \frac{h(12)}{2R_o} < 5$

$$B' = \left(0.015 + 0.041\frac{h(12)}{2R_o}\right) \tag{47}$$

for $5 < \frac{h(12)}{2R_o} < 80$

$$B' = \left(0.15 + 0.014\frac{h(12)}{2R_o}\right)$$

Buckling against nonuniform loads is adequate if

$$\frac{P_{bu} + P_{gu} + P_{wu} + P_{vu}}{P_{cr}} \leq 1 \tag{48}$$

Hydrostatic buckling resistance check

$$P'_{cr} = 0.5 C_a \overline{PS_{10}}\ \phi\ \phi' \tag{49}$$

C_a = 2 to 3 for soft soils but may be up to 6 for rigid encasement.

Buckling under hydrostatic loads is adequate if

$$\frac{P_{gu} + P_{vu}}{P'_{cr}} \leq 1 \qquad (50)$$

Comments

The state of the art of design of flexible conduits and especially plastic pipe is far from a fixed design procedure. Much study and research must be done before designers feel they have the most economical and safe structure using plastics. Experience and subsequent publications will no doubt result with revisions to this Technical Release.

Sample Problem

Design a 6-inch PVC perforated pipe to be installed in a coarse aggregate filter system under a dam. The maximum elevation of the seepage water is expected to be 2.0 feet above the pipe invert and the pipe flows full. The specifications require the coarse filter to have a density of 90%. The SML report shows the earthfill to have a moist density of 132.0 lbs/ft^3 at an optimum moisture of 15%. The maximum height of the gravel filter is 4.0 ft above the pipe invert and the maximum height of the earthfill above the pipe invert is 30 ft. A check of local suppliers indicated schedule 40 pipe meeting ASTM D 1785; PVC 1120 SDR 17 and SDR 21 meeting ASTM D 2241; and PVC pipe meeting ASTM F 758 are all locally available.

Problem

Design pipe system that will permit the contractor to select the pipe. Determine the fill height that the contractor may begin traversing the pipe with construction equipment.

Procedure

Known data	Comments and information
Earthfill:	
1. γ_m = 132 lb/ft^3 = 0.91667 psi per ft of height	*See assumption 1. under filter material which permitted the filter height to be included in the soil height.*
2. Fill height = h = 30 ft - 0.5 ft = 29.5 ft	
3. Optimum water content = 15%	
Filter material:	
1. For this problem assume filter material has same unit weight @90% density as earth fill does @100%	
2. Height of filter = 4.0 ft	
3. Height of groundwater = 2.0 - 0.5 = 1.5 ft	
4. Modulus of Soil Reaction, E' = 2000 psi	From table 4, coarse grained soil with little or no fines.

Known data

Pipe properties

	ASTM D 1785	ASTM D 2241	ASTM D 2241	ASTM F 758	Comments and Information
	Sch 40	SDR 21	SDR 17	PS 46	
Cell class	12454B	12454B	12454B	12454C	From ASTM spec shown
Designation	PVC 1120	PVC 1120	PVC 1120	——	From ASTM spec shown
E_0	400,000	400,000	400,000	400,000	Table 1 ASTM D 1784
Wall t	0.280	0.316	0.390	0.180	From ASTM spec shown
D	6.625	6.625	6.625	6.275	From ASTM spec shown
Mean D	6.345	6.309	6.6235	6.095	Calculate (D – t)
d	6.065	5.993	5.845	5.915	Calculate (D – 2t)
$\overline{CF}$	2.0	2.0	2.0	2.0	Industry standard
$\overline{PS}_0$	154	225	437	46	From ASTM or calculate see below
$\overline{PS}_{10}$	77	112.5	218.5	23	Calculate see below
ø	0.80	0.80	0.80	0.80	Recommended factors, may change with research and experience.
ø"	0.75	0.75	0.75	0.75	
ε_C	1.0	1.0	1.0	1.0	See page 19
ε_{Cu}	0.8	0.8	0.8	0.8	Reduced ultimate strain in creep. 80% of ε_C
ε_R	use 2 for non-perforated pipe use 3 for perforated pipe				Recommended by SNTC for ultimate strain in relaxation.
ε_{Ru}	use 1.6 for non-perforated pipe use 2.4 for perforated pipe				

Known data	Comments and information
Calculate pipe stiffness	
$\overline{PS_O} = \frac{4.47\ E_O}{(DR-1)^3}$	Eq (30)
$\overline{PS_{10}} = \frac{\overline{PS_o}}{\overline{CF}}$	Eq (44)
Design Check long-term components first then verify short-term load capability.	
1. Loads:	Loads computed in psi.
A. Earth	
$P_s = \frac{\gamma_s}{144}(h),\ psi$	Eq (21)
$P_s = \frac{132}{144}(29.5) = 27.04\ \ psi$	
$P_{su} = P_s\left(\overline{LF}\right) = 27.04\ \ (1.5)$ $P_{su} = 40.56\ \ psi$	Eq (22)
$P'_{su} = P_s\ (\overline{LF}\ ) = 27.04\ psi\ \ \ (0.8)$ $P'_{su} = 21.63\ \ psi$	Eq (23)
B. Buoyant earth	
$C_w = 1 - \frac{h_w}{3\ h} = 1 - \frac{1.5}{29.5\ (3)}$ $C_w = 0.983$	Eq (19)
$P_b = P_s C_w = 27.04\ (0.983)$ $P_b = 26.582\ \ psi$	
$P_{bu} = P_b\left(\overline{LF}\ \right) = 26.582\ (1.5)$ $P_{bu} = 39.872\ \ psi$	

Known data	Comments and information
C. Groundwater	
$P_g = 0.433\ h_w = 0.433\ (1.5)$	
$P_g = 0.650\ psi$	
$P_{gu} = P_g(\overline{LF}) = 0.650\ (1.0)$	
$P_{gu} = 0.650\ psi$	
D. Vehicle loading	Assume 10,000 lbs wheel load Refer to SCS, West Tech Note 1 "External Loads on Rigid Pipe Conduits" 9/82
$P_{wh} = 0.48\ P_{wL} \dfrac{\left(\dfrac{D-t}{12}\right)^2 \left[\dfrac{2.67h}{\left(\dfrac{D-t}{12}\right)} - 0.5\right]}{2.67\ h^3 (D-t)(12)}$	Eq (24)
Pipe ASTM D 1785 Sch 40	
$P_{wh} = 0.48\ (10{,}000) \dfrac{\left(\dfrac{6.625-0.280}{12}\right)^2 \left[\dfrac{(2.67)(29.5)}{\left(\dfrac{6.625-0.280}{12}\right)} - 0.5\right]}{2.67\ (29.5)^3 (6.625-0.280)(12)}$	
$P_{wh} = 0.038\ psi$	
$Impact\ Factor = 1 + \dfrac{P_{wh}}{P_{wh} + P_s} = 1 + \dfrac{0.038}{0.038 + 27.04}$	Eq (20)
$Impact\ Factor = 1.001$	
$P_w = P_{wh}(Impact\ Factor) = 0.0382(1.001) =$	Eq (26)
$P_w = 0.038\ psi$	
$P_{wu} = P_w(\overline{LF}) = 0.038\ (1.8) = 0.069\ psi$	Max load Eq (27)
$P'_{wu} = 0$	Min load Eq (28)
It is apparent from observation that the wheel load is insignificant at the design depth. For this sample problem no further consideration of the wheel load will be needed for the long term analysis.	

Known data	Comments and information
E. Vacuum load Should not occur in a perforated pipe drain system.	
F. Internal pressure Internal pressure should not develop in a properly sized and installed open drain system	
2. Maximum long term deflection:	
A. Earth load	
Max load occurs when groundwater is below pipe invert. $D_L = 1.5$, Assume $K_b = 0.10$	
$$\frac{\Delta_s}{2R_m} = \frac{D_L K_b P_s}{0.149\,\overline{PS_o} + 0.061\,E'}$$	Eq (29)
Pipe ASTM D 1785 Sch 40	
$$\frac{\Delta_s}{2R_m} = \frac{1.5(0.10)(27.04)}{0.149(154) + 0.061(2000)} = 0.028 = 2.8\%$$	
Pipe ASTM D 2241 SDR 21	
$$\frac{\Delta_s}{2R_m} = \frac{1.5(0.10)(27.04)}{0.149(225) + 0.061(2000)} = 0.026 = 2.6\%$$	
Pipe ASTM D 2241 SDR 17	
$$\frac{\Delta_s}{2R_m} = \frac{1.5(0.10)(27.04)}{0.149(437) + 0.061(2000)} = 0.022 = 2.2\%$$	
$$\frac{\Delta_s}{2R_m} = \frac{1.5(0.10)(27.04)}{0.149(46) + 0.061(2000)} = 0.031 = 3.1\%$$	

Known data	Comments and information
B. Wheel load	
$D_L = 1.0, \; n_w = 0.50, \; K_b = 0.10$	See narrative page 24
$$\frac{\Delta_w}{2R_m} = \frac{D_L K_b P_w}{0.149\,\overline{PS}_O + 0.061\,E'\,n_w}$$	Eq (29a)
Obviously deflections caused by wheel loading at design depth are too small to consider.	
C. Installation deflection	Use Table 5
Must calculate pipe stiffness. Embedment material and density is from specifications.	
Pipe ASTM D 1785 Sch 40	
$\overline{PS}_O = 154$	
From table 5 $\frac{\Delta_i}{2R_m} = 2\%$	
Pipe ASTM D 2241 SDR 21	
$\overline{PS}_O = 225$	
From table 5 $\frac{\Delta_i}{2R_m} = 2\%$	
Pipe ASTM D 2241 SDR 17	
$\overline{PS}_O = 437$	
From table 5 $\frac{\Delta_i}{2R_m} = 2\%$	
Pipe ASTM F 758 PS 46	
$\overline{PS}_O = 46$	
From table 5 $\frac{\Delta_i}{2R_m} = 3\%$	

Known data	Comments and information

D. Total Deflection

$$\frac{\Delta}{2R_m} = \frac{\Delta_s}{2R_m} + \frac{\Delta_w}{2R_m} + \frac{\Delta_i}{2R_m}$$

Maximum long term deflect allowable is 5% .

Pipe ASTM D 1785 Sch 40

$$\frac{\Delta}{2R_m} = 2.8\% + 0.00\% + 2.0\% = 4.8\%$$

<5% design OK

Pipe ASTM D 2241 SDR 21

$$\frac{\Delta}{2R_m} = 2.61\% + 0.00\% + 2.0\% = 4.61\%$$

<5% design OK

Pipe ASTM D 2241 SDR 17

$$\frac{\Delta}{2R_m} = 2.17\% + 0.00\% + 2.0\% = 4.17\%$$

<5% design OK

Pipe ASTM F 758 PS 46

$$\frac{\Delta}{2R_m} = 3.1\% + 0.00\% + 3.0\% = 6.15\%$$

Exceeds 5% Eliminate this pipe.

Check strength design for pipes that meet the deflection requirements. Assume pipe to be haunched and good inspection

3. Ring Bending Strain:

Check strains assuming perforations are located at a critical point (invert, crown, springline). If strain is acceptable then perforations may be located at any point on the pipe. At the critical points the tensile bending strain is equal to the compressive bending strain times the perforation factor. $\overline{MF} = 0.75$

A. Earth

$$\varepsilon_{bsu} = 2.5\left(\frac{t}{R_m}\right)\overline{MF}\left(\frac{\Delta_s}{2R_m}\overline{LF}\right)$$

Eq (31a)

Known data	Comments and information
Pipe ASTM D 1785 Sch 40	
$\varepsilon_{bsu} = 2.5\left(\frac{0.280}{3.172}\right)(0.75)\,(0.028)(1.5)$	
$\varepsilon_{bsu} = 0.695\,\%$	
Pipe ASTM D 2241 SDR 21	
$\varepsilon_{bsu} = 2.5\left(\frac{0.316}{3.154}\right)(0.75)\,(0.026)(1.5)$	
$\varepsilon_{bsu} = 0.733\,\%$	
Pipe ASTM D 2241 SDR 17	
$\varepsilon_{bsu} = 2.5\left(\frac{0.390}{3.117}\right)(0.75)\,(0.022)(1.5)$	
$\varepsilon_{bsu} = 0.774\,\%$	
B. Wheel	
$\varepsilon_{bwu} = 2.5\left(\frac{t}{R_m}\right)\left(\overline{MF}\right)\left(\frac{\Delta_w}{2R_m}\overline{LF}\right)$	Insignificant at design depth. Eq 32a)
C. Installation:	
$\varepsilon_{biu} = 2.14\left(\frac{t}{R_m}\right)\left(\overline{MF}\right)\left(\frac{\Delta_i}{2R_m}\overline{LF}\right)$	Eq (33a)
Pipe ASTM D 1785 Sch 40	
$\varepsilon_{biu} = 2.14\left(\frac{0.28}{3.172}\right)(0.75)\,(0.020)(1.0)$	
$\varepsilon_{biu} = 0.283\,\%$	
Pipe ASTM D 2241 SDR 21	
$\varepsilon_{biu} = 2.14\left(\frac{0.316}{3.154}\right)(0.75)\,(0.020)(1.0)$	
$\varepsilon_{biu} = 0.322\,\%$	
Pipe ASTM D 2241 SDR 17	
$\varepsilon_{biu} = 2.14\left(\frac{0.39}{3.117}\right)(0.75)\,(0.020)(1.0)$	
$\varepsilon_{biu} = 0.402\,\%$	

Known data	Comments and Information

D. Total Ring Bending Strain

$$\varepsilon_{bu} = \varepsilon_{bsu} + \varepsilon_{bwu} + \varepsilon_{biu}$$

Eq (34a)

Pipe ASTM D 1785 Sch 40

$$\varepsilon_{bu} = 0.695\% + 0.0\% \quad 0.283\% = 0.978\%$$

Pipe ASTM D 2241 SDR 21

$$\varepsilon_{bu} = 0.733\% + 0.0\% \quad 0.322\% = 1.055\%$$

Pipe ASTM D 2241 SDR 17

$$\varepsilon_{bu} = 0.774\% + 0.0\% \quad 0.402\% = 1.176\%$$

4. Ring Tension Strain:

Not a concern in this problem.

Internal pressure equals external pressure

5. Ring Compression Strain:

In an open drainage system such as this, ring compression can only be induced by the soil load and wheel load. At this depth the effects of the wheel load are ignored. Therefore only calculate maximum and minimum ring compression strain for the soil.

A. Earth

$$\varepsilon_{csu} = \frac{R_o}{t\,E_o} P_{su}$$

Maximum comp. strain
Eq (36)

$$\varepsilon'_{csu} = \frac{R_o}{t\,E_o} P'_{su}$$

Minimum comp strain
Eq (36a)

Pipe ASTM D 1785 Sch 40

$$\varepsilon_{csu} = \frac{3.312}{0.28\ (400{,}000)}(40.56) = 0.12\%$$

$$\varepsilon'_{csu} = \frac{3.312}{0.28\ (400{,}000)}(21.63) = 0.06\%$$

Known data	Comments and information
Pipe ASTM D 2241 SDR 21	
$\varepsilon_{csu} = \frac{3.312}{0.316\ (400{,}000)}(40.56) = 0.10\%$	
$\varepsilon'_{csu} = \frac{3.312}{0.316\ (400{,}000)}(21.63) = 0.06\%$	
Pipe ASTM D 2241 SDR 17	
$\varepsilon_{csu} = \frac{3.312}{0.390\ (400{,}000)}(40.56) = 0.086\%$	
$\varepsilon'_{csu} = \frac{3.312}{0.390\ (400{,}000)}(21.63) = 0.046\ \%$	
6. Check strength index using interaction equations.	
Maximum Compression	
$\frac{\varepsilon_{bu}}{\varepsilon_{Ru}} + \frac{\varepsilon_{csu}}{\varepsilon_{Cu}} = \leq 1$	Eq (40)
Pipe ASTM D 1785 Sch 40	
$\frac{0.978}{2.4} + \frac{0.12}{0.80} = 0.557$	<1 Design OK
Pipe ASTM D 2241 SDR 21	
$\frac{1.056}{2.4} + \frac{0.10}{0.80} = 0.565$	<1 Design OK
Pipe ASTM D 2241 SDR 17	
$\frac{1.164}{2.4} + \frac{0.086}{0.80} = 0.593$	<1 Design OK
Maximum Tension	
$\overline{RF}$ (Rerounding Factor) = 1.0 for an open system (non-pressurized).	Because of nonpressure system
$\varepsilon_{tu} = 0$	
$\frac{\overline{PF}\ (\varepsilon_{bu})}{\varepsilon_{Ru}} - \frac{\varepsilon'_{csu}}{\varepsilon_{Cu}} \leq 1$	Eq (41)

Known data	Comments and information
Pipe ASTM D 1785 Sch 40 $\frac{2.3\,(0.978)}{2.4} - \frac{0.06}{0.80} = 0.862$	<1 Design OK
Pipe ASTM D 2241 SDR 21 $\frac{2.3\,(1.055)}{2.4} - \frac{0.06}{0.80} = 0.937$	<1 Design OK
Pipe ASTM D 2241 SDR 17 $\frac{2.3\,(1.176)}{2.4} - \frac{0.046}{0.80} = 1.069$	<1 Design not valid
The Sch 40 and the SDR 21 meet the design requirements. Can the design be revised to make the SDR 17 acceptable? Yes, there are several options open to the designer:	
1. Design again using E' = 3000 psi. If the new design passes specifications must be written to include embedment material and density that will result in an E' of 3000 psi.	
2. Design the perforations to be installed at some point other than the maximum strain points (invert, crown, or springline).	
This designer chooses to try option 2.	
Use the equation for strain when perforations are located at some angle, θ, from the vertical or horizontal axis through the center of the pipe.	
Try $\theta = 10°$ $C_m = 0.2349$	Moment Coeff. from Table 6
Use equation: $\overline{PF}\ \varepsilon_{bsu} = 10\ \frac{t}{R_m}\ C_m\ \overline{MF}\ \frac{\Delta_s}{2R_m}\ \overline{LF}\ \overline{PF}$	Eq (31)
Ring Bending Strain @ 10°:	
A. Earth	
$\overline{PF}\ \varepsilon_{bsu} = 10\left(\frac{0.390}{3.117}\right)(0.2349)\,(0.75)\,(2.168\%)\,(1.5)\,(2.3)$	
$\overline{PF}\ \varepsilon_{bsu} = 1.648$	

Known data	Comments and Information
B. Installation	
$\overline{PF}\ \varepsilon_{biu} = 8.56 \left(\frac{0.390}{3.117}\right) (0.2349)(0.75)(2.0\%)(1.0)(2.3)$	
$\overline{PF}\ \varepsilon_{biu} = 0.8678$	
C. Total Ring Bending Strain @ 10°	
$\overline{PF}\ \varepsilon_{bu} = \overline{PF}\ \varepsilon_{bsu} + \overline{PF}\ \varepsilon_{biu}$	Eq (34)
$\overline{PF}\ \varepsilon_{bu} = 1.648 + 0.868 = 2.516$	
Ring Compression Strain @ 10°	
A. Earth:	
$\varepsilon_{csu} = \frac{(3.312)(40.56)}{0.390\ (400{,}000)} = 0.086$	Maximum Compression
$\varepsilon'_{csu} = \frac{(3.312)(21.63)}{0.390\ (400{,}000)} = 0.046$	Minimum Compression
Check strength index using the interaction equations.	
Revised maximum compression @ 10° :	
Because the strength index check for compression was acceptable at the critical points, there is no reason to check again.	
Revised maximum tension @ 10° :	
$\frac{\overline{PF}\ (\varepsilon_{bu})}{\varepsilon_{Ru}} - \frac{\varepsilon'_{csu}}{\varepsilon_{Cu}} \leq 1$	Eq (41)
$\frac{2.516}{2.4} - \frac{0.046}{0.80} = 0.991$	<1 Design OK
These computations indicate the SDR 17 is satisfactory but the perforations must be installed between 10° to 80° from the vertical line through the center of the pipe. Some tolerance for construction must be allowed. This designer would specify 22.5° to 67.5°	

Known data	Comments and information

NOTE:
Three pipes meet the requirements for this design. However the *HEAVIEST PIPE, SDR 17 HAS THE MOST SEVERE RESTRICTIONS* For this reason it is necessary that any pipe other than the specified pipe be checked by the design procedure.

7. Check buckling capacity:

Modified AWWA Formula:

$$P_{cr} = \left[\left(\frac{\left(1 - \frac{\Delta}{2 R_m}\right)^3}{\left(1 + \frac{\Delta}{2 R_m}\right)^2} \right) C_w \ B' \ E' \ \phi' \ \overline{PS_{10}} \ \phi'' \right]^{0.5}$$

Eq (45)

$$C_w = 0.983 \qquad \phi' = 0.5$$

Pipe ASTM D 1785 Sch 40

$$\frac{h}{2 R_o} = \frac{29.5}{\frac{2(3.312)}{(12)}} = 53.44$$

$$B' \quad 0.15 + 0.014(53.44) = 0.898$$

Eq (46)

$$P_{cr} = 0.77 \left[\left(\frac{1 - 0.048}{(1 + 0.048)^2} \right)^3 0.983(0.898) \ 2000(0.5) \ (77) \ (0.75) \right]^{0.5}$$

Eq (45)

$$P_{cr} = 140.30$$

$$\text{if} \quad \frac{P_{bu}}{P_{cr}} \le 1 \quad \textit{then design is OK}$$

$$\frac{39.87}{140.30} = 0.284$$

<1 Design OK

Pipe ASTM D 2241 SDR 21

$$\frac{h}{2 R_o} = \frac{29.5}{\frac{2(3.312)}{(12)}} = 53.44$$

$$B' = 0.898$$

Known data	Comments and information
$P_{cr} = 0.77\left[\left(\frac{1-0.046}{(1+0.046)^2}\right)^3 0.983\,(0.898)\,2000\,(0.5)\,112.5\,(0.75)\right]^{0.5}$	Eq (45)
$P_{cr} = 171.10$	
if $\frac{P_{bu}}{P_{cr}} \leq 1$ *then design is OK*	
$\frac{39.87}{171.10} = 0.233$	<1 Design OK
Pipe ASTM D 2241 SDR 17	
$\frac{h}{2\,R_o} = \frac{29.5}{\frac{2\,(3.312)}{(12)}} = 53.44$	
$B' = 0.898$	
$P_{cr} = 0.77\,2\left[\left(\frac{1-0.042}{(1+0.042)^2}\right)^3 20.983(0.898)\,2000\,(0.5)\,118.5\,(0.75)\right]^{0.5}$	Eq (45)
$P_{cr} = 275.46$	
if $\frac{P_{bu}}{P_{cr}} \leq 1$ *then design is OK*	
$\frac{39.87}{275.46} = 0.1447$	<1 Design OK
Hydrostatic buckling resistance	
$P'_{cr} = 0.5\,C_a\,\overline{PS}_{10}\;\phi'\;\phi''$	Eq (49)
Pipe ASTM D 1785 Sch 40	
$P'_{cr} = 0.5\,(3)\,(77)\,(0.5)\,(0.75)$	
$P'_{cr} = 43.31$	
$\frac{P_{gu}}{P'_{cr}} = \frac{0.650}{43.31} = 0.015$	<1 Design OK

Known data	Comments and information
Pipe ASTM D 2241 SDR 21	
$P'_{cr} = 0.5\ (3)\ (112.5)\ (0.5)\ (0.75)$ $P'_{cr} = 43.28$	
$\dfrac{P_{gu}}{P'_{cr}} = \dfrac{0.650}{63.28} = 0.010$	<1 Design OK
Pipe ASTM D 2241 SDR 17	
$P'_{cr} = 0.5\ (3)\ (218.5)\ (0.5)\ (0.75)$ $P'_{cr} = 122.9$	
$\dfrac{P_{gu}}{P'_{cr}} = \dfrac{0.650}{122.9} = 0.005$	<1 Design OK
Short-term analysis	
At what point during construction can the contractor stop hand compaction and begin traversing the pipe with heavy equipment? The short-term loading conditions and parameters are used for this analysis.	Usually this point will be between 2 and 4 feet above the pipe.
Short-term allowable deflection = 3% Short-term deflection lag factor = 1.0	
Deflection is usually the critical element in the short-term analysis. The designer must assume various fill heights until one is found that results in a deflection of less than 3%.	
Loads Assume fill 2.8' above the top of the pipe	Even though 2.6' is within the filter this load can be used. See assumptions in long term analysis.
Earth	
$P_s = \dfrac{132}{144}(2.8) = 2.567\ psi$	Eq (21)
$P_{su} = P_s\,(\overline{LF}) = 2.567\ (1.5) = 3.85\ psi$	Eq (22)

Known data	Comments and Information
$P'_{su} = P_s(\overline{LF}) = 2.567\ (0.8) = 2.054\ psi$	Eq (23)
Buoyant earth Assume pipe trench maintained in dry condition during construction. $C_w = 1.0$	
Groundwater Assume pipe trench maintained in dry condition during construction.	
Vehicle Assume 10,000 lb point load	
$P_{wh} = 0.48\, P_{wL} \dfrac{\left(\dfrac{D-t}{12}\right)^2 \left[\dfrac{2.67\,h}{\left(\dfrac{D-t}{12}\right)} - 0.5\right]}{2.67\,(h)^3\,(D-t)\ \ (12)}$	Eq (24)
Pipe ASTM D 1785 Sch 40	
$P_{wh} = 0.48\,(10{,}000) \dfrac{\left(\dfrac{6.625-0.28}{12}\right)^2 \left[\dfrac{2.67\,(2.8)}{\left(\dfrac{6.625-0.28}{12}\right)} - 0.5\right]}{2.67\,(2.8)^3\,(6.625-0.28)\ \ (12)}$	Eq (24)
$P_{wh} = 4.101\,psi$	
$\text{Impact Factor} = 1 + \dfrac{P_{wh}}{P_{wh} + P_s}$	Eq (20)
$\text{Impact Factor} = 1 + \dfrac{4.101}{4.101 + 2.57} = 1.615$	
$P_w = P_{wh}\ (\text{Impact Factor}) = 4.10\,(1.615)$ $P_w = 6.623\,psi$	Eq (26)
$P_{wu} = P_w(\overline{LF}) = 6.623\ (1.8) = 11.92\ psi$	Eq (27)
$P'_{wu} = 0$	Eq (28)

Known data	Comments and Information
Pipe ASTM D 2241 SDR 21	
$P_{wh} = 0.48\,(10{,}000)\dfrac{\left(\dfrac{6.625-0.316}{12}\right)^2\left[\dfrac{2.67\,(2.8)}{\left(\dfrac{6.625-0.316}{12}\right)}-0.5\right]}{2.67\,(2.8)^3\,(6.625-0.316)\;(12)}$	Eq (24)
$P_{wh} = 4.102\ psi$	Use same values as for SCH 40
Pipe ASTM D 2241 SDR 17	
$P_{wh} = 0.48\,(10{,}000)\dfrac{\left(\dfrac{6.625-0.390}{12}\right)^2\left[\dfrac{2.67\,(2.8)}{\left(\dfrac{6.625-0.390}{12}\right)}-0.5\right]}{2.67\,(2.8)^3\,(6.625-0.390)\;(12)}$	Eq (24)
$P_{wh} = 4.104\ psi$	Use same values as for SCH 40
Vacuum load	
Not Applicable	
Internal pressure	
Not Applicable	
Short-term deflection	
Earth load	
$\dfrac{\Delta_s}{2\,R_m} = \dfrac{D_L\,K_b\,P_s}{0.149\;\overline{PS_o} + 0.061\;E'}$	Eq (30)
Pipe ASTM D 1785 Sch 40	
$\dfrac{\Delta_s}{2\,R_m} = \dfrac{1.0\,(0.10)\,(2.567)}{0.149\,(154) + 0.061\,(2000)} = 0.177\%$	
Pipe ASTM D 2241 SDR 21	
$\dfrac{\Delta_s}{2\,R_m} = \dfrac{1.0\,(0.10)\,(2.567)}{0.149\,(225) + 0.061\,(2000)} = 0.165\%$	

Known data	Comments and information
Pipe ASTM D 2241 SDR 17	
$\frac{\Delta_s}{2R_m} = \frac{1.0(0.10)(2.567)}{0.149(437) + 0.061(2000)} = 0.137\%$	
Wheel load	
$D_L = 1.0, \quad n_w = 0.50, = K_b = 0.10$	See narrative page 24
$\frac{\Delta_w}{2R_m} = \frac{D_L K_b P_w}{0.149\overline{PS_o} + 0.061E' n_w}$	Eq (29a)
Pipe ASTM D 1785 Sch 40	
$\frac{\Delta_w}{2R_m} = \frac{1.0(0.10)(6.623)}{0.149(154) + 0.061(2000)(0.5)}$	
$\frac{\Delta_w}{2R_m} = 0.789\%$	
Pipe ASTM D 2241 SDR 21	
$\frac{\Delta_w}{2R_m} = \frac{1.0(0.10)(6.623)}{0.149(225) + 0.061(2000)(0.5)}$	
$\frac{\Delta_w}{2R_m} = 0.701\%$	
Pipe ASTM D 2241 SDR 17	
$\frac{\Delta_w}{2R_m} = \frac{1.0(0.10)(.623)}{0.149(437) + 0.061(2000)(0.5)}$	
$\frac{\Delta_w}{2R_m} = 0.525\%$	
Installation deflection	
Must calculate pipe stiffness. Embedment material and density is from specifications.	
Pipe ASTM D 1785 Sch 40	
$\overline{PS_o} = 154$	Use Table 5
From Table 5 $\frac{\Delta_i}{2R_m} = 2\%$	

Known data	Comments and Information
Pipe ASTM D 2241 SDR 21	
$\overline{PS_o} = 225$	
From Table 5 $\frac{\Delta_i}{2R_m} = 2\%$	
Pipe ASTM D 2241 SDR 17	
$\overline{PS_o} = 437$	
From Table 5 $\frac{\Delta_i}{2R_m} = 2\%$	
Total Short Term Deflection	
$\frac{\Delta}{2R_m} = \frac{\Delta_s}{2R_m} + \frac{\Delta_w}{2R_m} + \frac{\Delta i}{2R_m}$	Maximum short term deflect allowable is 3%
Pipe ASTM D 1785 Sch 40	
$\frac{\Delta}{2R_m} = 0.177\% + 0.789\% + 2.0\% = 2.966\%$	< 3% design OK
Pipe ASTM D 2241 SDR 21	
$\frac{\Delta}{2R_m} = 0.165\% + 0.710\% + 2.0\% = 2.866\%$	< 3% design OK
Pipe ASTM D 2241 SDR 17	
$\frac{\Delta}{2R_m} = 0.137\% + 0.525\% + 2.0\% = 2.66\%$	< 3% design OK
Check strength requirements	
Assume pipe to be haunched and good inspection	Use same basic equations as for long term strain but use short term values.
Ring bending strain	
Earth:	
Pipe ASTM D 1785 Sch 40	
$\varepsilon_{bsu} = 2.5\left(\frac{0.280}{3.172}\right)(0.75)(0.002)(1.5)$	Eq (31a)
$\varepsilon_{bsu} = 0.044\%$	

Known data	Comments and information
Pipe ASTM D 2241 SDR 21	
$\varepsilon_{bsu} = 2.5\left(\frac{0.316}{3.154}\right)(0.75)(0.002)(1.5)$	
$\varepsilon_{bsu} = 0.046\%$	
Pipe ASTM D 2241 SDR 17	
$\overline{PF}\ \varepsilon_{bsu} = 10\frac{t}{R_m}C_m\ \overline{MF}\ \frac{\Delta_s}{2R_m}\ \overline{LF}\ \overline{PF}$	Must use Eq (31) since the perforation locations are being specified.
$\overline{PF}\ \varepsilon_{bsu} = 10\ \frac{0.390}{3.117}(0.235)(0.75)(0.001)(1.5)(2.3)$	
$\overline{PF}\ \varepsilon_{bsu} = 0.104\%$	
Wheel	
Pipe ASTM D 1785 Sch 40	
$\varepsilon_{bwu} = 2.5\left(\frac{0.28}{3.172}\right)(0.75)(0.008)(1.8)$	Eq (32a)
$\varepsilon_{bwu} = 0.235\%$	
Pipe ASTM D 2241 SDR 21	
$\varepsilon_{bwu} = 2.5\left(\frac{0.316}{3.154}\right)(0.75)(0.007)(1.8)$	Eq (32a)
$\varepsilon_{bwu} = 0.237\%$	
Pipe ASTM D 2241 SDR 17	
$\overline{PF}\ \varepsilon_{bwu} = 10\frac{t}{R_m}C_m\ \overline{MF}\ \frac{\Delta_w}{2R_m}\ \overline{LF}\ \overline{PF}$	Eq (32)
$\overline{PF}\ \varepsilon_{bwu} = 10\ \frac{0.390}{3.117}(0.235)(0.75)(0.008)(1.8)(2.3)$	
$\overline{PF}\ \varepsilon_{bwu} = 0.720\%$	

Known data	Comments and information
Installation	
$\varepsilon_{biu} = 2.14\left(\frac{t}{R_m}\right)\overline{MF}\left(\frac{\Delta_i}{2R_m}\right)(\overline{LF})$	Eq (33a)
Pipe ASTM D 1785 Sch 40	
$\varepsilon_{biu} = 2.14\left(\frac{0.28}{3.172}\right)(0.75)(0.020)(1.0)$	Eq (33a)
$\varepsilon_{biu} = 0.283\%$	
Pipe ASTM D 2241 SDR 21	
$\varepsilon_{biu} = 2.14\left(\frac{0.316}{3.154}\right)(0.75)(0.020)(1.0)$	Eq (33a)
$\varepsilon_{biu} = 0.321\%$	
Pipe ASTM D 2241 SDR 17	
$\overline{PF}\ \varepsilon_{biu} = 8.56\frac{t}{R_m}C_m\overline{MF}\frac{\Delta_i}{2R_m}\overline{LF}\ \overline{PF}$	Eq (33) Accounts for location of perforations.
$\overline{PF}\ \varepsilon_{biu} = 8.56\frac{0.390}{3.117}(0.235)(0.75)(0.020)(1.0)(2.3)$	
$\overline{PF}\ \varepsilon_{biu} = 0.868\%$	
Total ring bending strain	
$\varepsilon_{bu} = \varepsilon_{bsu} + \varepsilon_{buu} + \varepsilon_{biu}$	Eq (34a)
Pipe ASTM D 1785 Sch 40	
$\varepsilon_{bu} = 0.044\% + 0.196\% + 0.283\% = 0.523\%$	
Pipe ASTM D 2241 SDR 21	
$\varepsilon_{bu} = 0.046\% + 0.197\% + 0.321\% = 0.564\%$	
Pipe ASTM D 2241 SDR 17	
$\varepsilon_{bu} = 0.104\% + 0.720\% + 0.868\% = 1.692\%$	
Ring Compression Strain	
Earth	
$\varepsilon_{csu} = \frac{R_o}{t\,E_0}P_{su}$	Maximum Comp. strain Eq (36)
$\varepsilon'_{csu} = \frac{R_o}{t\,E_0}P'_{su}$	Minimum comp. strain Eq (36a)

Known data	Comments and Information
Pipe ASTM D 1785 Sch 40	
$\varepsilon_{csu} = \dfrac{3.312}{0.28\,(400{,}000)}(3.85) = 0.01\%$	
$\varepsilon'_{csu} = \dfrac{3.312}{0.28\,(400{,}000)}(2.054) = 0.006\%$	
Pipe ASTM D 2241 SDR 21	
$\varepsilon_{csu} = \dfrac{3.312}{0.316\,(400{,}000)}(5.85) = 0.010\%$	
$\varepsilon'_{csu} = \dfrac{3.312}{0.316\,(400{,}000)}(2.54) = 0.005\%$	
Pipe ASTM D 2241 SDR 17	
$\varepsilon_{csu} = \dfrac{3.312}{0.390\,(400{,}000)}(2.54) = 0.05\%$	
$\varepsilon'_{csu} = \dfrac{3.312}{0.390\,(400{,}000)}(2.054) = 0.004\%$	
Wheel	
$\varepsilon_{cwu} = \dfrac{R_o}{t\,E_o}\,P_{wu}$	Maximum comp. strain Eq (37)
$\varepsilon'_{cwu} = \dfrac{R_o}{t\,E_o}\,P'_{wu} = 0$	Minimum comp. strain Eq (37a)
Pipe ASTM D 1785 Sch 40	
$\varepsilon_{cwu} = \dfrac{3.312}{0.28\,(400{,}000)}(11.92) = 0.03\%$	
$\varepsilon'_{cwu} = 0$	
Pipe ASTM D 2241 SDR 21	
$\varepsilon_{cwu} = \dfrac{3.312}{0.316\,(400{,}000)}(11.92) = 0.010\%$	
$\varepsilon'_{cwu} = 0$	

Known data	Comments and Information
Pipe ASTM D 2241 SDR 17	
$\varepsilon_{cwu} = \dfrac{3.312}{0.390\ (400{,}000)}\ (11.92) = 0.025\%$	
$\varepsilon'_{cwu} = 0$	
Check strength index using the interaction equations	
Maximum compression	
$\dfrac{\varepsilon_{bu}}{\varepsilon_{Ru}} + \dfrac{\varepsilon_{csu} + \varepsilon_{cwu}}{\varepsilon_{Cu}} \leq 1$	Eq (40)
Pipe ASTM D 1785 Sch 40	
$\dfrac{0.523}{2.4} + \dfrac{0.0001 + 0.0003}{0.80} = 0.218$	<1 Design OK
Pipe ASTM D 2241 SDR 21	
$\dfrac{0.564}{2.4} + \dfrac{0.0001 + 0.0003}{0.80} = 0.235$	<1 Design OK
Pipe ASTM D 2241 SDR 17	
$\dfrac{1.693}{2.4} + \dfrac{0.0008 + 0.0025}{0.80} = 0.709$	<1 Design OK
Maximum tension	
$\overline{RF}$ (Rerounding Factor) = 1.0 for an open system (non-pressurized).	Because nonpressure system
$\varepsilon_{tu} = 0$	
$\dfrac{\overline{PF}\ (\varepsilon_{bu})}{\varepsilon_{Ru}} - \dfrac{\varepsilon'_{csu} + \varepsilon'_{cwu}}{\varepsilon_{Cu}} \leq 1$	Eq (41)
Pipe ASTM D 1785 Sch 40	
$\dfrac{2.3\ (0.523)}{2.4} - \dfrac{0.00006 + 0.00}{0.80} = 0.501$	<1 Design OK
Pipe ASTM D 2241 SDR 21	
$\dfrac{2.3\ (0.523)}{2.4} - \dfrac{0.00005 + 0.00}{0.80} = 0.501$	<1 Design OK
Pipe ASTM D 2241 SDR 17	
$\dfrac{2.3\ (0.523)}{2.4} - \dfrac{0.00004 + 0.00}{0.80} = 0.501$	<1 Design OK

Known data	Comments and information
Check buckling capacity:	
Modified AWWA formula	
$P_{cr} = 0.77\left[\left(\dfrac{1-\dfrac{\Delta}{2R_m}}{\left(1+\dfrac{\Delta}{2R_m}\right)^2}\right)^3 C_w\, B'\, E'\, \phi' \overline{PS_{10}}\, \phi''\right]^{0.5}$	Eq (45)
$C_w = 0.1 \qquad \phi' = 0.5$	
Pipe ASTM D 1785 Sch 40	
$\dfrac{h}{2R_o} = \dfrac{3.5}{\dfrac{2(3.312)}{(12)}} = 6.340$	
$B' = 0.15 + 0.014(6.340) = 0.239$	
$P_{cr} = 0.77\left[\left(\dfrac{1-0.030}{(1+0.030)^2}\right)^3 1.0(0.239)\,2000\,(0.5)\,77\,(0.75)\right]^{0.5}$	Eq (45)
$P_{cr} = 79.175$	
if $\dfrac{P_{bu}+P_{wu}}{P_{cr}} \le 1$ then design is OK	Use $P_{bu} = P_{su}$ because of no water
$\dfrac{3.85 + 11.92}{79.175} = 0.199$	<1 Design OK
Pipe ASTM D2241 SDR 21	
$\dfrac{h}{2R_o} = \dfrac{3.5}{\dfrac{2(3.312)}{(12)}} = 6.340$	
$B' = 0.240$	
$P_{cr} = 0.77\left[\left(\dfrac{1-0.029}{(1+0.029)^2}\right)^3 1.0(0.239)\,2000\,(0.5)\,112.5\,(0.75)\right]^{0.5}$	Eq (45)
$P_{cr} = 96.11$	

Known data	Comments and information
if $\frac{P_{bu} + P_{wu}}{P_{cr}} \le 1$ then design is OK	Eq (48) See comment previous page
$\frac{3.85 + 11.922}{96.11} = 0.164$	<1 Design OK
$\frac{h}{2 R_o} = \frac{3.5}{\frac{2(3.312)}{(12)}} = 6.340$	
$B' = 0.239$	
Pipe ASTM D 2241 SDR 17	
$P_{cr} = 0.77\left[\left(\frac{1 - 0.027}{(1 + 0.027)^2}\right)^3 1.0(0.239)\ 2000\ (0.5)\ 218\ (0.75)\right]^{0.5}$	Eq (45)
$P_{cr} = 158.27$	
if $\frac{P_{bu} + P_{wu}}{P_{cr}} \le 1$ then design is OK	See comment previous page
$\frac{3.85 + 11.922}{158.27} = 0.997$	<1 Design OK

Hydrostatic buckling

No check necessary. Initial assumption was that trench would be kept free of water during construction.

Installation Guidelines

When installing a buried plastic pipe, the objectives are to minimize pipe deflections induced by, or resulting from, the installation process, and to provide a firm, stable permanent support for the pipe when the installation is subjected to loads. This section deals with factors that are especially critical in obtaining such an installation.

Terminology

Terminology that describes buried pipe installations varies among regions of the country and also among various specifying authorities. The terminology that follows is used throughout this report. A general arrangement of the pipe embedment system describing the terminology is shown in figure 2.

Foundation. A foundation is an imported material used under the bedding. It may be required when trench bottom instability, rock, or excess water is encountered.

Embedment System. The embedment system, which also may be the drainage envelope for perforated underdrains, includes bedding, haunching, and initial backfill.

Bedding. Bedding is the portion of the embedment that is prepared and in place before installing the pipe. Where *in-situ* soil conditions and drainage characteristics permit, the *in-situ* trench bottom may serve as bedding. Bedding may or may not contain a groove conforming to the pipe curvature, depending on installation requirements.

Haunching. This is a layer of embedment material that extends from the top of the bedding to the springline of the pipe.

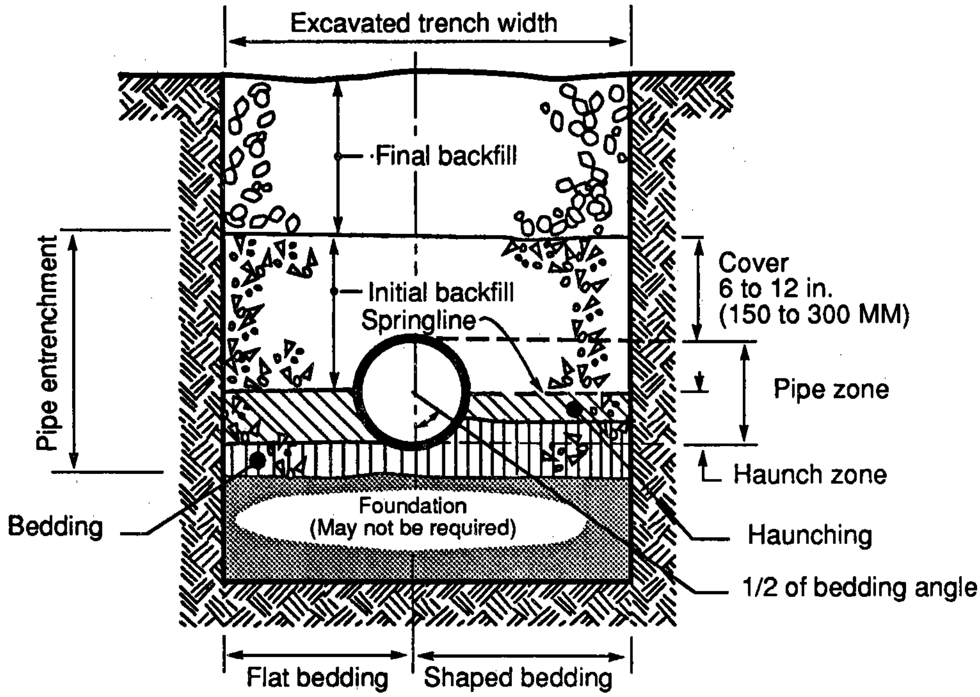
Haunch Zone. This zone is defined as the area between the invert and the springline of the pipe (haunches).

Initial Backfill. Initial backfill is the portion of the embedment system that extends from the top of the haunching to 150 to 300 mm (6 to 12 in) above the crown of the pipe.

Final Backfill. Final backfill is that portion of the installation that lies between the top of the initial backfill and the top of the trench.

Pipe Zone. This zone lies adjacent to the pipe over its full height.

Figure 2. ***Pipe embedment system terminology***



Pipe-Embedment System

The objectives that must be achieved in the installation of a flexible buried plastic pipe for drainage are as follows:

1. The line and grade of a drainage piping system should be constructed to provide the gravity flow requirements anticipated in design.

2. The cross section of the installed pipe should be within specified deflection limits immediately after construction and remain reasonably circular for the indefinite future. This means that distortion built in during installation, or caused by construction, service traffic, or earth loadings, should remain within tolerable limits. Overdeflection is an indication of excessive strain in the pipe wall; it may restrict cleaning devices and cause gasketed joints to leak.

3. When buried pipe is used for underdrains, the embedment system also serves as a drainage envelope, and must permit free drainage for the design life of the installation. This means that the envelope must be designed and constructed to allow passage of water with minimum transport of fines into or through the pipe-envelope system. Movement of fines from the *in-situ* trench may clog the envelope. Movement of fines into the pipe through perforations can clog the pipe or cause loss of structural support by embedment materials.

An acceptable installation results from the proper choice of materials and construction techniques that recognize the factors that contribute to both successful and unsuccessful installation performance.

Key structural considerations

Deflection is a practical indication of the state of stress or strain in the wall of a flexible pipe. Most design methods and design criteria for flexible pipe are based on deflection and its control. Deflection is easy to measure and it has been traditionally used as a measure of adequacy of flexible pipe installations. The objective of the installation, then, is to ensure that the pipe is installed with tolerable deflections and that deflections do not increase significantly during the lifetime of the system.

Many sources of deflection in a buried flexible pipe are possible. The two primary sources are those resulting from installation and those arising from subsequent earth and traffic loads.

Plastic pipe is flexible and can be deformed rather readily during the installation process. If suitable methods and materials are not used in the installation, the excessive deflections that may result can seriously detract from, or even exceed, the overall design deflection budget. Generally, installation deflections reduce with increasing pipe stiffness. Improper construction, however, can result in overdeflection of stiff pipe, whereas proper construction can result in negligible deflection of flexible pipe.

Plastic pipe depends on the embedment or envelope material for its support. Theory, laboratory and field tests, and experience with failures, all point to the necessity of providing uniform and continuous support around the flexible pipe. *The properties of the surrounding embedment material have more influence on pipe behavior under earth and wheel loads than the stiffness of the pipe itself.*

The design and execution of the installation must recognize that a primary part of the pipe-soil structure is being constructed in the field. Field conditions are usually difficult, particularly in trenches where ledge, boulders, frozen material, water, and unstable conditions are encountered. Materials used for embedment may be inherently variable by nature. Handling and feasibility of obtaining required density and uniformity of embedment can vary widely depending on properties such as grain size and moisture content. Obviously, the more that can be done to improve the reliability of the construction under difficult field conditions, the greater the chances for a successful installation. Reliability is a function of both the materials specified and furnished and the procedures used in construction of the embedment envelope.

Functions and Requirements of Pipe Installation

The key requirements governing the success of a buried plastic pipe installation have been discussed. This section is devoted to the various components of the pipe installation and their principal roles in achieving satisfactory performance.

Foundation

A specially constructed foundation layer may or may not be required depending on subsurface conditions. When used, the foundation provides a sound, firm base both in the event that the trench bottom is unstable and in the case of overexcavation. It serves to level out the bottom of trenches cut in rock and provides a cushion layer above a rock or hard earth trench bottom. It may also serve as a drainage layer to drain ground water entering the trench near the work, or water flowing into the work area from adjacent trench sections. Where water conditions are severe, underdrains may be incorporated into this layer to speed drainage to sumps, drainage ditches, or other means of water removal. As discussed later, foundation materials must be carefully selected to be compatible with both *in situ* and embedment materials and to facilitate removal of flowing water in the trench, if present.

In all locations except dams and water impounding structures, the bedding need not be compacted immediately under the pipe except as necessary to provide a uniform, smooth cushion that is in contact with the pipe along its entire axes. In dams and other locations where compaction is needed to prevent leakage, the bedding material must be trimmed to a smooth surface to fit the pipe and provide uniform contact along its axes.

Embedment

The embedment material consists of the bedding, haunching, and the initial backfill. Material placed in the haunch zone below the springline, and which may be comprised of either the bedding or the haunching , or both, is a vital part of the installation. This whole zone supports the pipe wall under vertical loads applied to the pipe, and hence it plays a significant role in structural performance of the installation. It also provides a significant portion of the lateral support to the pipe wall. Judgement, theory, tests, and evaluation of field failures all lead to the conclusion that the support at the haunches of any buried pipe should be uniform rather than concentrated, and plastic pipe provides no exception to this. The desired support in the haunch zone is a uniform "cradle" of embedment material extending over the entire haunch zone for the full pipe length. Undesirable support is a line reaction applied to the invert only. The least desirable support results if this line support is absent along portions of the pipe length or, even worse, if this support reduces to a point load caused by a cobble or boulder in the bedding. These principles hold for any pipe, and any means used in the field to provide uniform bedding is acceptable.

Clearly then, the installation design should recognize the importance of supporting the haunches of plastic pipe. A shaped bedding groove that closely conforms to the bottom of the pipe may be provided before installation. Alternately, it may prove more convenient to tamp embedment material underneath the pipe haunches to provide the desired uniform support, as is the practice for embedment of some types of conventional pipe. Granular embedment materials can be compacted readily and are desirable as materials for the haunch zone.

The embedment materials placed in the pipe zone at the sides of the pipe are also critical to the success of a flexible plastic pipe installation. This material, including that in the haunch zone, must provide uniform lateral support for the pipe wall to minimize ovaling or deflection. Like the bedding, material adjacent to the pipe should provide a continuous uniform cradle extending for the full height and length of the pipe, and any discontinuities in density of materials or presence of cobbles or other debris may result in erratic or excessive deflections.

The upper portion of the initial backfill material above the crown of the pipe is also important in installations where significant wheel loads may be applied at the top of the trench. In this case, the maximum stresses in the pipe are at the crown. Thus, the initial backfill directly above the pipe can be considered as an inverted bedding. The quality of this part of the embedment must be similar to that previously described for bedding and haunching.

Final Backfill

The final backfill material applied above the embedment system usually has little practical importance in pipe performance. It should, of course, be free of boulders and debris to prevent high localized loads on the pipe embedment system, because such inclusions are a known source of overdeflection and failure. In installations located under pavements, the backfill material should be compacted as required for the adjacent materials below pavements to minimize differential settlement of the trench and subsequent loss of support to the pavement.

Considerations in Materials Selection

Because the nature and placement of embedment materials may have more influence on pipe deflection than the pipe itself, selection of embedment materials is a primary consideration in installation design. Key factors in this selection are discussed in the following.

Compaction or density

Theoretically and practically, the component of deflection of the pipe that results from applied load decreases with increasing stiffness or density of the embedment material. In one sense, the applied load tends to densify the embedment, and the pipe deflects to accommodate the associated change in volume. Conversely, the lower the installed density, the higher the amount of pipe deflection that takes place under superimposed loads.

Specified density of the embedment material should be high to minimize the amount of subsequent deformation. A minimum density of 95 percent of maximum dry density (ASTM D698) is usually appropriate.

Field tests demonstrated that dumped granular initial backfill, although meeting a density requirement of 80 percent of the maximum dry density (ASTM D698), results in highly variable deflections. Pipe embedded in the same material compacted by positive means (vibratory compactor) to a slightly higher density of 85 percent of the maximum dry density (ASTM D698) displayed much less variability. This finding is also consistent with laboratory tests. As a rule, any installation should receive positive compaction, and a density of 90 percent of maximum dry density (ASTM D698), or higher, should be considered in specifications for installations. Higher densities may be called for depending on design or field conditions.

Construction Considerations

For the most part, trench proportions and construction procedures for plastic pipe follow practice for conventional piping installations. There are several important considerations bearing on the flexible pipe installation that deserve emphasis.

Trench width

To keep the trench width as narrow as possible is generally considered good practice. Long standing theories have held that friction that develops between the trench wall and the backfill relieves the pipe of some vertical load. The theoretical amount of load reduction varies with properties of the soils involved, water conditions, depth-to-width ratio of the trench, and pipe stiffness. Although, as a rule, minimizing trench width remains good practice, it is much less important in typical shallow buried drainage applications where other factors can prove more critical.

The trench must be wide enough to allow elbow room for mechanics to place and compact material into the haunch zone. Placement can also be done by shovel. A trench width that allows a clearance of 300 mm (12 in) on either side of the pipe at springlines is generally the minimum space needed to work in the trench and place haunching material. This clearance depends somewhat on pipe size and depth and, in any event, should be made large enough to accommodate compaction equipment. Care should be used to avoid damaging pipe when pneumatic compactors are used.

Use of shields and sheeting

Shields, sheeting, and other supports may be required to support trench walls for safety of personnel or if the walls are unstable. A key consideration in flexible plastic pipe installations is to ensure that these devices allow room to place and compact materials. Thus, they should provide working room and the clearances previously discussed for trench width.

Portions of sheeting in the embedment zone should be left in place, unless methods are employed that allow for its removal without disturbing the embedment system. Sheeting that is left in place must be selected to survive for the lifetime of the installation; otherwise, deterioration may cause gradual loss of support of the pipe.

Movable shields should be positioned and moved in a manner that will minimize disturbance of embedment materials and uncoupling of the pipe.

Bedding the pipe

An ideal bedding for any pipe is a uniform, smooth shaped bedding groove that conforms closely to the lower half of the pipe. A bedding groove provides advantages over the use of tamped material in the lower part of the haunch zone. The bedding groove can be prepared from above and inspected before the pipe is laid. The groove is practically a necessity in holding corrugated PE piping true to line and grade during installation.

When a bedding groove is used, it must fit the pipe within close tolerances in the longitudinal direction as well as in cross section. If the radius of the groove is significantly greater than that of the pipe, the gap between the pipe and the bedding may be difficult or impossible to fill during subsequent tamping or compaction operations. For this reason, an oversize bedding groove may do more harm than good. Obviously, the use of a standard shovel to provide curvature of the bedding groove is inappropriate unless the curvature of the shovel bottom conforms closely to that of the pipe. A template or other means of obtaining a semi-circular groove is preferred. The bedding must be shaped along the pipe length, except for bell holes, to provide uniform continuous support.

Many types of plastic pipe have belled ends. A small pocket should be made in the bedding to accommodate the bell and to prevent localized large reactions from point support at the thickened bell.

If the bedding is not grooved, haunching material should be tamped into the lower part of the haunch zone. But tamping is a blind operation, the degree of compaction is not readily controlled or measured, inspection is nearly impossible, and tamping below lightweight pipe may displace the pipe. Despite these shortcomings, field tests and general field experience indicate that tamping material in the haunch zone, if done properly, can provide good deflection control.

Haunching and initial backfill

Placement of haunching and initial backfill materials around plastic pipe follows procedures used in installing more conventional pipe. The key special consideration is that plastic pipe systems are very flexible compared to conventional pipe systems, and, hence, they may experience excessive deflection during installation unless proper procedures are followed. Some plastic pipe is brittle, particularly in cold weather, and this also must be recognized during installation of the backfill.

The following are important considerations related to installation of the initial backfill and haunching materials:

a. Material should be carefully placed and tamped into the entire haunch zone of the pipe, uniformly, over the whole length of the pipe.

b. Material should not be dumped onto the pipe from the top of the trench. Chutes or other means should be used to direct or divert the flow of material to the sides of the trench and to prevent impact on the pipe. The pipe should be stabilized by mounding material at intervals along its length, during placement of embedment material, or by other suitable means, as required to minimize lateral movements of the pipe during placement of the critical backfill.

c. For pipe 203 mm (8 in) in diameter and larger, embedment material should be placed to the springline and compacted by tamping, vibratory compactors, or other means. Compaction equipment should not be allowed to contact the pipe to avoid gouging, impact, and possible excessive deflection. Lift thickness should be compatible with the compaction method to achieve required compaction through the entire thickness of the lift. The remainder of the initial backfill should be compacted in appropriate lift thickness. Material at the sides of the pipe should be compacted before compacting material lying directly above the pipe, and this material should not be compacted until sufficient cover is provided. These steps tend to minimize deflections induced during installation.

d. Lift thickness becomes impracticably thin when material is placed to the springline of pipe less than 203 mm (8 in) in diameter. Furthermore, small diameter pipe is easily displaced when embedment material is compacted at this level. Thus, embedment of smaller pipe should be placed to the level of the top of the pipe before the sidefill is compacted. Precautions given previously for larger pipe should be observed.

Final backfill

Final backfill installation is similar in most respects to that for conventional pipe. A key consideration, however, is to avoid excessive deflection of the pipe caused by placing and compacting the backfill. Large boulders and other debris should be eliminated from the backfill, and material should not be dumped onto the embedment from a significant height.

A protective earth cover should be provided over the top of the pipe before heavy equipment is allowed either in or on the top of the trench. Most state agency specifications require that the contractor furnish a suitable cover depth to protect pipe from construction damage. Where construction traffic is anticipated, the final backfill should be compacted to a density sufficient to minimize rutting. Deep ruts can seriously diminish the actual earth cover provided to shallowly buried pipe, and the pipe installation may be seriously disturbed if not protected by adequate cover.

Special considerations for corrugated plastic tubing

Corrugated plastic tubing has several characteristics that deserve special consideration during installation. They are related to the longitudinal flexibility of the tubing introduced by the corrugations and the light weight of the tubing.

Corrugated tubing in diameters up to 152 or 203 mm (6 or 8 in) is available in coils for convenience in shipping and handling. It may be difficult to obtain straight lengths of tubing after uncoiling, particularly at the larger pipe diameters. This is aggravated by cold weather. This problem can be minimized by only allowing coiling of pipe that is 101 mm (4 in) in diameter or less; larger sizes should be furnished in straight lengths (usually 6 m (20 ft)). Even "straight" lengths, however, may exhibit significant residual warping or undulations.

The inherent longitudinal variations discussed earlier, combined with the low weight of corrugated tubing, present some problems of obtaining tolerances of line and grade that are more readily obtainable with smooth-wall pipe. Once laid in place and straightened, warped tubing will tend to return to its warped configuration unless it is either warmed by the sun, anchored in place with wire hoops located at intervals along its length, or held in a tight fitting bedding groove. Furthermore, the process of tamping material in the haunch zone tends to both lift the lightweight tubing and shove it laterally. Wire hoops help to prevent this shifting, and shaped bedding minimizes or eliminates the necessity for tamping material in the haunch zone.

The use of a shaped bedding groove, where practical, is the preferred method for achieving uniformity of line and grade in a corrugated pipe installation. Where the gradation of the bedding does not permit accurate shaping, closely spaced wire hoops should be used to hold the pipe in place until initial backfill is installed. Shaped bedding is readily obtained with specially equipped automated installation equipment.

The corrugation pattern interrupts the longitudinal structural continuity of corrugated tubing. This makes the tubing vulnerable to longitudinal "stretch" during installation. That is, the tubing can be elongated significantly by axial forces applied during uncoiling, dragging the pipe, or by excessive drag within automated installation equipment. Elongation results in deformations in the corrugation configuration and lowers pipe stiffness. Thus, field installation procedures should ensure that longitudinal elongation of the installed pipe is within tolerable limits, which is typically set at 5 percent.

Highly automated installation equipment has been developed to install conventional agricultural drainage tile and smooth-wall or corrugated plastic pipe and tubing. Because corrugated plastic tubing has received the most use in United States agricultural applications, most experience with this equipment pertains to installing corrugated tubing rather than smooth-wall plastic pipe.

The automated installation equipment is comprised of several main components, the details of which vary depending on machine manufacture and application. A machine used to install shoulder underdrains in Illinois has the following features.

a. A tractor located at the front end provides locomotion.

b. A chain-type trencher is mounted on a "floating" boom. The depth of the trench can be controlled automatically by a mechanism activated by a remote laser bench mark, or the trench can be made a fixed depth below grade.

c. Either spiral worm screws or conveyor belts are mounted below the trencher chain to deflect the excavated spoil falling from the scoops to each side of the trench.

d. A "boot" functioning as a trench shield fits into the trench, supports the trench walls, and excludes crumbs while the tubing feeds through it.

e. The Illinois installation design calls for a bedding groove in the trench bottom. A "groover," located on the leading edge of the boot, forms a semicircular (180 deg) bedding groove in the bottom of the trench.

f. A hopper that retains and distributes select materials for the drainage envelope is mounted on the trailing edge of the boot. A small vibrating compactor located within the hopper compacts the embedment material at a level 127 mm (5 in) above the crown of the pipe.

g. A second compactor located on the trailing edge of the boom compacts the top of the trench. Alternately, the top of the trench can be compacted in a separate operation. This machine installed tubing at a rate of about 4.8 km (3 m) per day in the Illinois installation.

Other variations in the equipment used in agricultural drainage installations employ gravel hoppers behind trenching equipment. The tubing is fed through a metal sleeve as select envelope material is placed completely around the tubing. These devices do not compact the embedment material.

Overall, it appears that automated machine installation, in addition to being efficient, is the preferred method for installing corrugated plastic tubing. Mainly, the difficulties of installing, bedding, and embedding lightweight and flexible tubing by hand methods are minimized, and, as Illinois measurements show, deflection control can be closely maintained.

Handling of Pipe

Each type of plastic pipe has different handling characteristics that should be familiar to the qualified installation contractor. As with any pipe materials, specific limits cannot be placed on how plastic pipe is handled in the field or on how any misuse may affect subsequent performance. Hence, the following is offered only as guidelines that may prove helpful in field control.

Rough handling

By many standards, plastic pipe is rugged. However, there are a number of reasons why rough treatment should be avoided in spite of this desirable characteristic.

A primary concern relates to impact. If impact stresses are sufficient, the pipe will fracture, and this is aggravated by cold weather and extended prior exposure to sunlight. Fractured pipe can be detected readily and replaced. Impact damage possibly may reduce the capacity of the pipe to resist sustained stress or strain in the buried condition, although this has not been specifically validated for buried nonpressure pipe.

Rough handling can also gouge and scratch the plastic pipe. Most plastics used in buried pipe are "notch sensitive," and therefore such damage can lower impact strength and general durability of the product. Fatigue resistance is also compromised, and badly gouged pipe should not be used in installations where significant traffic loads are expected.

Storage in sunlight

Sunlight can cause significant reductions in impact strength and elongation to failure from those properties measured immediately after manufacture. The effects of UV deterioration, if extensive, can be detected by a *chalking of the surface or a color change towards a brownish or yellowish shade, or both.* Such changes are most readily detected by comparing the color of pipe that has received UV exposure, such as outer pipe in a stack, to that of pipe stored in a protected location within the stack.

UV deterioration can be minimized if appropriate ingredients are included in the pipe formulation. This is seldom done in practice, however, and hence plastic pipe and tubing should be protected from extended exposure to sunlight. As a guideline, pipe should be covered if it is exposed to the sun for periods greater than a few weeks. This period should be reduced in arid regions or elevated locations where UV intensity may be high. More information is becoming available on specific acceptable time limits for UV exposure.

Distortions during storage

Plastic pipe can distort severely if not properly stored. One type of distortion is longitudinal bowing. Bowing makes it difficult to achieve specified line and grade. Furthermore, bowed pipe may not properly conform to straight bedding grooves provided, if any. Pipe that is bowed to an extent that line and grade tolerances or proper bedding cannot be achieved should be rejected.

Bowing can be minimized by proper storage. Stored pipe should be supported at intervals spaced to prevent visible sagging. Sag will increase with storage time and with temperature of storage.

Another type of distortion resulting from improper storage is out-of-roundness or ovaling. Ovaling makes it difficult to achieve proper fit at connections. Furthermore, if the minor axis of the oval is oriented in a vertical direction during installation, the ovaling will deduct from the vertical deflection budget. This may cause expensive problems of rejection of the buried pipe if deflection criteria are exceeded.

Ovaled pipe meeting the following conditions should be acceptable:

a. The deflection resulting from ovaling should not exceed one-half of the deflection limit specified for the installation.

b. Pipe should be installed with the major axis of the oval in a vertical position.

c. Joint integrity should not be affected.

d. The installation must meet specified deflection limits.

Otherwise, ovaled pipe should be rejected before installation.

Field Tests for Deflection

Traditionally, deflection or vertical diameter change has been used as an indication of the potential performance of buried flexible plastic and metal pipe. In the case of plastics, deflection measurements provide a valuable quality control check on field work. The requirements of the approach to deflection testing of plastic pipe depend on the experience and philosophy of the specifying authorities, as follows:

1. The agricultural industry does not require field measurements of deflection for corrugated PE drainage tubing.

2. Some municipal users of PVC and ABS sewer pipe do not require deflection measurements, but full-time monitoring of the installation is frequently provided.

3. Some municipal users of PVC and ABS sewer pipe provide inspection and also require complete deflection testing for the full length of the installation.

4. In transportation drainage, the State of Illinois, for example, uses sophisticated deflectometers in their research to develop and refine installation techniques. They find it impractical to specify or measure deflection in actual installations, because there is no

practical access in their underdrain installations.

Overall, field measurements of deflection on installed pipe are a highly desirable check of installation quality. Such measurements may not be feasible in underdrain pipe, where access for testing is not normally provided. It seems prudent that at least the first section installed on a contract should be tested for deflection to verify that the construction method produces the desired result. Once the method has been shown to be satisfactory, it must be consistently maintained throughout the job.

Deflection devices

Practical methods of field testing buried plastic pipe installations include go-no-go plugs, deflectometers, and video systems. These devices represent different levels of sophistication of field instrumentation and of information provided.

Go-no-go plug

The simplest device used in deflection measurement is the go-no-go plug, which consists of a more or less cylindrical mandrel that is pulled through the pipe. The plug is sized to a diameter that corresponds to the minimum specified deflected diameter of the pipe. Thus, the plug will not pass an area of overdeflected pipe. Mandrels can also be made adjustable, so that many sizes of pipe can be measured with the same device. The major advantage of this system is that no instrumentation is required other than the mandrel, itself, which can be constructed to withstand field abuse.

Deflectometers.

The second form of deflection testing is by deflectometer, which is a device that measures pipe diameter continuously or intermittently, while it is drawn through the pipe. Deflectometers have been made with numerous levels of sophistication, from devices that read only vertical diameter and are manually pulled through the pipe and read at selected intervals, to devices that provide continuous readout of both vertical and horizontal diameter. The type of transducer, the instrumentation required, and associated reliability vary significantly. All are nonstandard. Advantages of the deflectometer are that the measuring operation can be completed without interruption for repair of overdeflected regions (most deflectometers can tolerate high deflections without damage) and that a profile of the entire pipeline is obtained for analysis. Deflectometers that read both vertical and horizontal diameters have the added benefit of a self-check. That is, if an area of pipe shows a reduced vertical diameter and an increased horizontal diameter of about equal magnitudes, the reading is assumed to be accurate. If the measured vertical diameter is reduced, however, while the horizontal diameter is unchanged, a deposit of soil in the invert may be present, which affects only the vertical reading.

Deflectometers generally involve some form of electronic instrumentation and must be operated by qualified technical personnel. Adequate checkout procedures must be performed both prior to and after each use to ensure that the instrument is operating properly. Tests are required to determine that the deflectometer maintains the proper orientation within the pipe. This can be a problem in measuring pipe systems that have horizontal sweeps.

Overall, the features of deflectometer devices are that the actual field deflections are known and that they provide good background for the assessment of overall quality of the installation. In addition, a statistical distribution of deflections can be established, which provides a desirable base for evaluation and acceptance of the installed system.

Video systems.

The most sophisticated form of pipe inspection involves video systems, generally closed circuit television. These devices require operation by qualified technical personnel. They provide a fairly good first-hand view of the inside of the pipe for detection of defects such as major breaks or leaking joints. Their resolution and angle of view do not allow detection of any small cracks and the like. Video systems can also be used to record hanges in scale of deflectometers that are drawn through the pipe in tandem with the video unit. Furthermore, a picture of the deflectometer provides a check on the orientation of the probe and allows evaluation of the readings, such as whether or not the invert is filled with soil.

Considerations in deflection measurement

Several important considerations are involved in obtaining reliable deflection measurements. Any soil or other debris in the pipe may be seen by a deflection measuring device as an area of reduced diameter or excessive deflection. This may cause rejection of an otherwise properly installed section of pipe. Thus, it is desirable to clean the pipe using water jet or other means before obtaining measurements.

The time that elapses between the installation of a pipe and the deflection check can be very important because deflections increase with time after installation. Most research indicates that deflections stabilize within a year of installation; however, to wait this long before evaluating an installation is impractical. In general, the time required for an installation to stabilize varies with the quality of backfill. Crushed stone or well compacted granular backfill will normally exhibit a very small increase in deflection after the installation is completed, while finer grained soils that have low density and poorly compacted fills can show significant increases. Trench geometry also may affect rate of development of the final deflection. Generally the final deflection will not exceed 1.5 times the deflection at installation, although much higher values have been recorded, and lower values are possible. Judgment must be used in the selection of the length of time between installation and deflection measurements. The longer the time, the more likely the installation has approached its maximum deflection. Thirty days appears to be a reasonable minimum period. In any event, deflections should be determined before installing paving or other permanent structures to avoid costly dig-up of pipe that does not meet performance criteria.

Although conceptually elementary, practically it is not a simple task to establish a reference diameter for the pipe that can be used as a base for deflection measurements. For example, for most pipe the outside diameter is controlled, and the inside diameter is allowed to vary below a maximum value set by the minimum wall thickness. An oversize wall deducts from the deflection control limit, even while providing more material than specified. The problem becomes more serious with corrugated PE tubing, where the inside diameter is controlled to ±3 percent according to specifications; this 6 percent gross variation may be about the same as the deflection limit set for the tubing.

In recognition of the foregoing problems, the following approach, as used by the State of Wisconsin appears appropriate for establishing the reference diameter as a base for deflection measurements. The reference diameter is taken either as the minimum average diameter obtained in conformance tests or as the following diameters obtained from specified dimensions, whichever is less.

1. ABS and PVC smooth-wall pipe — the average specified outside diameter of the pipe minus the specified tolerance on the specified diameter minus two times 110 percent of the specified minimum wall thickness.

2. ABS composite pipe — the specified average minimum inside diameter.

A practical solution to the dilemma offered by corrugated PE tubing, is not apparent, where the permitted variation in manufactured diameter may exceed the deflection limit established.

Although plastic pipe is manufactured in a reasonably circular configuration, it can oval permanently during shipment and storage. Overall, ovaling may detract from the deflection budget. Theoretically, if the working strain criterion is used as a guideline for determining deflection control limits, the permanent strains induced during ovaling should be deducted from the working strain. Thus, no allowance for ovaling induced after manufacture should be taken in the deflection limit budget.

Field Monitoring

Field monitoring of installations of plastic pipe should be given high priority. Deflection limits established on the basis of working strain criteria are fairly stringent, particularly for perforated underdrain pipe and tubing. This means that good construction practice must be maintained throughout the job to maintain deflection control. Monitoring is particularly important if deflection control is not required for the complete installation.

Also, performance of the flexible plastic pipe installation as measured by deflection depends to a major extent on embedment quality. The embedment structure is constructed in the field, using variable materials, under typically difficult trench conditions. Thus, there is further justification for field monitoring the installation.

Obviously, the contractor retains responsibility for construction of the installation as specified. However, experience shows that competent field monitoring helps to prevent costly construction problems in systems where success depends strongly on field workmanship quality. Plastic pipe installations, unfortunately, provide no exception to this rule.

Summary and Conclusions

Plastic pipe has been used extensively and successfully in many applications, such as municipal sanitary sewers and storm drains; corrugated perforated tubing in agricultural land drainage, water distribution systems, irrigation, and corrugated tubing systems for subsurface drainage of transportation facilities. These applications provide extensive experience in the underground use of plastic pipe.

This TR provides guidelines, to those interested in the use of buried plastic pipe, in the selection, design and installation of plastic pipe systems and to engineering and construction personnel responsible for the installation of such pipe in the field.

These guidelines incorporate information obtained from the state of the art and findings of significance from several recent studies.

Because available plastic pipe systems appropriate for SCS application are much less stiff than conventional flexible pipe of the same diameter, such as corrugated metal conduit, this makes plastic pipe much more susceptible to deformation during installation than conventional products. This entails closer installation control for plastic pipe systems than for conventional pipe.

References

Advances in Underground Pipeline Engineering, Proceedings of the International Conference, American Society of Civil Engineers, NY, 1985.

Allman, W.B., *Dupont's Design Approach to Buried Flexible Pipe*, E.I. Dupont de Nemours & Co., Inc., Wilmington, DE. Plastics Pipe Institute Annual Meeting, April 1977.

"Structural Plastics Design Manual," *ASCE Manuals and Reports on Engineering Practice* , No. 63, American Society of Civil Engineers, NY, 1984.

AWAA C950–81, AWWA Standard for Glass–Fiber Reinforced Thermosetting–Resin Pressure Pipe. American Water Works Association.

Cedergren, H.R., *Drainage of Highway and Airfield Pavements*, John Wiley & Sons, NY, 1974.

Chambers, R. E., and Heger, F.J., *Buried Plastic Pipe for Drainage of Transportation Facilities—Intrim Report*, Gumpertz & Heger Inc., Cambridge, MA, National Cooperative Highway Research Program, Project 4–11. Washington, DC, September 1975.

Chambers, R.E., McGrath, T.J., and Heger F.J. , *Plastic Pipe for Subsurface Drainage of Transportation Facilities*, NCHRP Report 225. Transportation Research Board, Washington, DC, 1980.

"Design and Construction of Sanitary and Storm Sewers," *WPCF Manual of Practice,* No. 9, Water Pollution Control Federation, Washington, DC, 1970.

Designing with Unplasticised Polyvinyl Chloride, Technical Service Note W121, ICI Plastics Division, Welwyn Garden City, Herts, England.

Driscopipe Systems Design Manual, Phillips 66 Driscopipe, Inc., Phillips Petroleum Co., Dallas, TX, 1981.

Handbook of Steel Drainage in Highway Construction Products, Second Edition, American Iron & Steel Institute, NY,1971.

Howard, A.K., *Diametral Elongation of Buried Flexible Pipe*, Paper presented at International Conference on Underground Plastic Pipe, New Orleans, LA, March 1981.

Howard, A.K., *Modulus of Soil Reaction (E') Values for Buried Flexible Pipe*, Report REC–ERC–77–1, Bureau of Reclamation, Denver, CO, January 1977.

Howard, A.K., *Modulus of Soil Reaction Values for Buried Flexible Pipe*, Journal of Geotechnical Division, ASCE, Vol. 103, January, 1977.

Implementation Package for Drainage Blanket in Highway Pavement Systems, Federal Highway Administration, Washington, DC, May 1972.

Jason, L.E., *Plastic Pipe in Sanitary Engineering*, Celanese Systems, A Division of Celanese Plastics Co., NY, 1974.

Krizek, R.J., Parmelee, R.A., Kay, J.N., and Elnaggar, H.A., *Structural Analysis and Design of Pipe Culverts*, NCHRP Report 116, Highway Research Board, 1971:155 pp.

Mascunna, I, *Final Report—Storm Sewer Plastic Pipe Evaluation*, Project IHD–18. State of Illinois Department of Transportation, August 1978.

Pipeline Materials and Design, Proceedings, Pipeline Division of the American Society of Civil Engineers, American Society of Civil Engineers, NY, 1984.

Plastic Piping Manual, First Edition, The Society of the Plastic Industry, New York, NY, 1976.

Poulos, H.G., and Davis, E.H., *Elastic Solutions for Soil and Rock Mechanics*, John Wily & Sons Inc., NY, 1974.

"PVC Pipe – Design and Installation," *Manual of Water Supply Practices,* AWWA No. M23, American Water Works Association, 1980.

Seely, F.B., and Smith, J.O., *Advanced Mechanics of Materials,* Second Edition, John Wiley & Sons, NY.

"Soil Burial Tests of Materials and Structures," *The Bell System Technical Journal*, V51, NI (January 1972). Recomendations for Presentation of Plastics Design Data. Part IV, Environmental and Chemical Effects, BS4618, British Standards Institution, London, November 1973.

Spangler, M.G., *The Structural Design of Flexible Pipe Culverts,* Iowa Engineering Experiment Station Bulletin No. 153, Ames, IA, 1941.

Standard Specifications for Sewer and Water Construction in Wisconsin, Third Edition. Engineers and Scientists of Milwaukee, Inc., Milwaukee, WI, 1976.

Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part I, Specifications, Eleventh Edition, The American Association of State Highway and Transportation Officials, Washington, D C, September 1974.

Thermal Expansion and Contraction of Plastic Pipe, Technical Report TR21. Plastics Pipe Institute, NY. 1973.

Vertical Pressure on Culverts Under Wheel Loads on Concrete Pavement Slabs, Publication No. ST–65. Portland Cement Association, Skokie, Ill, 1951.

Watkins, R.K., and M.G. Spangler. *Some Characteristics of the Modulus of Passive Resistance of Soil; A Study of Similitude*, Highway Research Board Proceedings, Vol 37, Washington, DC, 1958.

Wilging, R.C., and Rice, F.G., "Thermoplastic Pipe Earth Loads," *Public Works Magazine*, June 1977.

Appendix

Appendix A. *Pipe materials classification*

Material		Type & Grade	Cell Class Required	Hydro-static Design Stress (HDS)	Min Tensile Strength (psi)	Mod. of Elasticity (psi)
ASTM D 1788						
ABS	1208	Type 1, Grade 2	5–2–2	800	4000	220,000
	1210	Type 1, Grade 2	5–2–2	1000	4500	240,000
	1316	Type 1, Grade 3	3–5–5	1600	7000	340,000
	2112	Type 2, Grade 1	4–4–5	1250	7000	340,000
ASTM D 1248						
PE	1404	Class C, Grade–P14	IC–P14	400	2800	100,000
	2305	Class C, Grade–P23	IIC–P23	500	1800	90,000
	2306	Class C, Grade–P23	IIC–P23	630	1800	90,000
	3306	Class C, Grade–P33	IIIC–P33	630	3200	120,000
	3406	Class C, Grade–P34	IIIC–P34	630	3200	120,000
ASTM D 1784						
PVC	1120	Type I, Grade 1	12454–B	2000	7000	400,000
	1220	Type I, Grade 2	12454–C	2000	7000	400,000
	2110	Type II, Grade 1	14333–D	1000	6000	320,000
	2112	Type II, Grade 1	14333–D	1250	6000	320,000
	2116	Type II, Grade 1	14333–D	1600	6000	320,000
	2120	Type II, Grade 1	14333–D	2000	6000	320,000
CPVC	4116	Type IV, Grade 1	23447–B	1600	7000	360,000
	4120	Type IV, Grade 1	23447–B	2000	7000	360,000

Appendix B. *Nominal properties of various pipe materials*

Material	ABS	PE	PVC
	ABS 1208 ABS 1210 ABS 1316 ABS 2112	PE 1404 PE 3306 PE 2305 PE 3406 PE 2306	PVC 1120 PVC 2116 PVC 1220 PVC 2120 PVC 2110 CPVC 4116 PVC 2112 CPVC 4120
Specific gravity	1.1	0.91 – 0.96	1.4
Modulus of elasticity at 73°F			
Short–term (Minutes) (psi)	See Appendix A	See Appendix A	See Appendix A
Long–term (10 years)(psi)	110,000	16,000 – 33,000	133,000 – 170,000
Tensile strength at 73°F			
Short–term test (psi)	5,000	1,800 – 3,200	6,000 – 7,000
Long–term (10 years) (psi)	Unknown	Unknown	Unknown
Coefficient of thermal expansion (in / in /°F)	55×10^{-6}	80×10^{-6}	30×10^{-6}
Poissons ratio	0.35	0.45	0.38
Fire properties	Burns	Burns	Burns
UV resistance	Low	Moderate	Low

Appendix C. *Hydrostatic design basis[1] (strength catagories) for thermoplastic pipe compounds determined with water at 23 °C (73.4 °F)*

ASTM material designation[2]	HDB Hydrostatic design basis (psi) 23 °C (73.4 °F)[3]
PE 1404	800
PE 2305	1000
PE 2306	1250
PE 3306	1250
PE 3406	1250
PE 3408	1600
PVC 1120	4000
PVC 1200	4000
PVC 2110	2000
PVC 2112	2500
PVC 2116	3150
PVC 2120	4000
CPVC 4120	4000
ABS 1208	1600
ABS 1210	2000
ABS 1316	3150
ABS 2112	2500
CAB MH08	1600
CAB S004	800
PB 2110	2000
PP 1110	2000
PP 1208	1600
PP 2105	1000
POP 2125	5000

1. Per ASTM D 2837.

2. The last two digits code the maximum traditionally accepted hydrostatic design stress (HDS), expressed in hundreds of psi, $HDS = \frac{HDB}{2}$, where 2 is the generally accepted maximum value for the design factor. The first terms code the material according to short term properties.

3. Because thermoplastics, even though of the same ASTM designation, may be affected differently by increasing temperature, HBD's at higher temperatureres must be established for each specific commercial product. A number of such products have HDB's for temperature as high as 180°. Consult the most current PPI Technical Report TR-4 for the latest listing of HDB's of commercial pipe compounds.

Appendix D. *List of standards for plastic piping system components referenced by NSF standard No. 14*

Description	ANSI	ASTM	FS	Other
Potable water pipe				
Rigid unplasticized polyvinyl chloride pipe		D 1785		
Polyvinyl chloride (PVC) plastic pipe (SDR–PR and class T)	B72.2–67	D 2241		AWWA C900
Specification for polyvinyl chloride (PVC) plastic tubing		D 2740		
Bell end PVC plastic pipe		D 2672		
Potable water pipe — ABS				
ABS plastic pipe, schedules 40 and 80	B72.1–67	D 1527		
Acrylonitrile–butadiene–styrene (ABS) plastic pipe fittings, (SDR–PR)		D 2282		
Potable water pipe — PE				
Polyethylene (PE) plastic pipe, schedules 40 and 80 based on outside diameter	B72.1–67	D 2447	L–P–315a	
Polyethylene (PE) plastic pipe, schedule 40		D 2104		
Polyethylene (PE) plastic pipe (SDR–PR)		D 2239		
Polyethylene (PE) plastics pipe (SDR–PR) based on controlled outside diameter		D 3035		
Polyethylene (PE) plastic tubing		D 2737		
AWWA standard for polyethylene (PE) pressure pipe tubing and fittings				AWWA C901
Potable water pipe — CPVC				
Chlorinated polyvinyl chloride (CPVC) pipe, fittings solvent cements and adhesives for potable hot water systems		D 2846		
Chlorinated polyvinyl chloride (CPVC) plastic pipe schedules 40–80		F 441		
Chlorinated polyvinyl chloride (CPVC) plastic pipe (SDR–PR)		F 442		
Socket–type chlorinated polyvinyl chloride (CPVC) plastic pipe fitting, sch.40		F 438		
Socket–type chlorinated polyvinyl chloride (CPVC) plastic pipe fittings, sch.80		F 439		
Threaded chlorinated polyvinyl chloride CPVC) plastic pipe fitting, sch 80		F437		
Bell end chlorinated polyvinyl chloride (CPVC)		F 443		
Potable water pipe — PE				
Specification for polyethylene (PE) plastic tubing		D 2737		
Polybutylene (PB) plastic pipe (SDR–PR)		D 2662		
Polybutylene (PB) plastic tubing		D 2666		
Polybutylene (PB) plastic pipe (SDR–PR) based on O.D.		D 3000		
Polybutylene (PB) plastic hot–water distribution system		D 3309		

Appendix D. *List of standards for plastic piping system components referenced by NSF standard No. 14* — Continued

Description	ANSI	ASTM	FS	Other
Potable water — well casing				
Thermoplastic water well casing pipe and couplings made in Standard Dimension Ratios (SDR)		F 480		
Potable water fittings — PVC				
Threaded polyvinyl chloride (PVC) plastic pipe fittings, sch. 80		D 2464		
Socket–type polyvinyl chloride (PVC) plastic pipe fittings, sch. 40		D 2466		
Socket–type polyvinyl chloride (PVC) plastic pipe fittings, sch. 80		D 2467		
Potable water fittings — ABS				
Socket–type acrylonitrile–butadiene–styrene (ABS) plastic pipe fittings,sch.40		D 2468		
Socket–type acrylonitrile–butadiene–styrene (ABS) Plastic pipe fitting, sch. 80		D 2469		
Potable water fittings — PE				
Standard specification for plastic insert fittings for polyethylene (PE) plastic pipe	B16.27–62	D 2609		
Butt heat fusion polyethylene (PE) plastic fittings for polyethylene (PE) plastic pipe and tubing		D 3261		
DWV pipe and fittings — PVC				
Polyvinyl chloride (PVC) plastic drain, waste & vent pipe and fittings		D 2665	L–P–320a	
Polyvinyl chloride (PVC) for 3 inch thinwall		D 2949		
DWV pipe and fittings — ABS				
Acrylonitrile–butadiene–styrene (ABS) plastic drain, wast & vent pipe and fittings		D 2661	L–P–322a	
Acrylonitrile–butadiene–styrene (ABS) plastic drain, waste & vent piping having a foam core		F 628		
DWV pipe and fittings —ABS —PVC				
Drain, wast & vent (DWV) plastic fittings patterns		D 3311		
Tubular pipe and fittings (PVC, ABS,PP)				
Thermoplastic accessible and replacable plastic tube and tubular fittings		F 409		
Sewer and drain pipe				
Acrylonitrile–butadiene–styrene (ABS) sewer pipe and fittings		D 2751		
Polyvinyl Chloride (PVC) sewer pipe and fittings		D 3033 D 3034		
Corrugated polyethylene tubing and fittings		F 405		

Appendix D. *List of standards for plastic piping system components referenced by NSF standard No. 14* — Continued

Description	ANSI	ASTM	FS	Other
Solvent cements				
Solvent cements for ABS plastic pipe and fittings		D 2235		
Solvent cements for PVC plastic pipe and fittings		D 2564		
Solvent cements for joining ABS pipe and fittings to PVC pipe and fittings for nonpressure applications		D 3138		
Solvent cements for chlorinated polyvinyl chloride plastic pipe and fittings		F 493		
Thermoset plastic piping sytem components				
Filament–wound reinforced thermosetting resin pipe		D 2996		
Centrifugally cast reinforced thermosetting resin pipe		D 2997		
Reinforced plastic mortar pressure pipe		D 3517		

List of standards for thermoplastic materials for plastic piping system components

Description	ANSI	ASTM	FS	Other
PVC				
Rigid polyvinyl chloride compounds and chlorinated polyvinyl chloride compounds		D 1784		
ABS				
Rigid acrylonitrile–butadiene–styrene (ABS) plastics		D 1788		
PE				
Polyethylene plastics molding and extrusion materials		D 1248		
Polyethylene plastics pipe and fitting materials		D 3350		
PP				
Polypropylene plastic molding and extrusion materials		D 2146		
PB				
Polybutylene plastics		D 2581		
PS				
Styrene–butadiene molding and extrusion materials		D 1892		

Note: Copies of the ASTM Standards may be obtained from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103

Appendix E. *Coefficients of linear thermal expansion of piping materials*

Material[a]	Nominal coefficients[b] x 10^{-5}, in / in /°F
ABS	4.0 – 6.0
PE – type I	10.00
type II	8.0 – 9.0
type III	7.0
High molecular weight (Type IV)	6.0
PVC type I	3.0 – 3.5
type II	3.0 – 5.0
CPVC	3.5
SR	3.3 – 5.0
PB	7.2
PP	4.0 – 4.8
CAB	8.0 – 9.5
Steel	0.65
Cast iron	0.55
Copper	0.98

a. The abbreviations for the plastics are in accordance with ASTM D 883, D 1600 and F 412, PPI–TR1–NOV 1968, Plastic pipe standards, and common usage, and are as follows:

- ABS – Acrylonitrile–butadiene–styrene
- PVC type I – Rigid or unplasticized polyvinyl chloride; covers PVC 1120 and PVC 1220 compounds.
- PVC type II – Rubber modified polyvinyl chloride; covers PVC 2110, 2112, 2116 and 2120 compounds.
- PB – polybutylene
- PE – polyethylene
- CPVC – Chlorinated polyvinyl chloride. Formerly designated as PVC 4120
- SR – styrene–rubber
- CAB – cellulose acetate butyrate

b. These values are independent of pipe diameter

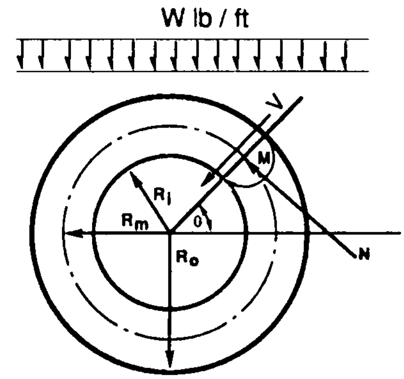
Appendix F
Derivation of Equations and Coefficients in Strain Computations

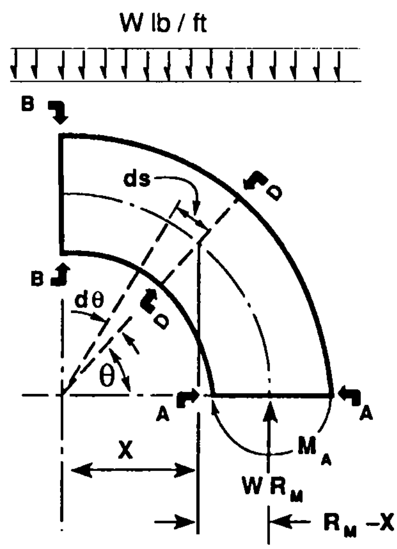
COMPUTATION SHEET
SCS ENG 522A
Rev. 8-69

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
GPO 1978-0725733

STATE SNTC		PROJECT Design of Flexible Pipe		
BY MNL	DATE 3–88	CHECKED BY SRW	DATE 3–88	JOB NO.
SUBJECT Derivation of Equation & Coefficient in Strain Computations				SHEET 1 OF 5

Assume Uniform Load





Reference: "Advanced Mechanics of Materials" by: Fred Seely and James Smith

$$ds = R_m \, d\theta$$

The bending moment at any section DD located at an angle θ from section AA is the algebraic sum of the moments of the forces that lie to one side of the section.

$$M_{DD} = M_A - W R_m (R_m - X) + W (R_m - X) \frac{R_m - X}{2}$$

where $X = R_m \cos \theta$

COMPUTATION SHEET
SCS ENG 522A
Rev. 8-69

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
GPO 1978-0725733

STATE SNTC		PROJECT Design of Flexible Pipe	
BY MNL	DATE 3–88	CHECKED BY SRW	DATE 3–88	JOB NO.
SUBJECT **Derivation of Equation & Coefficient in Strain Computations**			SHEET 2 OF 5

$$M_{DD} = M_A - WR_m\,(R_m - R_m \cos\theta) + W\,(R_m - R_m \cos\theta)\left(\frac{R_m - R_m \cos\theta}{2}\right)$$

Combine terms:

$$M_{DD} = M_A - WR^2_m\,(1 - \cos\theta) + \frac{WR_m^2}{2}(1 - \cos\theta)(1 - \cos\theta)$$

Must calculate the value M_A

Consider the elastic behavior of a beam. The elastic rotation of any section is equivalent to the change in slope of the beam at the section because of the loads.

Let sections AA and BB remain at right angles to each other, therefore the change in the angle between AA and BB is equal to zero.

Therefore:

$$\int_o^{\frac{\pi}{2}} \frac{M\ R_m}{E\ I}\,d\theta = 0$$

where M is at any angle θ from AA to BB.

Because *R*,*E*, and *I* are constant for any individual pipe the equation may be simplified to:

$$\int_o^{\frac{\pi}{2}} M\ d\theta\ ™ = 0$$

In this case $M = M_{DD}$ Therefore

$$\int_o^{\frac{\pi}{2}} M_{DD}\ d\theta = 0$$

Substitute for M_{DD}:

$$\int_o^{\frac{\pi}{2}} \left[M_A - W\ R_m^2\,(1 - \cos\theta) + \frac{W\ R_m^2}{2}(1 - \cos\theta)(1 - \cos\theta)\right] d\theta = 0$$

$$\int_o^{\frac{\pi}{2}} M_A\,d\theta - \int_o^{\frac{\pi}{2}} WR_m^2\ d\theta + \int_o^{\frac{\pi}{2}} WR_m^2 \cos\theta\ d\theta + \frac{1}{2}WR_m^2 \int_o^{\frac{\pi}{2}} (1 - \cos\theta)^2 d\theta = 0$$

COMPUTATION SHEET
SCS ENG 522A
Rev. 8-69

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
GPO 1979-0725733

STATE SNTC		PROJECT Design of Flexible Pipe		
BY MNL	DATE 3-88	CHECKED BY SRW	DATE 3-88	JOB NO.
SUBJECT Derivation of Equation & Coefficient in Strain Computations				SHEET ____ OF ____

$$M_A\,\theta\Big|_0^{\frac{\pi}{2}} - W\,R_m^2\,\theta\Big|_0^{\frac{\pi}{2}} + W\,R_m^2\,\sin\theta\Big|_0^{\frac{\pi}{2}} + \frac{1}{2}W\,R_m^2\left[\theta - \sin\theta + \frac{\theta}{2} + \frac{\sin\theta}{A}\right]_0^{\frac{\pi}{2}} = 0$$

$$M_A\,\frac{\pi}{2} - W\,R_m^2\,\frac{\pi}{2} + W\,R_m^2 + \frac{W\,R_m^2}{2}\left[\frac{\pi}{2} - 2 + \frac{\pi}{4} + 0\right] = 0$$

$$M_A\,\frac{\pi}{2} = W\,R_m^2\,\frac{\pi}{2} - \frac{W\,R_m^2\,\pi}{4} - W\,R_m^2\,\frac{\pi}{8}$$

$$M_A = \frac{1}{4}W\,R_m^2$$

The forces on any section DD are:

$M_{DD} = \frac{1}{4}W\,R_m^2 - W\,R_m^2\,(1-\cos\theta) + \frac{1}{2}W\,R_m^2\,(1-\cos\theta)^2$	Moment
$N = W\,R_m\,\cos\theta$	Normal to R_m
$V = W\,R_m\,\sin\theta$	Shear

Castigliano's theorem for the relationship of external loads and elastic deflection of a curved beam states:

> If external forces act on an elastic structure, the displacement in the direction of any one of the forces at the point of application of the force is equal to the partial derivative of the total strain energy, *u*, in the member with respect to the force.

COMPUTATION SHEET
SCS ENG 522A
Rev. 8-69

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
GPO 1979-0725733

STATE SNTC		PROJECT Design of Flexible Pipe			
BY MNL	DATE 3-88	CHECKED BY SRW	DATE 3-88	JOB NO.	
SUBJECT Derivation of Equation & Coefficient in Strain Computations				SHEET 4	OF 7

$$\Delta_p = \frac{\partial U}{\partial P}$$

The partial derivative of the moment M_{DD} with respect to the force, WR_m:

$$\frac{\partial M_{DD}}{\partial (W\ R_m)} = \frac{1}{4}R_m - R_m - \cancel{R_m \mathrm{Cos}\,\theta} + \frac{1}{2}R_m - \cancel{R_m \mathrm{Cos}\,\theta} + \frac{1}{2}R_m \mathrm{Cos}^2\theta$$

$$= \frac{1}{4}R_m + \frac{1}{2}R_m \cos^2\theta$$

The partial derivitive of the normal load, N, with respect to the force, WR_m:

$$\frac{\partial N}{\partial (W\ R_m)} = \cos\theta$$

The partial derivitative of the shear load, V, with respect to the force, WR_m:

$$\frac{\partial V}{\partial (W\ R_m)} = \sin\theta$$

The elastic strain energy per unit volume due to N is $\frac{1}{2}\frac{N^2}{a^2 E}$

a=cross sectional area of the beam.

and the volume equals $a\ ds$ where ds equals the arc length of the pipe section at its centroid. The work done by the normal force, N, is

$$d\ U_n = \frac{1}{2}\frac{N^2}{E\ a^2} a\ ds = \frac{1}{2}\frac{N^2 ds}{E\ a}$$

$$\text{since } N = W\ R_m \cos\theta$$

COMPUTATION SHEET
SCS ENG 522A
Rev. 8-69

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
GPO 1979-0725733

STATE SNTC	PROJECT Design of Flexible Pipe			
BY MNL	DATE 3-88	CHECKED BY SRW	DATE 3-88	JOB NO.
SUBJECT Derivation of Equation & Coefficient in Strain Computations				SHEET ____ OF ____

$$dU_n = \frac{1}{2}\frac{(W R_m \cos\theta)^2}{E a} ds$$

Total strain energy for the quadrant produced by the load *N* is :

$$U_n = \frac{1}{2}\int_0^{\frac{\pi}{2}} \frac{N^2 ds}{E a}$$

Using the same rationale the strain energy due to shear and bending moment is:

$$U_v = \frac{1}{2}\int_0^{\frac{\pi}{2}} \frac{V^2}{G a} ds$$

$$U_m = \frac{1}{2}\int_0^{\frac{\pi}{2}} \frac{M_{DD}^2 ds}{E a y_0 R_m}$$

G= shearing modulus of elasticity

y_0= distance of the neutral axis from the centroidal axis.

Total strain energy is the sum of the values:

$$U = \frac{1}{2}\int \frac{N^2 ds}{E a} + \frac{1}{2}\int \frac{V^2}{G a} ds + \frac{1}{2}\int \frac{M_{DD}^2 ds}{E a y_0 R_m}$$

Total deflection at the point of application of the load is found by taking the partial derivative with respect to the load.

$$\Delta_p = \frac{\partial u}{\partial p} = \int \frac{N}{E a}\frac{\partial N}{\partial P} + \int \frac{V}{G a}\frac{\partial V}{\partial P} ds + \int \frac{M_{DD}}{EI}\frac{\partial M_{DD}}{\partial P} ds$$

In most cases the direct stress and shear stress is negligible compared to the influence of the bending moment. Therefore the first two terms may by neglected. The equation for deflection then becomes:

$$\Delta_p = \int \frac{M_{DD}}{E I}\frac{\partial M_{DD}}{\partial P} ds$$

COMPUTATION SHEET
SCS ENG 522A
Rev. 8-69

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
GPO 1979-0725733

STATE SNTC		PROJECT Design of Flexible Pipe	
BY MNL	DATE 3–88	CHECKED BY SRW	DATE 3–88	JOB NO.
SUBJECT Derivation of Equation & Coefficient in Strain Computations			SHEET ____ OF ____

However, the deflection in any quadrant caused by the load $W R_m$ that is equal to 1/2 P is only 1/2 of the total deflection (by rules of symmetry) therefore:

$$\frac{\Delta_p}{2} = \Delta_{W\ R_m} = \int_0^{\frac{\pi}{2}} \frac{M_{DD}}{E\ I} \frac{\partial\ M_{DD}}{\partial\ (W\ R_m)} ds$$

Substitute values

$$\frac{\Delta_p}{2} = \Delta_{W\ R_m} = \int_0^{\frac{\pi}{2}} \left(\frac{1}{4} W\ R_m^2 - W\ R_m^2\ (1 - \cos\theta) + \frac{1}{2} W\ R_m^2\ (1 - \cos\theta)^2 \right) \left(-\frac{1}{4} R_m + \frac{1}{2} R_m \cos^2\theta \right) (R_m\ d\theta)$$

Combine terms and integrate:

$$\frac{\Delta_p}{2} = \Delta_{W\ R_m} = 0.049942\ \frac{R_m^4 W}{E\ I}$$

Total deflection:

$$\Delta_p = 2\ \Delta_{W\ R_m} = 0.09988\ \frac{W\ R_m^4}{E\ I}$$

Maximum moment occurs at $\theta = \frac{\pi}{2}$

Moment @ $\theta = \frac{\pi}{2}$ *is* $M = \frac{1}{4} W\ R_m^2$

Strain = $\frac{f}{E}$ $\quad f = \frac{Mc}{I}$

Strain $\varepsilon = \frac{Mc}{I} \frac{1}{E}$ $\quad c = \frac{t}{2}$

COMPUTATION SHEET
SCS ENG 522A
Rev. 8-69

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
GPO 1979-672573

STATE SNTC		PROJECT Design of Flexible Pipe		
BY MNL	DATE 3-88	CHECKED BY SRW	DATE 3-88	JOB NO.
SUBJECT Derivation of Equation & Coefficient in Strain Computations				SHEET ____ OF ____

in the deflection equation solve for E:

$$E = 0.09988 \frac{W R_m^4}{\Delta_p I}$$

Substitute values into the equation for strain:

$$\varepsilon = \frac{Mc}{EI} = \frac{\frac{1}{4} W R_m^2 \left(\frac{t}{2}\right)}{\left(\frac{0.09988 WR_m^2}{\Delta_p I}\right) I}$$

reduce terms:

$$\varepsilon = \frac{\frac{1}{8} t}{\frac{0.09988 R_m^2}{\Delta_p}} = \frac{1.25 \, t \, \Delta_p}{R_m^2} = 1.25 \frac{t}{R_m} \frac{\Delta_p}{R_m}$$

Deflection is usually reported as a ratio to the mean diameter, therefore must multiply numerator and denominator by 2.

$$\varepsilon = 2.50 \frac{t}{R_m} \frac{\Delta_p}{2 R_m}$$

or if all terms are a ratio of the mean diameter

$$\varepsilon = 5.00 \frac{t}{D_m} \frac{\Delta_p}{D_m}$$

A similiar analysis was done for the point loading condition and the only change from the strain equation above was the coefficient. It changed from 5.00 to 4.28. Published research shows the coefficient to be as high as 10. A decision was made to use 5.00 as the coefficient when computing the bending strain from the soil and wheel loads and to use 4.28 as the coefficient when computing the bending strain that may develop from the installation.

Glossary

Acrylonitrile-butadiene-styrene (ABS) pipe and fitting plastics - plastics containing polymers and/or blends of polymers, in which the minimum butadiene content is 6%, the minimum acrylonitrile content is 15%, the minimum styrene and/or substituted styrene content is 15% and the maximum content of all other monomers is not more than 5%, and lubricants, stabilizers and colorants.

Aging, n. - (1) the effect on materials of exposure to an environment for an interval of time, (2) the process of exposing materials to an environment for an interval of time.

Antioxidant - a compounding ingredient added to a plastic composition to retard possible degradation from contact with oxygen (air), particularly in processing at, or exposures to, high temperatures.

Compound - the intimate admixture of a polymer or polymers with other ingredients such as fillers, softeners, plasticizers, catalysts, pigments, dyes, curing agents, stabilizers, or antioxidants.

Creep, n. - the time-dependent part of strain resulting from stress, that is, the dimensional change caused by the application of load over and above the elastic deformation and in time.

Deflection temperature - the temperature at which a specimen will deflect a given distance at a given load under prescribed conditions of test. See ASTM D 648. Formerly called heat distortion.

Degradation, n. - a deleterious change in the chemical structure of a plastic.

Dimension ratio - the diameter of a pipe divided by the wall thickness. Each pipe can have two dimension ratios depending on whether the outside or inside diameter is used. In practice, the outside diameter is used if the standards requirement and manufacturing control are based on this diameter. The inside diameter is used when this measurement is the controlling one.

Elastomer - a material which at room temperature can be stretched repeatedly to at least twice its original length and, upon immediate release of the stress, will return with force to its approximate original length.

Elevated temperature testing - tests on plastic pipe above 23 °C (73.4 °F).

Environmental stress cracking - cracks that develop when the material is subjected to stress in the presence of specific chemicals.

Ethylene plastics - plastics based on resins made by the polymerization of ethylene or copolymerization of ethylene with one or more other unsaturated compounds, the ethylene being in greatest amount by weight.

Fiber stress - the unit stress, usually in pounds per square inch (psi), in a piece of material that is subjected to an external load.

Fungi resistance - the ability of plastic pipe to withstand fungi growth and/or their metabolic products under normal conditions of service or laboratory tests simulating such conditions.

Heat joining - making a pipe joint by heating the edges of the parts to be joined so that they fuse and become essentially one piece with or without additional material.

Hoop stress - the tensile stress, usually expressed in pounds per square inch (psi), in the circumferential orientation in the wall of the pipe when the pipe contains a gas or liquid under pressure.

Hydrostatic design stress - the estimated maximum tensile stress in the wall of the pipe in the circumferential orientation due to internal hydrostatic pressure that can be applied continuously with a high degree of certainty that failure of the pipe will not occur.

Hydrostatic strength (quick) - the hoop stress calculated by means of the ISO equation at which the pipe breaks due to an internal pressure build-up, usually within 60 to 70 seconds.

ISO equation - an equation showing the interrelations between stress, pressure and dimensions in pipe, namely

$$f = \frac{P_f\ (d + t)}{2t} \text{ or } \frac{P_f\ (D - t)}{2t}$$

where f = stress
P_f = pressure
d = average inside diameter
D = average outside diameter
t = minimum wall thickness

Reference: ISO R161 - 1960 Pipes of Plastics Materials for the Transport of Fluids (Outside Diameters and Nominal Pressures) Part I, Metric Series.

Joint - the location at which two pieces of pipe or a pipe and a fitting are connected together. The joint may be made by an adhesive, a solvent cement or a mechanical device such as threads or a ring seal.

Long-term burst - the internal pressure at which a pipe or fitting will break due to a constant internal pressure held for 100,000 hours (11.43 years).

Long-term hydrostatic strength - the estimated tensile stress in the wall of the pipe in the circumferential orientation (hoop stress) that when applied continuously will cause failure of the pipe at 100,000 hours (11.43 years). These strengths are usually obtained by extrapolation of log-log regression equations or plots.

Monomer - a relatively simple chemical which can react to form a polymer.

Outdoor exposure - plastic pipe placed in service or stored so that it is not protected from the elements of normal weather conditions, the sun's rays, rain, air and wind. Exposure to industrial and waste gases, chemicals, engine exhausts. are not considered normal "outdoor exposure."

Pipe stiffness - a measure of how a flexible conduit will behave under burial conditions. Refer also to ASTM Method D 2412.

Plastic, n. - a material that contains as an essential ingredient, one or more organic polymeric substance of large molecular weight, is solid in its finished state, and, at some stage in its manufacturer or in its processing into finished articles, can be shaped by flow.

Note 1 - the above definition may be used as a separate meaning to the definitions contained in the dictionary for the adjective "plastic."

Note 2 - the plural form may be used to refer to two or more plastic materials, for example, plastics industry. However, when the intent is to distinguish "plastic products" from "wood products" or "glass products," the singular form should be used. As a general rule, if the adjective is to restrict the noun modified with respect to type of material, "plastic" should be used; if the adjective is to indicate that more than one type of plastic material is or may be involved, "plastics" is permissible.

Plasticizer - a material incorporated in a plastic to increase its workability and its flexibility or distensibility.

Note - the addition of the plasticizer may lower the melt viscosity, the temperature of the second-order transition, or the elastic modulus of the plastic.

Plastic conduit - plastic pipe or tubing used as an enclosure for electrical wiring.

Plastic pipe - a hollow cylinder of a plastic material in which the wall thicknesses are usually small when compared to the diameter and in which the inside and outside walls are essentially concentric.

Reworked material (thermoplastic) - a plastic material that has been reprocessed, after having been previously processed by molding, extrusion, etc. in a fabricator's plant.

Schedule - a pipe size system (outside diameters and wall thicknesses) originated by the iron pipe industry.

Note - actual values will depend on the method of test. Sometimes referred to as softening point.

Solvent cement - in the plastic piping field a solvent adhesive that contains a solvent that dissolves or softens the surfaces being bonded so that the bonded assembly becomes essentially one piece of the same type of plastic.

Stabilizer - a compounding ingredient added to a plastic composition to retard possible degradation on exposure to high temperatures, particularly in processing. An antioxidant is a specific kind of stabilizer.

Standard dimension ratio - a selected series of numbers in which the dimension ratios are constants for all sizes of pipe for each standard dimension ratio and which are the ANSI Preferred Number Series 10 modified by + 1 or – 1. If the outside diameter (OD) is used the modifier is +1. If the inside diameter is used the modifier is – 1.

Some of the numbers are as follows:

RIO Preferred Number Series	OD Control	ID Control
5.0	6.0	4.0
6.3	7.3	5.3
8.0	9.0	7.0
10.0	11.0	9.0
12.5	13.5	11.5
16.0	17.0	15.0
20.0	21.0	19.0
25.0	26.0	24.0
31.5	32.0	30.5
40.0	41.0	39.0
50.0	51.0	49.0
63.0	64.0	62.0

Reference: ANSI Preferred Numbers, Z17.1

Standard thermoplastic pipe materials designation code - A means for easily identifying a thermoplastic pipe material by means of three elements. The first element is the abbreviation for the chemical type of the plastic in accordance with ASTM D 1600. The second is the type and grade (based on properties in accordance with the ASTM materials specification); in the case of ASTM specifications which have no types and grades or those in the cell structure system, two digit numbers are assigned by the PPI that are used in place of the larger numbers. The third is the recommended hydrostatic design stress (RHDS) for water at 23 °C (73.4 °F) in pounds per square inch divided by 100 and with decimals dropped, e.g. PVC 1120 indicates that the plastic is poly (vinyl chloride). Type I Grade 1 according to ASTM D 1784 with a RHDS of 2000 psi for water at 73.4 °F. PE 3306 indicates that the plastic is polyethylene, Type III Grade 3 according to ASTM D 1248 with a RHDS of according to ASTM D 1248 with a RHDS of 630 psi for water at 73.4 °F. PP 1208 is polypropylene, Class I-19509 in accordance with ASTM D 2146 with a RHDS of 800 psi for water at 73.4 °F; the designation of PP 12 for polypropylene class I-19509 will be covered in the ASTM Standards for polypropylene pipe when they are issued.

Stiffness factor - a physical property of plastic pipe that indicates the degree of flexibility of the pipe, when subjected to external loads. See ASTM D 2412.

Strain - the ratio of the amount of deformation to the length being deformed caused by the application of a load on a piece of material.

Strength - the stress required to break, rupture or cause a failure.

Stress - when expressed with reference to pipe: the force per unit area in the wall of the pipe in the circumferential orientation due to internal hydrostatic pressure.

Stress-crack - external or internal cracks in a plastic caused by tensile stresses less than that of its short-time mechanical strength.

Note - the development of such cracks is frequently accelerated by the environment to which the plastic is exposed. The stresses which cause cracking may be present internally or externally or may be combinations of these stresses. The appearance of a network of fine cracks is called crazing.

Stress relaxation - the decrease of stress with respect to time in a piece of plastic that is subject to a constant strain.

Sustained pressure test - a constant internal pressure test for 1000 hours.

Thermoplastic, n. - a plastic that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and that in the softened state can be shaped by flow into articles by molding or extrusion.

Thermoplastic, adj. - capable of being repeatedly softened by heating and hardened by cooling though a temperature range characteristic of the plastic and that in the softened state can be shaped by flow into articles by molding or extrusion.

Note - thermoplastic applies to those materials whose change upon heating is substantially physical.

Thermoset, n. - a plastic which, when cured by application of heat or chemical means, changes into a substantially infusable and insoluble product.

Thermoset, adj. - pertaining to the state of a resin in which it is relatively infusible.

Thermosetting - capable of being changed into a substantially infusible or insoluble product when cured under application of heat or chemical means.

Vinyl chloride plastics - plastics based on resins made by the polymerization of vinyl chloride or copolymerization of vinyl chloride with other unsaturated compounds, the vinyl chloride being in greatest amount by weight.

Virgin material - a plastic material in the form of pellets, granules, powder, floc, or liquid that has not been subjected to use or processing other than that required for its original manufacture.

Flow Chart
Structural Design of Flexible Conduit

1. List Known & Assumed Data

2. Select Pipe & List Properties

3. Calculate Loads
Soil load
Buoyant soil load
Groundwater load
Wheel load
Internal loads

4. Calculate Deflection
Soil load
Vehicle load
Installation
Total deflection

5. Calculate Strains
Ring bending strain
Ring tension strain
Ring compression strain

6. Calculate Strength Index

7. Solid Pipe
Rerounding factor
Tensile strength index

8. Perforated Pipe
Ring bending strain at the perforations
Total bending ring strain in tension at the perforations
Strength index in tension at the perforation

9. Calculate Buckling Resistance

Modified AWWA formula
Buckling resistance

Check bucking under hydrostatic loads
Bucking resistance

1. List Known & Assumed Data

Fill height, h, ft
Soil density, γ_s, #/ft³
Vehicle load, P_{wL}, lbs
Groundwater conditions
Embedment material
Modulus of soil reaction, E', psi
Capacity reduction factor for pipe strength, $\phi = 0.80$
Capacity reduction factor for pipe stiffness, $\phi'' = 0.75$

Capacity reduction factor for modulus of soil reaction,
- in buckling, $\phi' = 0.50$
- with wheel load, $n_w = 0.50$

Load factors
- Soil, $\overline{LF}$, = 1.5 maximum
- Soil, $\overline{LF}$, = 0.8 minimum
- Wheel, $\overline{LF}$, = 1.8 maximum
- Installation, $\overline{LF}$, 1.0

Deflection lag factor, D_L
- Short term = 1.0
- Long term = 1.5

Ultimate long term strength
- Creep, $\varepsilon_C = 1$
- Relaxation, $\varepsilon_R = 2$ for solid PVC; $\varepsilon_R = 3$ for perforated PVC
- Perforation factor, $\overline{PF}$, see narrative Table 7

2. Select Pipe & List Properties

Cell class, from ASTM
Designation, from ASTM
Initial modulus of elasticity, psi
Wall thickness, t, in.
Outside diameter, D, in.
Mean diameter, D_m, in.
Mean radius, R_m, in.
Inside diameter, d, in.
Creep factor,

$$\frac{E_0}{E_{10}} = 2$$

Initial pipe stiffness,

$$\overline{PS_o} = 4.47\,\frac{E_o}{\left(\frac{D}{t}-1\right)^3}$$

Long term pipe stiffness,

$$\overline{PS_{10}} = \frac{\overline{PS_o}}{\overline{CF}}$$

3. Calculate Loads

Soil load

$$P_s = \frac{\gamma_m}{144}\,h$$

$P_s = P_s\,\overline{LF}$ Factored soil load

$P'_{su} = P_s\,\overline{LF}$ Minimum factored soil load

Buoyant soil load

$$C_w = 1 - \frac{h_w}{3\,h_s}$$

$$P_b = P_s C_w$$

$P_{bu} = P_b\,\overline{LF}$ Factored Buoyant soil load

Groundwater load

$$P_g = 0.433\,h_w$$

$P_{gu} = P_g\,\overline{LF}$ Factored groundwater load

Wheel load

If pipe $D - t < (2.67)[h\,12]$

$$P_{wh} = \frac{0.48\,P_{wL}\left(\frac{D-t}{12}\right)^2}{2.67\,h^3\,(D-t)\,(12)}\left[\frac{2.67\,h}{\frac{D-t}{12}} - 0.5\right]$$

If pipe $D - t \geq (2.67)[h\,12]$

$$P_{wh} = \frac{0.64\,P_{wL}}{h\,(D-t)\,12}$$

Impact Factor

$$\overline{IF} = 1 + \frac{P_{wh}}{P_{wh} + P_s}$$

Wheel load adjusted for impact

$$P_w = P_{wh}\,(\overline{IF})$$

Wheel load adjusted for load factor

Maximum: $P_{wu} = P_w\,(\overline{LF})$

Internal loads

Vacuum, P_v, *psi*
Pressure, P_f, *psi*

4. Calculate Deflection

Soil load

$$\frac{\Delta_s}{2R_m} = \frac{K_b P_s D_L}{0.149\ \overline{PS_o} + 0.061\ E'}$$

Vehicle load

$$\frac{\Delta_w}{2R_m} = \frac{K_b P_w D_L}{0.149\ \overline{PS_o} + 0.061\ E'\ n_w}$$

Installation

$$\frac{\Delta i}{2R_m} = \text{See Table 5}$$

Total deflection

$$\frac{\Delta}{2R_m} = \frac{\Delta_s}{2R_m} + \frac{\Delta_w}{2R_m} + \frac{\Delta_i}{2R_m}$$

Is total short term deflection ≤ 3%
Is total long term deflection ≤ 5%

- YES
  - Proceed to 5
- NO
  - Return to 1. Change embedment material to increase modulus of soil reaction.
  - Return to 2. Select another pipe and list properties.

5. Calculate Strains

Ring bending strain

Due to soil loads

$$\varepsilon_{bsu} = 2.5\ \frac{t}{R_m}\ \overline{MF}\ \frac{\Delta_s}{2R_m}\ \overline{LF}$$

Due to wheel loads

$$\varepsilon_{bwu} = 2.5\ \frac{t}{R_m}\ \overline{MF}\ \frac{\Delta_w}{2R_m}\ \overline{LF}$$

Due to installation

$$\varepsilon_{biu} = 2.14\ \frac{t}{R_m}\ \overline{MF}\ \frac{\Delta_i}{2R_m}\ \overline{LF}$$

Total ring bending strain

$$\varepsilon_{bu} = \varepsilon_{bsu} + \varepsilon_{bwu} + \varepsilon_{biu}$$

Proceed to 6

Ring tension strain

Total ring bending strain

$$\varepsilon_{tu} = \frac{P_{fu}\ R_i}{t\ E_o}$$

Proceed to 6

Ring compresssion strain

Due to earth load

$$\text{Maximum}\quad \varepsilon_{csu} = \frac{R_o\ P_{su}}{t\ E_o}$$

$$\text{Minimum}\quad \varepsilon'_{csu} = \frac{R_o\ P'_{su}}{t\ E_o}$$

Due to wheel load

$$\text{Maximum}\quad \varepsilon_{cwu} = \frac{R_o\ P_{wu}}{t\ E_o}$$

Due to groundwater

$$\varepsilon_{cgu} = \frac{R_o\ P_{gu}}{t\ E_o}$$

Due to vacuum

$$\varepsilon_{cvu} = \frac{R_i\ P_{vu}}{t\ E_o}$$

Proceed to 6

6. Calculate Strength Index

Maximum compressive strength index

$$\frac{\varepsilon_{bu}}{\varepsilon_{Ru}} + \frac{\varepsilon_{csu} + \varepsilon_{cwu} + \varepsilon_{cvu} + \varepsilon_{cgu}}{\varepsilon_{Cu}}$$

→ Is the sum ≤ 1.0 ?

- NO →
  - Change embedment material to increase modulus of soil reaction. Return to 1.
  - Select another pipe and list properties. Return to 2
- YES → Continue strain check

7. Solid Pipe

Rerounding factor

Non-pressure pipe

$$\overline{RF} = 1.0$$

Pressure pipe

$$\overline{RF} = 1.0\left[\left(1 + \frac{2\,P_f\,R_i}{(P_s + P_w)\,R_o}\right)\left(\frac{\Delta}{2\,R_m}\right)\right]^{-1}$$

Tensile strength index

$$\frac{\overline{RF}\;\varepsilon_{bu}}{\varepsilon_{Ru}} + \frac{\varepsilon_{tu}}{\varepsilon_{Cu}} - \frac{\varepsilon'_{csu} + \varepsilon_{cg} + \varepsilon_{cv}}{\varepsilon_{Cu}}$$

Is the sum ≤ 1.0

- YES → Proceed to 9 Buckling Resistance Continue design check
- NO →
  - Return to 2 Select another pipe
  - Return to 1 Change embedment material

8. Perforated Pipe

The tensile strength must be checked at the perforations. A perforation factor, and the term C_m which is a coefficient based on the angle between the perforations and the vertical centerline of the pipe.

Ring bending strain at the perforations

Due to soil load

$$\overline{PF}\;\varepsilon_{bsu} = 10\,\frac{t}{R_m}\,C_m\,\overline{MF}\,\frac{\Delta_s}{2\,R_m}\,\overline{LF}\;\overline{PF}$$

Due to wheel load

$$\overline{PF}\;\varepsilon_{bwu} = 10\,\frac{t}{R_m}\,C_m\,\overline{MF}\,\frac{\Delta_w}{2\,R_m}\,\overline{LF}\;\overline{PF}$$

Due to installation

$$\overline{PF}\;\varepsilon'_{biu} = 8.56\,\frac{t}{R_m}\,C_m\,\overline{MF}\,\frac{\Delta_i}{2\,R_m}\,\overline{LF}\;\overline{PF}$$

Total ring bending strain in tension at the perforations

$$\overline{PF}\;\varepsilon_{bsu} = \overline{PF}\;\varepsilon_{bsu} + \overline{PF}\;\varepsilon_{bwu} + \overline{PF}\;\varepsilon_{biu}$$

Strength index in tension at the perforation

$$\frac{\overline{PF}\;\varepsilon_{bu}}{\varepsilon_{Ru}} - \frac{\varepsilon'_{csu} + \varepsilon_{cgu}}{\varepsilon_{Cu}}$$

Is the sum ≤ 1.0

- YES → Proceed to 9 Buckling Resistance Continue design check
- NO →
  - Return to 2 Select another pipe
  - Return to 1 Change embedment material

9. Calculate Buckling Resistance

Check both procedures

Modified AWWA formula

$$P_{cr} = 0.77 \sqrt{\left(\frac{1 - \frac{\Delta}{2R_m}}{\left(1 + \frac{\Delta}{2R_m}\right)^2}\right)^3 Cw\, B'\, E'\, \phi\, \overline{PS_{10}}\, \phi''}$$

$$C_w = 1 - \frac{h_w}{3h}$$

If $0 < \frac{h\,(12)}{2R_o} < 5$

then $B' = \left(0.015 + 0.041 \frac{h}{2R_o}\right)$

If $5 < \frac{h\,(12)}{2R_o} < 80$

then $B' = \left(0.150 + 0.014 \frac{h}{2R_o}\right)$

Buckling resistance

$$\frac{P_{bu} + P_{gu} + P_{vu} + P_{wu}}{P_{cr}}$$

Is the value ≤ 1.0

- YES → All requirements have been met. The design is complete.
- NO →
  - Return to 2. Select another pipe
  - Return to 1. Change embedment material

Check buckling under hydrostatic loads

$$P'_{cr} = 0.5\, C_a\, \overline{PS_o}\, \phi'\, \phi''$$

C_a = 2 to 3 for soft soils but may be up to 6 for rigid encasement

Buckling resistance

$$\frac{P_{gu} + P_{vu}}{P'_{cr}}$$

Is the value ≤ 1.0

- YES → All requirements have been met. The design is complete.
- NO →
  - Return to 2. Select another pipe
  - Return to 1. Change embankment material

All requirements have been met.
The design is complete.

☆U.S. Government Printing Office : 1990 - 261-486/20129