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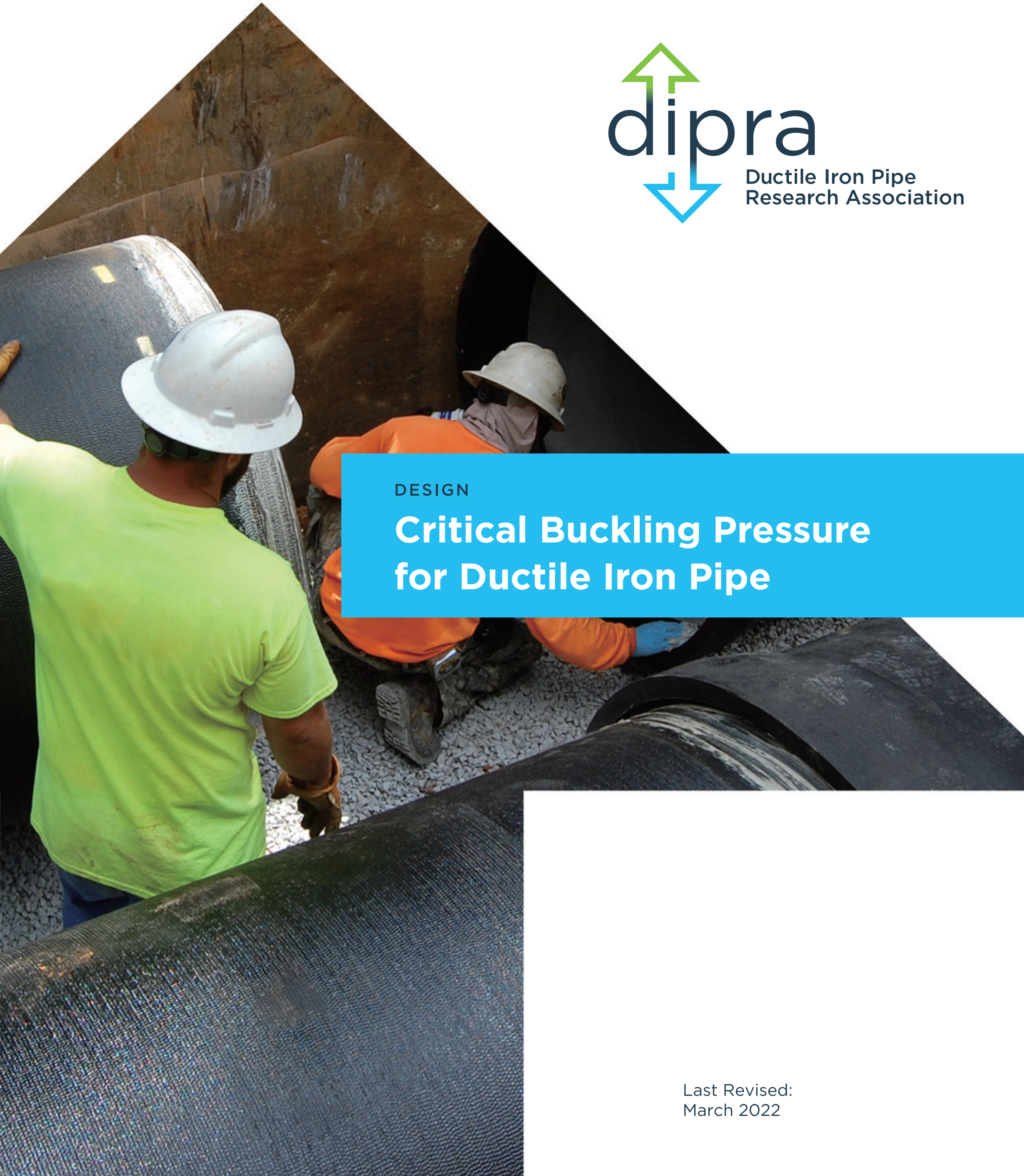

DESIGN

Critical Buckling Pressure for Ductile Iron Pipe

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Critical Buckling Pressure for Ductile Iron Pipe

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When external pressure is increased on a pipeline, it may reach a level (the critical buckling pressure, P_{CR}) where the structure becomes suddenly unstable and collapses due to general buckling. Collapse is sudden inversion of curvature of the pipe wall. The more flexible the pipe, the more unstable the wall structure will be in resisting buckling. In the case of buried pipes, the surrounding soil generally provides some support to the pipe, creating a higher critical buckling pressure than in unsupported applications.

While to our knowledge there has never been buckling collapse failure of a Ductile iron pipeline, the new larger sizes may suggest an examination of bucking design in certain situations. Therefore, in applications where a Ductile iron pipeline may be subject to internal negative pressure conditions (vacuum*) and/or external hydrostatic pressure, a prudent design engineer will want to include calculations to assure that the pipe will not collapse due to buckling.

Buckling with No Support from Surrounding Soil Structure

The worst case (lowest critical bucking pressure) occurs when the pipeline is exposed to the atmosphere or liquid media with no support for surrounding soil structure.

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* Vacuum is a common expression for internal negative pressure and/ or external fluid pressure.

For this case the critical buckling pressure is given by[1] :

$$P_{CR} = \frac{2E}{(1 - \gamma^2)} \left(\frac{t_1}{D_M} \right)^3 \quad (Eq.1\ )$$

where:

P_{CR} = Critical buckling pressure (psi)
E = Modulus of elasticity of the pipe material (24 x10^6 psi for ductile iron)
γ = Poisson's ratio for the pipe material (0.28 for ductile iron)
D_M = Mean diameter of the pipe
t_1 = Minimum manufacturing thickness of the pipe (inch)

TABLE 1
Standard Pressure Classes and Nominal Thicknesses of Ductile Iron Pipe

Size (inches)	Outside Diameter (inches)	Pressure Class				
		150	200	250	300	350
3	3.96	-	-	-	-	0.25*
4	4.80	-	-	-	-	0.25*
6	6.90	-	-	-	-	0.25*
8	9.05	-	-	-	-	0.25*
10	11.10	-	-	-	-	0.26
12	13.20	-	-	-	-	0.28
14	15.30	-	-	0.28	0.30	0.31
16	17.40	-	-	0.30	0.32	0.34
20	21.60	-	-	0.33	0.37	0.38
24	25.80	-	0.33	0.37	0.40	0.43
30	32.00	0.34	0.38	0.42	0.45	0.49
36	38.30	0.38	0.42	0.47	0.51	0.56
42	44.50	0.41	0.47	0.52	0.57	0.63
48	50.80	0.46	0.52	0.58	0.64	0.70
54	57.56	0.51	0.58	0.65	0.72	0.79
60	61.61	0.54	0.61	0.68	0.76	0.83
64	65.67	0.56	0.64	0.72	0.80	0.87

* Calculated thicknesses for these sizes and pressure ratings are less than those shown above. These are the lowest nominal thicknesses currently available in these sizes.

Pressure classes are defined as the rated water working pressure of the pipe in psi. The thicknesses shown are adequate for the rated water working pressure plus a surge allowance of 100 psi. Calculations are based on a minimum yield strength in tension of 42,000 psi and 2.0 safety factor times the sum of working pressure and 100 psi surge allowance.

Thickness can be calculated for rated water working pressure and surges other than the above by use of the design procedure detailed in ANSI/AWWA C150/A21.50.

Ductile iron pipe can be utilized for water working pressure greater than 350 psi and is available in thicknesses greater than Pressure Class 350. Contact DIPRA member companies regarding specific requirements.

Table 2
Allowances for Casting Tolerance

Size (inches)	Casting Tolerance (inches)
3-8	0.05
10-12	0.06
14-42	0.07
48	0.08
54-64	0.09

The lowest critical buckling pressure (P_{CR}) corresponds to the smallest t_1/D_M value with no support from surrounding soil structure. The smallest value of t_1/D_M for domestically manufactured Ductile iron pipe corresponds to 64-inch Pressure Class 150 (see Table 1). To calculate the critical buckling pressure for this size Ductile iron pipe exposed to the atmosphere, apply Equation 1:

$$P_{CR} = \frac{2E}{(1 - \gamma^2)} \left(\frac{t_1}{D_M} \right)^3$$

where:

$E = 24 \text{ x} 10^6 \text{ psi}$
$\gamma = 0.28$
$t_1 = 0.56 - .09 = 0.47$ inch (from Tables 1 & 2)
$D_M = 65.67 - 0.47 = 65.20$ (from Table 1)

$$\therefore P_{CR} = \frac{(2)\,(24\ x\ 10^6)}{(1 - 0.28^2)} \left(\frac{0.47}{65.20} \right)^3 = 19.51 psi$$

Therefore, 64-inch Pressure Class 150 Ductile iron pipe exposed to the atmosphere and subjected to 10 psi internal vacuum would have a safety factor of approximately 2.0 $(S_f = \frac{19.51}{10} = 1.95)$ against failure due to buckling. Higher pressure rated 64-inch diameter pipe as well as all smaller diameter Ductile iron pipe would have an even higher safety factor.

For example, 24-inch diameter pressure Class 200 Ductile iron pipe would have a critical buckling pressure (P_{CR}) of 54.95 psi, giving it a safety factor of 5.5 against failure due to buckling when exposed to the atmosphere and subjected to 10 psi internal vacuum. The stiffness and buckling resistance of all sizes of Ductile iron pipe with minimum wall thicknesses are significantly greater than that of flexible pipe of other materials. Table 3 shows the lowest critical buckling pressure of pressure class Ductile iron pipe when exposed to the atmosphere or liquid media (worst case).

TABLE 3
Minimum Critical Buckling Pressure of Ductile Iron Pipe Exposed to the Atmosphere or Liquid Media (worst case)

	Pressure Class				
	150	200	250	300	350
Size (in)	Critical Buckling Pressure (psi)				
3	-	-	-	-	7,838.36
4	-	-	-	-	4,280.70
6	-	-	-	-	1,385.37
8	-	-	-	-	601.12
10	-	-	-	-	321.74
12	-	-	-	-	210.79
14	-	-	140.37	185.16	210.79
16	-	-	125.19	161.33	203.95
18	-	-	100.78	144.16	179.19
20	-	-	94.20	131.26	160.79
24	-	54.95	84.81	113.28	147.59
30	32.09	48.75	70.43	90.40	122.52
36	28.30	40.86	61.23	81.76	113.36
42	23.77	38.87	55.53	76.43	107.82
48	22.30	34.74	51.16	72.13	98.24
54	20.68	32.97	49.39	70.58	97.18
60	20.75	32.12	47.08	69.22	93.58
64	19.51	31.38	47.33	68.00	90.46

Buckling of Buried Ductile Iron Pipe

Ulrich Luscher studied the case of thin, cylindrical tubes surrounded by a concentric ring of soil and found that the surrounding soil tremendously increases the buckling resistance of a flexible tube over that of an unsupported tube[4]. He found that the modulus of elastic support provided by the soil is mathematically equivalent to the modulus of resistance of the soil cylinder to uniform pressure applied at the inner boundary. Luscher also found that elastic buckling occurs when the uniform applied pressure on the outside of the soil ring exceeds a critical value (the critical buckling pressure, P_{CR}) expressed as:

$$P_{CR} = \left[\frac{32EIBE_S}{D_M^3} \right]^{1/2} \qquad (Eq.2\ )$$

where:

P_{CR} = Critical buckling pressure (psi)
E = Modules of elasticity of the pipe material (24×10^6 psi for Ductile Iron)
I = Moment of inertial of the pipe per inch (in.^{4}/in.)
D_M = Mean diameter of the pipe (in.)
E_S = Soil modulus of elasticity (psi)
B = Coefficient of elastic support:

$$B = \frac{1 - \left[\dfrac{D_M}{D_M + 2h} \right]^2}{1.3 + 0.52 \left[\dfrac{D_M}{D_M + 2h} \right]^2}$$

where:

h = Depth of cover (inch)

Glascock proposed substituting the modulus of soil reaction (E') for E_S in Luscher's equation and, in order to make predictions agree with results of soil box and buried vacuum tests, proposed modification of B as follows[5] :

$$B' = \left[\begin{array}{ll} 0.015 + 0.041 \left(\dfrac{h}{D_M} \right) & \mathit{for}\ 0 \le \dfrac{h}{D_M} \le 5 \\ 0.015 + 0.041 \left(\dfrac{h}{D_M} \right) & \mathit{for}\ 5 \le \dfrac{h}{D_M} \le 80 \end{array} \right]$$

Standard laying conditions and conservative E' values for Ductile iron pipe from ANSI/AWA C150/A21.50 are given in Table 4.

TABLE 4

Standard Pipe Laying Conditions

Laying Conditions [†]	Description	E' (psi)	Bedding Angle (degrees)	K_O	K_x
Type 1[††]	Flat-bottom trench.[†††] Loose backfill.	150	30	0.235	0.106
Type 2	Flat-bottom trench. Backfill lightly consolidated to centerline of pipe.	300	45	0.210	0.105
Type 3	Pipe bedded in 4-in. minimum loose soil.[††††] Backfill lightly consolidated to top of pipe.	400	60	0.189	0.103
Type 4	Pipe bedded in sand, gravel, or crushed stone to depth of $^1/_8$ pipe diameter, 4-in. minimum. Backfill compacted to top of pipe. (Approx. 80 percent Standard Proctor, AASHTO T-99-[†††††]	500	90	0.157	0.096
Type 5	Pipe bedded to its centerline in compacted granular material, 4-in. minimum under pipe. Compacted granular or select [††††] material to top of pipe. (Approx. 90 percent Standard Proctor, AASHTO T-99.[†††††]	700	150	0.128	0.085

[†] Sec Figure 1.

[††] For pipe 14-inch and larger, consideration should be given to the use of laying conditions other than Type 1.

[†††] Flat-bottom is defined as "undisturbed earth."

[††††] Loose soil or select material is defined as "native soil excavated from the trench, free of rocks, foreign material, and frozen earth."

[†††††] AASHTO T-99, "Moisture Density Relations of Soils Using a 5.5-pound Rammer 12-inch Drop."

In order to reduce E' when the pipeline was submerged, Glascock also introduced a groundwater buoyancy reduction factor (R_W):

$$R_W = 1 - 0.33\frac{h_w}{h}$$

where:

h_W = Height of groundwater above pipe (inch)

h = Depth of cover (inch)

Glascock and Cagle later reanalyzed the buckling tests based on new data on much larger pipes and concluded that B' may be more a function of soil depth (h) than of the depth-to-diameter ratio and revised B' as follows[6]:

$$B' = \frac{1}{1 + 4e^{-0.065H}}$$

where:

H = Depth of cover (feet)

Therefore, the critical buckling pressure (P_{CR}) for buried pipe becomes:

$$P_{CR} = \left[\frac{32\, R_w\, E\, I\, B' E'}{D_M^3}\right]^{1/2} \qquad (Eq.3\ )$$

where:

P_{CR} = Critical buckling pressure (psi)

R_w = Water buoyancy factor

$$= 1 - 0.33\left(\frac{h_W}{h}\right) ;\ 0 \leq h_W \leq h$$

where:

h_W = Height of groundwater above pipe (inch)

h = Depth of cover (inch)

E = Modulus of elasticity of the pipe material (24 x 10^6 psi for Ductile iron pipe)

I = Moment of inertia of the pipe per inch (in.$_4$/in.)

B' = Empirical coefficient of elastic support

$$= \frac{1}{1 + 4e^{-0.065H}}$$

where:

H = Depth of cover (feet)

E' = Modulus of soil reaction (psi)

D_M = Mean diameter of the pipe (inch)

For Ductile iron pipe this equation reduces to :

$$P_{CR} = 8{,}000 \left[R_w B' E' \left(\frac{t_1}{D_M} \right)^3 \right]^{1/2} \qquad (Eq.4)$$

When designing for buried installation, the critical buckling pressure divided by a safety factor (normally 2), should be greater than or equal to the combined soil overburden pressure, external hydrostatic pressure, and internal vacuum. Normally, simultaneous applications of live-load and internal-vacuum transients need not be considered. Therefore, for vacuum conditions:

$$P_{CR} \geq R_w P_{prism} + P_{hydrostatic} + P_{vacuum}$$

$$\frac{P_{CR}}{S_f} \geq R_w \left(\frac{wH}{144} \right) + \frac{\gamma_w H_w}{144} + P_{vacuum} \qquad (Eq.5)$$

where:

w = Soil weight (120 lb./ft^3)

H = Depth of cover (ft)

γ_w = Specific weight of water (62.4 lb./ft^3)

H_w = Height of groundwater above pipe (ft)

S_f = Safety factor (normally 2)

Example:

A 36-inch diameter Pressure Class 150 Ductile iron pipeline is to be installed with 4 feet of cover and a Type 3 laying condition. The pipeline could be subjected to as much as 10 psi internal vacuum and a water table 2 feet above the pipe. Using a design safety factor of 2, check for collapse due to buckling. What is the actual safety factor against this type of failure?

Using Eq. 4:

$$P_{CR} = 8{,}000 \left[R_w B' E' \left(\frac{t_1}{D_M} \right)^3 \right]^{1/2}$$

$$R_w = 1 - 0.33 \left(\frac{h_w}{h} \right)$$

$$= 1 - 0.33 \left(\frac{24}{48} \right)$$

$$= 0.835$$

$$B' = \frac{1}{1 + 4e^{-0.065H}}$$

$$= \frac{1}{1 + 4e^{-0.065(4)}}$$

$$= 0.245$$

E' = 400 psi (From Table 4)

t_1 = Nominal thickness - casting tolerance (from Tables 1 & 2)

= 0.38 - 0.07

= 0.31 inch

$$D_M = \text{O.D.} - t_1 \qquad \text{(O.D. from Table 1)}$$

$$= 38.3 - 0.31$$

$$= 37.990 \text{ inch}$$

$$\therefore P_{\text{CR}} = 8{,}000 \left[(0.835)\,(0.245)\,(400) \left(\frac{0.31}{37.99} \right)^3 \right]^{1/2}$$

$$= 53.344 psi$$

Using Eq. 5:

$$\frac{P_{\text{CR}}}{S_{\text{f}}} \geq R_{\text{w}} \left(\frac{wH}{144} \right) + \frac{\gamma_{\text{w}} H_{\text{w}}}{144} + P_{vacuum}$$

$$\frac{53.344}{2} \geq (0.835) \left[\frac{(120)\,(4)}{144} \right] + \left[\frac{(62.4)\,(2)}{144} \right] + 10$$

$$26.672 \geq 2.783 + 0.867 + 10$$

$$26.672 \geq 13.65 \quad \therefore \quad OK$$

$$Actual\ Safety\ Factor = \frac{P_{\text{CR}}}{P_{\text{actual}}}$$

$$= \frac{53.344}{13.65}$$

$$= 3.91$$

In the American National Standard for the Thickness Design for Ductile Iron Pipe (ANSI/AWWA C150/A21.50)[2], the wall thickness required for external load is based on two design considerations: limitation of ring bending stress and ring deflection. Based on these design considerations, Table 5 provides the maximum depth of cover for Ductile Iron pipe with cement lining based on laying conditions and assumed earth prism/traffic loadings.

TABLE 5
Maximum Depth of Cover for Ductile Iron Pipe with Cement Lining

Pipe size (in)	Pressure Class	Nominal Thickness Class	Laying Condition				
			Type 1	Type 2	Type 3	Type 4	Type 5
			Maximum Depth of Cover, ft[A]				
3	350	0.25	78	88	99	B	B
4	350	0.25	53	61	69	85	B
6	350	0.25	26	31	37	47	65
8	350	0.25	16	20	25	34	50
10	350	0.26	11**	15	19	28	45
12	350	0.28	10**	15	19	28	44
14	250	0.28	C	11**	15	23	36
	300	0.30		13	17	26	42
	350	0.31		14	19	27	44
16	250	0.30	C	11**	15	24	34
	300	0.32		13	7	26	39
	350	0.34		15	20	28	44
18	250	0.31	C	10**	14	22	31
	300	0.34		13	17	26	36
	350	0.36		15	19	28	41
20	250	0.33	C	10	14	22	30
	300	0.36		13	17	26	35
	350	0.38		15	19	28	38
24	200	0.33	C	8**	12	17	25
	250	0.37		11	15	20	29
	300	0.40		3	7	24	32
	350	0.43		15	19	28	37
30	150	0.34	C	-	9	14	22
	200	0.38		8**	12	16	24
	250	0.42		10	5	19	27
	300	0.45		12	16	21	29
	350	0.49		15	19	25	33
36	150	0.38	C	-	9	14	21
	200	0.42		8**	12	15	23
	250	0.47		10	14	18	25
	300	0.51		12	16	20	28
	350	0.56		15	19	24	32
42	150	0.41	C	-	9	13	20
	200	0.47		8	12	15	22
	250	0.52		10	14	17	25
	300	0.57		12	16	20	27
	350	0.63		15	19	23	32
48	150	0.46	C	-	9	13	20
	200	0.52		8	11	5	22
	250	0.58		10	13	7	24
	300	0.64		12	15	19	27
	350	0.70		15	18	22	30
54	150	0.51	C	-	9	13	20
	200	0.58		8	11	14	22
	250	0.65		10	13	16	24
	300	0.72		13	15	19	27
	350	0.79		15	18	22	30
60	150	0.54	C	5**	9	13	20
	200	0.61		8	11	14	22
	250	0.68		10	13	16	24
	300	0.76		13	15	19	26
	350	0.83		15	18	22	30
64	150	0.56	C	5**	9	13	20
	200	0.64		8	11	14	21
	250	0.72		10	13	16	24
	300	0.80		12	15	19	26
	350	0.87		15	17	21	29

** Minimum allowable depth of cover is 3 ft.

A These pipes are adequate for depth of cover from 2.5 ft up to the maximum shown including an allowance for a single H-20 truck with 1.5 impact factor unless noted.

B Calculated maximum depth of cover exceeds 100 ft.

C For pipe 14-inch and larger, consideration should be given to the case of laying conditions other than Type 1.

1. Ring deflection limited to 3%, minimum safety factor of 2.
2. Earth load (P_e) is based on soil weight of 120 pcf.

Although it may be unlikely to experience such a combination of adverse conditions in practice, it is possible to calculate the allowable depth of cover for Ductile iron pipe classes by the procedures outlined in this paper assuming an internal vacuum of 10 psi, water table even with the surface of the ground, and a safety factor of 2. When this is done, invert case greater depths of cover are allowed but this buckling design procedure than are allowed by current standard ANSI/AWWA C150/A21.50 design procedures. Additionally, the stiffening effect of the pipe bell cross-section and pipe joint overlap is conservatively ignored in this procedure. It is obvious, therefore, that a designer need not normally be concerned with bucking collapse of Ductile iron pipe. However, there are some extreme conditions, such as evacuation of a large diameter pipeline installed under great depths of water, where buckling design may be necessary.

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For more information contact DIPRA or any of its member companies.

Ductile Iron Pipe Research Association

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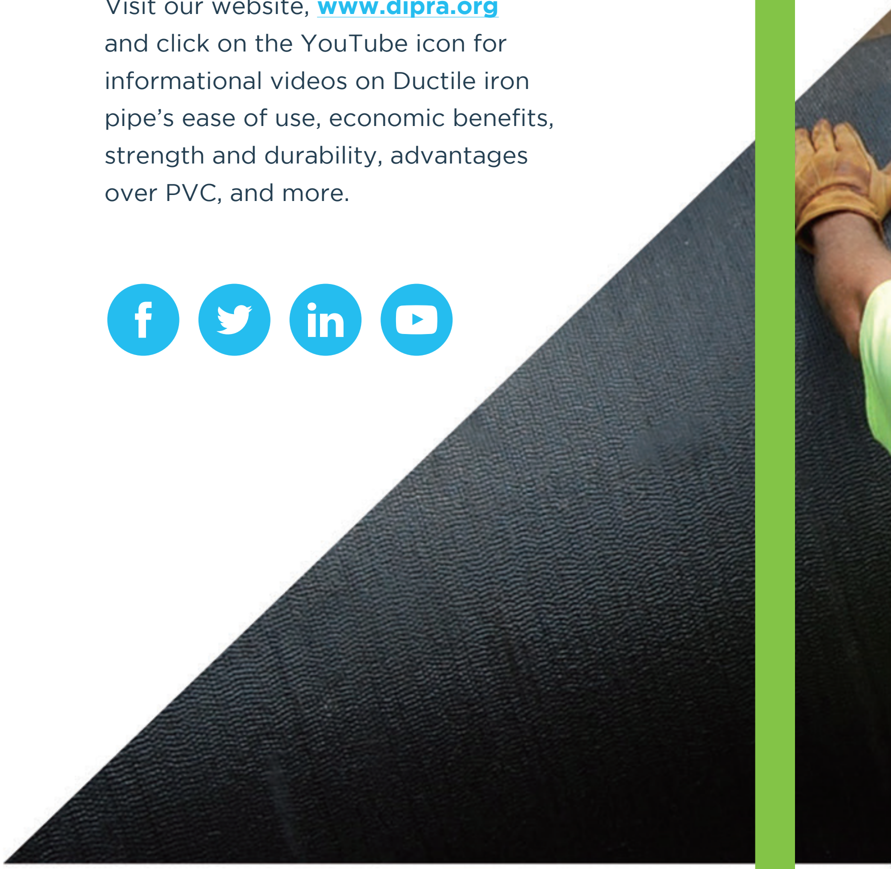

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