Structural Pipe Design

Paul Imm, P.Eng. – Cambridge, Ontario, Canada

Riley Dvorak, P.E. – Maple Grove, MN

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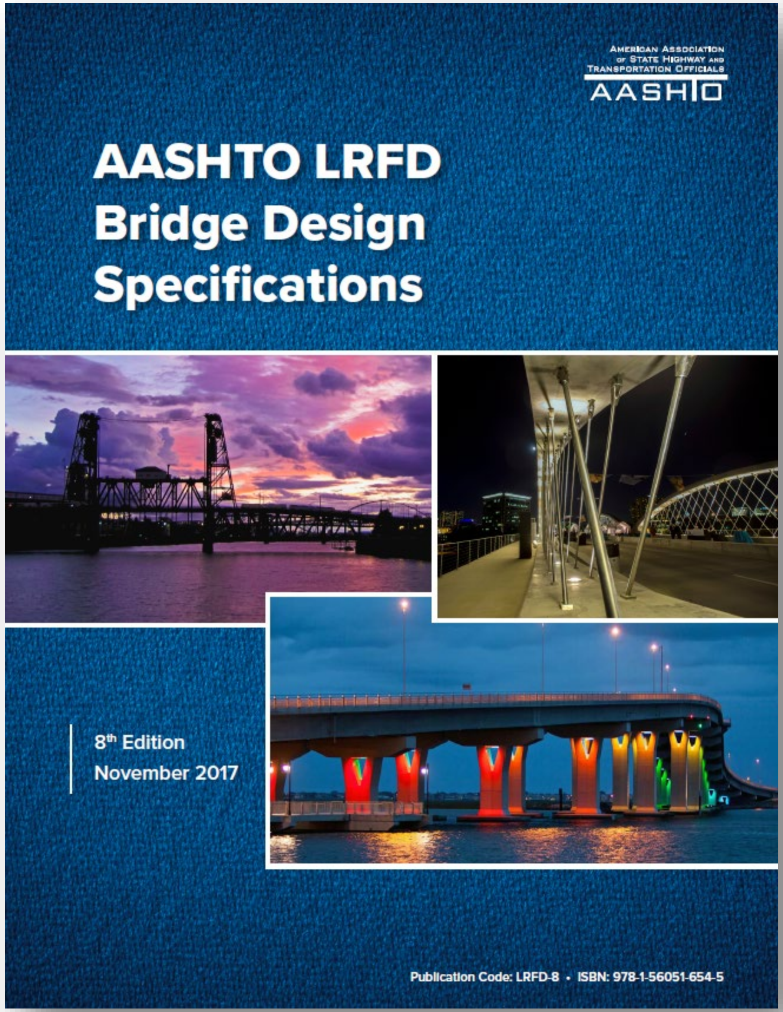
OVERVIEW

- Rigid vs flexible pipe behavior
- Design methods in AASHTO LRFD Section 12 Buried Structures:
  - Concrete pipe – Indirect Design with Standard Installations
  - Plastic pipe – Limit states design
- Summary

STRUCTURAL DESIGN OF BURIED PIPE



These structures become part of a composite system comprised of the pipe and the soil envelope.

12.10 – Reinforced Concrete Pipe

- Direct Design Method
- Indirect Design Method

12.12 – Thermoplastic Pipes

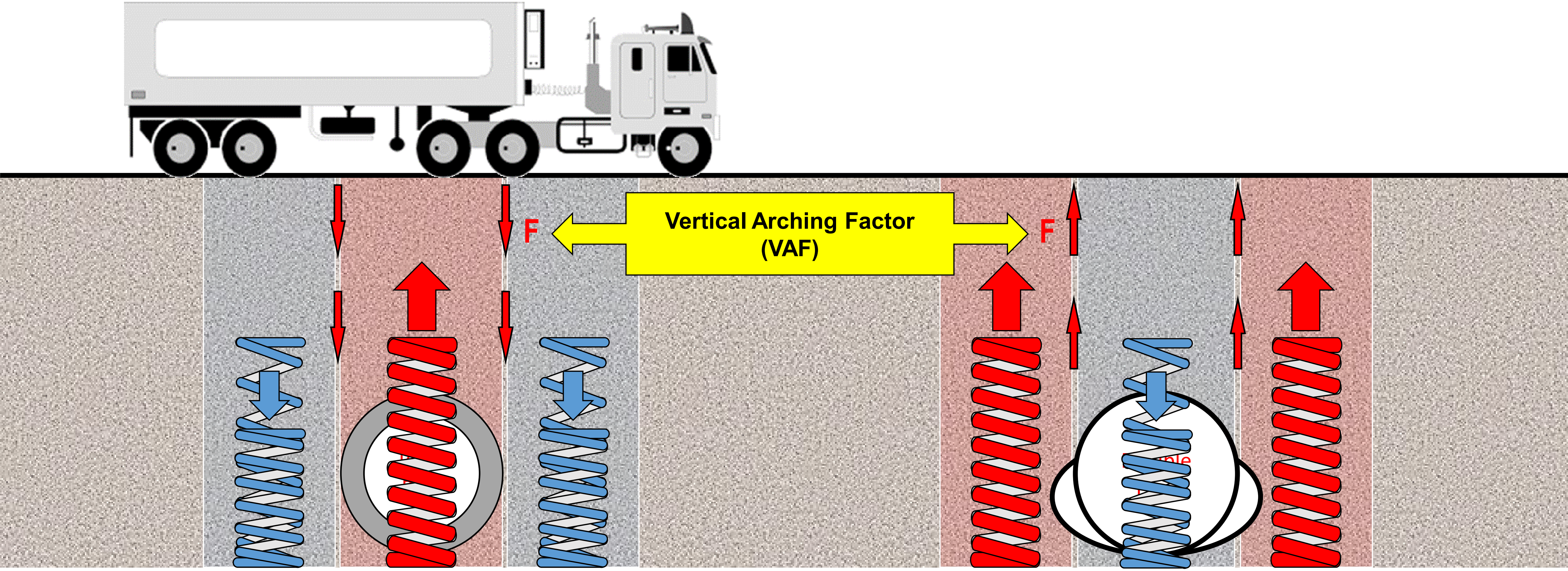
- Strength Limit States
- Service Limit States

ENGINEER OF RECORD RESPONSIBILITY

The professional engineer responsible for preparation of engineering drawings is also responsible for the structural design of pipe installations.

In all cases, designers shall keep a record of structural design calculations associated with each project. Design calculations for specific projects shall be provided to the City upon request.

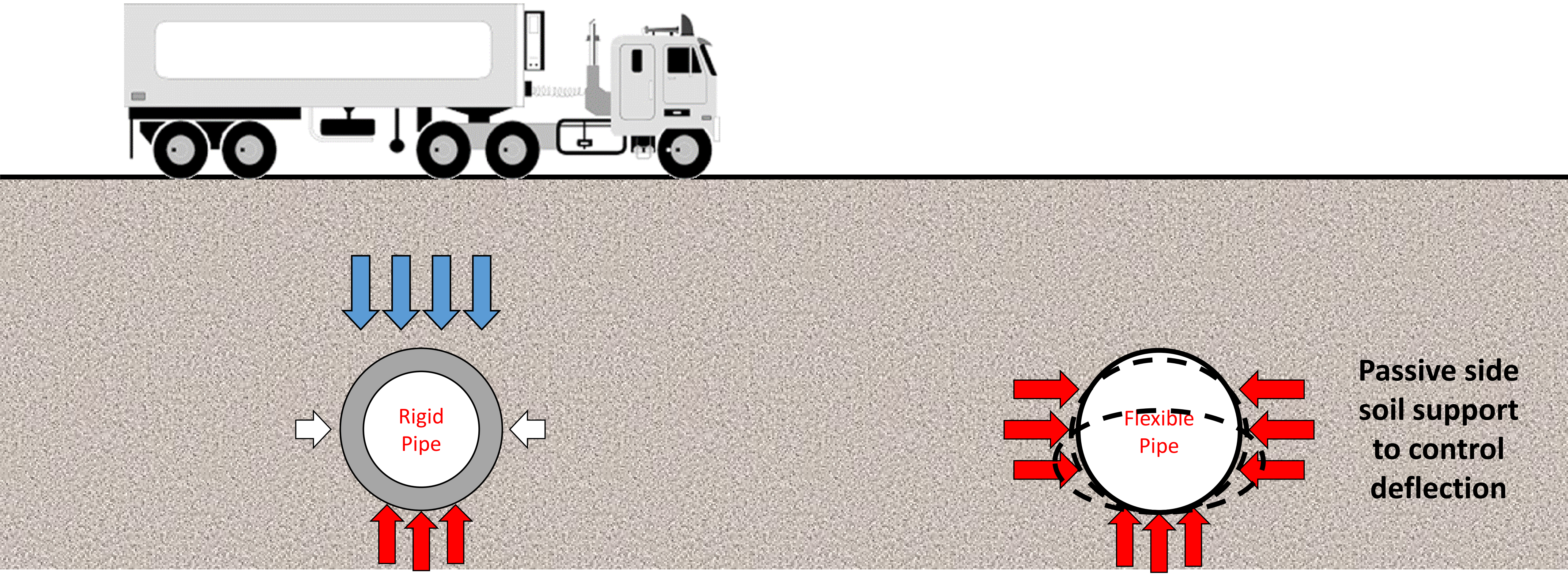
RIGID vs FLEXIBLE PIPE



Rigid Pipe: VAF > 1.0
the pipe carries most of the load

Flexible Pipe: VAF < 1.0
embedment soil carries most of the load

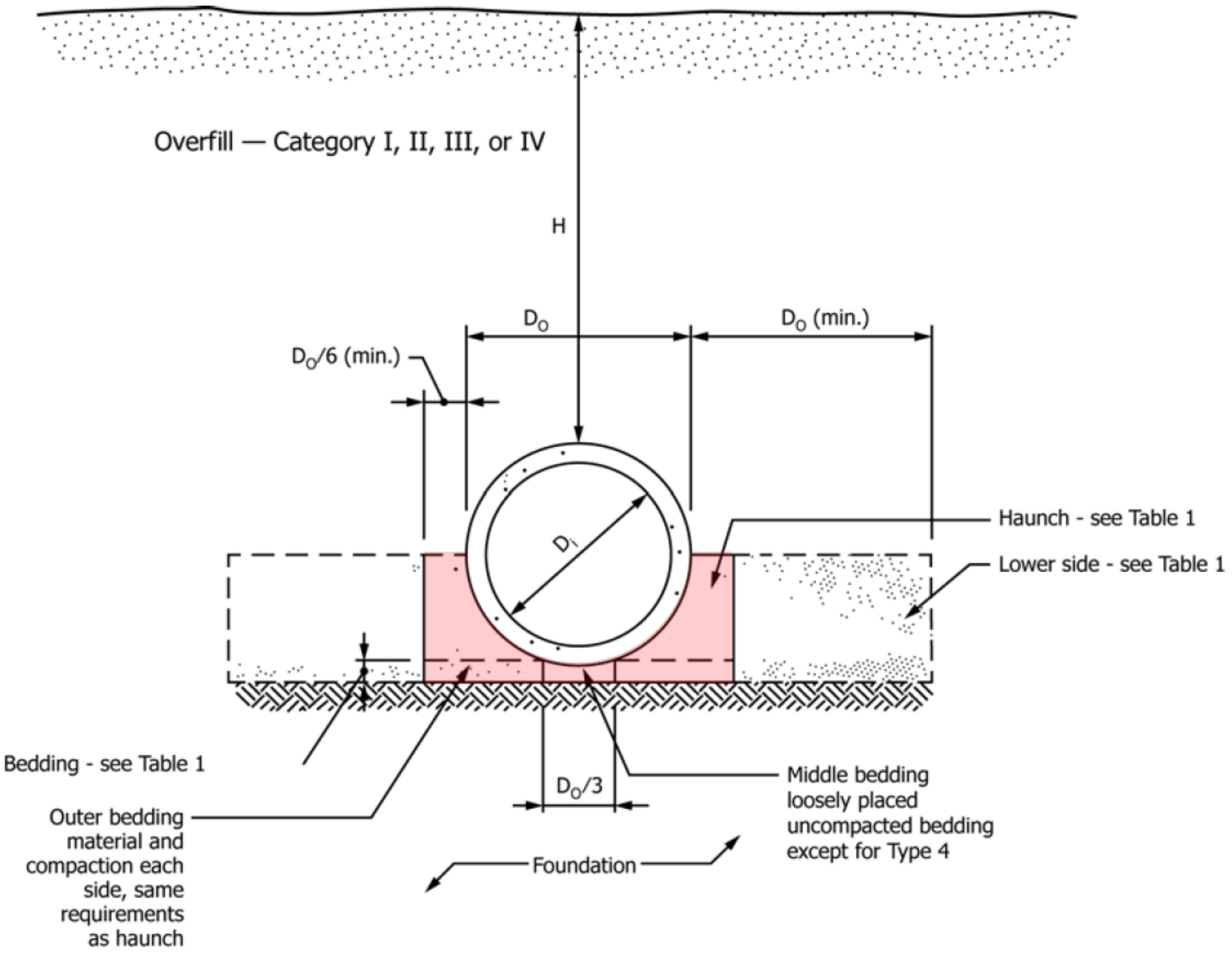
RIGID vs FLEXIBLE PIPE



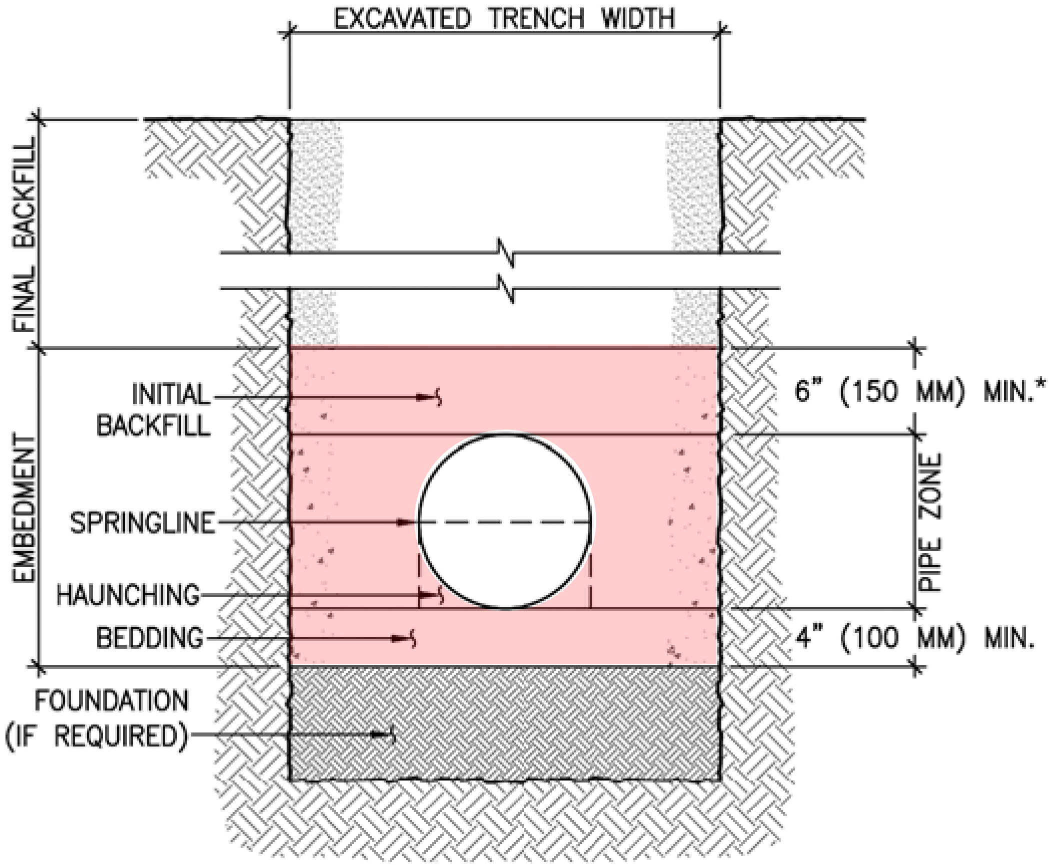
4 bedding types & 5 pipe classes
for economical design options

Installation sensitive and
complex design method

INSTALLATION DETAILS

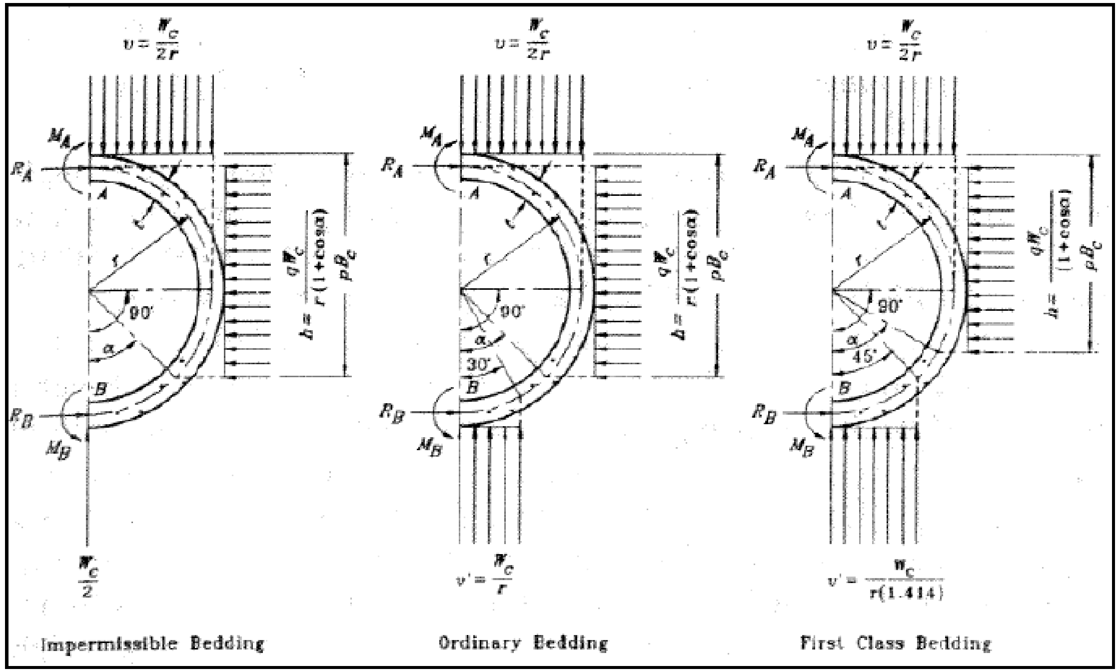


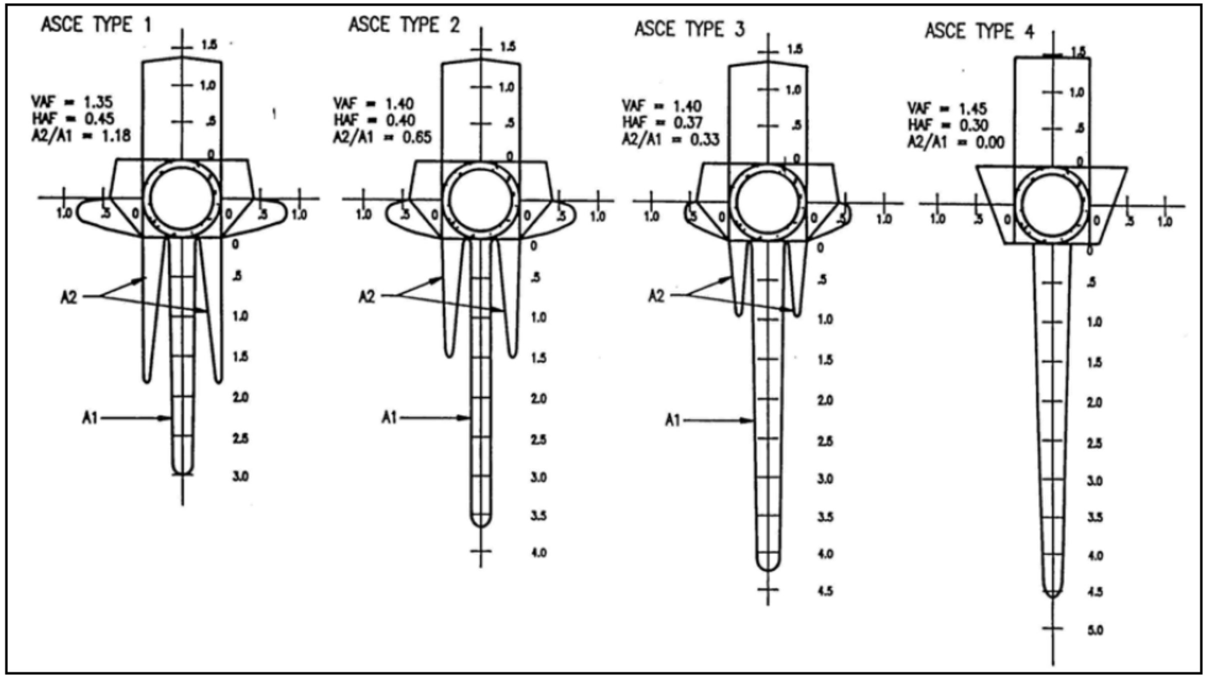
ASTM C1479 for Concrete Pipe



ASTM D2321 for Plastic Pipe

EVOLUTION OF RCP DESIGN





1930s – Marston-Spangler Model

Traditional Beddings – Class A, B, C, D

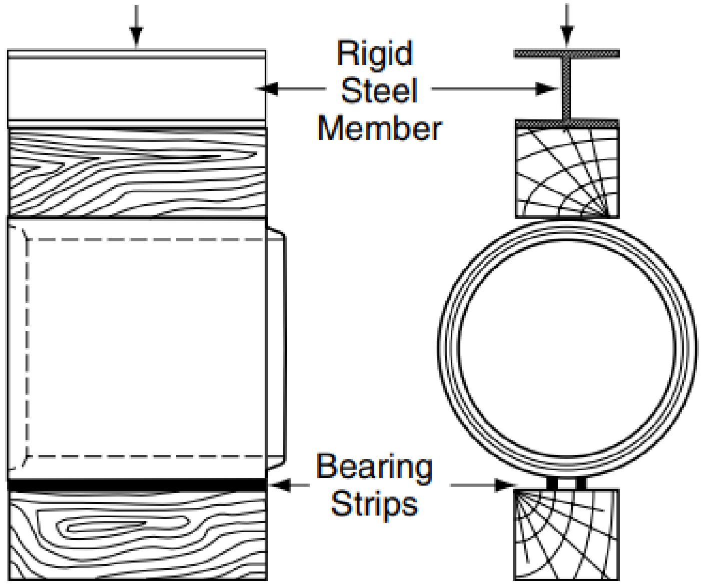
Indirect Design Method only

1980s – Heger Pressure Distribution

Standard Installation Beddings – Type 1, 2, 3, 4

Direct Design or Indirect Design Methods

3-EDGE BEARING TEST (D-LOAD TEST)



Criteria in ASTM C497:

- 0.01 in. design crack (D-Load)
- Ultimate strength

Dime is 0.053" thick
5 times the D-Load

RCP STRENGTH CLASSIFICATIONS

ASTM C76	$D_{0.01}$ (lbs/ft/ft)	D_{ult} (lbs/ft/ft)
Class I	800	1200
Class II	1000	1500
Class III	1350	2000
Class IV	2000	3000
Class V	3000	3750

Example:

What is the minimum load required for a 18 inch Class V pipe in a 3EB Test?

$D_{0.01}$ = Strength x Pipe length x Inside Dia

= (3000 lbs/ft/ft)(8 ft)(1.5 ft)

= 36,000 lbs

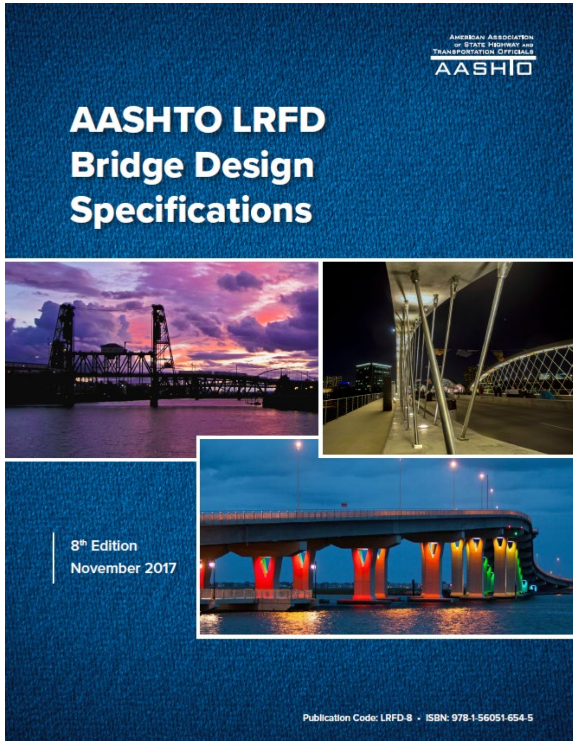
D_{ult} = (3750 lbs/ft/ft)(8 ft)(1.5 ft)

= 45,000 lbs

Reinforced Concrete Pipe Design

Indirect Design Method with Standard Installations

CONCRETE PIPE DESIGN OPTIONS



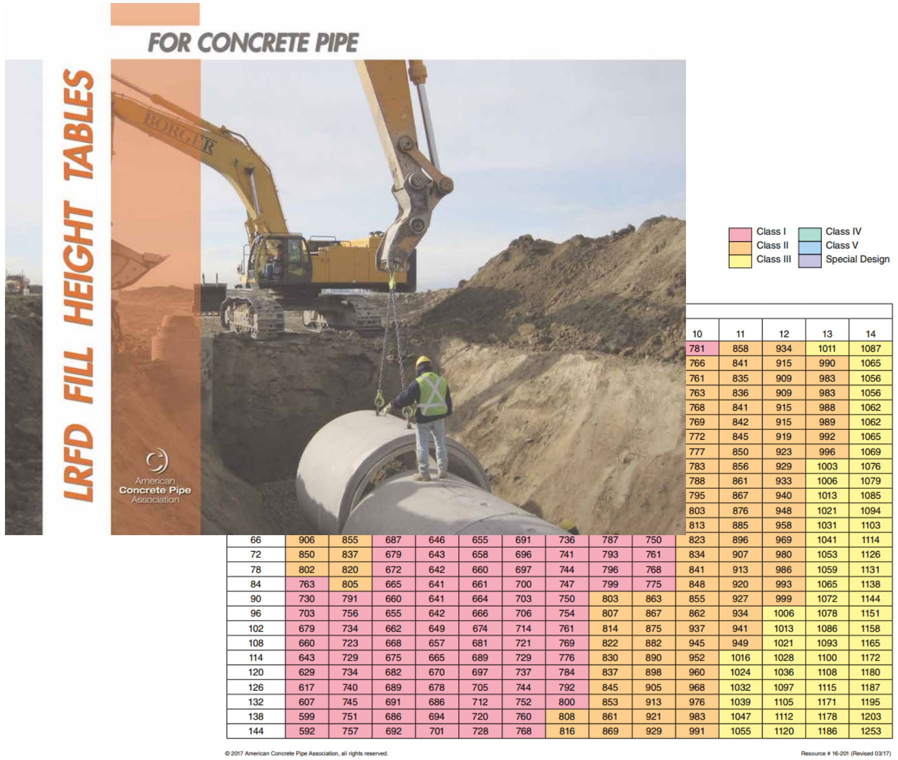
First Principles

Accurate, but tedious

PipePac software

www.pipepac.com

Efficient, but understand design principles



Fill Height Tables

Quick, but understand the assumptions used

INDIRECT DESIGN OVERVIEW

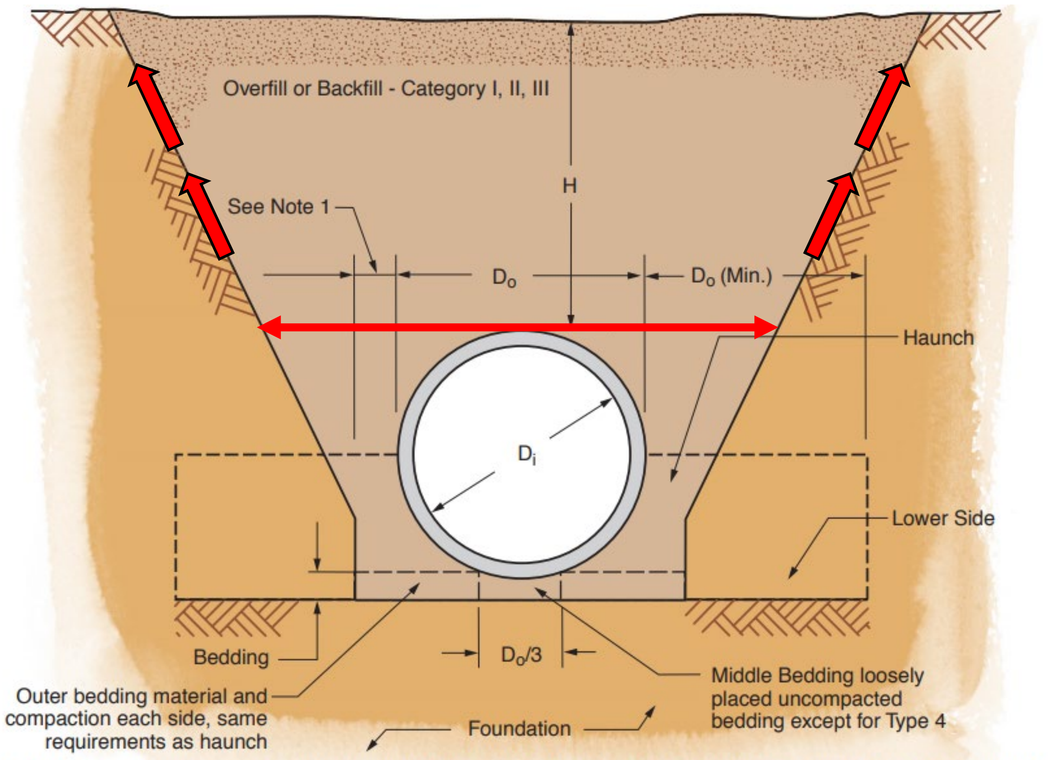
See **ACPA Design Data 9**
Standard Installations and Bedding Factors for the Indirect Design Method

$$D_{0.01} = \left(\frac{W_E + W_F}{B_{FE}} + \frac{W_L}{B_{FLL}}\right)\left(\frac{FS}{Dia}\right)$$

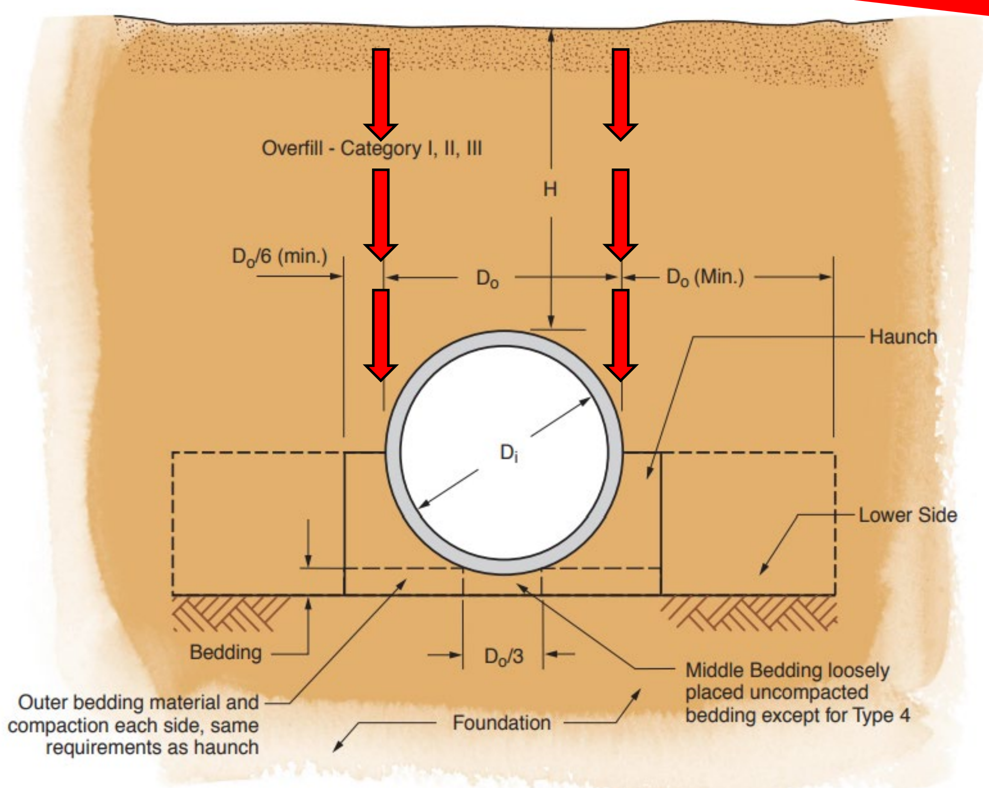
- Determine all loads – Earth (W_E), Live (W_L), Fluid (W_F), Surcharge
- Select a Standard Installation bedding type
- Determine Bedding Factors (B_{FE} & B_{FLL})
- Apply a Factor of Safety (FS) = 1.0 for $D_{0.01}$
- Calculate D-Load to produce 0.01" crack ($D_{0.01}$ in lb/ft/ft)
- Select a standard pipe strength class

RCP INSTALLATION TYPES

Assume the Worst-Case
Use **positive projection embankment** for design



Note 1: Clearance between pipe and trench wall shall be adequate to enable specific compaction, but not less than $D_o/6$.



Trench Installation

Upward friction from trench walls
reduces the earth load

Embankment Installation

Drag down friction from side soil
increases the earth load

WEIGHT OF THE PIPE

$$\text{A wall} = \frac{D_i}{12}$$

$$\text{B wall} = \frac{D_i}{12} + 1$$

$$\text{C wall} = \frac{D_i}{12} + 1.75$$

Where:
D_i = inside diameter in inches

- Concrete pipe wall thickness may vary by producer

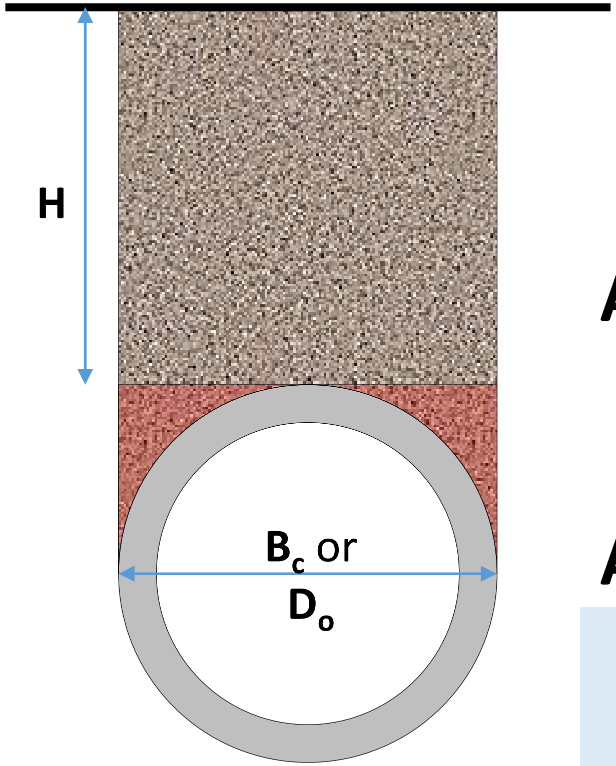
Direct Design – must consider pipe self-weight

Indirect Design – pipe self-weight is ignored since already accounted for in the 3EB Test

EARTH LOAD (W_E)

$$D_{0.01} = \left(\frac{W_E + W_F}{B_{FE}} + \frac{W_L}{B_{FLL}}\right)\left(\frac{FS}{Dia}\right)$$

W_E = Vertical Arching Factor (VAF) x Prism Load (PL)



AASHTO (12.10.2.1-1):

$$W_E = F_e w B_c H$$

VAF

ACPA (Design Data 9):

$$W_E = VAF \cdot w\left[H + \frac{D_o(4-\pi)}{8}\right]D_o$$

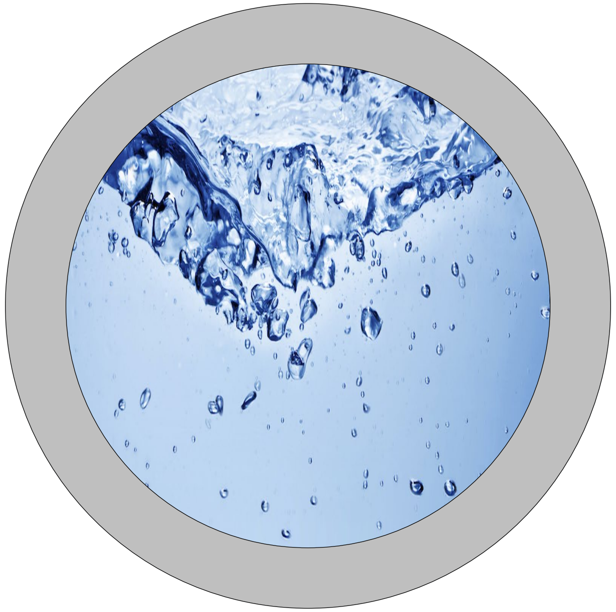
AASHTO 12.10.2.1:
Unit weight of soil (w) cannot be < 110 lb/ft³.
Typically **120 lb/ft³** used

VAF for Embankment:

Standard Installation	VAF
Type 1	1.35
Type 2	1.40
Type 3	1.40
Type 4	1.45

FLUID LOAD (W_F)

$$D_{0.01} = \left(\frac{W_E + W_F}{B_{FE}} + \frac{W_L}{B_{FLL}}\right)\left(\frac{FS}{Dia}\right)$$



AASHTO 12.10.2.2: Weight of fluid inside the pipe must be considered in design

- Fluid Load is assumed to be supported by lower part of the pipe (like earth load)

$$W_F = \gamma_w \cdot \pi \left(\frac{D_i}{24}\right)^2$$

Where:

D_i = inside diameter in inches

γ_w = unit weight of water = 62.4 lb/ft^3

$$D_{0.01} = \left(\frac{W_E + W_F}{B_{FE}} + \frac{W_L}{B_{FLL}}\right)\left(\frac{FS}{Dia}\right)$$

LIVE LOAD (W_L)

AASHTO 3.6.1.2.6a: For single span culverts – live load (truck) is negligible when depth of fill is greater than 8 ft and exceeds the span.

Highway Loads – ACPA Design Data 1

Aircraft Loads – ACPA Design Data 2

Railroad Loads – ACPA Design Data 3

$$D_{0.01} = \left(\frac{W_E + W_F}{B_{FE}} + \frac{W_L}{B_{FLL}}\right)\left(\frac{FS}{Dia}\right)$$

BEDDING FACTORS (B_f)

B_f = ratio of max. moments in pipe wall: $B_f = \frac{M_{Test}}{M_{Field}}$ → $M_{Test} = B_f \cdot M_{Field}$

Embankment Earth Load Bedding Factors (B_{FE}):

Pipe Dia (in.)	Standard Installation			
	Type 1	Type 2	Type 3	Type 4
12	4.4	3.2	2.5	1.7
24	4.2	3.0	2.4	1.7
36	4.0	2.9	2.3	1.7
72	3.8	2.8	2.2	1.7
144	3.6	2.8	2.2	1.7

Live Load Bedding Factors (B_{FLL}):

Pipe Dia (in.)	Fill Height (ft.)	
	< 2.0 ft	≥ 2.0 ft
12	3.2	2.4
18	3.2	2.4
24	3.2	2.4
30 and larger	2.2	2.2

Note: These B_{FLL} in LRFD (8^{TH} Ed) is not the same as the 7^{th} Ed or the ACPA DD9.

ACPA LRFD FILL HEIGHT TABLES

- Based on **Indirect Design** as per LRFD Bridge Design Specification (7TH Ed)
- **Positive Projecting Embankment**
- **C wall** for all sizes >> max. prism load
- Soil unit weight = **120 lb/ft^3**
- AASHTO **HL-93** live load
- For Type 1: D-Loads increased by multiplying installation factor of **1.10** (AASHTO 12.10.4.3.1)

Table 3: Reinforced Pipe Classes for 0.01 inch Crack Per ASTM C 76 (lbs/ft/ft)

Class I	≤ 800
Class II	≤ 1000
Class III	≤ 1350
Class IV	≤ 2000
Class V	≤ 3000
Special Design	> 3000

8

oad (lb/ft/ft) for Type 2 Bedding

Class I, Class II, Class III, Class IV, Class V, Special Design

onditions

TYPE 2

Pipe Size (in)	Fill Height in Feet 1	2	3	4	5	6	7	8	9	10	11	12	13	14
12	1492	1322	880	727	694	705	741	788	704	781	858	934	1011	1087
15	1434	1272	851	707	676	688	724	771	691	766	841	915	990	1065
18	1358	1240	834	697	668	680	717	763	688	761	835	909	983	1056
21	1220	1218	824	692	665	678	715	762	689	763	836	909	983	1056
24	1202	1203	818	690	665	680	717	764	694	768	841	915	988	1062
27	1344	1205	819	694	668	684	721	768	696	769	842	915	989	1062
30	1471	1213	823	701						772	845	919	992	1065
33	1347	1168	805	693						777	850	923	996	1069
36	1244	1137	789	687						783	856	929	1003	1076
42	1084	1059	759	673						788	861	933	1006	1079
48	966	935	732	663						795	867	940	1013	1085
54	923	899	712	655						803	876	948	1021	1094
60	948	875	696	650	654	688	731	781	740	813	885	958	1031	1103
66	906	855	687	646	655	691	736	787	750	823	896	969	1041	1114
72	850	837	679	643	658	696	741	793	761	834	907	980	1053	1126
78	802	820	672	642	660	697	744	796	768	841	913	986	1059	1131
84	763	805	665	641	661	700	747	799	775	848	920	993	1065	1138
90	730	791	660	641	664	703	750	803	863	855	927	999	1072	1144
96	703	756	655	642	666	706	754	807	867	862	934	1006	1078	1151
102	679	734	662	649	674	714	761	814	875	937	941	1013	1086	1158
108	660	723	668	657	681	721	769	822	882	945	949	1021	1093	1165
114	643	729	675	665	689	729	776	830	890	952	1016	1028	1100	1172
120	629	734	682	670	697	737	784	837	898	960	1024	1036	1108	1180
126	617	740	689	678	705	744	792	845	905	968	1032	1097	1115	1187
132	607	745	691	686	712	752	800	853	913	976	1039	1105	1171	1195
138	599	751	686	694	720	760	808	861	921	983	1047	1112	1178	1203
144	592	757	692	701	728	768	816	869	929	991	1055	1120	1186	1253

11

Fill Height Tables are based on:
1. γs = 120 pcf
2. AASHTO HL-93 live load
3. Positive Projecting Embankment Condition -

tions

D-Load (lb/ft/ft) for Type 3 Bedding

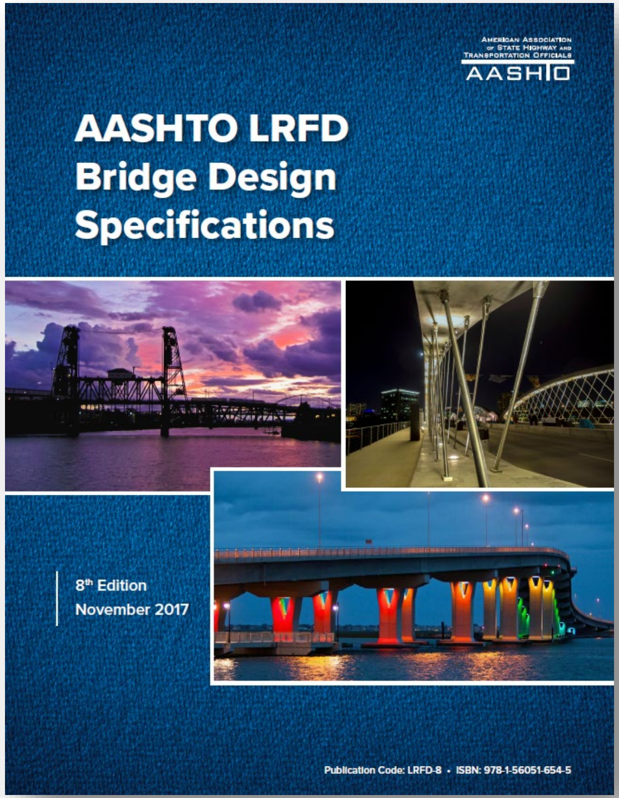
Class I, Class II, Class III, Class IV, Class V, Special Design

TYPE 3

Fill Height in Feet 6	7	8	9	10	11	12	13	14
838	896	964	902	1000	1098	1196	1294	1392
815	872	939	880	975	1070	1165	1260	1355
804	860	926	870	963	1057	1150	1243	1337
799	855	921	867	959	1051	1144	1236	1329
798	854	920	868	960	1051	1143	1235	1327
804	860	925	872	963	1055	1147	1238	1330
812						1153	1245	1337
813						1162	1254	1345
815						1172	1264	1356
815						1179	1271	1363
817						1189	1281	1373
822						1201	1293	1385
828	891	961	939	1031	1123	1216	1308	1400
835	900	970	954	1046	1138	1231	1323	1416
843	909	981	969	1062	1154	1247	1340	1433
847	913	985	977	1070	1162	1255	1348	1440
852	918	991	986	1079	1171	1263	1355	1448
857	924	996	1076	1088	1180	1272	1364	1456
862	930	1003	1083	1097	1189	1281	1373	1464
872	939	1012	1092	1174	1198	1290	1382	1473
882	949	1022	1102	1184	1208	1299	1391	1482
892	959	1032	1112	1194	1277	1309	1400	1492
902	969	1042	1121	1203	1287	1319	1410	1501
912	979	1052	1131	1213	1297	1382	1420	1511
922	989	1062	1141	1223	1307	1391	1477	1521
932	999	1072	1152	1233	1317	1401	1487	1531
943	1010	1082	1162	1244	1327	1411	1497	1583

Plastic Pipe Design

PLASTIC PIPE DESIGN METHOD



12.12 Thermoplastic Pipes

Strength Limit States:

- Thrust
- Buckling
- Combined strains

Service Limit States:

- Deflection

Also, check flotation

AASHTO LRFD assumes that native soil is stiff and ignores the transfer of load to the in-situ trench walls.

Commentary C12.12.3.5:

The width of structural backfill is an important consideration when the in situ soil in the trench wall or the embankment fill at the side of the structural backfill is soft. Currently, only AWWA Manual M45, The Fiberglass Pipe Design Manual, addresses this issue.

FILL HEIGHT TABLES

Common assumptions used in plastic pipe fill height tables:

- Pipe is installed in accordance with ASTM D2321
- Water table is below the pipe (no hydrostatic pressure)
- Native soil is very stiff

Example: 48 in. HDPE pipe with Class 2 backfill compacted to 95%

Maximum Cover			
JM Eagle Eagle Corr PE (Dual Wall)	Prinsco GoldFlo (Dual Wall)	Haviland Smooth Flow (Dual Wall)	ADS N-12 (AASHTO)
30 ft	24 ft	22 ft	17 ft

PLASTIC PIPE PROPERTIES

- Pipe performance depends on profile wall geometry which vary significantly
  - Moment of inertia (I)
  - Radius to centroid of pipe profile (R)
  - Spacing of corrugations (ω)
  - Wall area (A_g) and effective wall area (A_{eff})
- Short and long-term mechanical properties vary by type of plastic pipe
  - See LRFD Table 12.12.3.3-1

Source: NCHRP Report 631

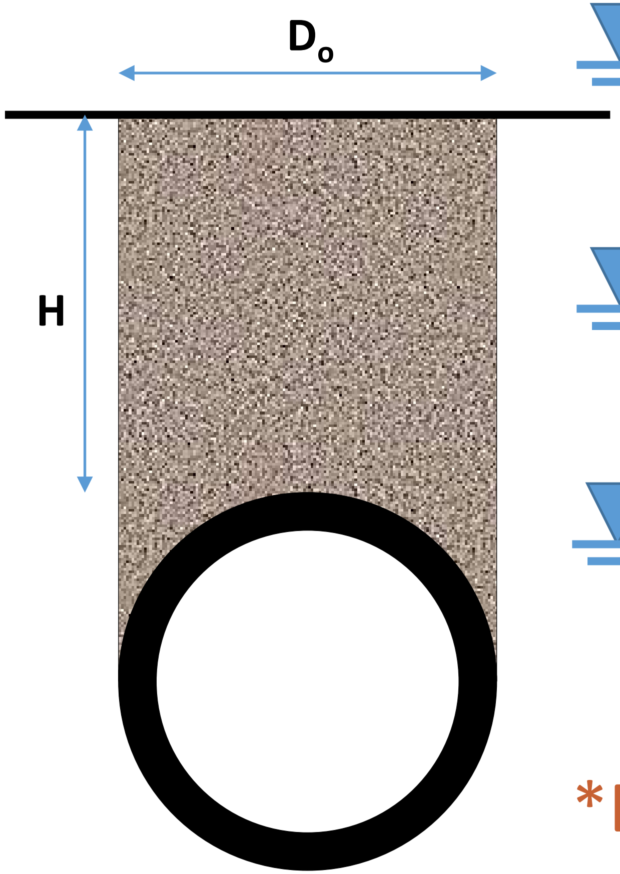
C12.12.3.2

Historically, AASHTO bridge specifications have contained minimum values for the moment of inertia and wall area of thermoplastic pipe; however, these values have been minimum values and are not meaningful for design. This is particularly so since provisions to evaluate local buckling were introduced in 2001. These provisions require detailed profile geometry that varies with manufacturer. Thus, there is no way to provide meaningful generic information on section properties. A convenient method for determining section properties for profile wall pipe is to make optical scans of pipe wall cross-sections and determine the properties with a computer drafting program.

SOIL PRISM PRESSURE (P_{sp})

Also check for FLOTATION

P_{sp} is calculated for 3 possible conditions:



1. Water table above top of pipe and at or above the ground surface

$$P_{sp} = \frac{\left(H + 0.11\frac{D_o}{12}\right)\gamma_b}{144}$$

2. Water table above top of pipe and below the ground surface

$$P_{sp} = \frac{1}{144}\left[\left[\left(H_W - \frac{D_o}{24}\right) + 0.11\frac{D_o}{12}\right]\gamma_b + \left[H - \left(H_w - \frac{D_o}{24}\right)\right]\gamma_s\right]$$

3. Water table below top of pipe

$$P_{sp} = \frac{\left(H + 0.11\frac{D_o}{12}\right)\gamma_s}{144}$$

*Evaluate multiple conditions if water table fluctuates.

THRUST

$$T_u = \left[\eta_{EV}\left(\gamma_{EV}K_{\gamma E}K_2 VAF\, P_{sp} + \gamma_{WA}P_w\right) + \eta_{LL}\gamma_{LL}P_L\, C_L F_1 F_2\right]\frac{D_o}{2} \quad (12.12.3.5\text{-}1)$$

Live Load

Soil Load (reduced by VAF)

Groundwater

Factored compressive strain

$$\varepsilon_{uc} \leq \Phi_T \varepsilon_{yc}$$

Factored compressive strain limit

$$\varepsilon_{uc} = \frac{T_u}{1000\left(A_{eff}E_p\right)}$$

Factored thrust

- Check both **springline** & **crown** of pipe
- Total load contributes – **soil load**, **live load** & **hydrostatic load**
- Short & long-term material properties need to be evaluated due to time-dependent nature of plastic pipe

in which:

$$VAF = 0.76 - 0.71\left(\frac{S_H - 1.17}{S_H + 2.92}\right) \quad (12.12.3.5\text{-}3)$$

$$S_H = \frac{\phi_s M_s R}{E_p A_g} \quad (12.12.3.5\text{-}4)$$

$$C_L = \frac{L_w}{D_o} \leq 1.0 \quad (12.12.3.5\text{-}5)$$

$$F_1 = \frac{0.75 D_o}{L_w} \geq F_{min} \quad (12.12.3.5\text{-}6)$$

$$F_{min} = \frac{15}{D_i} \geq 1 \quad (12.12.3.5\text{-}7)$$

$$F_2 = \frac{0.95}{1 + 0.6 S_H} \quad (12.12.3.5\text{-}8)$$

BUCKLING

- Pipe wall must have sufficient stiffness to remain stable under compression loads.

Poor soil support decreases pipe's ability to resist buckling

$$\varepsilon_{bck} = \frac{1.2C_n\left(E_p I_p\right)^{\frac{1}{3}}}{A_{eff}E_p}\left[\frac{\phi_s M_s\left(1-2\nu\right)}{\left(1-\nu\right)^2}\right]^{\frac{2}{3}} R_h \qquad (12.12.3.10.1e\text{-}2)$$

in which:

$$R_h = \frac{11.4}{11+\frac{D}{12H}} \qquad (12.12.3.10.1e\text{-}3)$$

Resistance factor = 0.7

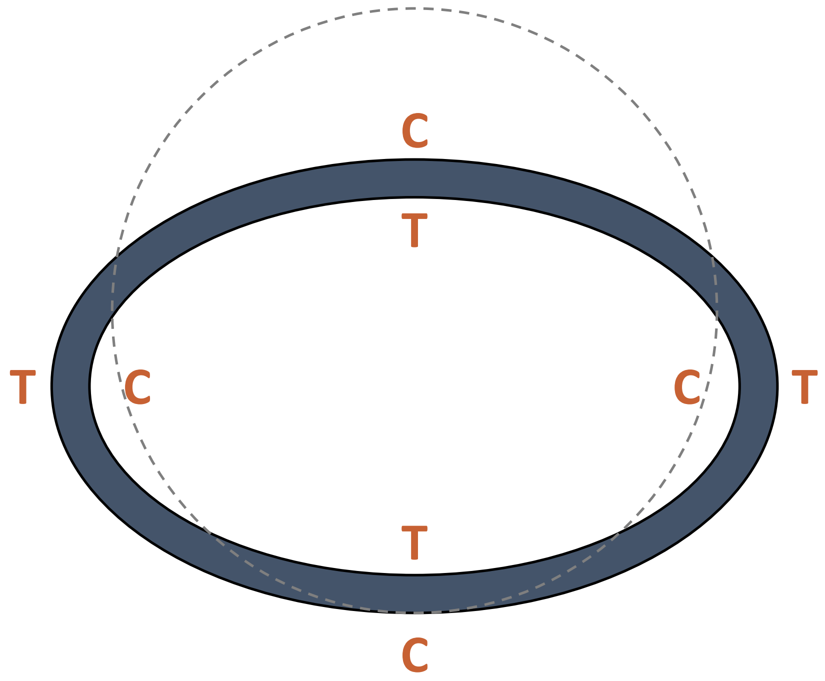
$$\varepsilon_{uc} \leq \Phi_{bck}\varepsilon_{bck}$$

Factored compressive strain

Buckling strain capacity of pipe

COMBINED STRAINS

- Must check combined strains at extreme fibers since bending strain from deflection creates tension (T) and compression (C) zones



12.12.3.10.2b—Combined Strain

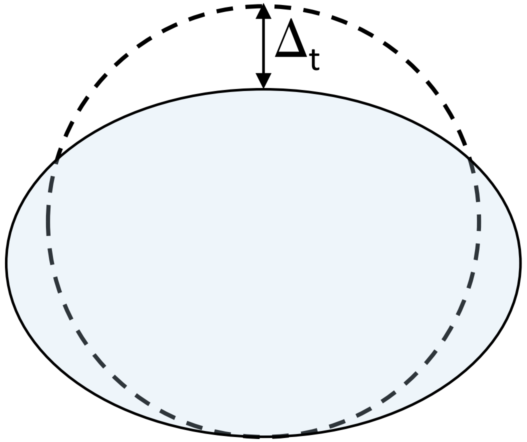
If summation of axial strain, ε_{uc}, and bending strain, ε_f, produces tensile strain in the pipe wall, the combined strain at the extreme fiber where flexure causes tension shall satisfy:

$$\varepsilon_f - \varepsilon_{uc} < \phi_f \varepsilon_{yt} \qquad (12.12.3.10.2b\text{-}1)$$

The combined strain at the extreme fiber where flexure causes compression shall satisfy:

$$\varepsilon_f + \varepsilon_{uc} < \phi_T \left(1.5\varepsilon_{yc}\right) \qquad (12.12.3.10.2b\text{-}2)$$

DEFLECTION



Soil Load

Live Load

Circumferential Shortening

$$\Delta_t = \frac{K_B\left(D_L P_{sp} + C_L P_L\right)D_o}{1000\left(\frac{E_p I_p}{R^3} + 0.061 M_s\right)} + \varepsilon_{sc} D$$

Pipe Stiffness

Soil Stiffness

- Caused by bending deformation plus circumferential shortening due to thrust
- Controlled by proper soil support and must be verified with a deflection test
- Maximum allowable deflection **= 5.0%**

SECANT CONSTRAINED SOIL MODULUS (M_s)

- All backfill soils are combined into three broad groups
  - **Sn** – sands and gravels
  - **Si** – silts
  - **Cl** – clays

- More useful than E' soil stiffness for deep installations since M_s increases with depth

Table 12.12.3.5-1—*M_s* Based on Soil Type and Compaction Condition

P_{sp} Stress Level (psi)	Sn-100 (ksi)	Sn-95 (ksi)	Sn-90 (ksi)	Sn-85 (ksi)
1.0	2.350	2.000	1.275	0.470
5.0	3.450	2.600	1.500	0.520
10.0	4.200	3.000	1.625	0.570
20.0	5.500	3.450	1.800	0.650
40.0	7.500	4.250	2.100	0.825
60.0	9.300	5.000	2.500	1.000
P_{sp} Stress Level (psi)		Si-95 (ksi)	Si-90 (ksi)	Si-85 (ksi)
1.0		1.415	0.670	0.360
5.0		1.670	0.740	0.390
10.0		1.770	0.750	0.400
20.0		1.880	0.790	0.430
40.0		2.090	0.900	0.510
60.0				
P_{sp} Stress Level (psi)		Cl-95 (ksi)	Cl-90 (ksi)	Cl-85 (ksi)
1.0		0.530	0.255	0.130
5.0		0.625	0.320	0.175
10.0		0.690	0.355	0.200
20.0		0.740	0.395	0.230
40.0		0.815	0.460	0.285
60.0		0.895	0.525	0.345

EMBEDMENT SOIL & DEFLECTION

Plastic pipe is extremely INSTALLATION SENSITIVE !

Given:

D_i = 48 in.
D_o = 54.26 in.
R = 25.27 in.
E_{Pi} = 110 ksi
E_{P75} = 21 ksi
I_P = 0.65 in^4/in

H = 25 ft
K_B = 0.1
D_L = 1.5
C_L = 1.0
P_{sp} = 21.2 psi
P_L = 0.336 psi

P_W = 0 psi
A_g = 0.441 in^2/in
A_{eff} = 0.305 in^2/in

$$\Delta_t = \frac{K_B(D_L P_{sp} + C_L P_L)D_o}{1000\left(\frac{E_p I_p}{R^3} + 0.061 M_s\right)} + \varepsilon_{sc} D$$

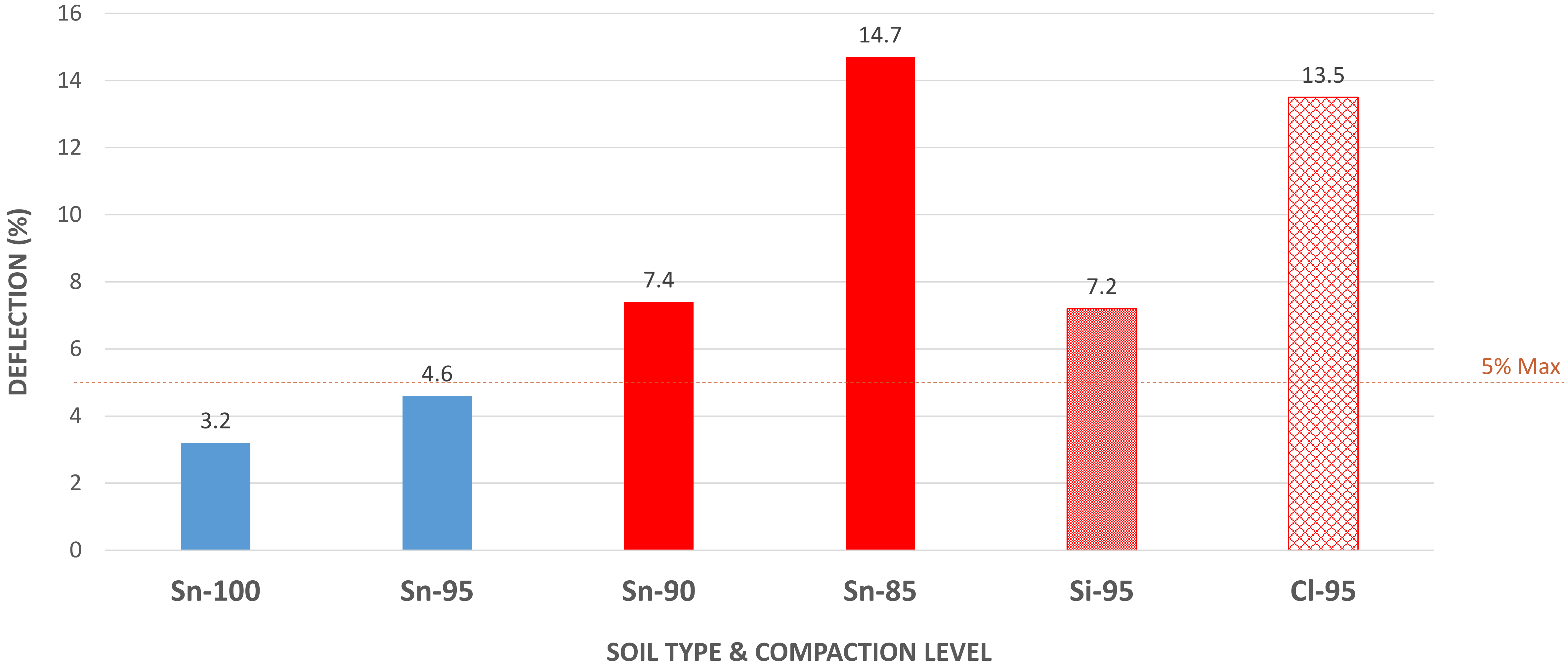
Various soils @ 95% compaction:

Soil Type & Compaction	M_s	Deflection
Sn-95	3.50	4.6 %
Si-95	1.89	**7.2 %**
Cl-95	0.75	**13.5 %**

Sn soil with various compaction:

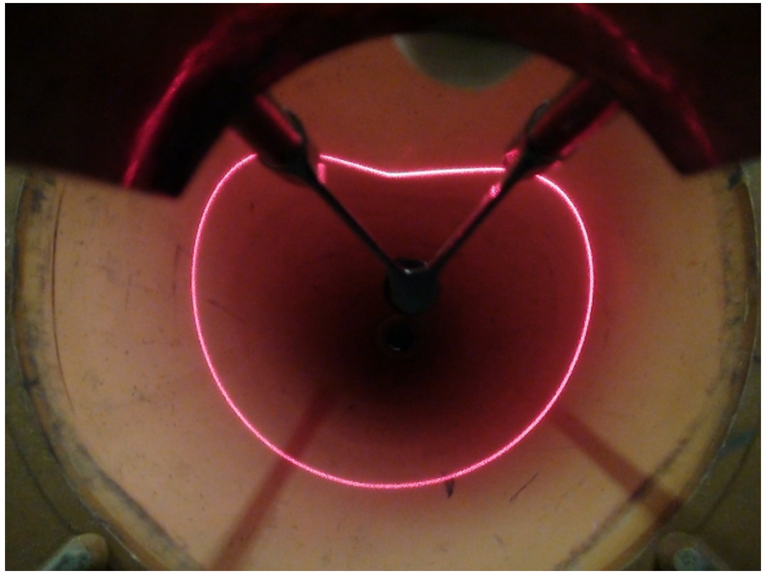
Soil Type & Compaction	M_s	Deflection
Sn-100	5.63	3.2 %
Sn-95	3.50	4.6 %
Sn-90	1.82	**7.4 %**
Sn-85	0.66	**14.7 %**

EMBEDMENT SOIL & DEFLECTION



DEFLECTION TESTING

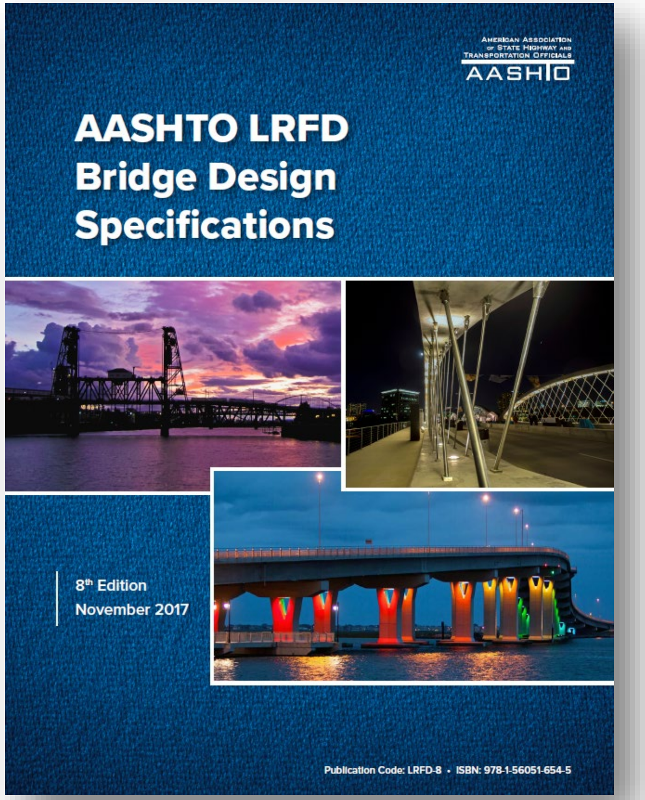
- Plastic pipe requires a deflection test to verify proper soil embedment
- Frequency of deflection tests:
  - No sooner than 30 days after backfill – AASHTO Section 30
  - Prior to final acceptance or end of warranty
  - As part of on-going pipe maintenance
- Plastic pipe products have different *Base Inside Diameters*



Load Lag, Deflection Lag, and Time Lag
Amster Howard
TECH NOTE: Supplement to Pipeline Installation

"… the maximum load on a pipe does not occur until three to six months after backfilling…"

PLASTIC PIPE DESIGN METHOD SUMMARY



12.12 Thermoplastic Pipes

Strength Limit States:

- Thrust – *Compressive limits of the pipe material*
- Buckling – *Dependant on both soil and pipe properties*
- Combined strains – *Material limits with deflection strains added*

Service Limit States:

- Deflection – *Installation sensitive, verify with deflection test.*

Also, check flotation

FUNDAMENTAL DIFFERENCES IN DESIGN

RIGID CONCRETE PIPE

- Standard strength classes
- Indirect or Direct Design
- Primary structure is pipe (60-75%)
- Structure built & tested at plant with 3EB test
- Design life based on historical performance data
- Design software available

FLEXIBLE PLASTIC PIPE

- Wide range of pipe products/profiles
- Direct design only
- Primary structure is soil (50-90%)
- Structure built & tested in field with deflection test
- Design life based on time-dependent behavior of material

American Concrete Pipe Association

THANK YOU