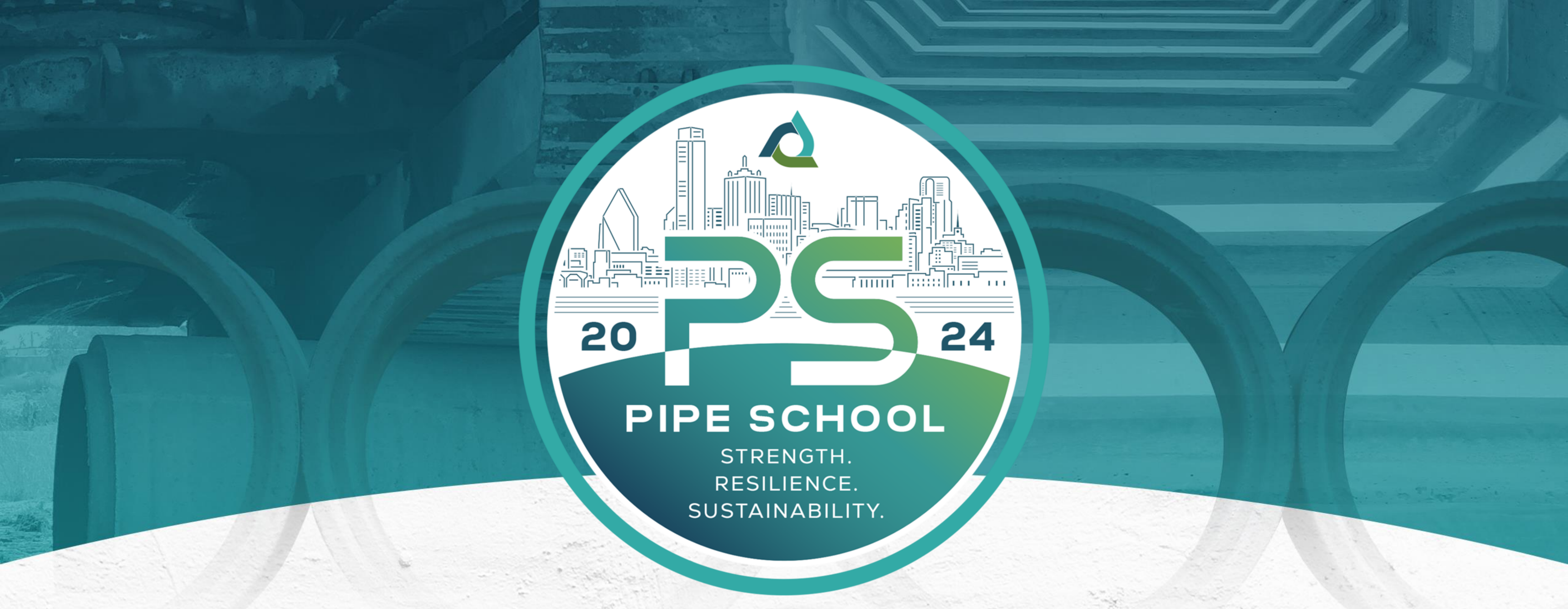

20 PS 24

PIPE SCHOOL

STRENGTH.
RESILIENCE.
SUSTAINABILITY.

NEW ASTM C1924 STANDARD OF DESIGN FOR LOW HEAD PRESSURE PIPE

Margarita Takou, Ph.D., P.E., ENV SP

American Concrete Pipe Association

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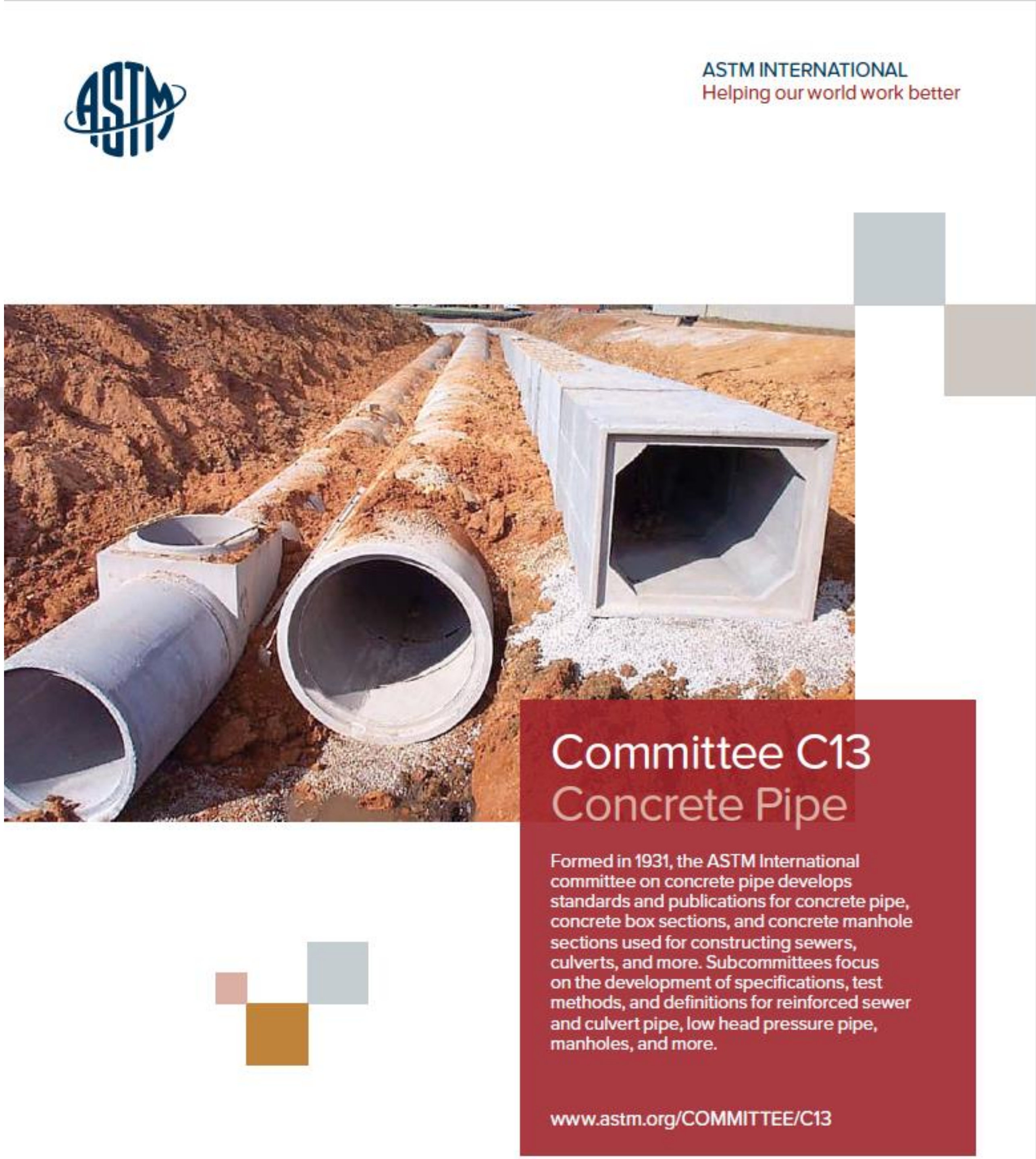

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Committee C13
Concrete Pipe

Formed in 1931, the ASTM International committee on concrete pipe develops standards and publications for concrete pipe, concrete box sections, and concrete manhole sections used for constructing sewers, culverts, and more. Subcommittees focus on the development of specifications, test methods, and definitions for reinforced sewer and culvert pipe, low head pressure pipe, manholes, and more.

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C1924 Practice for Design of Buried Precast Concrete Low-Head Pressure Pipe

- Scope of C1924
- Installation Requirements
- Applied Loads
- Pressure Distribution
- Performance Mode
- Design Conditions
- Reinforcement Arrangements
- Joints

ACPA

ASTM C1924 Standard Scope

- Design of buried pipes subject to internal pressure not exceeding a pressure head of 125 ft (54 psi)

- Loads applied:
  - **Self weight**
  - **Earth load**
  - **Water load**
  - **Internal pressure (up to 125 ft. @springline)**
  - Live load.

- Construction requirements covered by ASTM C361 Standard Specification for Reinforced Concrete Low-Head Pressure Pipe

Installation Requirements

Installation

- Trench to provide cushion material to a depth T below the bottom of the pipe uncompacted granular material
- Additional depth of 6 in. if native material is soft or unsuitable for a foundation

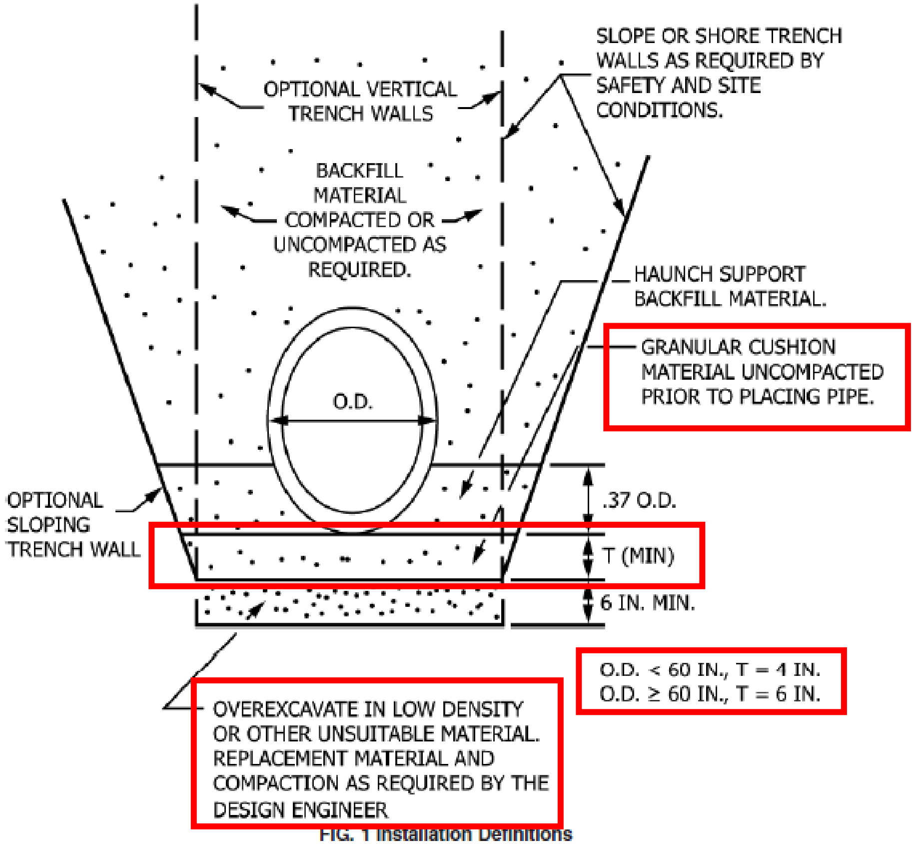


FIG. 1 Installation Definitions

Installation

- Haunch support backfill good graded material to a height of 0.37 times the outside diameter of the pipe
- The backfill material placed above that level shall be compacted or uncompacted to the requirements of the design

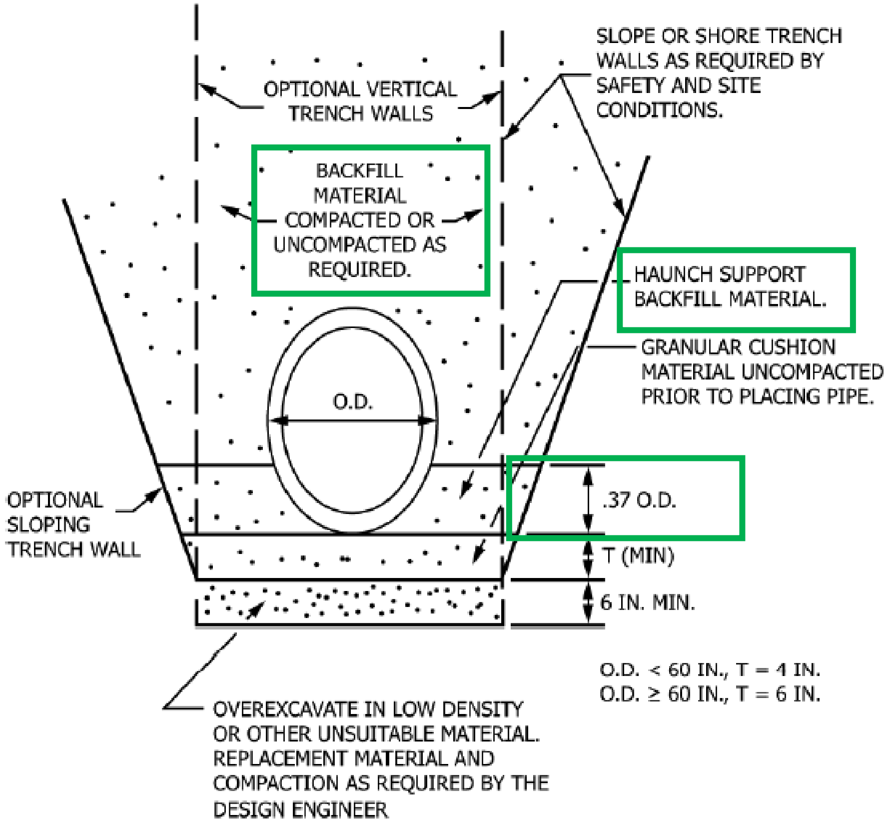


FIG. 1 Installation Definitions

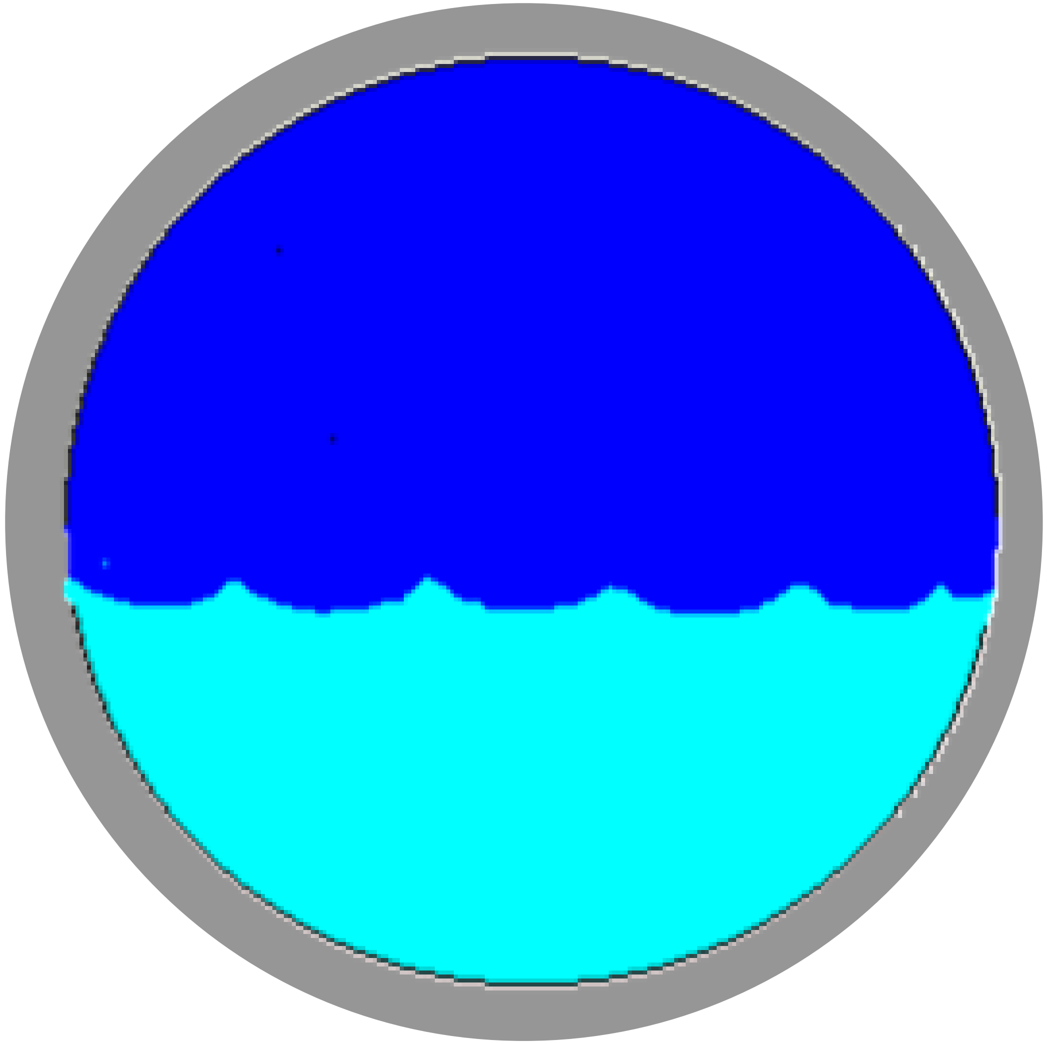
Applied Loads

Applied Loads

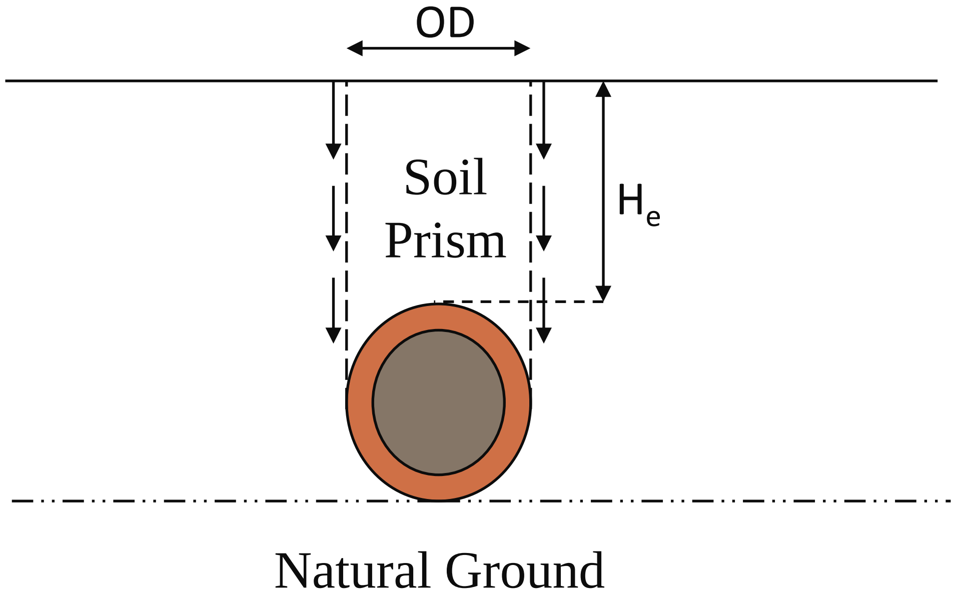
- Self weight
- Water load
- Internal pressure (up to 125 ft. @springline)
- Earth load
- Live load

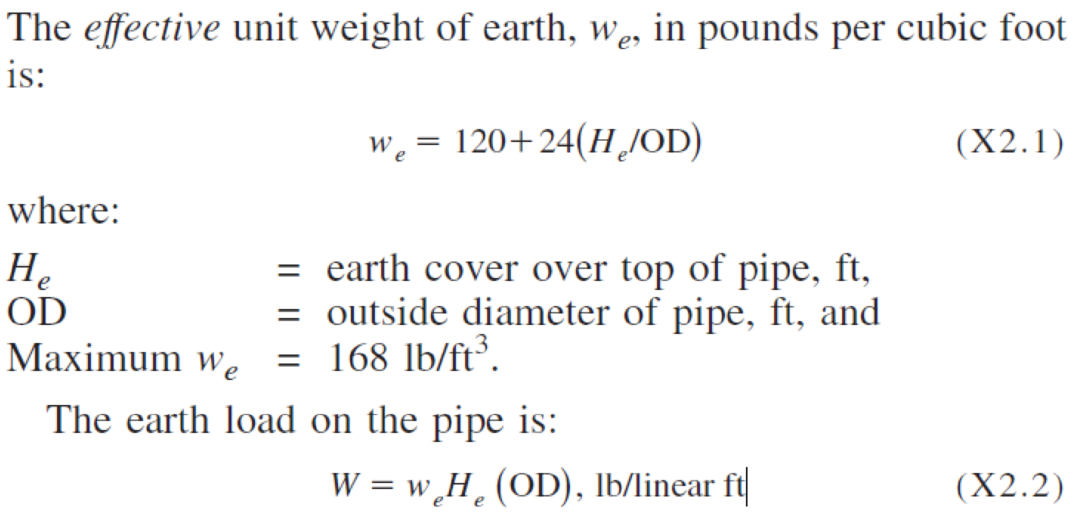
Dead Load

- **Self weight:** The dead load of the pipe weight, W_p (lbs/ft), shall be considered in the design and shall be based on a reinforced concrete unit weight of 150 lb/ft^3, unless otherwise specified.
- **Fluid wights:** The dead load of fluid in the pipe, W_f (lbs/ft), shall be based on a unit weight of 62.4 lb/ft^3, unless otherwise specified.



Soil Load





The *effective* unit weight of earth, w_e, in pounds per cubic foot is:

$$w_e = 120 + 24(H_e/\text{OD}) \qquad (\text{X2.1})$$

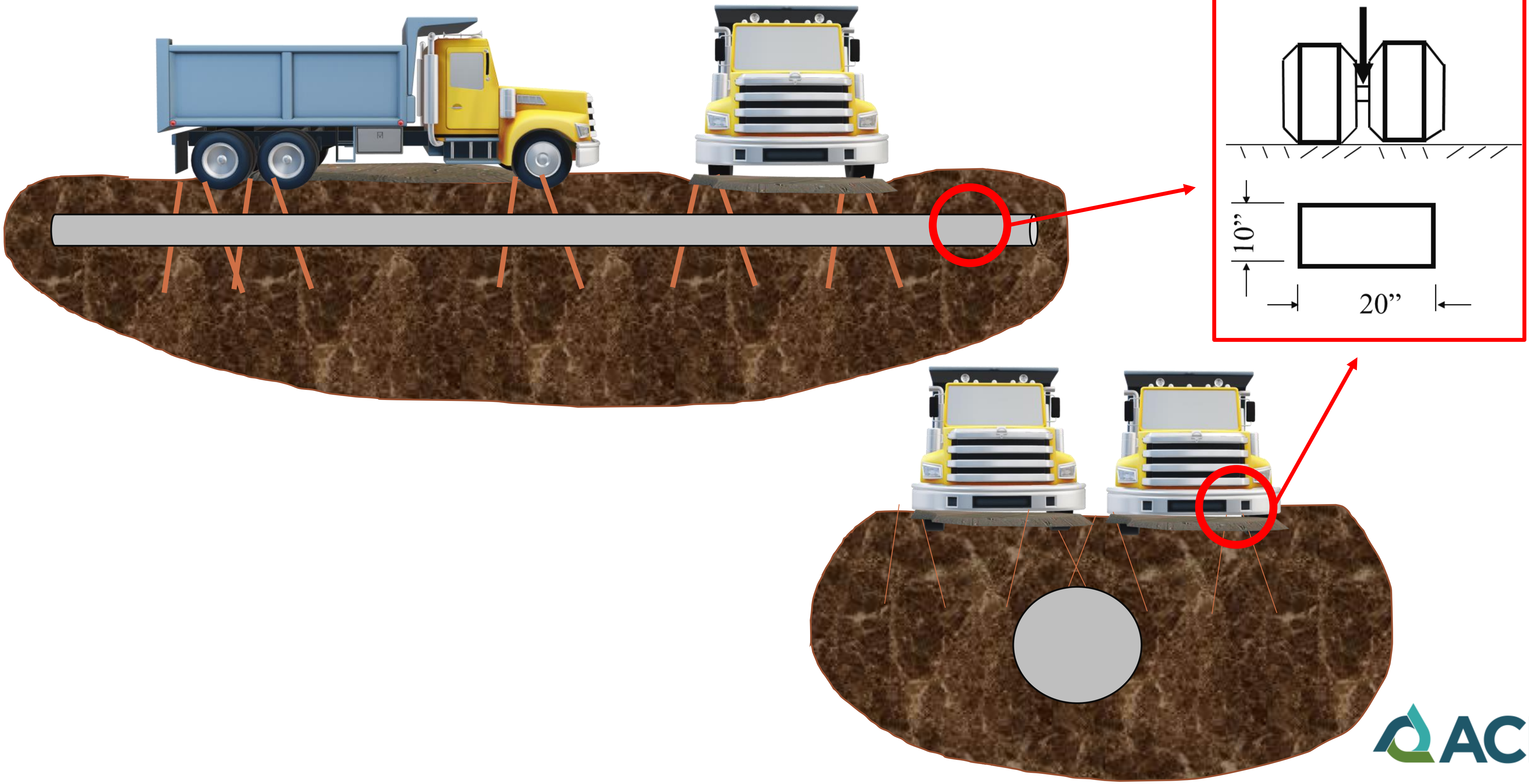
where:

H_e = earth cover over top of pipe, ft,
OD = outside diameter of pipe, ft, and
Maximum w_e = 168 lb/ft^3.

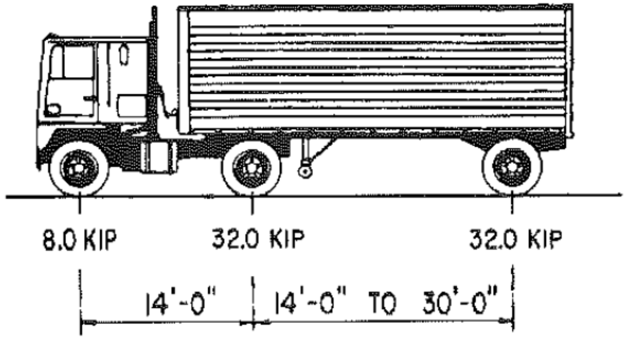
The earth load on the pipe is:

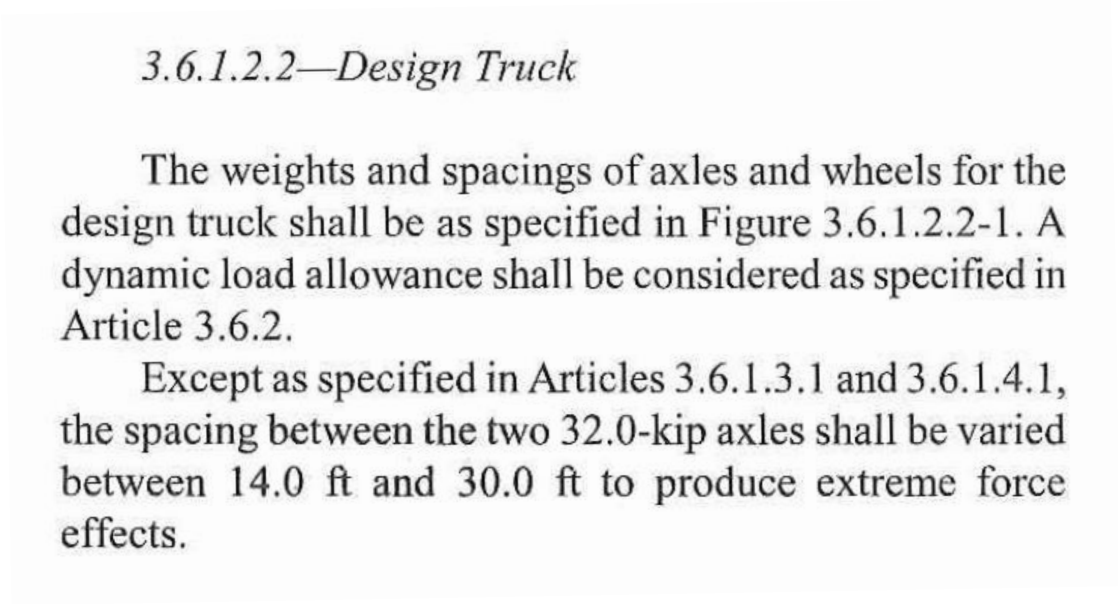
$$W = w_e H_e (\text{OD}), \text{ lb/linear ft} \qquad (\text{X2.2})$$

Live Load - AASHTO HL - 93



Live Load - AASHTO HL - 93

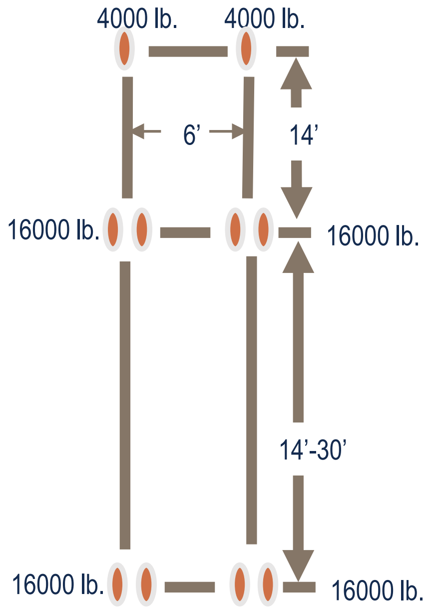


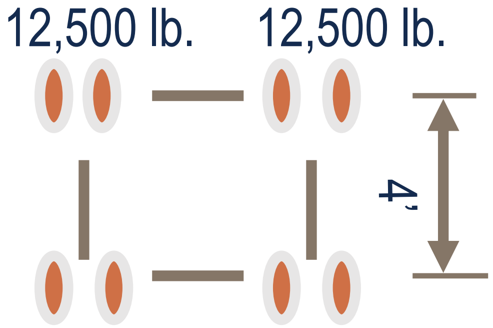


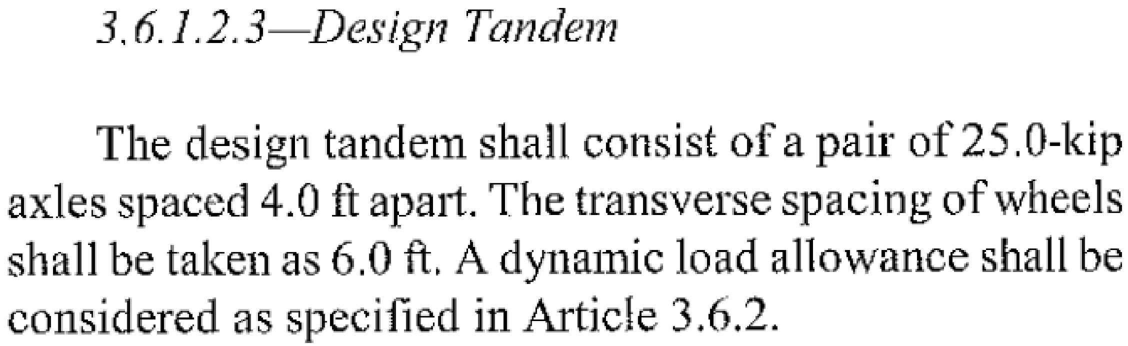
3.6.1.2.2—Design Truck

The weights and spacings of axles and wheels for the design truck shall be as specified in Figure 3.6.1.2.2-1. A dynamic load allowance shall be considered as specified in Article 3.6.2.

Except as specified in Articles 3.6.1.3.1 and 3.6.1.4.1, the spacing between the two 32.0-kip axles shall be varied between 14.0 ft and 30.0 ft to produce extreme force effects.





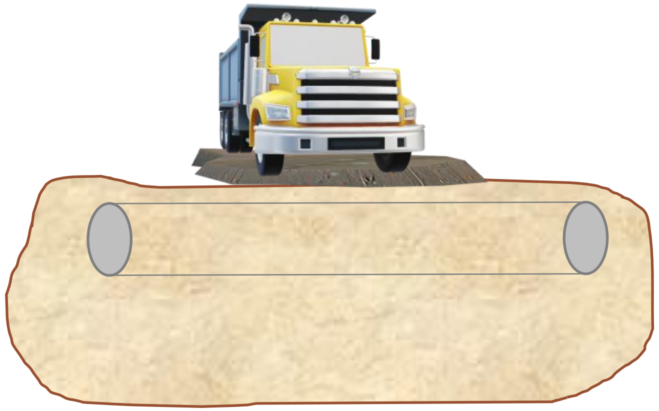


3.6.1.2.3—Design Tandem

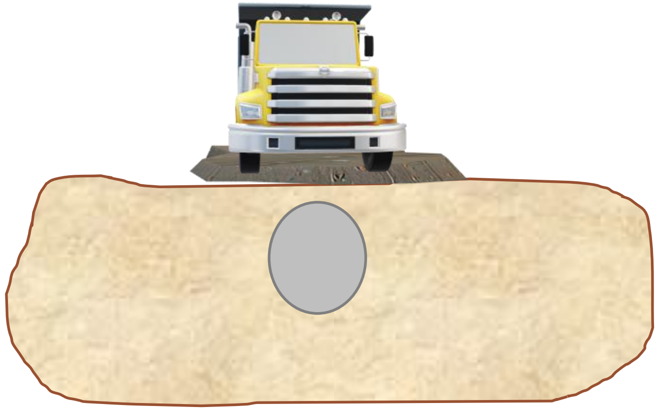
The design tandem shall consist of a pair of 25.0-kip axles spaced 4.0 ft apart. The transverse spacing of wheels shall be taken as 6.0 ft. A dynamic load allowance shall be considered as specified in Article 3.6.2.

Live Load

- Traffic Travelling Parallel to the span
    - Single Axle Load – one lane
    - Tandem Load – one lane



- Traffic traveling perpendicular to the span
    - Single Axle Load – one lane
    - Single Axle Load – two lanes
    - Tandem Load – one lane
    - Tandem Load – two lanes



Live Load

- Live load area = $l_w * w_w$

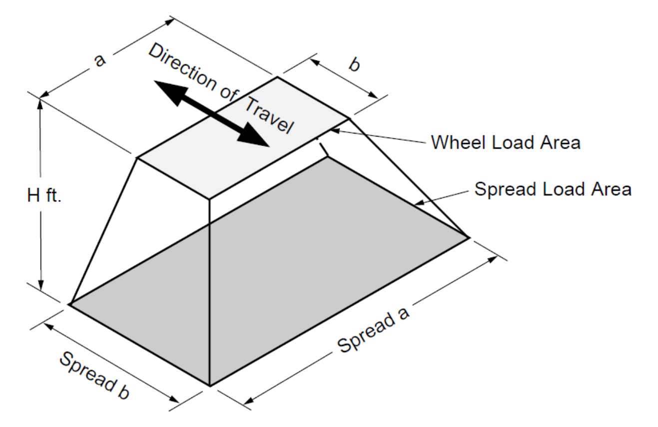
- $IM = 33 * (1.0 - 0.125 * D_E) \geq 0\%$

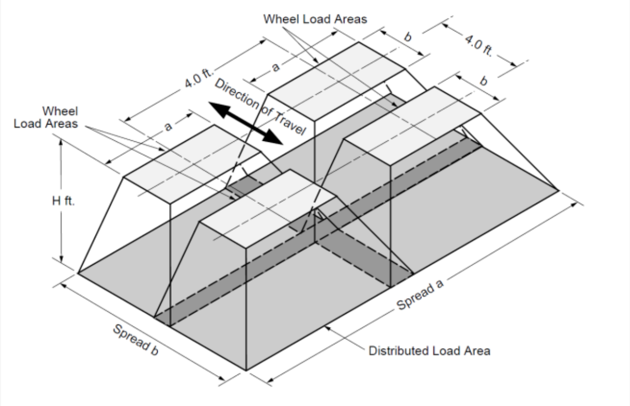
  D_E minimum depth of earth above the structure (ft)

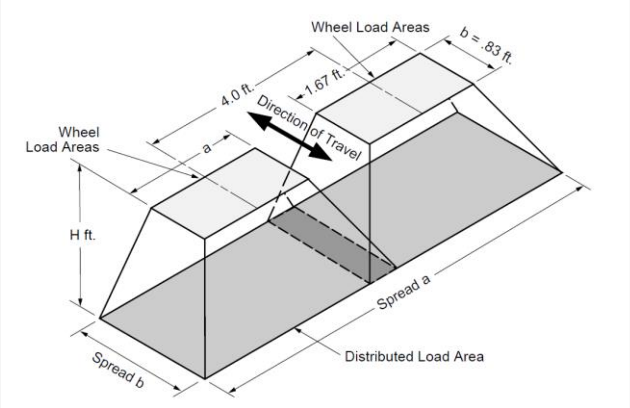
- Applied pressure at the top of the pipe:

$$P_L = \frac{P * \left(1 + \frac{IM}{100}\right) * mpf}{A_{LL}}$$

  P is the load applied from either the wheel or axle, depending on if there is overlap





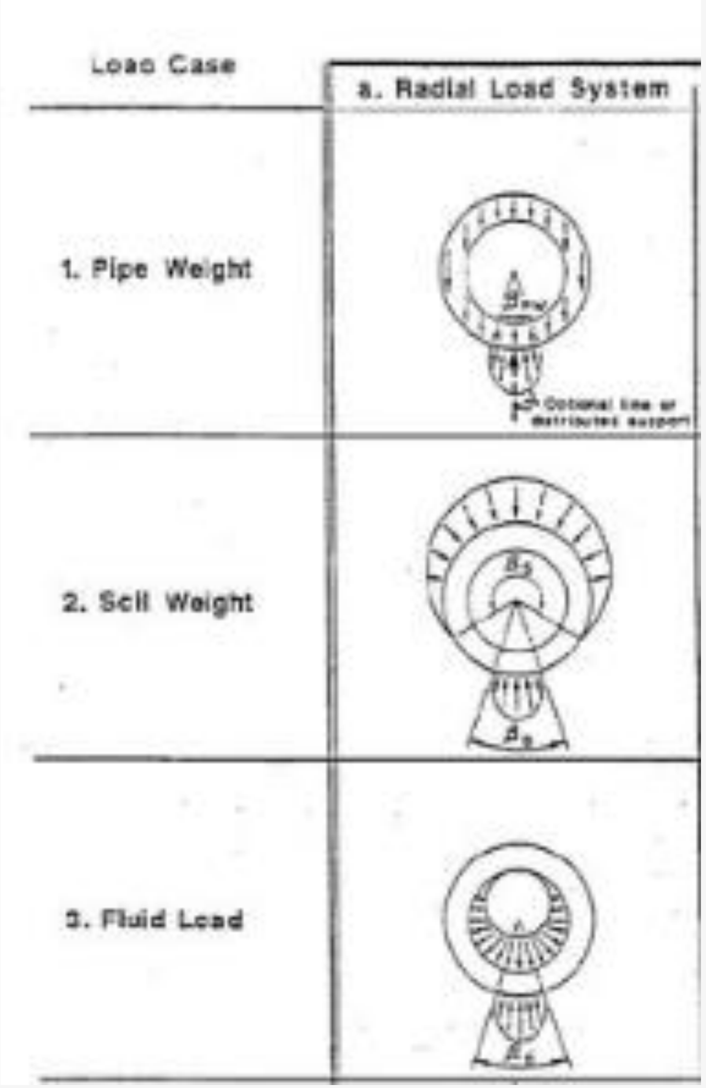


Pressure distribution

Pressure distribution

- For **pipe weight**, a radial pressure distribution at the pipe support Bedding angle assumption 45º
- For **earth weight**, a radial pressure distribution at the pipe shall Bedding angle assumption 90º
- For **fluid weight**, a radial pressure distribution at the pipe Bedding angle assumption 90º

Radial pressure distribution based on theory by Olander[1]



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[1] Olander, H.C., Stress Analysis of Concrete Pipe, Engineering Monograph No. 6, U.S. Bureau of Reclamation, October 1950

Live Load distribution

Combination of a uniformly distributed surcharge of any width and a cosine-shaped radial bedding reaction over 90° pressure are assumed.

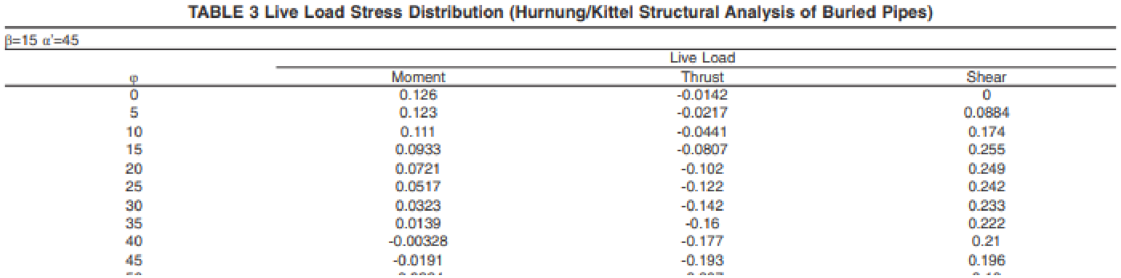
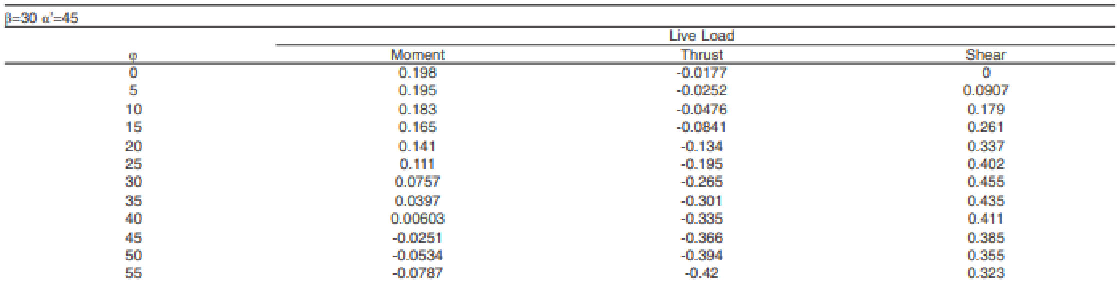


TABLE 3 Live Load Stress Distribution (Hurnung/Kittel Structural Analysis of Buried Pipes)

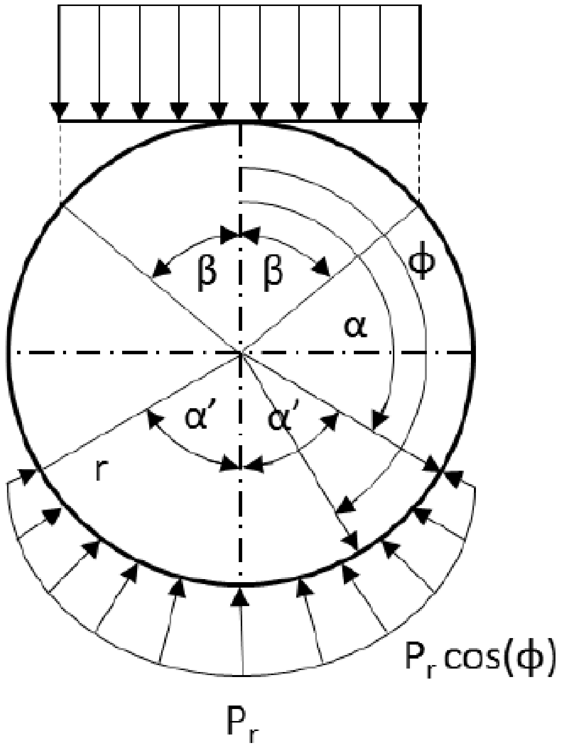
β=15 α'=45

	Live Load		
φ	Moment	Thrust	Shear
0	0.126	-0.0142	0
5	0.123	-0.0217	0.0884
10	0.111	-0.0441	0.174
15	0.0933	-0.0807	0.255
20	0.0721	-0.102	0.249
25	0.0517	-0.122	0.242
30	0.0323	-0.142	0.233
35	0.0139	-0.16	0.222
40	-0.00328	-0.177	0.21
45	-0.0191	-0.193	0.196



β=30 α'=45

	Live Load		
φ	Moment	Thrust	Shear
0	0.198	-0.0177	0
5	0.195	-0.0252	0.0907
10	0.183	-0.0476	0.179
15	0.165	-0.0841	0.261
20	0.141	-0.134	0.337
25	0.111	-0.195	0.402
30	0.0757	-0.265	0.455
35	0.0397	-0.301	0.435
40	0.00603	-0.335	0.411
45	-0.0251	-0.366	0.385
50	-0.0534	-0.394	0.355
55	-0.0787	-0.42	0.323



Moment, Shear, Thrust

Stress Analysis

- For **pipe weight**:

$$M_P = W_P \frac{D_m}{2} C_{mP}$$

$$N_P = W_P\, C_{nP}$$

$$V_P = W_P\, C_{vP}$$

$M_P, N_P, and\ V_P$ = pipe weight moment, thrust, and shear respectively (in.-lb/ft, lb/ft, and lb/ft)

$C_{mP}, C_{nP}, and\ C_{vP}$ = pipe weight moment coefficient, thrust coefficient, and shear coefficient respectively

W_P = weight of pipe (lb/ft)

D_m = mean radius of pipe (in.)

- For **earth load**

$$M_E = W_E \frac{D_m}{2} C_{mE}$$

$$N_E = W_E\, C_{nE}$$

$$V_E = W_E C_{vE}$$

$M_E, N_E, and\ V_E$ = earth weight moment, thrust, and shear respectively (in.-lb/ft, lb/ft, and lb/ft)

$C_{mE}, C_{nE}, and\ C_{vE}$ = earth weight moment coefficient, thrust coefficient, and shear coefficient respectively

W_E = total weight of earth above the pipe acting on a length b (lb/ft)

- **For fluid load**

Similar procedure

Stress Analysis

- For **live load**:

$$M_L = W_L \left(\frac{D_m}{2}\right)^2 C_{mL}$$

$$N_L = W_L \left(\frac{D_m}{2}\right) C_{nL}$$

$$V_L = W_L \left(\frac{D_m}{2}\right) C_{vL}$$

M_L, N_L, *and* V_L = live load moment, thrust, and shear respectively (in.-lb/ft, lb/ft, and lb/ft)

C_{mL}, C_{nL}, *and* C_{vL} = live load moment coefficient, thrust coefficient, and shear coefficient respectively

W_L = total live load pressure applied to the top of the pipe acting on a length b (lb/ft/in.).

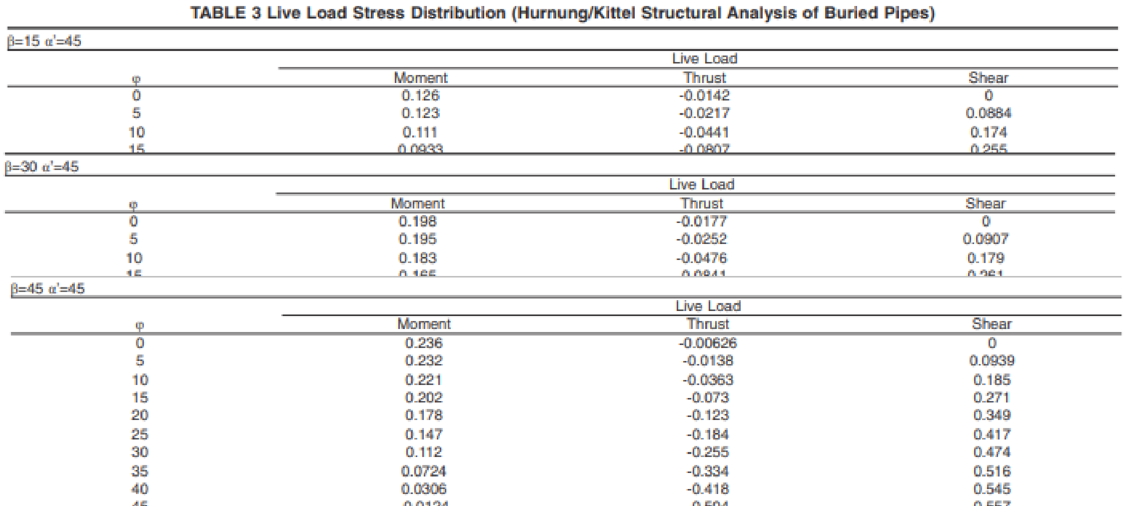


TABLE 3 Live Load Stress Distribution (Hurnung/Kittel Structural Analysis of Buried Pipes)

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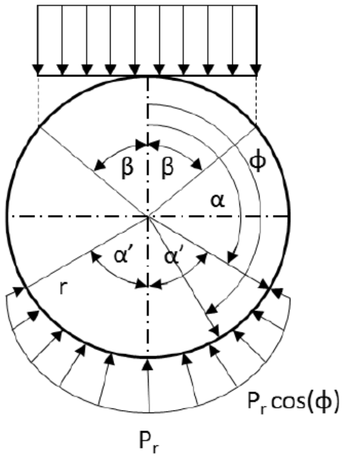
5	0.123	-0.0217	0.0884
10	0.111	-0.0441	0.174
15	0.0933	-0.0807	0.255

β=30 α'=45

φ	Live Load Moment	Live Load Thrust	Live Load Shear
0	0.198	-0.0177	0
5	0.195	-0.0252	0.0907
10	0.183	-0.0476	0.179
[illegible]	[illegible]	[illegible]	[illegible]

β=45 α'=45

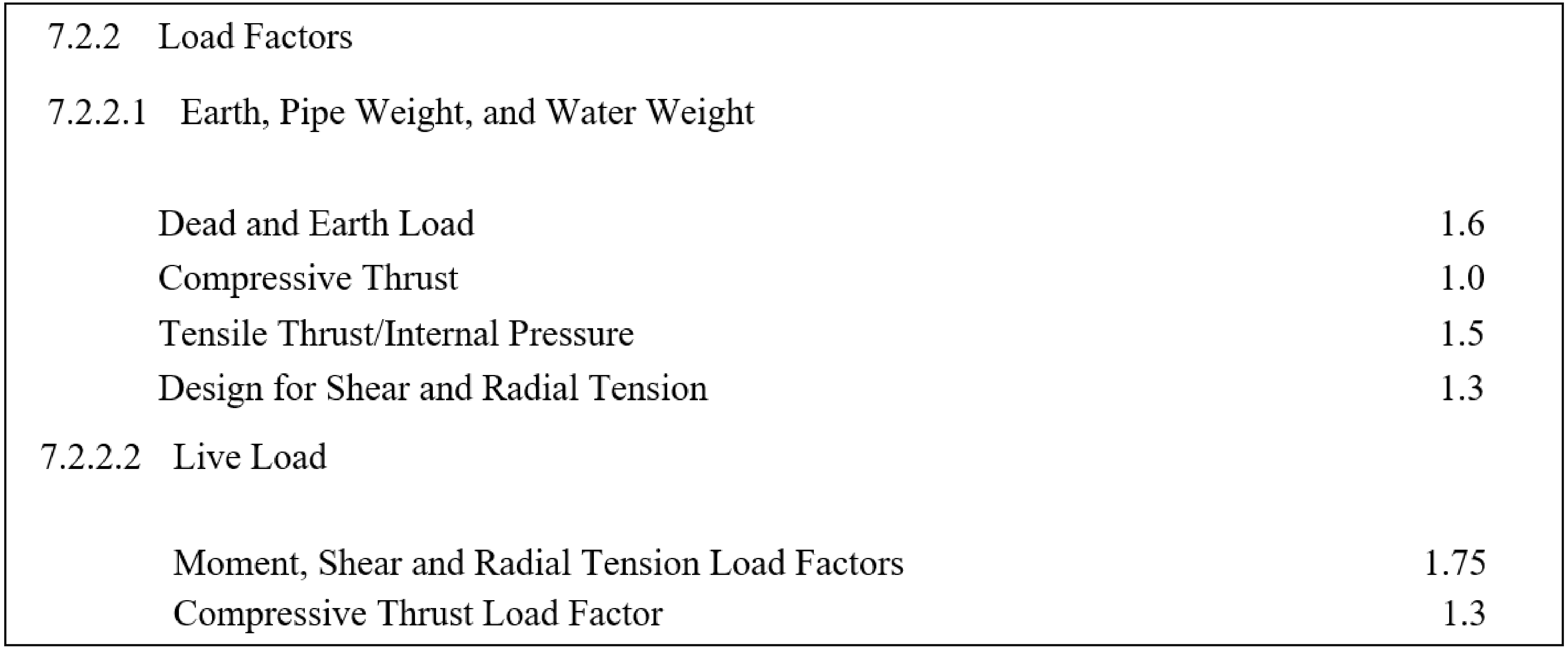
φ	Live Load Moment	Live Load Thrust	Live Load Shear
0	0.236	-0.00626	0
5	0.232	-0.0138	0.0939
10	0.221	-0.0363	0.185
15	0.202	-0.073	0.271
20	0.178	-0.123	0.349
25	0.147	-0.184	0.417
30	0.112	-0.255	0.474
35	0.0724	-0.334	0.516
40	0.0306	-0.418	0.545
[illegible]	[illegible]	[illegible]	[illegible]



β will change based on the fill height

Reference: Hurnung/Kittel Structural Analysis of Buried Pipes

Load and strength factors



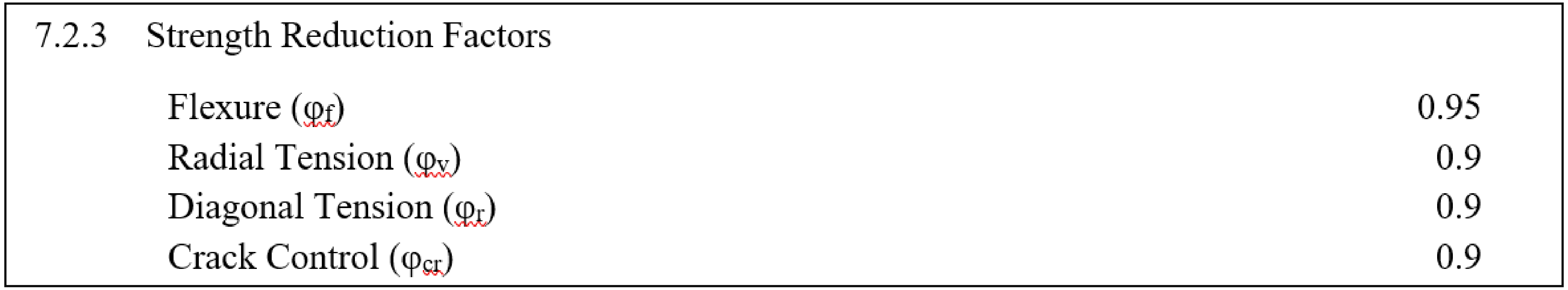
7.2.2 Load Factors

7.2.2.1 Earth, Pipe Weight, and Water Weight

Dead and Earth Load	1.6
Compressive Thrust	1.0
Tensile Thrust/Internal Pressure	1.5
Design for Shear and Radial Tension	1.3

7.2.2.2 Live Load

Moment, Shear and Radial Tension Load Factors	1.75
Compressive Thrust Load Factor	1.3



7.2.3 Strength Reduction Factors

Flexure (φ_f)	0.95
Radial Tension (φ_v)	0.9
Diagonal Tension (φ_r)	0.9
Crack Control (φ_{cr})	0.9

Performance Mode/Limit States

- Flexure (max limits)
- Shear
- Crack

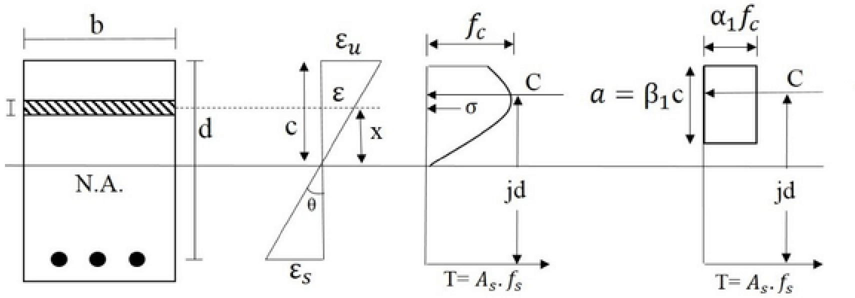
Flexure – ultimate limit state

Produced at locations of tension by effect of bending and axial thrust

- Calculate the depth of compressive stress block α and then the required reinforcement As

$$a = d\left[1 - \sqrt{1 - \frac{2M_{ure}}{0.85\, f'_c b d^2}}\right]$$

$$A_s = \frac{0.85\, f'_c a b}{f_y} - \frac{N_{ure}}{f_y}$$



(a) Cross Section (b) Strain Diagram (c) Stress Diagram (d) Equivalent Rectangular Stress Diagram

M_{ure} = factored moment caused by external loads

N_{ure} = factored thrust
when compression +
when tension -

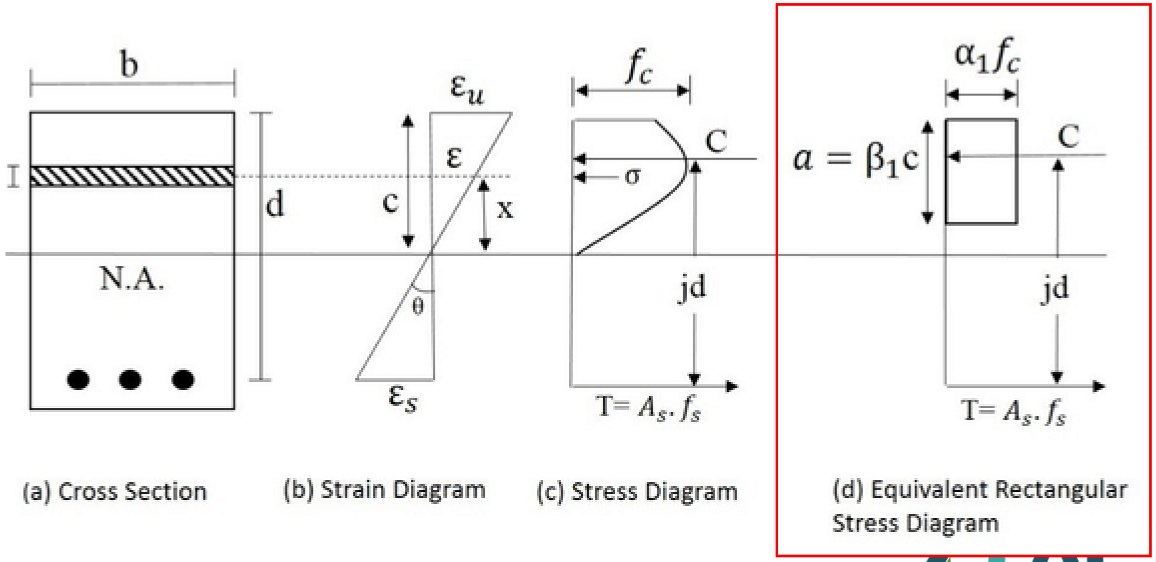
Maximum Flexural Reinforcement Limits

Concrete Compression: Maximum *As* limited to ensure a level of ductile behavior by limiting the ratio of reinforcement to 0.75 of the ultimate compressive strength based on a rectangular stress box without compression reinforcement and without stirrups.

$$A_{s\,max} = 0.75 * \rho_b * b * d = 0.75 * \left(0.85 * b * d * \beta_1 * \ f'_c * \left(\frac{87{,}000}{\left(87{,}000 + \ f_y\right) * f_y}\right) - \frac{N_{ure}}{f_y}\right)$$

$$0.65 \le \beta_1 = 0.85 - 0.05\,\frac{\left(f'_c - 4{,}000\right)}{1{,}000} \le 0.85$$

If $A_{s\,max}$ compression limit is smaller than the flexural reinforcement, re-design using:
- higher concrete strength or
- thicker section.



(a) Cross Section

(b) Strain Diagram

(c) Stress Diagram

(d) Equivalent Rectangular Stress Diagram

Maximum Flexural Reinforcement Limits

Radial Tension: Caused by bending from external load only, internal pressure does NOT produce radial tension

- Caused by tension forces within the radial reinforcement
- These tension forces act to straighten out curved steel, causing it to pipe wall

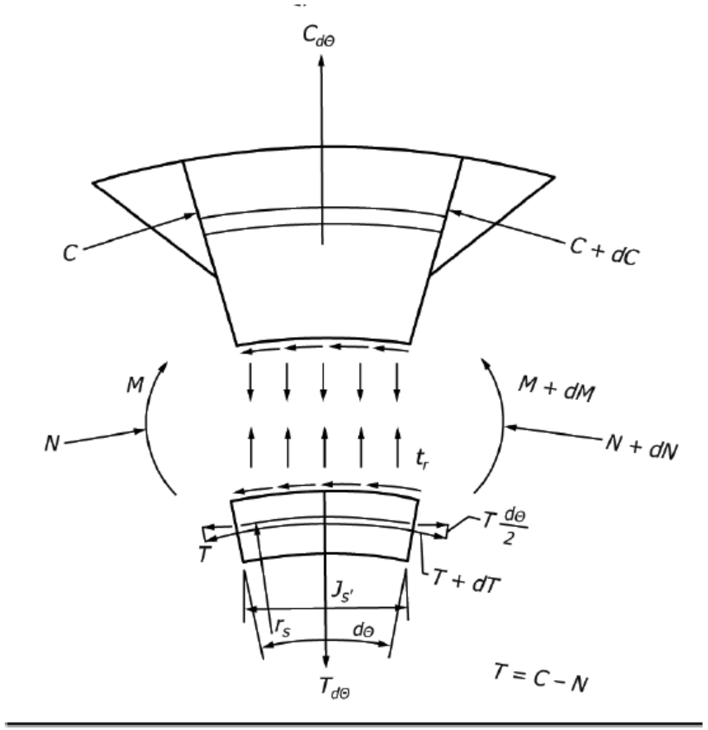


FIG. 2 Radial Tension in Curved Flexural Member at Cracked Section

$$A_{s\,max} = \left(\frac{b}{12}\right)\frac{\left[16\, r_s F_{rp}\sqrt{f'_c}\left(\frac{\varphi_r}{\varphi_f}\right)F_{rt}\right]}{f_y}$$

F_{rp} = process and material factor
ϕ = stress reduction factor
F_{rt} = factor for size effect that increases the strength for diameter smaller than 72” to account for the decreased stress concentration effects from the decreasing flexural tension forces in the curved circumferential reinforcing as pipe size and reinforcement area decreases below 72 in. diameter. Decrease of strength is calculated for larger diamaters than 72”

Maximum Flexural Reinforcement Limits

If radial tension limit is smaller than the flexural reinforcement, re-design with:

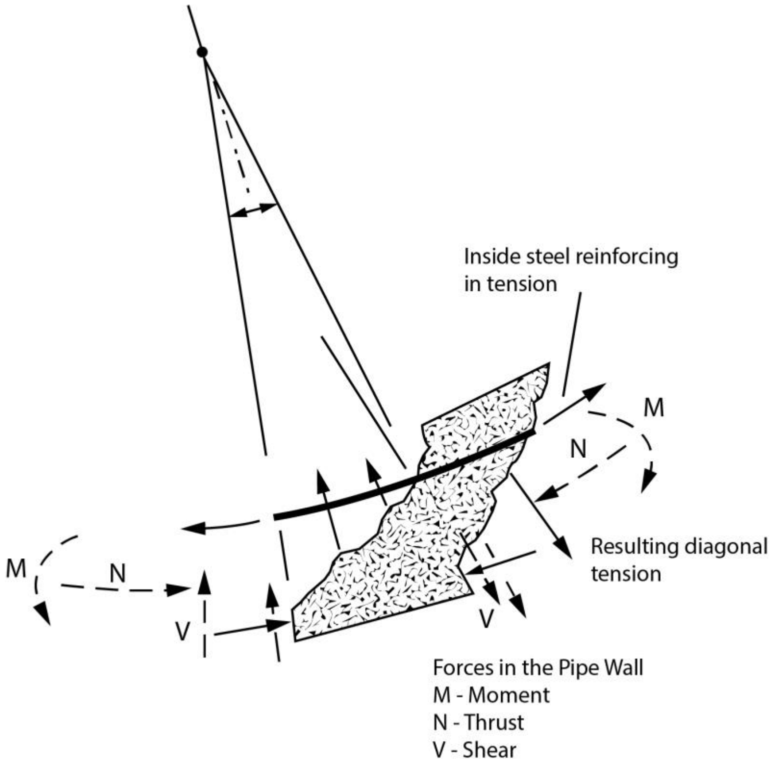
- higher concrete strength
- thicker section, or
- stirrups (explained later)

Shear (a.k.a. diagonal tension)

Shear stirrups are NOT required when $V_{uv}<V_c$.

V_{uv} is the factored shear force at the section of maximum shear in length b from external load only.

V_c is the shear strength provided by concrete without stirrups at section of maximum shear.



- Presence of tensile thrust reduces the shear strength of the pipe wall.
- Recent research has shown that this reduction can be controlled by limiting the strain in the circumferential reinforcement, based on the assumption of a cracked section.
- The method that calculates the allowable shear capacity of the pipe wall incorporates the reinforcing strain based on tests on pressure pipe in loading condition including shear, bending, and tensile thrust.

Shear a.k.a. diagonal tension (cont.)

V_c is the shear strength provided by concrete without stirrups at section of maximum shear.

$$V_c = 2\,\varphi_v\, b\, dF_{vp}\sqrt{f'_c}\left[\frac{F_d F_{\varepsilon x}}{F_c}\right]$$

F_{vp} = process and material factor for shear strength = 1.0, unless a higher value substantiated by test data obtained in accordance with Specification C655 is approved by the Engineer,

F_d = size factor that accounts for the increased shear stress capacity exhibited by small diameter pipe with thin walls,

Fc = curvature factor that accounts for the small additional shear associated with the effects of curvature on the pipe wall thrust,

$F\varepsilon x$ = strain factor to account for the reduction in aggregate interlock from higher tensile strains.

Shear

$F_{\varepsilon x}$ = strain factor to account for the reduction in aggregate interlock from higher tensile strains

$$F_{\varepsilon x} = 2.2\left(1 - 2.75\,{\varepsilon_{xu}}^{0.25}\right)$$

$$0 < \varepsilon_{xu} < 0.002$$

$$\varepsilon_{xu} = \frac{\left(\frac{M_{uv}}{0.9d}\right) + 0.5\,V_{uv}\,\cot\theta_v - 0.4\,N_{uv}}{E_s\,A_{si}}$$

$$\theta_v = \frac{37}{F_d}, \text{ degrees}$$

M_{uv}=factored moment caused by all loads section of maximum shear, based on load factor for shear, in.-lb/ft

V_{uv}=factored shear force at section of maximum shear produced by all loads, lb/ft

θ_v=approximate inclination of diagonal tension crack, degrees

N_{uv}=factored compressive thrust at section of maximum shear produced by all loads except internal pressure (+ when compressive, - when tensile), based on load factor for compressive thrust, lb/ft

Es =modulus of elasticity of steel, psi

ε_{xu} = strain in reinforcement produced by factored moments, thrusts and shears at section of maximum shear

Crack – Service Load Limit

The circumferential reinforcement to resist the cracking of the concrete shall be determined in this section.

When thrust is compressive:

$$F_{cr} = \frac{B_1}{A_s\, 30{,}000\, \varphi_f d}\left[\frac{M_s + N_s\left(d - \frac{h}{2}\right)}{i\, j} - C_1\, b\, h^2 \sqrt{f'_c}\right]$$

$$j = 0.74 + 0.1\frac{e}{d} \leq 0.9 \qquad e = \frac{M_s}{N_s} + d - \frac{h}{2}$$

$$i = \frac{1}{1 - \frac{jd}{e}}$$

$$B_1 = \sqrt[3]{\frac{t_b s}{2n}}$$

When thrust is tensile:

ed<1.15

$$F_{cr} = \frac{B_1}{A_s\, 30{,}000\, \varphi_f d}\left[1.1\, M_s - 0.6\, N_s\, d - C_1\, b\, h^2 \sqrt{f'_c}\right]$$

$F_{cr} < 1$, the probability of an 0.01-inch crack is reduced

$F_{cr} > 1$, the probability of an 0.01-inch crack width is increased, then the required reinforcement, A_s, is increased

by the ratio of the strength reduction factor by the crack control value.

Design Conditions

Condition 1 - Internal Pressure Acting Alone

The concrete stress produced by the tensile thrust resulting from the internal pressure is:

$$f_{ct} = \frac{0.433 H_w D_i}{2h}$$

$$f_{ct,max} = 4.5\sqrt{f'_c}$$

The reinforcement stress produced by the internal pressure, based on the reinforcement resisting the full circumferential tension is:

$$A_s = \frac{6\,(0.433\ H_w) D_i}{f_{sd,max}}$$

$$f_{sd,max} = 17{,}000 - 35\ H_w$$

- Equations are provided to limit the tensile stresses in both the reinforcement and concrete so that no cracking of the concrete is expected to occur under internal pressure.
- The steel area calculated for internal pressure is the entire steel area in the wall and may be divided between the inner and outer reinforcement cages.

Condition 2- Reinforcement for External Load Without Internal Pressure

Flexure Design:

- Required flexural steel based on the applied forces,
- Maximum radial tension limit,
- Maximum concrete compression limit, and

Crack control Design

Shear Design

Condition 3 - Reinforcement for External Load and Internal Pressure

- Tensile forces in reinforcement produced by internal pressure do not cause radial tension in the concrete wall
- Maximum concrete compression results from external loads without internal pressure
- No reinforcement limits

Flexure Design - same as Condition 2

Crack Design – same as condition 2

Shear Design – same as condition 2 except:

$$\varepsilon_{xu} = \frac{\left(\frac{M_{uv}}{0.9d}\right) + 0.5\,V_{uv}\ \cot\theta_v - 0.4\,N_{uv} - 0.5\,N_{up}}{E_s\,A_{si}}$$

M_{uv} = factored moment at section of maximum shear due to all loads, (external and internal), (in.-lb/ft), always positive

V_{uv} = factored shear force at section of maximum shear due to all loads (external and internal), (lb/ft), always positive

N_{uv} = factored thrust force at section of maximum shear due to all loads except internal pressure (lb/ft), compression is positive, tension is negative.

N_{up} = factored thrust force due to internal pressure, (lb/ft) always negative

Reinforcement Arrangement

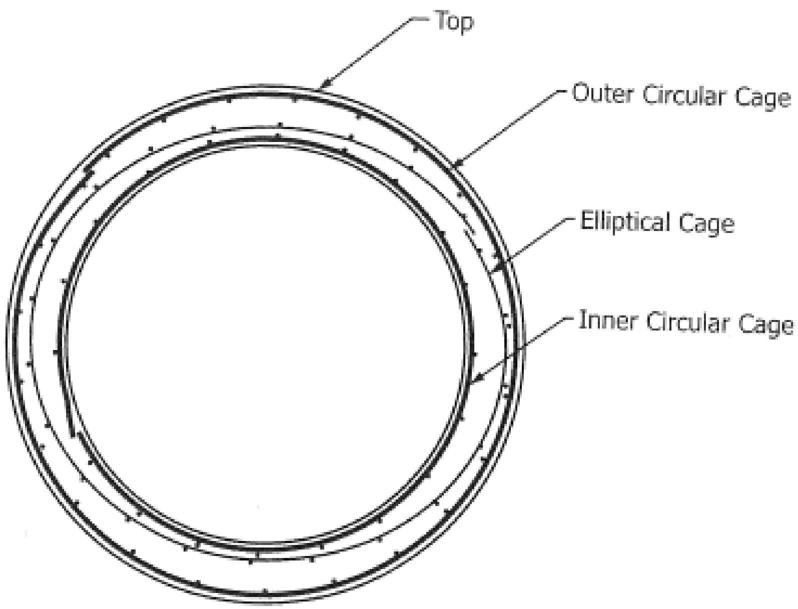
Circumferential reinforcement

- elliptical cage

- one or more circular cages

- combination

ASTM C361 section 7.4 for details



Stirrups for Radial Tension

If stirrups are required for radial tension design process is same as that used for non pressure pipe:

$$A_{vr} = \frac{1.1\, s_v (M_{ure} - 0.45\, N_{ure} \varphi_r d)}{f_v\, r_s\, \varphi_r\, d}$$

fv – maximum developable strength of stirrup material, lb/in^2
sv – circumferential spacing of stirrups, in.
Mure – factored moment caused by external loads
Nure – factored thrust caused by external loads
ϕr – strength reduction factor for radial tension

Stirrups for Shear

If stirrups are required for shear they are conservatively designed for excess shear and full radial tension forces.

$$A_{vs} = \frac{1.1\, s_v}{f_v\, \varphi_r\, d}\left[V_{uv}\, F_c - V_c\right] + A_{vr}$$

V_{uv} =factored shear force at section of maximum shear produced by all loads, lb/ft

F_c =curvature factor that accounts for the small additional shear associated with the effects of curvature on the pipe wall thrust

V_c =shear strength provided by concrete without stirrups in length b, lb/ft

The maximum concrete shear strength that can be used in combination with stirrup reinforcement strength is:

$$maxV_c = 2\varphi_v b d F_{vp}\sqrt{f_c'}$$

Stirrups Spacing

Circumferential max spacing: $s_{v\,max} = 0.75\,\varphi_v d$

Longitudinal: Stirrups shall have the same longitudinal spacing as the inside circumferential reinforcement.

The maximum longitudinal spacing of stirrups in members with curvature that are subject to radial tension is the spacing between adjacent wires or bars.

Extend of Stirrups and Anchorage

Extend over a basic length on each side of the invert or crown where $V_{uv} > V_c$ plus an additional minimum arc length 0.5 l_θ from each end of the basic arc length to allow for installation variations up to the orientation angle, θ, where:

$$l_\theta = \frac{\pi\,\theta}{180}\left(D_i + 2\,t_b\right) + h$$

If stirrups are also required at the springline region (may occur in very high loading conditions), they shall extend around the entire pipe circumference.

Anchorage: Both ends of the stirrup shall be sufficient to develop the factored strength in the stirrup. Tests have demonstrated that some stirrups can develop their design strength if they are anchored around tension reinforcing at one end with their other end anchored in the concrete on the compression side.

Joints

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Joint Design

Joints shall conform to the requirements of ASTM C361 as required by the owner and shall conform to the requirements of this practice.

- For Hw > 25 ft. the rubber gaskets shall be solid gaskets of circular cross section
- For Hw =< 25 ft. the gaskets shall be solid circular or non-circular gaskets

Joint Design

ASTM C361 requires circumferential and longitudinal reinforcement in both concrete bells and concrete spigots of the pipe.

- The spigot is reinforced with an extension of one cage from the pipe wall.
- The bell is reinforced with an extension of one cage in the wall or a separate cage lapped with the wall cage.

The area of the bell cage is required to be sufficient to resist the hydrostatic, hydrodynamic and gasket pressures

Joint Design

Appendix section of ASTM C361 contains a table of minimum bell reinforcement quantities and placement.

USBR and the ASTM C361 tables serve as a good reference for guidance.

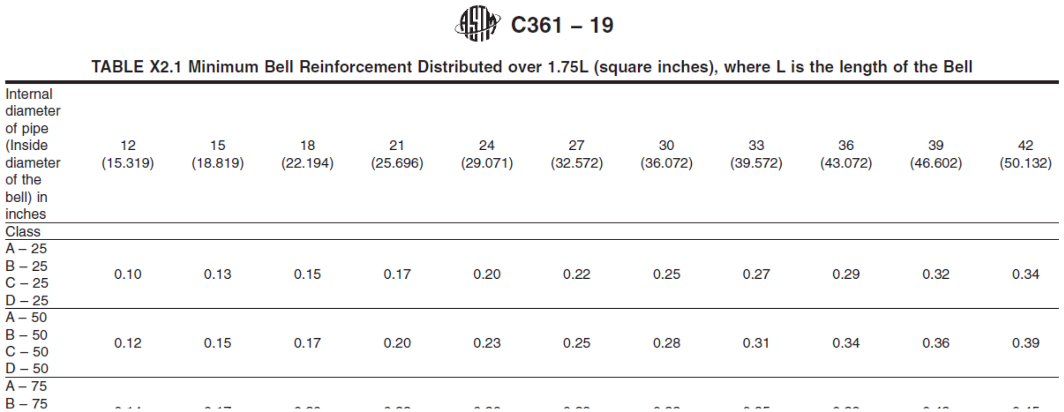

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TABLE X2.1 Minimum Bell Reinforcement Distributed over 1.75L (square inches), where L is the length of the Bell

Internal diameter of pipe (Inside diameter of the bell) in inches	12 (15.319)	15 (18.819)	18 (22.194)	21 (25.696)	24 (29.071)	27 (32.572)	30 (36.072)	33 (39.572)	36 (43.072)	39 (46.602)	42 (50.132)
Class											
A – 25 B – 25 C – 25 D – 25	0.10	0.13	0.15	0.17	0.20	0.22	0.25	0.27	0.29	0.32	0.34
A – 50 B – 50 C – 50 D – 50	0.12	0.15	0.17	0.20	0.23	0.25	0.28	0.31	0.34	0.36	0.39
A – 75 B – 75											

Reference: USBR M-1, Standard Specifications for Reinforced Concrete Pressure Pipe, U.S. Bureau of Reclamation, Washington, DC, 1991

ASTM C1924 includes calculation for loads applied to joints:

- Bell force from gasket (maximum of 200lb/in./gasket)
- Differential settlement across the joint
- Impact of earth load on the pipe

Thank you

mtakou@concretepipe.org

972.894.2902

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