Standard Practice for Structural Design of Thermoplastic Corrugated Wall Stormwater Collection Chambers[1]

1. Scope*

1.1 This practice standardizes structural design of thermoplastic corrugated wall arch-shaped chambers used for collection, detention, and retention of stormwater runoff. The practice is for chambers installed in a trench or bed and subjected to earth and live loads. Structural design includes the composite system made up of the chamber arch, the chamber foot, and the soil envelope. Relevant recognized practices include design of thermoplastic culvert pipes and design of foundations.

1.2 This practice standardizes methods for manufacturers of buried thermoplastic structures to design for the time dependent behavior of plastics using soil support as an integral part of the structural system. This practice is not applicable to thermoplastic structures that do not include soil support as a component of the structural system.

1.3 This practice is limited to structural design and does not provide guidance on hydraulic, hydrologic, or environmental design considerations that may need to be addressed for functional use of stormwater collection chambers.

1.4 Stormwater chambers are most commonly embedded in open graded, angular aggregate which provide both structural support and open porosity for water storage. Should soils other than open graded, angular aggregate be specified for embedment, other installation and functional concerns may need to be addressed that are outside the scope of this practice.

1.5 Chambers are produced in arch shapes to meet classifications that specify chamber rise, chamber span, minimum foot width, minimum wall thickness, and minimum arch stiffness constant. Chambers are manufactured with integral footings.

1.6 Polypropylene chamber classifications are found in Specification F2418. Specification F2418 also specifies chamber manufacture and qualification.

1.7 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D2487 Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)

D2990 Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

D6992 Test Method for Accelerated Tensile Creep and Creep-Rupture of Geosynthetic Materials Based on Time-Temperature Superposition Using the Stepped Isothermal Method

F2418 Specification for Polypropylene (PP) Corrugated Wall Stormwater Collection Chambers

2.2 *AASHTO LRFD Bridge Design Specifications:*[3]

Section 3 Loads and Load Factors, 3.5 Permanent Loads; 3.6 Live Loads

Section 10 Foundations, 10.6 Spread Footings

Section 12 Buried Structures and Tunnel Liners, 12.12 Thermoplastic Pipes

2.3 *AASHTO Standard Specifications:*[3]

M 43 Standard Specification for Size of Aggregate for Road and Bridge Construction

M 145 Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes

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[1] This practice is under the jurisdiction of ASTM Committee F17 on Plastic Piping Systems and is the direct responsibility of Subcommittee F17.65 on Land Drainage.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] *AASHTO LRFD Bridge Design Specifications-Dual Units*, 4th Edition, 2007 and *AASHTO Standard Specifications for Transportation Materials and Sampling*, 28th edition, 2008. Available from American Association of State Highway and Transportation Officials (AASHTO), 444 N. Capitol St., NW, Suite 249, Washington, DC 20001.

***A Summary of Changes section appears at the end of this standard**

T 99 Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop

2.4 *AWWA Manual:*[4]

M 45 Manual of Water Supply Practices: Fiberglass Pipe Design

3. Terminology

3.1 *Definitions:*

3.1.1 Definitions used in this specification are in accordance with the definitions in Terminology F412, and abbreviations are in accordance with Terminology D1600, unless otherwise indicated.

3.1.2 *chamber*—an arch-shaped structure manufactured of thermoplastic with an open-bottom that is supported on feet and may be joined into rows that begin with, and are terminated by, end caps (see Fig. 1).

3.1.3 *classification*—the chamber model specification that identifies nominal height, nominal width, rise, span, minimum foot width, wall thickness, and arch stiffness constant.

3.1.4 *corrugated wall*—a wall profile consisting of a regular pattern of alternating crests and valleys connected by web elements (see Fig. 2).

3.1.5 *crest*—the element of a corrugation located at the exterior surface of the chamber wall, spanning between two web elements (see Fig. 2).

3.1.6 *crown*—the center section of a chamber typically located at the highest point as the chamber is traversed circumferentially.

3.1.7 *embedment*—backfill material against the sides of chambers and end caps and in between rows of chambers from the foundation stone below to a specified dimension over the top of the chambers (see Fig. 3).

3.1.8 *end cap*—a bulkhead provided to begin and terminate a chamber, or row of chambers, and prevent intrusion of surrounding embedment materials.

3.1.9 *foot*—a flat, turned out section that is manufactured with the chamber to provide a bearing surface for transfer of vertical loads to the foundation (see Fig. 1).

3.1.10 *foot area*—the actual contact area of the foot with the foundation.

3.1.11 *local buckling*—compression failure of built-up plate sections with high width-to-thickness ratios.

3.1.12 *nominal height*—a designation describing the approximate outside vertical dimension of the chamber at its crown (see Fig. 1).

3.1.13 *nominal width*—a designation describing the approximate outside horizontal dimension of the chamber at its feet (see Fig. 1).

3.1.14 *rise*—the vertical distance from the chamber base (bottom of the chamber foot) to the inside of a chamber wall valley element at the crown as depicted in Fig. 1.

3.1.15 *span*—the horizontal distance from the interior of one sidewall valley element to the interior of the other sidewall valley element as depicted in Fig. 1.

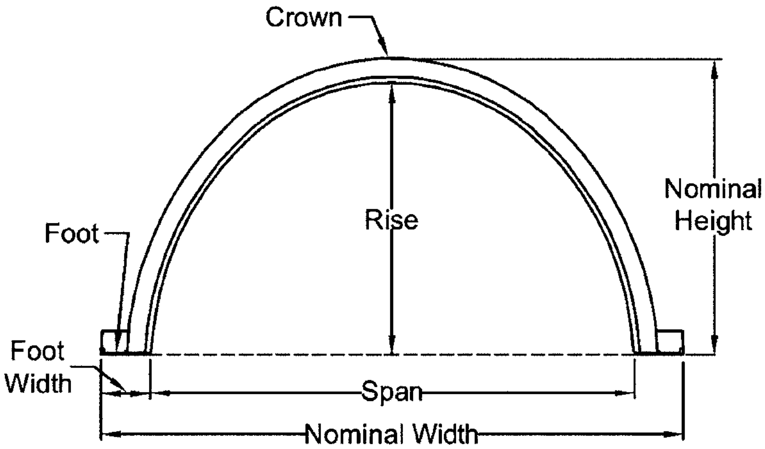
3.1.16 *valley*—the element of a corrugation located at the interior surface of a chamber wall, spanning between two web elements (see Fig. 2).

3.1.17 *viscoelasticity*—the response of a material to load that is dependent both on load magnitude (elastic) and load rate (viscous).

3.1.18 *web*—the element of a corrugated wall that connects a crest element to a valley element (see Fig. 2).

4. Significance and Use

4.1 This practice provides a rational method for structural design of thermoplastic stormwater chambers. The loads, capacities, and limit states are based on accepted load and resistance factor design for thermoplastic pipes; however,



NOTE 1—The model chamber shown in this standard is intended only as a general illustration.

FIG. 1 Chamber Terminology (Typical)

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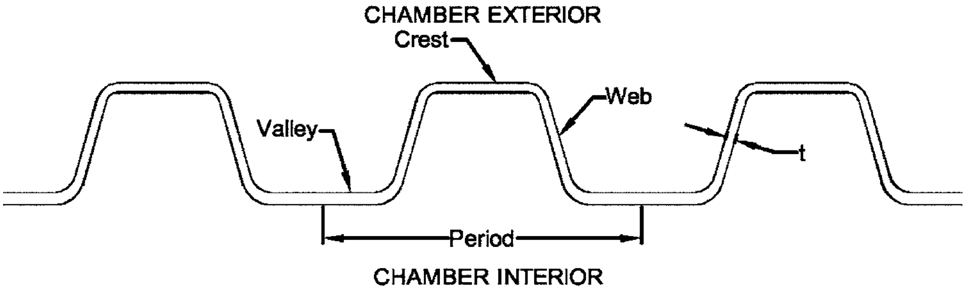
[4] *AWWA Manual of Water Supply Practices M45: Fiberglass Pipe Design*, 2nd Edition, 2005. Available from the American Water Works Association (AWWA), 6666 W. Quincy Ave., Denver, CO 80235.



NOTE 1—The corrugation profile shown in this standard is intended only as a general illustration.

FIG. 2 Corrugation Terminology (Typical)

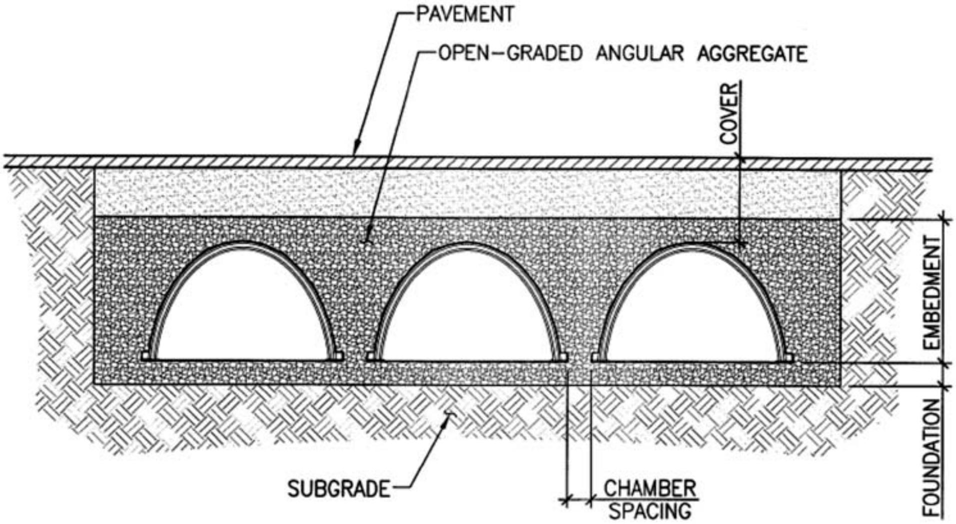


FIG. 3 Installation Terminology (Typical)

existing design specifications for thermoplastic pipes do not adequately address the design of chambers due to *(1)* open-bottom geometry, *(2)* support on integral foot, *(3)* varying circumferential corrugation geometry, and *(4)* manufacture with alternative thermoplastic resin. This practice standardizes recommendations for designers to adequately address these aspects of chamber design.

4.2 This practice is written to allow chamber manufacturers to evaluate chambers meeting existing classifications and to design chambers for new classifications as they are developed.

5. Basis of Design

5.1 Design is based on AASHTO LRFD Bridge Design Specifications and publications for static soil-structure-interaction analysis for thermoplastic pipes. Users should verify that these recommendations meet particular project needs.

5.2 Chamber installations shall be designed for the critical combination of live load and dead load, see Section 7.

5.3 Chambers shall be designed for service limit states and safety against structural failure, see Section 8.

5.3.1 *Service Limit State*—Service design shall limit vertical displacements at the ground surface. Chambers shall be evaluated for detrimental structural deformation.

5.3.2 *Safety Against Structural Failure*—Structural design shall evaluate chambers for buckling, compression, tension, and foundation bearing.

5.4 Buckling capacity is based on material stress limits. Compression and tension capacities are based on material strain limits. Foundation bearing capacity is based on soil ultimate bearing capacity.

5.5 Chambers shall be designed using closed-form solutions (verified by analysis) or finite element analysis (FEA). Designs shall be validated by testing.

NOTE 1—The soil-chamber system complexity generally precludes the use of closed-form solutions for determination of design force effects. While specific solutions may be developed for individual chamber geometries, general solutions have not been developed to accurately predict behavior for the many possible variations in chamber geometry. In most cases FEA must be employed to calculate design force effects on the chamber or as verification of closed-form solutions.

5.6 Chamber material properties shall be based on tests.

5.7 Chamber section properties shall be calculated from the geometry of the chamber cross-section.

5.8 Soil properties shall be based on generally accepted published properties for the specified soil classifications or by tests on site-specific materials.

6. Analysis for Design

6.1 The design shall include structural modeling of the chamber under loads in the installed soil environment. Analysis models shall include critical anticipated live loads and soil cover heights that provide deflections for serviceability design and force effects to design for safety against structural failure.

6.2 Analysis shall consider the following:

6.2.1 *Chamber Structure*—Two-dimensional FEA shall use beam elements with effective section properties to model the chamber wall. Each beam element shall represent not more than 10 degrees of the chamber circumference. Nodes at beam ends shall be located at the center of the gravity (cg) of the corrugated chamber wall cross-section. Three-dimensional FEA shall employ shell elements.

6.2.2 *FEA Program*—Acceptable FEA programs include *(1)* CANDE (Culvert Analysis and Design), *(2)* similarly featured and verified culvert design software, or *(3)* general purpose finite element analysis software with capability to model nonlinear static soil-structure-interaction.

6.2.3 *Creep*—The time-dependent response (creep) of thermoplastic chamber materials shall be included in the analysis. Acceptable methods are *(1)* multiple linear-elastic models with successive stiffness reductions for creep effects, and *(2)* nonlinear chamber models that include the creep response. Values of creep modulus shall be determined by test in accordance with Test Methods D2990 or Test Method D6992.

6.2.4 *Soil*—Models shall include accurate representation of the structural backfill envelope and boundary conditions. The backfill envelope includes foundation, embedment, and cover. Boundary conditions typically include the size of the soil embedment zone, distance to trench walls, subgrade under the backfill envelope, weight and stiffness of soils above the backfill envelope, and boundary for application of live loads. Structural backfill soils shall be modeled with nonlinear properties that incorporate the effects of confinement. Acceptable soil models include *(1)* soil hardening models that increase soil stiffness for confinement, *(2)* elastic-plastic models that allow failure in shear, or *(3)* large-deformation models. Soils outside the backfill envelope and further than two times the chamber span from the chamber may be modeled as linear-elastic. Soil continuum elements shall be either fully bonded to the chamber beam elements or modeled with a friction interface.

6.2.5 *Live Load*—Models shall include live loads, see Section 7.

6.2.6 *Chamber Beds*—Structural effects of adjacent chambers shall be analyzed. When two-dimensional plane-strain analysis is used, changes in geometry along the length of chamber runs, including intermediate stiffeners or diaphragms, shall be addressed using separate models.

7. Structural Loads

7.1 The design load on a chamber shall include dead load and live load.

7.2 *Dead Load (DL)*—Dead load shall be computed from permanent soil cover over chambers. The soil unit weight shall not be less than 120 lb/ft^3 (18.9 kN/m^3) unless otherwise determined by tests. Dead load shall be calculated for each installation.

7.3 *Dead Load Factor* (γ_{DL})—The dead load factor shall be 1.95.

7.4 *Live Load (LL)*—Live load calculation is provided in Annex A1. Live load includes transient loads (passing vehicles) or sustained loads (stationary non-permanent loads). Live load computation is based on the AASHTO HL-93 design vehicular live load applied to a single-loaded lane.

7.4.1 *HL-93*—The HL-93 load is a combination of the design truck or design tandem, whichever is critical, applied with the design lane load.

7.4.2 *Design Truck*—The design truck shall be the AASHTO Design Truck as specified in AASHTO LRFD Bridge Design Specifications, Section 3.6.1.2.2.

7.4.3 *Design Tandem*—The design tandem shall be the AASHTO Design Tandem as specified in AASHTO LRFD Bridge Design Specifications, Section 3.6.1.2.3.

7.4.4 Thermoplastic chamber structures have a structural response that is dependent on load duration. Chamber response to live load is computed using appropriate creep moduli for instantaneous response (transient loads) and longer-duration response (sustained loads). As a minimum, design for live load shall include evaluation of instantaneous response (due to moving vehicles), using a short duration (≤ 1 min) creep modulus, with multiple presence and impact factors in the live load computation, and a sustained load response (due to parked vehicle) using a 1 week creep modulus with no multiple presence or impact factors included in the live load computation.

7.5 *Live Load Factor* (γ_{LL})—The live load factor shall be 1.75.

8. Structural Design

8.1 The resistance of a chamber to design loads shall be based on the critical limit state for *(1)* serviceability requirements, *(2)* stability of the chamber to global buckling, *(3)* strength of the chamber to local buckling, *(4)* strength of the chamber material relative to tensile strain limits, *(5)* capacity of the foundation material to bearing from the chamber foot, and *(6)* capacity of the subgrade material to bearing from the foundation.

8.2 *Serviceability*—Chambers shall be designed to limit deflections that could adversely affect *(1)* displacements at the ground surface, *(2)* distribution of loads assumed in the analysis, or *(3)* hydraulic function. Deflection predictions shall be obtained from chamber design models using service loads. Unless otherwise specified, deflections (change in rise and span) shall be limited to 2.5 % of the nominal rise and span.

8.3 *Compression Strength Capacity*—The chamber is designed for compression local buckling by determination of an effective area to carry factored loads. The effective area is calculated by idealizing the corrugation into rectangular plates. The design is evaluated for the thrust only case, and for the combined thrust and bending case. The resulting safety factor is the ratio of allowable material strain to induced strain calculated by this procedure. The following steps provide the design procedure (for design example see Appendix X1).

8.3.1 *Idealized Wall Profile*—Corrugated wall cross-sections shall be idealized as straight (plate) elements. Each element is assigned a width based on the clear distance between the adjoining elements and the thickness at the center of the element. Fig. 4 illustrates idealization of a model corrugation. Where the cross-section is non-uniform around the chamber circumference, calculate idealized cross-section properties at locations separated not more than 30 degrees around the circumference.

8.3.2 *First-Order Wall Strain*—The first-order strain due to axial thrust, ε_T, at a wall cross-section is given in Eq 1. The first-order strain due to combined axial thrust and bending moment, ε_{Mi}, for each element at a wall cross-section is given in Eq 2. Strains are positive for compression.

$$\varepsilon_T = \frac{\gamma_{DL\max} T_{DL} + \gamma_{LL} T_{LL}}{AE_t} \tag{1}$$

$$\varepsilon_{Mi} = \frac{\gamma_{DL\max} T_{DL} + \gamma_{LL} T_{LL}}{AE_t} + \frac{(\gamma_{DL\max} M_{DL} + \gamma_{LL} M_{LL}) c_i}{IE_t} > 0 \tag{2}$$

where:

ε_T = first-order strain at a wall cross-section due to axial thrust (in./in.),

ε_{Mi} = first-order strain in each element at a wall cross-section due to combined axial thrust and bending moment (in./in.),

T_{DL} = *DL* thrust at a wall cross-section from models (lb/in.),

T_{LL} = *LL* thrust at a wall cross-section from models (lb/in.),

M_{DL} = *DL* bending moment at a wall cross-section from models (in.-lb/in.),

M_{LL} = *LL* bending moment at a wall cross-section from models (in.-lb/in.),

c_i = distance to each element center of gravity from the center of gravity of the wall cross-section (in.),

E_t = thermoplastic modulus of elasticity used in the model; *t* indicates load duration dependency (lb/in.^{2}),

A = gross area of the chamber wall cross-section (in.^{2}/in.), and

I = moment of inertia of the chamber wall cross-section (in.^{4}/in.)

8.3.3 *Slenderness and Effective Width*—The effective width, b_i, of each element in the cross-section for buckling shall be determined by Eq 3.

$$b_i = \rho_i w_i \tag{3}$$

$$\rho_i = \frac{\left(1 - \frac{0.22}{\lambda_i}\right)}{\lambda_i} \leq 1 \tag{4}$$

$$\lambda_i = \left(\frac{w_i}{t_i}\right) \sqrt{\frac{\varepsilon_i}{k_i}} > 0.673 \tag{5}$$

where:

b_i = effective width of each element (in.),

ρ_i = effective width factor,

λ_i = slenderness factor,

ε_i = strain in each element, evaluated for *Thrust* and *Thrust + Moment* (in./in.),

k_i = plate buckling edge support coefficient,

t_i = thickness of each element (in.), and

w_i = total clear width of element between supporting elements (in.).

NOTE 2—The plate buckling edge support coefficient can be approximated as 4.0 for simply supported edges, or 0.43 for free edges. A more exact value can be determined for specific cases based on methods presented in Timoshenko and Gere.[5]

8.3.4 *Effective Area*—The total effective area is determined as the summation of effective element areas in Eq 6.

$$A_{eff} = A - \frac{\sum (1 - \rho_i) w_i t_i}{\omega} \tag{6}$$

where:

A_{eff} = effective area of wall cross-section (in.^{2}/in.), and

ω = period of corrugation (in.).

8.3.5 *Total Factored Strain*—The total factored strains are given in Eq 7 and 8. The total factored strains are calculated at the extreme outer fiber of the cross-section.

$$\varepsilon_{Tf} = \frac{\gamma_{DL\max} T_{DL} + \gamma_{LL} T_{LL}}{A_{eff} E_t} \tag{7}$$

$$\varepsilon_{Mf} = \frac{\gamma_{DL\max} T_{DL} + \gamma_{LL} T_{LL}}{A_{eff} E_t} + \frac{(\gamma_{DL\max} M_{DL} + \gamma_{LL} M_{LL}) c_c}{IE_t} > 0 \tag{8}$$

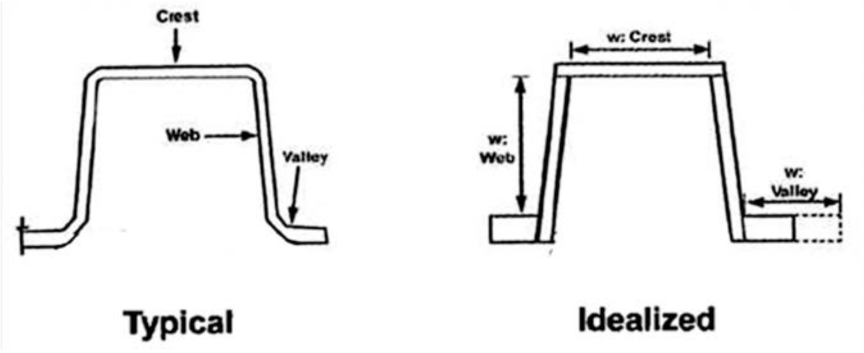


FIG. 4 Typical and Idealized Cross-Section of Corrugated Wall

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[5] Timoshenko, S. P. and Gere, J. M., *Theory of Elastic Stability*, McGraw Hill, New York, 1961.

where:

ε_{Tf} = total factored thrust compression strain (in./in.),
ε_{Mf} = total factored combined thrust and bending compression strain (in./in.), and
c_c = distance to extreme outer fiber from the center of gravity of the wall cross-section, for compression strain (in.).

8.3.6 *Compression Strength Check*—Chamber capacity is the thermoplastic yield strain, ε_{cy}. Yield strain may be determined from material compression tests. Compression strength is satisfied if Eq 9 and 10 are met.

$$\frac{\varepsilon_{cy}}{\varepsilon_{Tf}} \geq 1 \tag{9}$$

$$\frac{1.5\varepsilon_{cy}}{\varepsilon_{Mf}} \geq 1 \tag{10}$$

where:

ε_{cy} = chamber thermoplastic compression yield strain (in./in.).

NOTE 3—For typical thermoplastics, the values of stiffness and strength vary with temperature, load level, and load rate. However, research, testing, and analysis have shown that these same thermoplastics fail at a constant strain that is approximately independent of load application rate or duration. The strain is a function of the resin. The limiting strains theory is used for design of thermoplastic culvert pipes in AASHTO LRFD Bridge Design Specifications.

8.4 *Tensile Strength Capacity*—At any given wall cross-section, the maximum factored tensile strain shall not exceed the material tensile yield strain as in Eq 11.

$$\frac{\varepsilon_{ty}}{\varepsilon_t} \geq 1 \tag{11}$$

$$\varepsilon_t = \frac{\gamma_{DL}T_{DL}+\gamma_{LL}T_{LL}}{AE_t}+\frac{(\gamma_{DL}M_{DL}+\gamma_{LL}M_{LL})c_t}{IE_t}<0 \tag{12}$$

where:

ε_{ty} = chamber thermoplastic tension yield strain (in./in.),
ε_t = maximum tensile strain in the chamber wall; use $\gamma_{DL\max}$ or $\gamma_{DL\min}$ to get maximum tension strain (in./in.), and
c_t = distance to extreme outer fiber from the center of gravity of the wall cross-section, for tension strain (in.).

8.5 *Global Buckling:*

8.5.1 At any given wall cross-section, the critical buckling thrust, T_{CR}, shall be greater than the maximum factored thrust due to dead and live loads as shown in Eq 13. The thrust shall be obtained from chamber design models using service loads. Thrust is positive for compression.

$$\frac{T_{CR}}{T} \geq 1 \tag{13}$$

$$T = T_{DL}+T_{LL} \tag{14}$$

where:

T = maximum thrust due to dead loads and live loads (lb/in.)
T_{CR} = critical buckling thrust in Eq 15 (lb/in.).

8.5.2 The critical buckling thrust for a wall cross-section is given in Eq 15, following the approach adopted by the AWWA for global buckling of buried plastic pipe.Table 1

$$T_{CR} = \frac{1.2C_n(E_LI)^{0.33}(\varphi_sM_sk_\upsilon)^{0.67}R_h}{FS} \tag{15}$$

$$k_\upsilon = \frac{(1+\upsilon)(1-2\upsilon)}{1-\upsilon} \tag{16}$$

TABLE 1 Constrained Modulus M_s Based on Soil Type and Compaction Condition[A,B]

P_{sp} Stress level (ksf)	Sn-100 (ksi)	Sn-95 (ksi)	Sn-90 (ksi)	Sn-85 (ksi)
0.15	2.350	2.000	1.275	0.470
0.75	3.450	2.600	1.500	0.520
1.50	4.200	3.000	1.625	0.570
3.00	5.500	3.450	1.800	0.650
6.00	7.500	4.250	2.100	0.825
9.00	9.300	5.000	2.500	1.000
P_{sp} Stress level (ksf)		Si-95 (ksi)	Si-90 (ksi)	Si-85 (ksi)
0.15		1.415	0.670	0.360
0.75		1.670	0.740	0.390
1.50		1.770	0.750	0.400
3.00		1.880	0.790	0.430
6.00		2.090	0.900	0.510
9.00				
P_{sp} Stress level (ksf)		Cl-95 (ksi)	Cl-90 (ksi)	Cl-85 (ksi)
0.15		0.530	0.255	0.130
0.75		0.625	0.320	0.175
1.50		0.690	0.355	0.200
3.00		0.740	0.395	0.230
6.00		0.815	0.460	0.285
9.00		0.895	0.525	0.345

[A] The soil types are defined by a two-letter designation that indicates general soil classification. Sn for sands and gravels, Si for silts, and Cl for clays. Specific soil groups that fall into these categories, based on ASTM D2487 and AASHTO M 145, are listed in Table 2.

[B] The numerical suffix to the soil type indicates the compaction level of the soil as a percentage of maximum dry density determined in accordance with AASHTO T 99.

TABLE 2 Equivalent ASTM and AASHTO Soil Classifications

Basic Soil Type[A ,B]	ASTM D2487	AASHTO M 145
Sn (Gravelly sand, SW)	SW, SP[C] GW, GP sands and gravels with 12 % or less fines	A1, A3[C]
Si (Sandy silt, ML)	GM, SM, ML also GC and SC with less than 20 % passing a No. 200 sieve	A-2-4, A-2-5, A4
Cl (Silty clay, CL)	CL, MH, GC, SC also GC and SC with more than 20 % passing a No. 200 sieve	A-2-6, A-2-7, A5, A6

[A] The soil classification listed in parentheses is the type that was tested to develop the constrained soil modulus values in Table 1. The correlations to other soil types are approximate.

[B] Angular aggregate materials conforming to AASHTO M 43 are classified as Soil Type SN.

[C] Uniformly graded materials with an average particle size smaller than a No. 40 sieve shall not be used as backfill for thermoplastic culverts unless specifically allowed in the contract documents and special precautions are taken to control moisture content and monitor compaction levels.

$$R_h = \frac{11.4}{(11+D/h)} \qquad (17)$$

where:

T = maximum thrust due to dead loads and live loads (lb/in.)

FS = design factor = 2.5,

C_n = scalar calibration factor to account for nonlinear effects = 0.55,

φ_s = strength reduction factor for soil = 0.9,

υ = Poisson's ratio of the soil; in the absence of specific information, it is common to assume $\upsilon = 0.3$ giving $k_\upsilon = 0.74$,

M_s = constrained soil modulus (lb/in.^{2}), Table 1 ,

E_L = 50 yr. tensile creep modulus (lb/in.^{2}),

I = moment of inertia of the chamber wall cross-section (in.^{4}/in.),

D = nominal span of chamber (in.), and

h = height of soil cover over the chamber (in.).

NOTE 4—The critical buckling thrust given by Eq 15 is for cylindrical pipe. Corrugated stormwater chambers generally have adequate hoop stiffness that precludes global buckling.

8.6 *Foundation Strength*—Bearing of the chamber foot on the foundation and bearing of the foundation on the subgrade shall be checked versus ultimate bearing capacity. The chamber foot shall be idealized as a rectangular spread footing with load applied to the foundation. The load traveling from the chamber and any concentrated adjacent soil column shall be distributed through the foundation and applied as a spread footing to the subgrade. Calculations for bearing capacity shall be in accordance with AASHTO Section 10 for spread footings, with soil properties determined by a geotechnical engineer (for foundation design example see Appendix X2).

8.7 *Design of End Closures*—Closure pieces at the end of chambers such as end caps or end plates may be molded integrally with the chamber or may be formed as a separate structure. End closures made as separate structures shall be designed to interlock with the end corrugation at either end of a chamber row. An end cap may fit either over or under the end corrugation as long as there is sufficient interlock with the chamber so that the end cap does not collapse into the chamber row after the placement of backfill. End closures, whether integral with, or separate from, the chamber structure, shall be designed using the same engineering principles applied to the chambers.

9. Design Qualification

9.1 *Design Qualification*—The chamber design shall be qualified with full-scale installation testing of representative chambers under design earth and live loads.

9.1.1 Testing shall demonstrate safety against structural failure. Sufficient performance data shall be obtained on which to verify the design calculations.

9.1.2 A minimum of two tests shall be conducted including one sustained earth load test and one live load test (see Appendix X3).

10. Certification

10.1 *Design Certification*—If requested by the purchaser, the chamber manufacturer shall provide certification that the chamber design meets all requirements of this standard and submit test reports, calculations, installation specifications, and drawings showing conformance to this standard.

11. Keywords

11.1 chamber; corrugated; creep; local buckling; stormwater; structural design; thermoplastic

ANNEX

(Mandatory Information)

A1. COMPUTATION OF LIVE LOADS

A1.1 *Live Load Computation*—Live load includes transient loads (passing vehicles) or sustained loads (stationary non-permanent loads). Live load computation is based on the AASHTO HL-93 design vehicular live load applied to a single loaded lane. HL-93 live load is a combination of the design truck or design tandem, whichever is critical, applied with the design lane load.

NOTE A1.1—Thermoplastic chamber structures have a structural response that is dependent on load duration. Chamber structural design should include thermoplastic creep modulus that is consistent with the anticipated duration of live load. For example, the probable maximum duration of parked vehicles over the chambers should be accounted for in selecting the design modulus. Typical values for load duration are as follows: instantaneous (≤ 1 minute) with impact and multiple presence, to account for normal traffic; 1 week with no impact or multiple presence, to account for a vehicle parked over the chamber for a longer duration.

A1.1.1 *Design Truck*—The design truck is based on the AASHTO design truck. The weights and spacing of axles and wheels for the design truck shall be as specified in Fig. A1.1. The design truck has a single 8 kip (kip = 1000 lb) axle followed by two 32 kip axles, spaced 14 ft apart. Wheels on a single axle are spaced 6 ft apart. Wheel loads (*W*) shall be applied uniformly on tire contact areas.

NOTE A1.2—Typical stormwater chamber design will be based on a 32 kip axle, where low cover heights preclude interaction of adjacent axles.

A1.1.2 *Design Tandem*—The design tandem is based on the AASHTO Design Tandem. The weights and spacing of axles and wheels for the design tandem shall be as specified in Fig. A1.2. The design tandem has two 25 kip axles, spaced 4 ft apart. Wheels on a single axle are spaced 6 ft apart. Wheel loads are 12 500 lb on each wheel. Wheel loads (*W*) shall be applied uniformly on tire contact areas.

NOTE A1.3—Construction vehicles that exceed AASHTO design truck or design tandem loads must be evaluated on a case-by-case basis.

A1.1.3 *Design Lane Load*—The design lane load shall be applied as a uniform load of 64 lb/ft^2 occupying the full ground surface above the chamber. The service design lane load shall not be distributed for out-of-plane effects nor shall it be increased or reduced for any other effect.

A1.1.4 *Tire Contact Area (A_c)*—Wheel load shall be applied at the ground surface over tire contact areas. The tire contact area shall be a single rectangle whose width (w_w) is 20 in. and whose length (l_w) is 10 in. as in Figs. A1.1 and A1.2. The tire pressure shall be uniformly distributed over the contact area. The contact area is calculated in Eq A1.1.

$$A_c = w_w l_w \tag{A1.1}$$

where:

A_c = tire contact area = 200 in.^{2},
w_w = tire width = 20 in., and
l_w = tire length = 10 in.

A1.2 *Service Limit State*—Live load calculated in this Annex is used to design for the service limit state. Service live load calculation follows:

A1.2.1 *Multiple Presence Factor (m)*—A factor of 1.2 shall be applied to live load to account for the probability of an overloaded vehicle.

NOTE A1.4—Typical available stormwater chamber classifications have critical live load at low cover heights, where there is negligible interaction between multiple vehicles. A multiple presence factor greater than 1.0 results from statistical calibration of live load on the basis of pairs of vehicles instead of a single vehicle. Therefore, when a single vehicle is present, it can be heavier than each one of a pair of vehicles and still have the same probability of occurrence. It is therefore appropriate to use the multiple presence factor, which accounts for the probability of overloaded design vehicle, for this single-lane load condition.

A1.2.2 *Dynamic Load Allowance (IM)*—The dynamic load allowance shall be taken as in Eq A1.2. The dynamic load allowance shall be included in the magnitude of the service live load for chamber design but shall be excluded from the magnitude of the service live load for design of the chamber foot bearing and for all other foundation design.

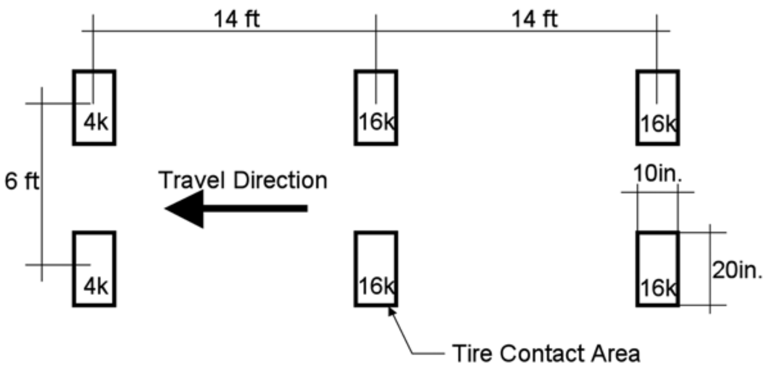


FIG. A1.1 Characteristics of Design Truck and Design Tire Contact Area

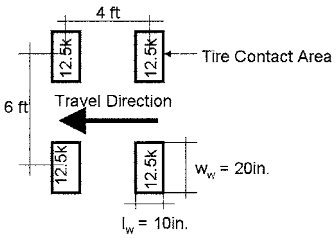


FIG. A1.2 Characteristics of Design Tandem

$$IM = 33\left(1.0 - 0.125\frac{h}{12}\right) \geq 0\,\% \qquad (A1.2)$$

where:

IM = dynamic load allowance, $0 \leq IM \leq 33\,\%$ (%), and
h = height of soil cover over the chamber (in.).

A1.2.3 *Live Load (LL)*—Live load shall include the critical design vehicle (truck or tandem) applied simultaneously with the design lane load as provided conceptually in Eq A1.3. The live load due to the design truck or design tandem shall be as calculated in Eq A1.4. The truck or tandem live load shall be applied uniformly on the tire contact area or the live load patch area. The design lane load shall be as provided in Eq A1.5. The lane load shall be applied as a uniform surface pressure.

$$LL = LL_t + LL_l \qquad (A1.3)$$

$$LL_t = W * m * \left(1 + \frac{IM}{100}\right) \qquad (A1.4)$$

$$LL_l = 64 \text{ lb/ft}^2 \qquad (A1.5)$$

where:

LL = total service live load, incl. surface pressure (lb/ft^2) and patch load (lb),
LL_t = service live load due to the design truck or tandem (lb),
LL_l = service lane load (lb/ft^2),
W = wheel load from design truck or design tandem (lb), and
m = multiple presence factor (see A1.2.1).

A1.3 *Safety Against Structural Failure*—Factored live load effects are used to design for safety against structural failure. Service live load shall be applied in design models of the chamber and resultant internal force effects of axial thrust and bending moment shall be factored by the live load factor and used to design for safety against structural failure. The Live Load Factor, γ_{LL}, shall be 1.75.

A1.3.1 *Live Load Distribution Factor (LLDF)*—Where the cover height is less than 1.5 ft, the effect of the cover on distribution of live load shall be neglected. Where the cover height exceeds 1.5 ft, live load shall be distributed over the cover height using a live load distribution factor. Wheel loads shall be uniformly distributed over a rectangular live load patch area with sides equal to the dimension of the tire contact area increased by the live load distribution factor times the cover height. Where such areas from several wheels overlap, the total load shall be uniformly distributed over the live load patch area. The *LLDF* for select granular fill is 1.15. For the specific application of two-dimensional finite element models for chamber design, the live load magnitudes shall be reduced only for the out-of-plane distribution (Fig. A1.3) in Eq A1.6.

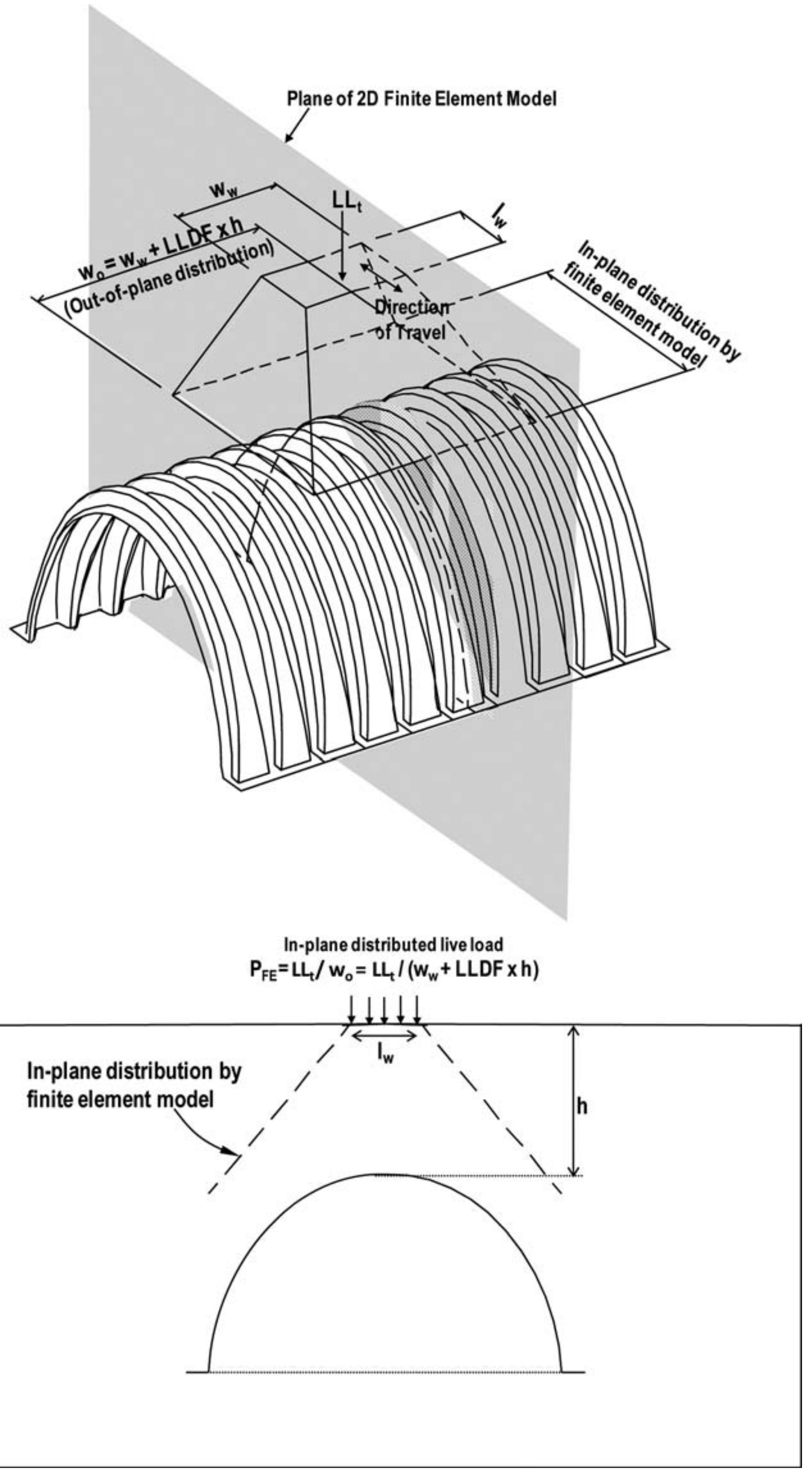
$$w_o = w_w + LLDF * h \qquad (A1.6)$$

The resulting live load is a line load given by:

$$P_{FE} = \frac{LL_t}{w_o} \qquad (A1.7)$$

which shall be applied as distributed or point loads at the ground surface (Fig. A1.3).

NOTE A1.5—Example for 2D FEA with 3 ft (36 in.) cover height: At 0 ft of cover, a typical load is 16 000 lb / 20 in. = 800 lb across a 10 in. in-plane tire length. In a 2D FEA model with 3 ft of cover, the live load patch length would grow from 20 in. to 61.4 in. (20 in. + 1.15*36 in. = 61.4 in.) over the cover height. To account for this in the model, the live load magnitude applied at the ground surface, which would spread over the patch length in a true 3D application, is reduced to 16 000 lb / 61.4 in. = 260 lb across the 10 in. in-plane length.



NOTE 1—Single wheel refers to half an axle. The figure assumes no interaction between wheels in an axle and wheels from different axles.

FIG. A1.3 Live Load Distribution for a Single Wheel in Two-Dimensional Finite Element Model

APPENDIXES

(Nonmandatory Information)

X1. EXAMPLE DESIGN USING 2-D FINITE ELEMENT ANALYSIS

X1.1 *Given Information*:

X1.1.1 *Installation Description*—Consider a buried storm water chamber with 3 ft of cover. Two live load durations are considered: a short term case that simulates a design truck driving over the chamber, and a 1 week live load application that simulates a design truck parked over the chamber for a duration of 1 week. The chamber short term creep modulus (≤ 1 minute) is 125 ksi, and the 1 week modulus is 70 ksi, reduced from 125 ksi to account for creep effects. The magnitude of the short term wheel load is determined using the AASHTO approach, including impact and multiple presence factors. The magnitude of the 1 week wheel load is determined without adjusting for impact and multiple presence, since the 1 week load represents a parked vehicle that would not have dynamic effects, with a low probability of overloaded parked vehicles for a 1 week duration over a typical chamber installation. The wheel loads are applied over the crown and shoulder in separate analyses. The chamber long term creep modulus (50 yr) is 25 ksi.

NOTE X1.1—Evaluation of live load over the chamber shoulder provides an example of the effects of eccentric load application, which for some chambers may be the limiting design condition.

X1.1.2 *Chamber Geometry and Material Properties*—Chamber geometry and material properties for this example problem are constant throughout the chamber and are given in Table X1.1. The corrugation design and the corresponding section properties for actual chambers vary to accomplish other objectives such as increased compressive strength in the lower parts of the chamber and stacking of chambers for shipping.

X1.1.3 *Soil Layers and Properties* —Consider soil layers with the material properties shown in Table X1.2. The Duncan/Selig soil model description can be found in the CANDE user manual. AASHTO SN soil designations referenced in the body of the standard are identical to Duncan/Selig SW soil designations used here, such that an SW95 soil in Duncan/Selig is equivalent to an SN95 soil in AASHTO.

X1.1.4 *Live Load*—The short term wheel load is evaluated as described in Annex A. Single wheel load on a two-dimensional finite element model is:

$$P_{FE} = \frac{W \cdot m \cdot \left(1 + \frac{IM}{100}\right)}{w_w + LLDF \cdot h} = 377 \text{ lb/in.} \qquad (X1.1)$$

where:

W = design wheel load = 16 000 lb,
w_w = wheel width = 20 in.,
IM = dynamic load allowance = $33\left(1.0 - 0.125\frac{36}{12}\right) = 20.6\,\%$,
m = multiple-presence factor = 1.2, and
$LLDF$ = live load distribution factor = 1.15 (select granular embedment and backfill).
h = soil cover ht.= 36 in..

NOTE X1.2—The magnitude of the 1 week wheel load is found with a similar procedure, setting IM = 0 and m = 1.0.

TABLE X1.1 Chamber Geometry and Material Properties

Property	Value
Cross Section Area	0.28 in.^{2}/in.
Moment of Inertia	0.35 in.^{4}/in.
Short Term Creep Modulus	125 ksi
1 Week Creep Modulus	70 ksi
Long Term Creep Modulus	25 ksi
Poisson's ratio	0.35

X1.2 *Finite Element Analysis*:

X1.2.1 *Two-Dimensional Finite Element Model*—A plane strain finite element model is constructed using the program CandeCAD PRO (Fig. X1.1). Adjacent rows of chambers are spaced at 6 in. clear spacing between chamber feet. Point loads representing the wheel load are applied at nodes over the length of the wheel. Lane load is distributed over the length of the model.

NOTE X1.3—Axial thrusts and bending moments are evaluated for the center chamber.

X1.2.2 *Analysis*—To account for strains due to the multiple load durations, three finite element models are constructed. The first model determines the strains due to the long-term (dead load) component, with no live load applied, using the long term creep modulus for the chamber beam elements. The second model determines the strains due to the short term live load, with the short term wheel load applied at the crown of the center chamber (first case) and shoulder of the center chamber (second case), using the short term creep modulus for the chamber beam elements. The third model determines the strains due to the 1 week live load, with the 1 week wheel load applied at the chamber crown (first case) and chamber shoulder (second case), using the 1 week creep modulus for the chamber beam elements. The chamber creep moduli for the three models are shown in Table X1.1.

X1.2.3 *Results*—The element axial thrusts and bending moments are tabulated in Table X1.3 (long term and short term results) and Table X1.4 (long term and 1 week results).

X1.3 *Strength Analysis*:

X1.3.1 *Local Buckling Analysis*—For simplicity, we show here the structural adequacy calculation for local buckling at the critical sections, due to axial thrust only and due to combined axial thrust and bending moment conditions, for a short term wheel load positioned over the crown (first case) and over the shoulder (second case). The final structural adequacy is the minimum of all the calculated adequacies.

X1.3.2 *Idealized Geometric Properties*—The elements shown in Fig. X1.2 represent the idealized typical chamber

TABLE X1.2 Material Properties of Soil Layers

Soil Layer	Constitutive Model	Young's Modulus (psi)	Poisson's Ratio	CANDE Soil Type	Constrained Modulus (psi)
Embedment	Duncan/Selig Modified Hyperbolic	–	–	SW95	1500
Foundation	Duncan/Selig Modified Hyperbolic	–	–	SW95	1500
Subgrade	Linear Elastic	3000	0.35	–	–

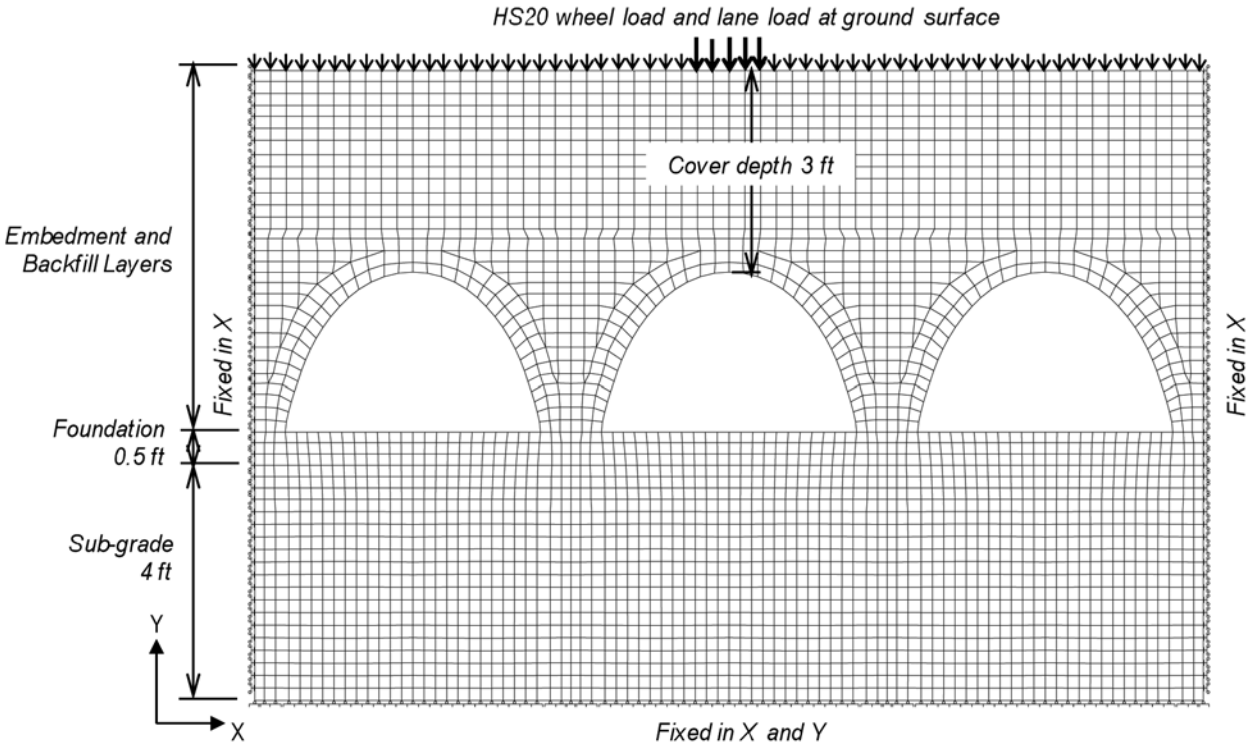


FIG. X1.1 CandeCAD PRO Finite Element Model

section. The idealized geometric properties are matched against the physical section's geometric properties so that the difference is less than 5 %. The widths and thicknesses of the idealized elements are presented in Table X1.5. The section properties are calculated as shown in Fig. X1.3 and Fig. X1.4.

X1.3.3 *Structural Adequacy Due to Axial Thrust Only*—For axial thrust only, the critical structural adequacies occur due to short term loading at beam element numbers 1 (or 36) and 36, due to short term wheel loads at the crown and shoulder, respectively. The controlling beam elements were found according to the procedure outlined in the following sections, considering the thrusts and moments computed from all loading cases for all of the beam elements. The procedure is presented here for only the controlling elements with the controlling load cases. The finite element results from Table X1.3 are summarized in Table X1.6 for the controlling elements. The factored hoop compression strain due to axial thrust is calculated as shown in Table X1.7. Using the total factored hoop compression strain ε_c, the slenderness and effective width factors due to axial thrust only are calculated and tabulated in Table X1.8. The structural adequacies due to axial thrust only are calculated as shown in Table X1.9.

X1.3.4 *Combined Thrust and Moment*—The effective area needs to be computed due to factored compression strain from combined axial thrust and bending moment. Following a similar procedure to the thrust only case, the minimum structural adequacies due to combined axial thrust and bending moment were found to occur in beam element number 3 (or 34) and beam element number 35, due to short term wheel loads at the crown and shoulder, respectively. The procedure is presented here for only the controlling elements and controlling load cases. These calculations need to be performed on all elements to determine which elements control. The finite element results from Table X1.3 are summarized in Table X1.10 for the controlling elements. The factored axial thrust and bending moments, and thrust strains, at these beam elements are calculated in Table X1.11. The factored compression strains due to bending and combined thrust and bending at the valley and crest are calculated as shown in Table X1.12. Using the total factored compression strains $\varepsilon_{c,valley}$ and $\varepsilon_{c,crest}$, the slenderness and effective width factors are recalculated and tabulated in Table X1.13. Only the effective area at the crest is shown since the strain due to bending at the crest is compressive, in addition to the compressive strain due to the

TABLE X1.3 Finite Element Analysis Results: Long Term and Short Term

		Long Term Results				Short Term Results			
		Dead Load (E = 25 ksi)		Dead Load (E = 125 ksi)		Dead + Live Loads (E = 125 ksi)			
Beam Element Location	Beam Element No.					Wheel Load at Crown		Wheel Load at Shoulder	
		Thrust[A]	Moment[B]	Thrust[A]	Moment[B]	Thrust[A]	Moment[B]	Thrust[A]	Moment[B]
Base	1	35.3	-0.6	56.5	-2.5	124.5	-4.8	115.5	-4.6
	2	33.3	-2.3	57.0	-6.5	133.5	-11.9	124.5	-11.6
	3	30.7	-3.4	56.7	-7.9	142.0	-13.6	133.0	-13.5
	4	28.4	-3.3	55.6	-7.5	146.5	-10.9	137.5	-11.1
⅓ Height	5	26.6	-3.1	54.1	-7.0	148.5	-7.8	140.0	-8.1
	6	25.2	-1.8	52.5	-4.3	149.0	1.9	141.0	0.7
	7	24.1	0.0	50.7	-0.3	148.0	16.2	140.5	13.2
	8	22.8	0.8	48.6	2.0	145.0	26.1	138.5	21.1
	9	21.3	1.3	46.0	3.4	140.0	32.3	135.0	25.4
⅔ Height	10	19.7	1.3	42.9	3.4	132.5	34.3	130.0	26.7
	11	17.8	1.1	39.4	2.5	123.0	33.3	123.5	26.8
	12	15.6	0.8	35.5	1.6	112.0	28.8	115.5	26.2
	13	13.5	0.7	31.5	1.2	99.0	22.1	106.0	26.4
	14	11.2	0.5	27.5	0.4	84.0	10.1	94.5	23.8
	15	8.6	-0.3	23.3	-1.8	67.2	-11.1	80.4	12.3
	16	5.8	-1.4	19.3	-4.5	49.7	-36.3	64.6	-6.7
	17	3.5	-2.7	16.1	-6.7	34.5	-57.5	48.6	-29.1
Crown	18	2.2	-3.5	14.4	-8.1	25.3	-68.4	34.7	-48.8
Crown	19	2.2	-3.5	14.4	-8.1	25.3	-68.4	26.5	-60.1
	20	3.5	-2.7	16.1	-6.7	34.5	-57.5	26.7	-62.4
	21	5.8	-1.4	19.3	-4.5	49.7	-36.3	35.5	-55.4
	22	8.6	-0.3	23.3	-1.8	67.2	-11.1	49.9	-38.5
	23	11.2	0.5	27.5	0.4	84.0	10.1	66.3	-17.3
	24	13.5	0.7	31.5	1.2	99.0	22.1	82.3	0.2
	25	15.6	0.8	35.5	1.6	112.0	28.8	97.0	14.6
	26	17.8	1.1	39.4	2.5	123.0	33.3	111.0	26.5
⅔ Height	27	19.7	1.3	42.9	3.4	132.5	34.3	123.0	32.7
	28	21.3	1.3	46.0	3.4	140.0	32.3	132.5	33.2
	29	22.8	0.8	48.6	2.0	145.0	26.1	140.0	27.8
	30	24.1	0.0	50.7	-0.3	148.0	16.2	144.5	17.8
	31	25.2	-1.8	52.5	-4.3	149.0	1.9	147.0	3.5
⅓ Height	32	26.6	-3.1	54.1	-7.0	148.5	-7.8	148.0	-6.0
	33	28.4	-3.3	55.6	-7.5	146.5	-10.9	147.5	-9.0
	34	30.7	-3.4	56.7	-7.9	142.0	-13.6	144.5	-11.8
	35	33.3	-2.3	57.0	-6.5	133.5	-11.9	137.0	-11.0
Base	36	35.3	-0.6	56.5	-2.5	124.5	-4.8	128.5	-4.6

[A] Units: lb/in. Positive for compression axial thrust.

[B] Units: lb/in.-in. Negative bending moment for tension inside the chamber.

axial thrust. Using the new effective areas, the structural adequacies due to combined axial thrust and bending moment are calculated as shown in Table X1.14. The structural adequacies are summarized in Table X1.15. A controlling structural adequacy ≥ 1.0 means the section meets design requirements.

X1.4 *Global Buckling Analysis*—A global buckling analysis is performed according to 8.5.

X1.4.1 *Given Information*—Relevant properties for the chamber and soil are presented below:

Chamber Span, D	55 in.
Chamber Wall Moment of Inertia, I	0.35 in.^{4}/in.
Chamber Long Term Creep Modulus, E_L	25 ksi
Cover Depth to Top of Chamber, h	36 in.
Soil Constrained Young's Modulus, M_s	1.5 ksi
Soil Poisson's Ratio, v	0.3

X1.4.2 *Critical Buckling Thrust*—Critical buckling thrust, T_{CR}, is calculated according to 8.5.2, with:

$$T_{CR} = \frac{1.2C_n(E_L I)^{0.33}(\varphi_s M_s k_\upsilon)^{0.67}R_h}{FS} \quad (X1.2)$$

where:

$$k_v = \frac{(1+\upsilon)(1-2\upsilon)}{1-\upsilon} = \frac{(1+0.3)(1-2*0.3)}{(1-0.3)} = 0.74\text{, and}$$

$$R_h = \frac{11.4}{(11+D/h)} = \frac{11.4}{11+55/36} = 0.91\text{, giving}$$

$$T_{CR} = \frac{1.2C_n(E_L I)^{0.33}(\varphi_s M_s k_\upsilon)^{0.67}R_h}{FS}$$

$$= \frac{1.2*0.55(25\,000*0.35)^{0.33}(0.9*1500*0.74)^{0.67}*0.91}{2.5}$$

$$T_{CR} = 491\text{ lb/in.}$$

X1.4.3 *Chamber Peak Axial Thrust*—The peak axial thrust is determined for a chamber beam element from the finite element analysis results, considering all loading cases. The peak axial thrust for the chamber was found to occur in Beam Element 6, for the live load case with the short term wheel load applied at the crown. The calculation is presented here for this beam element, but needs to be performed for all beam elements for each live load case to determine which beam element

TABLE X1.4 Finite Element Analysis Results: Long Term and 1 Week

Beam Element Location	Beam Element No.	Long Term Results		1 Week Results					
		Dead Load (E = 25 ksi)		Dead Load (E = 70 ksi)		Dead + Live Loads (E = 70 ksi)			
						Wheel Load at Crown		Wheel Load at Shoulder	
		Thrust[A]	Moment[B]	Thrust[A]	Moment[B]	Thrust[A]	Moment[B]	Thrust[A]	Moment[B]
Base	1	35.3	-0.6	49.9	-1.4	90.7	-2.6	85.1	-2.7
	2	33.3	-2.3	49.2	-4.2	95.9	-6.9	90.2	-7.2
	3	30.7	-3.4	47.8	-5.6	100.0	-8.8	94.3	-9.0
	4	28.4	-3.3	46.2	-5.4	101.5	-8.2	95.8	-8.3
⅓ Height	5	26.6	-3.1	44.5	-5.1	101.5	-7.4	96.1	-7.2
	6	25.2	-1.8	42.8	-3.1	100.5	-2.1	95.7	-2.0
	7	24.1	0.0	41.2	-0.1	99.1	6.3	94.7	5.8
	8	22.8	0.8	39.2	1.6	96.4	11.6	92.5	10.3
	9	21.3	1.3	36.9	2.5	92.2	14.5	89.2	12.5
⅔ Height	10	19.7	1.3	34.2	2.5	86.5	14.8	84.7	12.4
	11	17.8	1.1	31.2	1.9	79.2	13.7	79.1	11.5
	12	15.6	0.8	27.8	1.3	70.6	11.4	72.4	10.4
	13	13.5	0.7	24.3	1.1	61.0	8.8	64.9	10.2
	14	11.2	0.5	20.8	0.6	50.0	4.1	56.1	8.8
	15	8.6	-0.3	16.9	-1.1	37.4	-5.2	45.5	3.3
	16	5.8	-1.4	13.2	-3.2	24.5	-16.3	33.7	-5.5
	17	3.5	-2.7	10.1	-5.1	13.5	-25.2	22.1	-15.2
Crown	18	2.2	-3.5	8.4	-6.2	6.9	-29.3	12.6	-22.7
Crown	19	2.2	-3.5	8.4	-6.2	6.9	-29.3	7.8	-26.2
	20	3.5	-2.7	10.1	-5.1	13.5	-25.2	9.1	-26.5
	21	5.8	-1.4	13.2	-3.2	24.5	-16.3	16.3	-23.1
	22	8.6	-0.3	16.9	-1.1	37.4	-5.2	27.4	-15.3
	23	11.2	0.5	20.8	0.6	50.0	4.1	39.7	-5.8
	24	13.5	0.7	24.3	1.1	61.0	8.8	51.5	1.3
	25	15.6	0.8	27.8	1.3	70.6	11.4	62.5	6.7
	26	17.8	1.1	31.2	1.9	79.2	13.7	72.7	11.4
⅔ Height	27	19.7	1.3	34.2	2.5	86.5	14.8	81.5	14.1
	28	21.3	1.3	36.9	2.5	92.2	14.5	88.5	14.2
	29	22.8	0.8	39.2	1.6	96.4	11.6	93.8	11.3
	30	24.1	0.0	41.2	-0.1	99.1	6.3	97.4	5.9
	31	25.2	-1.8	42.8	-3.1	100.5	-2.1	99.9	-2.4
⅓ Height	32	26.6	-3.1	44.5	-5.1	101.5	-7.4	101.5	-7.4
	33	28.4	-3.3	46.2	-5.4	101.5	-8.2	102.0	-7.6
	34	30.7	-3.4	47.8	-5.6	100.0	-8.8	101.5	-7.7
	35	33.3	-2.3	49.2	-4.2	95.9	-6.9	98.5	-5.8
Base	36	35.3	-0.6	49.9	-1.4	90.7	-2.6	93.8	-2.1

[A] Units: lb/in. Positive for compression axial thrust.

[B] Units: lb/in.-in. Negative bending moment for tension inside the chamber.

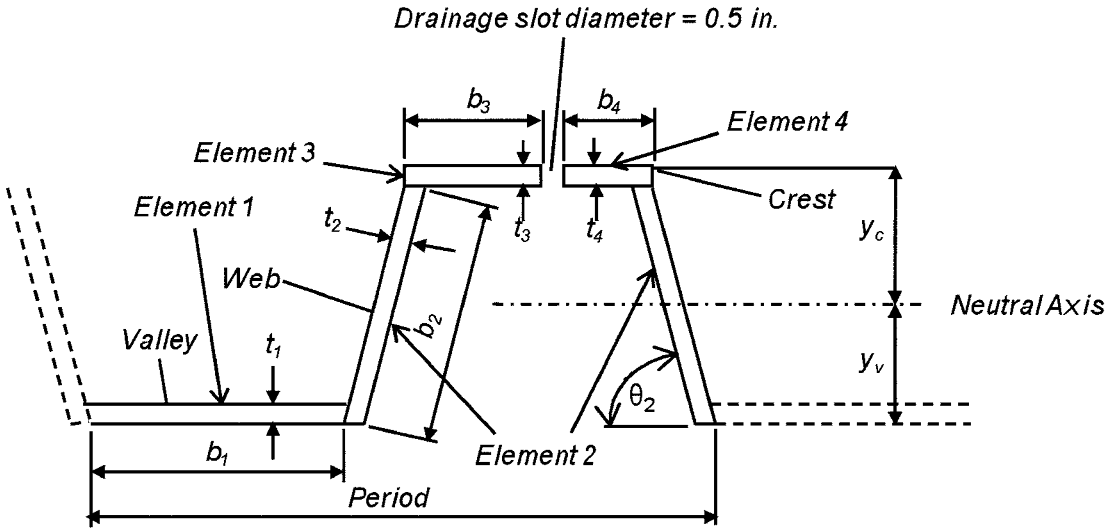


FIG. X1.2 Typical Chamber Section Elements

TABLE X1.5 Chamber Section Element Dimensions, Including Drainage Slot

Element No., i	Element Width, w_i (in.)	Element Thickness, t_i (in.)	Edge Support Coefficient, k_i	Angle with respect to Horizontal, θ_i (degrees)
1	4.000	0.180	4.00	–
2	2.523	0.180	4.00	85.0
3	1.495	0.180	0.43	–
4	0.945	0.180	0.43	–

controls. The peak axial thrust is determined as the greatest axial thrust found according to Eq 14.

$$T = \gamma_{DL\max} T_{DL} + \gamma_{LL} T_{LL} = \gamma_{DL\max}\left(T_{dead.long}\right) + \gamma_{LL}\left(T_{(dead+live).short} - T_{dead.short}\right)$$

$$T = 1.95(25.2) + 1.75(149.0 - 52.5) = 218 \text{ lb/in.}$$

X1.4.4 *Global Buckling Adequacy*—The global buckling adequacy is found as the ratio of the critical buckling thrust to the chamber peak axial thrust according to Eq 13. A global buckling adequacy greater than 1.0 provides design factor of safety in global buckling.

$$\frac{T_{CR}}{T} = \frac{491}{218} = 2.25 \geq 1.0$$

Chamber element dimensions

Index for defining the four section elements..... $i := 1 .. 4$

Element Number: $i =$	Total Width: $b_i :=$	Element Thickness: $t_i :=$	Number of elements per period: $n_i :=$
1	$4.000 \cdot in$	$0.180 \cdot in$	1
2	$2.703 \cdot in$	$0.180 \cdot in$	2
3	$1.675 \cdot in$	$0.180 \cdot in$	1
4	$1.125 \cdot in$	$0.180 \cdot in$	1

Effective Buckling Width Formulas:

$w_1 := b_1 \qquad w_2 := b_2 - t_1$

$w_3 := b_3 - t_2 \qquad w_4 := b_4 - t_2$

Width of slot.. $l_{slot} := 0.5 \cdot in$

Effective Width: $w_i =$ ($\cdot in$)	Eff. Width / Thickness: $w_i \cdot (t_i)^{-1} =$
4.000	22.222
2.523	14.017
1.495	8.306
0.945	5.250

Base angle.. $\boxed{\theta_2 := 85 \cdot deg}$

Period of the corrugations.. $\text{Period} := b_1 \cdot n_1 + \cos(\theta_2) \cdot b_2 \cdot n_2 + b_3 \cdot n_3 + l_{slot} + b_4 \cdot n_4$

$\boxed{\text{Period} = 7.7712 \cdot in}$

Area of Element 1... $A_1 := b_1 \cdot t_1$ $\qquad A_1 = 0.720 \cdot in^2$

Area of Element 2... $A_2 := b_2 \cdot t_2$ $\qquad A_2 = 0.487 \cdot in^2$

Area of Element 3... $A_3 := b_3 \cdot t_3$ $\qquad A_3 = 0.301 \cdot in^2$

Area of Element 4... $A_4 := b_4 \cdot t_4$ $\qquad A_4 = 0.203 \cdot in^2$

Gross area of 1 period of idealized geometry............... $A_g := A_1 \cdot n_1 + A_2 \cdot n_2 + A_3 \cdot n_3 + A_4 \cdot n_4$ $\qquad A_g = 2.197 \cdot in^2$

Unit area of idealized geometry.................................... $A_I := \dfrac{A_g}{\text{Period}}$ $\qquad \boxed{A_I = 0.2827 \cdot \dfrac{in^2}{in}}$

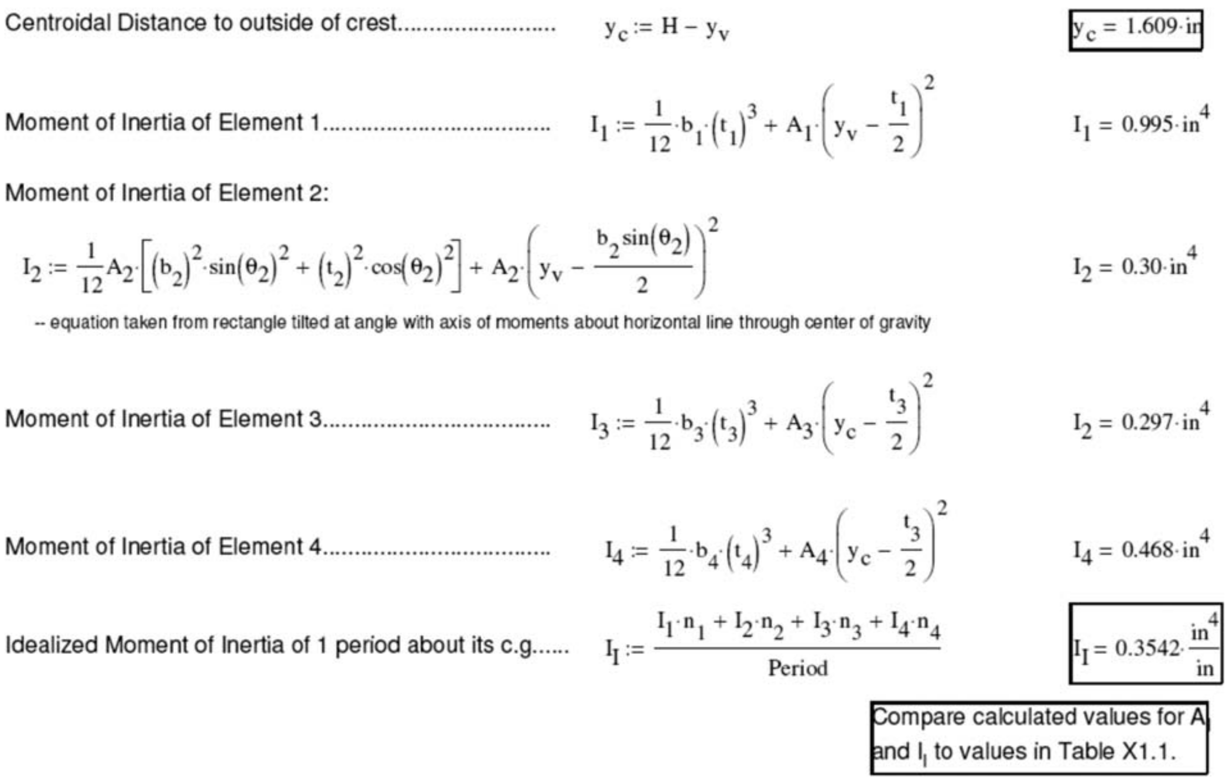
Section Moment of Inertia and Centroid Calculation

Height of section... $H := b_2 \cdot \sin(\theta_2) + t_1$ $\qquad H = 2.873 \cdot in$

Centroidal Distance from base of valley:

$$y_v := \frac{1}{A_g} \left[A_1 \cdot n_1 \cdot \frac{t_1}{2} + A_2 \cdot n_2 \cdot \frac{b_2 \cdot \sin(\theta_2)}{2} \ldots \atop + A_3 \cdot n_3 \cdot \left(H - \frac{t_3}{2} \right) + A_4 \cdot n_4 \cdot \left(H - \frac{t_4}{2} \right) \right] \qquad \boxed{y_v = 1.264 \cdot in}$$

FIG. X1.3



Centroidal Distance to outside of crest........................ $y_c := H - y_v$ $\boxed{y_c = 1.609 \cdot in}$

Moment of Inertia of Element 1.................................... $I_1 := \frac{1}{12} \cdot b_1 \cdot (t_1)^3 + A_1 \cdot \left(y_v - \frac{t_1}{2}\right)^2$ $I_1 = 0.995 \cdot in^4$

Moment of Inertia of Element 2:

$$I_2 := \frac{1}{12} A_2 \cdot \left[(b_2)^2 \cdot \sin(\theta_2)^2 + (t_2)^2 \cdot \cos(\theta_2)^2\right] + A_2 \cdot \left(y_v - \frac{b_2 \sin(\theta_2)}{2}\right)^2 \qquad I_2 = 0.30 \cdot in^4$$

-- equation taken from rectangle tilted at angle with axis of moments about horizontal line through center of gravity

Moment of Inertia of Element 3.................................... $I_3 := \frac{1}{12} \cdot b_3 \cdot (t_3)^3 + A_3 \cdot \left(y_c - \frac{t_3}{2}\right)^2$ $I_2 = 0.297 \cdot in^4$

Moment of Inertia of Element 4.................................... $I_4 := \frac{1}{12} \cdot b_4 \cdot (t_4)^3 + A_4 \cdot \left(y_c - \frac{t_3}{2}\right)^2$ $I_4 = 0.468 \cdot in^4$

Idealized Moment of Inertia of 1 period about its c.g...... $I_I := \frac{I_1 \cdot n_1 + I_2 \cdot n_2 + I_3 \cdot n_3 + I_4 \cdot n_4}{Period}$ $\boxed{I_I = 0.3542 \cdot \frac{in^4}{in}}$

Compare calculated values for A_I and I_I to values in Table X1.1.

FIG. X1.4

TABLE X1.6 Finite Element Analysis Results for Structural Adequacy Calculation due to Axial Thrust Only

Location of Wheel Load	Wheel Load at Crown	Wheel Load at Shoulder
Beam Element No.	1 (or 36)	36
a) Dead Load Only (Long Term Creep Modulus = 25 ksi):		
Axial thrust, $T_{dead.long}$ (lb/in.)	35.3	35.3
b) Dead Load Only (Short Term Creep Modulus = 125 ksi):		
Axial thrust, $T_{dead.short}$ (lb/in.)	56.5	56.5
c) Dead and Live Loads (Short Term Creep Modulus = 125 ksi):		
Axial thrust, $T_{(dead+live)short}$ (lb/in.)	124.5	128.5

TABLE X1.7 Calculation of Factored Hoop Compression Strain due to Axial Thrust Only

Calculation of Factored Hoop Compression Strain	Wheel Load Position	
	At Crown	At Shoulder
Beam Element No.	1 (or 36)	36
Short term load component only:		
Factored axial thrust, $T_{short} = \gamma_{LL} (T_{(dead+live)short} - T_{dead.short})$ (lb/in.)	119.0	126.0
Factored hoop compression strain, $\varepsilon_{c.short} = \frac{T_{short}}{E_{short} A_I}$ (in./in.)	3.366E-3	3.564E-3
Long term load component only:		
Factored axial thrust, $T_{long} = \gamma_{DL}(T_{dead.long})$ (lb/in.)	68.6	68.8
Factored hoop compression strain, $\varepsilon_{c.long} = \frac{T_{long}}{E_{long} A_I}$ (in./in.)	9.733E-3	9.733E-3
Total factored hoop compression strain, $\varepsilon_c = \varepsilon_{c.long} + \varepsilon_{c.short}$ (in./in.)	1.310E-2	1.330E-2

TABLE X1.8 Slenderness and Effective Width Factors due to Axial Thrust Only

Wheel Load Position	Beam Element	Slenderness Factor (Eq 5)		Effective Width Factor (Eq 4)		Number of Elements per Period		Effective Area (Eq 6) due to Axial Thrust Only (in.^{2}/in.)
Crown	1 (or 36)	λ_1	1.2717	ρ_1	0.6503	n_1	1	0.2211
		λ_2	0.8021	ρ_2	0.9048	n_2	2	
		λ_3	1.4496	ρ_3	0.5851	n_3	1	
		λ_4	0.9163	ρ_4	0.8293	n_4	1	
Shoulder	35	λ_1	1.2813	ρ_1	0.6465	n_1	1	0.2200
		λ_2	0.8082	ρ_2	0.9005	n_2	2	
		λ_3	1.4605	ρ_3	0.5815	n_3	1	
		λ_4	0.9232	ρ_4	0.8251	n_4	1	

TABLE X1.9 Calculation of Structural Adequacies due to Axial Thrust Only

Calculation of Factored Hoop Compression Strain	Wheel Load Position	
	At Crown	At Shoulder
Beam Element No.	1 (or 36)	36
Hoop compression strain due to short term load component only: $\varepsilon_{short} = T_{short}/(E_{short}A_{eff})$ (in./in.)	4.305E-3	4.580E-3
Hoop compression strain due to long term load component only: $\varepsilon_{long} = T_{long}/(E_{long}A_{eff})$ (in./in.)	1.245E-2	1.251E-2
Total hoop compression strain, $\varepsilon_{Tf} = \varepsilon_{short} + \varepsilon_{long}$ (in./in.)	1.675E-2	1.709E-2
Specified limiting compression strain, ε_{cy} (in./in.)^A	3.300E-2	3.300E-2
Adequacy due to thrust only (Eq 9)	1.97	1.93

^{A} Limiting compression strain should be appropriately determined from compression tests.

TABLE X1.10 Finite Element Results for Structural Adequacy Calculation due to Combined Axial Thrust and Bending

Location of Wheel Load	Wheel Load at Crown	Wheel Load at Shoulder
Beam Element No.	3 (or 34)	35
a) Dead Load Only (Long Term Creep Modulus):		
Axial thrust, $T_{dead.long}$ (lb/in.)	30.7	33.3
Bending moment, $M_{dead.long}$ (lb-in./in.)	3.4	2.3
b) Dead Load Only (Short Term Creep Modulus):		
Axial thrust, $T_{dead.short}$ (lb/in.)	56.7	57.0
Bending moment, $M_{dead.short}$ (lb-in./in.)	7.9	6.5
c) Dead and Live Loads (Short Term Creep Modulus):		
Axial thrust, $T_{(dead+live)short}$ (lb/in.)	142.0	137.0
Bending moment, $M_{(dead+live)short}$ (lb-in./in.)	13.6	11.0

TABLE X1.11 Calculation of Factored Hoop Compression Strain due to Combined Axial Thrust and Bending–Forces and Thrust Strains

Calculation of Factored Hoop Compression Strain	Wheel Load Position	
	At Crown	At Shoulder
Beam Element No.	3 (or 34)	35
Short term load component only:		
Factored axial thrust, $T_{short} = \gamma_{LL}\,(T_{(dead+live)short} - T_{dead.short})$ (lb/in.)	149.4	140.1
Factored bending moment, $M_{short} = \gamma_{LL}\,(M_{(dead+live)short} - M_{dead.short})$ (lb-in./in.)	9.8	7.9
Factored hoop compression strain, $\varepsilon_{c.short} = \frac{T_{short}}{E_{short}A_l}$ (in./in.)	4.227E-3	3.964E-3
Long term load component only:		
Factored axial thrust, $T_{long} = \gamma_{DL}\,(T_{dead.long})$ (lb/in.)	59.8	64.9
Factored bending moment, $M_{long} = \gamma_{DL}\,(M_{dead.long})$ (lb-in./in.)	6.7	4.5
Factored hoop compression strain, $\varepsilon_{c.long} = \frac{T_{long}}{E_{long}A_l}$ (in./in.)	8.464E-3	9.188E-3
Total factored hoop compression strain, $\varepsilon_c = \varepsilon_{c.long} + \varepsilon_{c.short}$ (in./in.)	1.269E-2	1.315E-2

TABLE X1.12 Calculation of Factored Compression Strain due to Combined Thrust and Bending at Valley and Crest–Bending and Combined Strains

Calculation of Factored Hoop Compression Strain (Positive sign for compression strain)	Wheel Load Position	
	At Crown	At Shoulder
Beam Element No.	3 (or 34)	35
Strain at valley outer fiber due to short term loading, $\varepsilon_{valley.short} = \frac{M_{short}y_V}{E_{short}I_l}$ (in./in.)	-2.808E-04	-2.266E-04
Strain at crest outer fiber due to short term loading, $\varepsilon_{crest.short} = \frac{M_{short}y_C}{E_{short}I_l}$ (in./in.)	3.574E-04	2.884E-04
Strain at valley outer fiber due to long term loading, $\varepsilon_{valley.long} = \frac{M_{long}y_V}{E_{long}I_l}$ (in./in.)	-9.554E-04	-6.472E-04
Strain at crest outer fiber due to long term loading, $\varepsilon_{crest.long} = \frac{M_{long}y_C}{E_{long}I_l}$ (in./in.)	1.216E-03	8.238E-04
Strain due to bending at valley, $\varepsilon_{valley} = \varepsilon_{valley.short} + \varepsilon_{valley.long}$ (in./in.)	-1.236E-03	-8.737E-04
Strain due to bending at crest, $\varepsilon_{crest} = \varepsilon_{crest.short} + \varepsilon_{crest.long}$ (in./in.)	1.574E-03	1.112E-03
Total factored compression strain at valley, $\varepsilon_{c.valley} = \varepsilon_c + \varepsilon_{valley}$ (in./in.)	1.145E-02	1.228E-02
Total factored compression strain at crest, $\varepsilon_{c.crest} = \varepsilon_c + \varepsilon_{crest}$ (in./in.)	1.426E-02	1.426E-02

TABLE X1.13 Slenderness and Effective Width Factors due to Combined Axial Thrust and Bending

Wheel Load Position	Beam Element	Slenderness Factor (Eq 5)		Effective Width Factor (Eq 4)		Number of Elements per Period		Effective Area (Eq 6) due to Combined Axial Thrust and Bending Moment (in.^{2}/in.)
Crown	3 (or 34)	λ_1	1.3270	ρ_1	0.6288	n_1	1	0.2150
	At crest	λ_2	0.8370	ρ_2	0.8809	n_2	2	
	of	λ_3	1.5127	ρ_3	0.5651	n_3	1	
	section	λ_4	0.9562	ρ_4	0.8054	n_4	1	
Shoulder	35	λ_1	1.3270	ρ_1	0.6286	n_1	1	0.2150
	At crest	λ_2	0.8370	ρ_2	0.8807	n_2	2	
	of	λ_3	1.5127	ρ_3	0.5649	n_3	1	
	section	λ_4	0.9562	ρ_4	0.8052	n_4	1	

TABLE X1.14 Calculation of Structural Adequacies due to Combined Axial Thrust and Bending

Calculation of Factored Hoop Compression Strain	Wheel Load Position	
	At Crown	At Shoulder
Beam Element No.	3 (or 34)	35
Hoop compression strain due to short term load component only: $\varepsilon_{short} = T_{short}/(E_{short}A_{eff.TM})$ (in./in.)	5.557E-3	5.212E-3
Hoop compression strain due to long term load component only: $\varepsilon_{long} = T_{long}/(E_{long}A_{eff.TM})$ (in./in.)	1.113E-2	1.208E-2
Total hoop compression strain, $\varepsilon_{Mf} = \varepsilon_{short} + \varepsilon_{long} + \varepsilon_{crest}$ (in./in.)	1.826E-2	1.840E-2
Specified limiting compression strain, ε_{cy} (in./in.)	3.300E-2	3.300E-2
Adequacy due to combined axial thrust and bending moment, Eq 10.	2.7	2.7

TABLE X1.15 Summary of Structural Adequacies

Load Combination	Wheel Load Position	
	At Crown	At Shoulder
Axial thrust only	1.97	1.93
Combined axial thrust and bending moment	2.7	2.7
	Controlling structural adequacy = 1.93	

X2. EXAMPLE CALCULATION OF BEARING ON BEDDING AND SUBGRADE

X2.1 *Given Information*:

X2.1.1 *Installation Description*—Consider a buried storm water chamber with cover heights between 1.5 ft and 8 ft. Live load is due to a 32-kip axle (16-kip wheel load) passing directly over the top of the chamber. The objective of this example calculation is to check bearing of the chamber foot on the foundation, and of the foundation on the subgrade, due to live load and soil weight against the bearing capacities of the two soil layers. Contribution of live load to the bearing at the foundation is highest when the axle is centered between two chambers as indicated in Fig. X2.1.

X2.1.2 *Chamber Geometry*—Chamber geometry parameters are assumed to be constant throughout the chamber and tabulated in Table X2.1 (refer to Fig. X2.1 for the definition of the parameters).

X2.1.3 *Soil Properties*—Consider soil with unit weight of 120 lb/ft^3. Cover height is between 1.5 ft and 8 ft. Below the chamber foot, foundation thickness is 9 in. The ultimate bearing capacity of the bedding stone determined from laboratory tests is 28 ksf. The ultimate bearing capacity of the subgrade based on geotechnical evaluation is 4 ksf.

X2.1.4 *Live Load*—In this example, consider a 32-kip axle (16-kip wheel load) on a two-dimensional problem as illustrated in Fig. X2.1, with the parameters tabulated in Table X2.2. The wheel load is distributed using the live load distribution factor at all cover heights, including those less than 2 ft. In the calculation, the live load is distributed out-of-plane and checked for interaction between the two wheels of the axle. If the effective load width after live load distribution (see Fig. X2.1) exceeds the crown-to-crown spacing, the fraction of wheel load that is transferred through the soil between two chambers is calculated by multiplying the effective pressure at the crown level with the crown-to-crown spacing (see calculation example in Section X2.3 for the details). This represents the distribution of some of the live load away from the soil between two chambers.

X2.2 *Bearing Calculation and Results*—The calculation is shown in Section X2.3. The calculation results are summarized in Table X2.3.

X2.3 *Example Calculation of Bearing Load on Foundation under Chamber Foot and at the Foundation Subgrade Level*—See Figs. X2.2-X2.5.

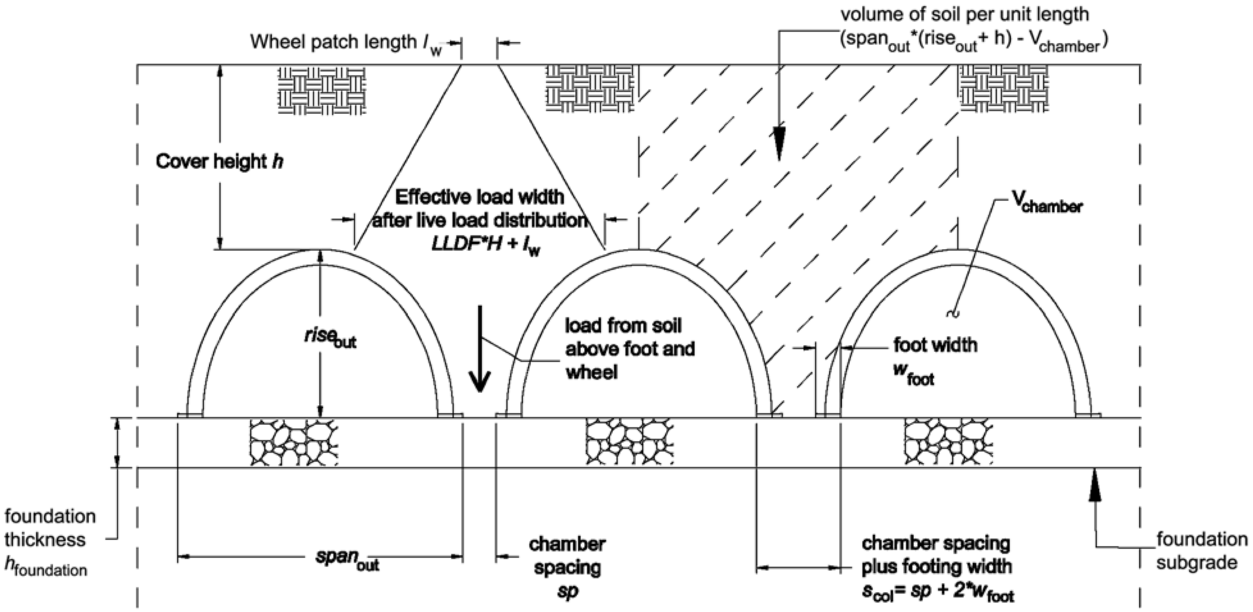


FIG. X2.1 Schematic of Bearing Problem

TABLE X2.1 Chamber Geometry

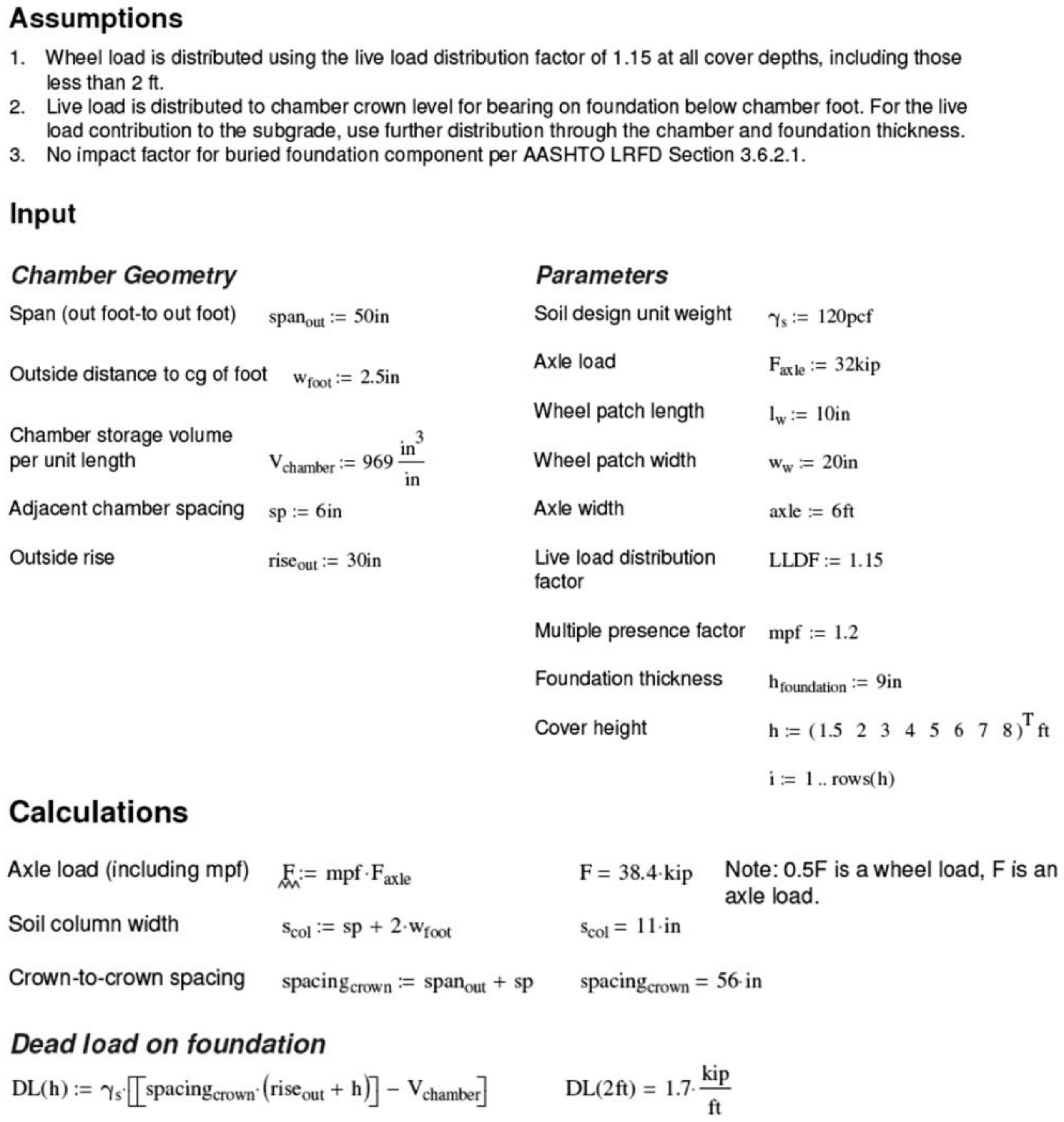
Property	Value
Span (out foot-to-out foot), $span_{out}$	50 in.
Distance from outside of foot to cg of foot, w_{foot}	2.5 in.
Adjacent chamber spacing, sp	6 in.
Soil column width, $s_{col} = sp + 2w_{foot}$	11 in.
Outside rise, $rise_{out}$	30 in.
Crown-to-crown spacing, $spacing_{crown} = span_{out} + sp$	56 in.
Chamber volume per unit length, $V_{chamber}$	969 in.^{3}/in.

TABLE X2.2 Live Load Parameters

Parameter	Value
Wheel length, l_w	10 in.
Wheel width, w_w	20 in.
Axle width, *axle*	6 ft
Multiple presence factor, *mpf*	1.2
Live load distribution factor, *LLDF*	1.15

TABLE X2.3 Summary of Calculation

Calculated Quantity	Value
Ultimate bearing capacity of foundation	28 ksf
Allowable bearing capacity of foundation subgrade	4 ksf
Pressure of foot on foundation, P_f	6.5 ksf (Factor of safety = 4.3 > 3, OK)
Pressure of foundation on subgrade, $P_{subgrade}$	3.43 ksf (less than allowable, 4.0, OK)



Assumptions

1. Wheel load is distributed using the live load distribution factor of 1.15 at all cover depths, including those less than 2 ft.
2. Live load is distributed to chamber crown level for bearing on foundation below chamber foot. For the live load contribution to the subgrade, use further distribution through the chamber and foundation thickness.
3. No impact factor for buried foundation component per AASHTO LRFD Section 3.6.2.1.

Input

Chamber Geometry

Span (out foot-to out foot)	$span_{out} := 50in$
Outside distance to cg of foot	$w_{foot} := 2.5in$
Chamber storage volume per unit length	$V_{chamber} := 969\,\frac{in^3}{in}$
Adjacent chamber spacing	$sp := 6in$
Outside rise	$rise_{out} := 30in$

Parameters

Soil design unit weight	$\gamma_s := 120pcf$
Axle load	$F_{axle} := 32kip$
Wheel patch length	$l_w := 10in$
Wheel patch width	$w_w := 20in$
Axle width	$axle := 6ft$
Live load distribution factor	$LLDF := 1.15$
Multiple presence factor	$mpf := 1.2$
Foundation thickness	$h_{foundation} := 9in$
Cover height	$h := (1.5\ \ 2\ \ 3\ \ 4\ \ 5\ \ 6\ \ 7\ \ 8)^T\,ft$
	$i := 1 .. rows(h)$

Calculations

Axle load (including mpf)	$F := mpf \cdot F_{axle}$	$F = 38.4 \cdot kip$
Soil column width	$s_{col} := sp + 2 \cdot w_{foot}$	$s_{col} = 11 \cdot in$
Crown-to-crown spacing	$spacing_{crown} := span_{out} + sp$	$spacing_{crown} = 56 \cdot in$

Note: 0.5F is a wheel load, F is an axle load.

Dead load on foundation

$$DL(h) := \gamma_s \cdot \left[\left[spacing_{crown} \cdot \left(rise_{out} + h\right)\right] - V_{chamber}\right] \qquad DL(2ft) = 1.7 \cdot \frac{kip}{ft}$$

FIG. X2.2

Live load on foundation - load distribution through soil

Step 1. Determine the in-plane live load distribution - if the effective load width after live load distribution exceeds the crown-to-crown spacing, the wheel live load should be recalculated using the crown-to-crown spacing.

Function definition - compute the effective live load width at the chamber crown

$w_{eff}(h) := l_w + LLDF \cdot h$ $\qquad$ $w_{eff}(2ft) = 3.1\,ft$

Function definition - compute the effective live load pressure at the chamber crown

$p_{crown}(F, h) := \dfrac{0.5F}{w_{eff}(h)}$ (this assumes no interaction between adjacent live load axles. $\qquad$ $p_{crown}(16kip, 2ft) = 2.6 \cdot \dfrac{kip}{ft}$

Function definition - compute live load through the 'soil column' between two adjacent chambers; use the crown-to-crown spacing if the effective live load width exceeds the crown-to-crown spacing.

$$LL_{in.plane.scaled}(F, h) := \left| \begin{array}{l} p_{crown}(F, h) \cdot w_{eff}(h) \quad \text{if } w_{eff}(h) \le spacing_{crown} \\ p_{crown}(F, h) \cdot spacing_{crown} \quad \text{if } w_{eff}(h) > spacing_{crown} \end{array} \right.$$

$LL_{in.plane.scaled}(16kip, 2ft) = 8 \cdot kip$

Step 2. Out-of-plane distribution - check if axle wheels interact, compute live load on foundation

Depth at which wheels on an axle interact $\qquad D_{axle} := \dfrac{axle - w_w}{LLDF}$ $\qquad D_{axle} = 3.8\,ft$

Depth to foundation $\qquad D_{foundation}(h) := h + rise_{out}$ $\qquad D_{foundation}(2ft) = 4.5\,ft$

Depth to subgrade $\qquad D_{subgrade}(h) := h + rise_{out} + h_{foundation}$ $\qquad D_{subgrade}(2ft) = 5.3\,ft$

Function definition - out-of-plane live load distribution pressure on foundation below chamber foot

$$LL_{foundation}(F, h) := \left| \begin{array}{ll} \dfrac{LL_{in.plane.scaled}(F, h)}{w_w + LLDF \cdot D_{foundation}(h)} \quad \text{if } D_{foundation}(h) < D_{axle} & \text{Axle wheels do not interact} \\ \dfrac{2 \cdot LL_{in.plane.scaled}(F, h)}{axle + w_w + LLDF \cdot D_{foundation}(h)} \quad \text{if } D_{foundation}(h) \ge D_{axle} & \text{Axle wheels interact} \end{array} \right.$$

$LL_{foundation}(F, 2ft) = 3 \cdot \dfrac{kip}{ft}$

Function definition - out-of-plane live load distribution pressure on subgrade

$$LL_{subgrade}(F, h, h_{foundation}) := \left| \begin{array}{ll} \dfrac{LL_{in.plane.scaled}(F, h)}{w_w + LLDF \cdot (D_{subgrade}(h))} \quad \text{if } D_{subgrade}(h) < D_{axle} & \text{Axle wheels do not interact} \\ \dfrac{2 \cdot LL_{in.plane.scaled}(F, h)}{axle + w_w + LLDF \cdot (D_{subgrade}(h))} \quad \text{if } D_{subgrade}(h) \ge D_{axle} & \text{Axle wheels interact} \end{array} \right.$$

$LL_{subgrade}(F, 2ft, h_{foundation}) = 2.8 \cdot \dfrac{kip}{ft}$

FIG. X2.3

Load Components for Chamber Foot Bearing on Foundation

$$\mathrm{DeadLoad}_i := \mathrm{DL}(h_i)$$

$$\mathrm{LiveLoad}_{\mathrm{foundation}_i} := \mathrm{LL}_{\mathrm{foundation}}(F, h_i)$$

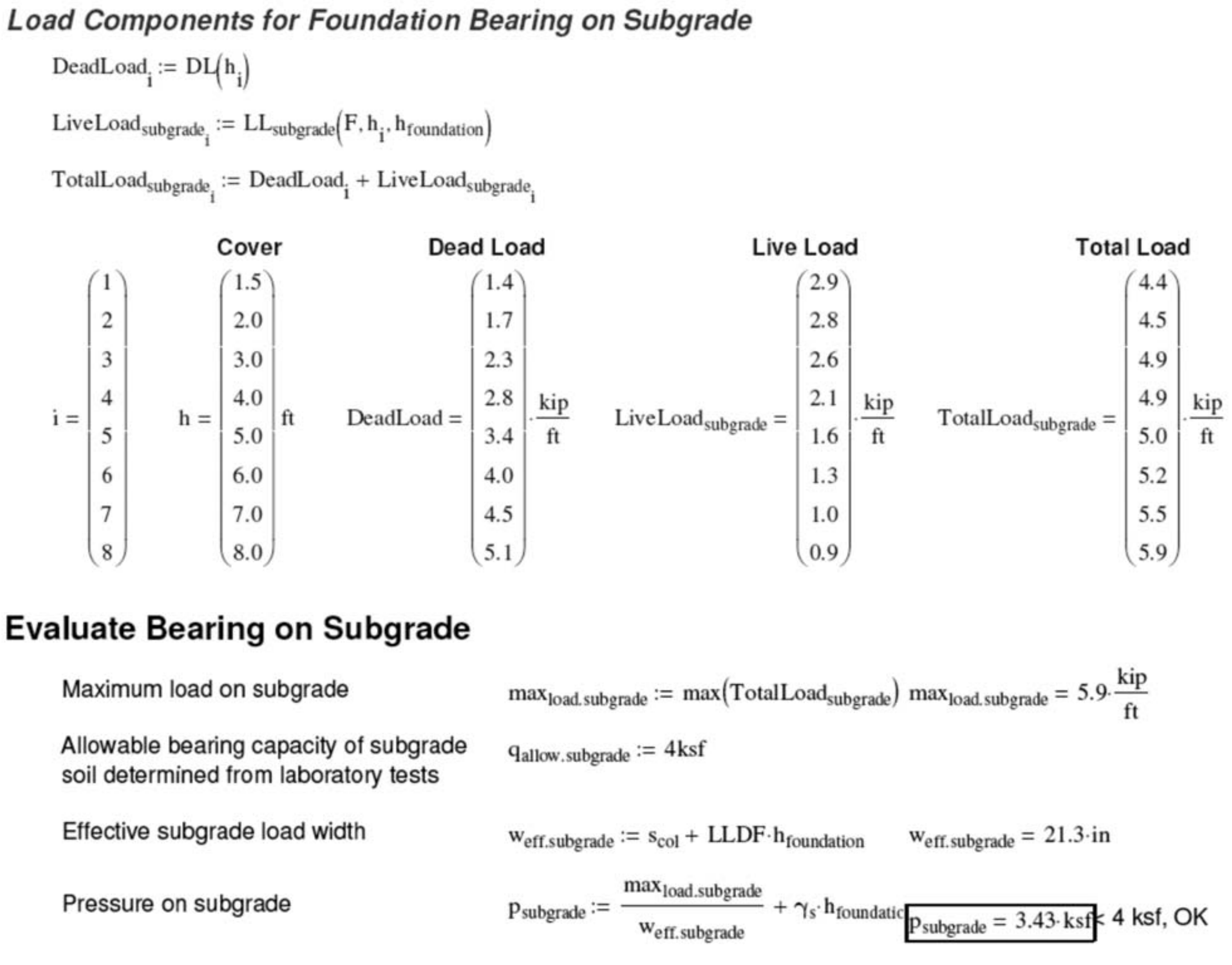
$$\mathrm{TotalLoad}_{\mathrm{foundation}_i} := \mathrm{DeadLoad}_i + \mathrm{LiveLoad}_{\mathrm{foundation}_i}$$

$$\begin{array}{ccccc}
 & \textbf{Cover} & \textbf{Dead Load} & \textbf{Live Load} & \textbf{Total Load} \\
i = \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \end{pmatrix} &
h = \begin{pmatrix} 1.5 \\ 2.0 \\ 3.0 \\ 4.0 \\ 5.0 \\ 6.0 \\ 7.0 \\ 8.0 \end{pmatrix} \mathrm{ft} &
\mathrm{DeadLoad} = \begin{pmatrix} 1.4 \\ 1.7 \\ 2.3 \\ 2.8 \\ 3.4 \\ 4.0 \\ 4.5 \\ 5.1 \end{pmatrix} \cdot \frac{\mathrm{kip}}{\mathrm{ft}} &
\mathrm{LiveLoad}_{\mathrm{foundation}} = \begin{pmatrix} 3.1 \\ 3.0 \\ 2.7 \\ 2.2 \\ 1.7 \\ 1.3 \\ 1.1 \\ 0.9 \end{pmatrix} \cdot \frac{\mathrm{kip}}{\mathrm{ft}} &
\mathrm{TotalLoad}_{\mathrm{foundation}} = \begin{pmatrix} 4.6 \\ 4.7 \\ 5.0 \\ 5.0 \\ 5.1 \\ 5.3 \\ 5.6 \\ 6.0 \end{pmatrix} \cdot \frac{\mathrm{kip}}{\mathrm{ft}}
\end{array}$$

Evaluate Bearing on Foundation Below Chamber Foot

Maximum load on foundation below chamber foot	$\mathrm{max}_{\mathrm{load}} := \max(\mathrm{TotalLoad}_{\mathrm{foundation}})$	$\mathrm{max}_{\mathrm{load}} = 6 \cdot \frac{\mathrm{kip}}{\mathrm{ft}}$
Ultimate bearing capacity of foundation stone determined from laboratory tests	$q_{\mathrm{u.foundation}} := 28\ \mathrm{ksf}$	
Pressure on foundation below chamber foot	$p_f := \mathrm{max}_{\mathrm{load}} \div s_{\mathrm{col}}$	$\boxed{p_f = 6.5 \cdot \mathrm{ksf}}$
Factors of Safety (Typical design factor of safety = 3)	$\mathrm{FS}_{\mathrm{foundation}} := \frac{q_{\mathrm{u.foundation}}}{p_f}$	$\boxed{\mathrm{FS}_{\mathrm{foundation}} = 4.3}$ > 3, OK

FIG. X2.4



Load Components for Foundation Bearing on Subgrade

$$\mathrm{DeadLoad}_i := \mathrm{DL}(h_i)$$

$$\mathrm{LiveLoad}_{\mathrm{subgrade}_i} := \mathrm{LL}_{\mathrm{subgrade}}(F, h_i, h_{\mathrm{foundation}})$$

$$\mathrm{TotalLoad}_{\mathrm{subgrade}_i} := \mathrm{DeadLoad}_i + \mathrm{LiveLoad}_{\mathrm{subgrade}_i}$$

$$i = \begin{pmatrix}1\\2\\3\\4\\5\\6\\7\\8\end{pmatrix} \quad \overset{\textbf{Cover}}{h = \begin{pmatrix}1.5\\2.0\\3.0\\4.0\\5.0\\6.0\\7.0\\8.0\end{pmatrix} \mathrm{ft}} \quad \overset{\textbf{Dead Load}}{\mathrm{DeadLoad} = \begin{pmatrix}1.4\\1.7\\2.3\\2.8\\3.4\\4.0\\4.5\\5.1\end{pmatrix} \cdot \frac{\mathrm{kip}}{\mathrm{ft}}} \quad \overset{\textbf{Live Load}}{\mathrm{LiveLoad}_{\mathrm{subgrade}} = \begin{pmatrix}2.9\\2.8\\2.6\\2.1\\1.6\\1.3\\1.0\\0.9\end{pmatrix} \cdot \frac{\mathrm{kip}}{\mathrm{ft}}} \quad \overset{\textbf{Total Load}}{\mathrm{TotalLoad}_{\mathrm{subgrade}} = \begin{pmatrix}4.4\\4.5\\4.9\\4.9\\5.0\\5.2\\5.5\\5.9\end{pmatrix} \cdot \frac{\mathrm{kip}}{\mathrm{ft}}}$$

Evaluate Bearing on Subgrade

Maximum load on subgrade $\max_{\mathrm{load.subgrade}} := \max(\mathrm{TotalLoad}_{\mathrm{subgrade}}) \quad \max_{\mathrm{load.subgrade}} = 5.9 \cdot \frac{\mathrm{kip}}{\mathrm{ft}}$

Allowable bearing capacity of subgrade soil determined from laboratory tests $q_{\mathrm{allow.subgrade}} := 4\mathrm{ksf}$

Effective subgrade load width $w_{\mathrm{eff.subgrade}} := s_{\mathrm{col}} + \mathrm{LLDF} \cdot h_{\mathrm{foundation}} \quad w_{\mathrm{eff.subgrade}} = 21.3 \cdot \mathrm{in}$

Pressure on subgrade $p_{\mathrm{subgrade}} := \frac{\max_{\mathrm{load.subgrade}}}{w_{\mathrm{eff.subgrade}}} + \gamma_s \cdot h_{\mathrm{foundatic}} \; \boxed{p_{\mathrm{subgrade}} = 3.43 \cdot \mathrm{ksf}} < 4$ ksf, OK

FIG. X2.5

X3. DESIGN QUALIFICATION TESTING

X3.1 The following are guidelines for the qualification testing of chambers.

X3.2 Chambers are field tested to verify their conformance to the structural adequacy requirements of this practice.

X3.3 Use chambers in field tests that represent the structural behavior of production chambers. Include features in test chambers that may reduce structural capacity, such as thickness variations, chamber joints, end caps, inspection ports, and cutouts.

X3.4 Chamber field testing includes full-scale installations under sustained dead loads due to maximum soil cover and live loads due to surface vehicles under minimum soil. The magnitude of the test load is based on calculated factored design loads.

X3.4.1 *Sustained Dead Load Test*—Bury chambers for a minimum of three months under carefully placed fill that simulates field installation conditions. Fill cover height should equal or exceed the maximum design cover height specified for the chamber. Place additional soil surcharge or employ other methods to produce a total load on the chamber equivalent to the factored design load.

X3.4.2 *Live Load Test*—Live load tests include the design truck axle applied as both static and dynamic loads at minimum design cover height specified for the chamber. Apply static load with the truck axle parked both centrically (over the crown of the chamber), and eccentrically to determine worst case response condition. Apply static load for a minimum duration of one minute. The dynamic load consists of the design truck traveling over the chamber in a direction perpendicular to the chamber axis. Simulate factored live loads by increasing the truck weight or reducing fill height to below minimum design cover.

X3.5 Monitor chambers during the tests for structural distress and deformations to ensure conformance to design requirements.

X3.6 Tests on chambers of one size may be used to qualify smaller chambers provided the conditions in X3.6.1 through X3.6.3 are met.

X3.6.1 Test chambers have a similar rise to span ratio, corrugation profile, and foot shape as the smaller chambers being qualified.

X3.6.2 Test chambers have similar wall thickness variability as the smaller chambers being qualified.

X3.6.3 Production specimens of the smaller chambers being qualified are verified by live load testing at design service (unfactored) loads.

SUMMARY OF CHANGES

Committee F17 has identified the location of selected changes to this standard since the last issue (F2787–11) that may impact the use of this standard.

(1) Editorial correction to Eq 6.
(2) Editorial corrections to Table X1.3, Table X1.4, Table X1.8, Table X1.9, Table X1.13, Table X1.14.
(3) Added X3.3 on additional guidance for design qualification testing of chambers.

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