Chapter 14

NONBUILDING STRUCTURE DESIGN REQUIREMENTS

14.1 GENERAL

14.1.1 Scope. Nonbuilding structures considered by these *Provisions* include all self-supporting structures which carry gravity loads, with the exception of buildings, vehicular and railroad bridges, electric power substation equipment, overhead power line support structures, buried pipelines, conduits and tunnels, lifeline systems, nuclear power generation plants, offshore platforms, and dams. Nonbuilding structures supported by the earth or by other structures shall be designed and detailed in accordance with these *Provisions* as modified by this chapter. Nonbuilding structures for which this chapter does not provide explicit direction shall be designed in accordance with engineering practices that are approved by the authority having jurisdiction and are applicable to the specific type of nonbuilding structure.

Architectural, mechanical, and electrical components supported by nonbuilding structures within the scope of chapter 14, and their supports and attachments, shall be designed in accordance with Chapter 6 of these *Provisions*.

> **Exception:** Storage racks, cooling towers, and storage tanks shall be designed in accordance with Chapter 14 of these *Provisions*.

14.1.2 References

14.1.2.1 Adopted references. The following references form a part of these *Provisions* to be used for the applications indicated in Table 14.1-1 as specified in this chapter.

ACI 313	*Standard Practice for the Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials*, American Concrete Institute, 1997.
ACI 350.3	*Seismic Design of Liquid-Containing Concrete Structures*, American Concrete Institute, 2001.
API 620	*Design and Construction of Large, Welded, Low Pressure Storage Tanks,* American Petroleum Institute, 2002.
API 650	*Welded Steel Tanks For Oil Storage,* American Petroleum Institute, 1998.
ASME BPV	*Boiler And Pressure Vessel Code*, American Society of Mechanical Engineers, including addenda through 2003.
AWWA D100	*Welded Steel Tanks for Water Storage,* American Water Works Association, 1996.
AWWA D103	*Factory-Coated Bolted Steel Tanks for Water Storage,* American Water Works Association, 1997.
AWWA D110	*Wire- and Strand-Wound Circular Prestressed Concrete Water Tanks,* American Water Works Association, 1995.
AWWA D115	*Circular Prestressed Concrete Tanks with Circumferential Tendons*, American Water Works Association, 1995.
RMI	*Specification for the Design, Testing, and Utilization of Industrial Steel Storage Racks*, Rack Manufacturers Institute, 1997 (Reaffirmed 2002).

NCEL R-939 Ebeling, R. M., and Morrison, E. E., *The Seismic Design of Waterfront Retaining Structures*, Naval Civil Engineering Laboratory, 1993.

Table 14.1-1 Adopted References

Application	**Reference**
Steel storage racks	RMI
Welded steel tanks for water storage	AWWA D100
Welded steel tanks for petroleum and petrochemical storage	API 650, API 620
Bolted steel tanks for water storage	AWWA D103
Piers and Wharves	
Concrete tanks for water storage	AWWA D115, AWWA D110, ACI 350.3
Pressure vessels	ASME BPV
Concrete silos and stacking tubes	ACI 313

14.1.2.2 Other references

ACI 371R *Guide for the Analysis, Design, and Construction of Concrete Pedestal Water Towers*, American Concrete Institute, 1998.

API 653 *Tank Inspection, Repair, Alteration, and Reconstruction*, American Petroleum Institute, 2001.

API Spec 12B *Bolted Tanks for Storage of Production Liquids*, American Petroleum Institute, 1995 (Reaffirmed 2000).

14.1.3 Definitions

Attachments: See Sec. 6.1.3.

Base: See Sec. 4.1.3.

Base shear: See Sec. 4.1.3.

Building: See Sec. 4.1.3.

Component: See Sec. 1.1.4.

Container: A large-scale independent component used as a receptacle or a vessel to accommodate plants, refuse, or similar uses.

Dead load: See Sec. 4.1.3.

Diaphragm: See Sec. 4.1.3.

Flexible component: See Sec. 6.1.3.

Flexible equipment connections: Those connections between equipment components that permit rotational and/or transitional movement without degradation of performance. Examples included universal joints, bellows, expansion joints, and flexible metal hose.

Live load: See Sec. 4.1.3.

Maximum considered earthquake ground motion: See Sec. 3.1.3.

Nonbuilding structure: A structure, other than a building, constructed of a type included in Chapter 14 and within the limits of Sec. 14.1.1.

Nonbuilding structure similar to building: A nonbuilding structure that is designed and constructed in a manner similar to buildings, with a basic seismic-force-resisting-system conforming to one of the types indicated in Table 4.3-1, usually with diaphragms or other elements to transfer lateral forces to the vertical seismic force resisting system.

Occupancy importance factor: See Sec. 1.1.4.

P-delta effect: See Sec. 5.1.2.

Plain masonry: See Sec. 11.1.3.

Reinforced masonry: See Sec. 11.1.3.

Rigid component: See Sec. 6.1.3.

Seismic Design Category: See Sec. 1.1.4.

Seismic force-resisting system: See Sec. 1.1.4.

Seismic forces: See Sec. 1.1.4.

Seismic Use Group: A classification assigned to the structure based on its use as defined in Sec. 1.3.

Storage racks: Industrial pallet racks, moveable shelf racks, and stacker racks made of cold-formed and hot-rolled structural members. Other types of racks such as drive-in and drive-through racks, cantilever racks, portable racks, or racks made of materials other than steel are not included.

Structure: See Sec. 1.1.4.

Supports: See Sec. 6.1.3.

14.1.4 Notation.

A_g See Sec. 7.1.4.

B Inside length of a rectangular tank, perpendicular to the direction of the earthquake force being investigated.

a_p See Sec. 6.1.4.

C_d See Sec. 4.1.4.

C_v A coefficient defined in 14.4.7.1(3) [Eq. (14.4-2)].

D See Sec. 4.1.4.

D_i Inside diameter of tank or vessel.

E See Sec. 4.1.4.

E_t Modulus of elasticity of tank or vessel wall material.

F_h Total unbalanced lateral dynamic earth and groundwater pressure acting on the outer wall of the tank or vessel.

F_y The yield stress.

g See Sec. 13.1.3.

H The height of liquid in a tank.

H_L Design liquid height inside tank or vessel.

H_w Height of tank or vessel wall (shell).

h Depth of tank wall embedment.

h_i, h_x The height above the base Level i or x, respectively.

I See Sec. 1.1.5.

I_p See Sec. 6.1.4.

k See Sec. 5.1.3.

k_h Horizontal ground acceleration (as used in the design of buried tanks and vessels).

L Inside length of a rectangular tank, parallel to the direction of the earthquake force being investigated.

M Overturning moment.

N_h Hydrodynamic hoop force in the wall of a cylindrical tank or vessel

R See Sec. 4.1.4.

R_p See Sec. 6.1.4.

S_a See Sec. 3.1.4.

S_{ac} The design spectral response acceleration for a convective mode.

S_{ai} The design spectral response acceleration for an impulsive mode.

S_{D1} See Sec. 3.1.4.

S_{DS} See Sec. 3.1.4.

T See Sec. 4.1.4.

T_0 See Sec. 3.1.4.

T_c The natural period of the first convective mode.

T_i The natural period of the first impulsive mode.

T_S See Sec. 3.1.4.

T_v The natural period of vertical vibration of the liquid and tank structural system.

t_w Thickness of tank or vessel wall.

V See Sec. 5.1.3.

V_c The total convective shear at the base of the structure in the direction of interest.

V_i The total impulsive shear at the base of the structure in the direction of interest.

V_{max} The peak local tangential shear per unit length as determined by Eq. 14.4-10.

$\tilde{V}$ See Sec. 5.1.3.

W See Sec. 1.1.5.

W_c The convective component of seismic weight.

W_i The impulsive component of seismic weight.

W_L Weight of the stored liquid.

W_p See Sec. 6.1.4.

W_r Weight of the tank roof.

W_w Weight of the tank or vessel wall (shell).

y Distance from base of the tank to level being investigated.

γ_L Unit weight of stored liquid.

δ_s The height of a sloshing wave.

δ_x See Sec. 4.1.4.

δ_{xe} The deflection of Level x at the center of the mass at and above Level x determined by an elastic analysis.

ρ See Sec. 4.1.4.

Ω_0 See Sec. 4.1.4.

14.1.5 Nonbuilding structures supported by other structures. If a nonbuilding structure is supported above the base by another structure and the weight of the nonbuilding structure is not more than 25 percent of the seismic weight, *W*, as defined in Sec. 5.2.1, the design seismic forces for the supported nonbuilding structure shall be determined in accordance with the requirements of Chapter 6.

> **Exception:** Storage racks, cooling towers, and storage tanks shall be designed in accordance with Chapter 14 of these *Provisions*.

If the weight of a supported nonbuilding structure is more than 25 percent of the seismic weight, *W*, as defined in Sec. 5.2.1, the design seismic forces shall be determined based on an analysis of the combined system (comprising the nonbuilding structure and supporting structure). For supported nonbuilding structures that have rigid component dynamic characteristics, the *R* factor for the supporting structural system shall be used for the combined system. For supported nonbuilding structures that have flexible component dynamic characteristics, the *R* factor for the combined system shall not be greater than 3. The supported nonbuilding structure, and its supports and attachments, shall be designed for the forces determined from the analysis of the combined system.

14.2 GENERAL DESIGN REQUIREMENTS

14.2.1 Seismic Use Groups and importance factors. The Seismic Use Group and importance factor, *I*, for nonbuilding structures shall be determined based on the function of the structure and the relative hazard of its contents. The value of *I* shall be the largest of the values determined using approved standards, Table 14.2-1, and other provisions in this chapter.

Table 14.2-1 Seismic Use Groups and Importance Factors for Nonbuilding Structures

Seismic Use Group	**I**	**II**	**III**
Function [a]	F-I	F-II	F-III
Hazard [b]	H-I	H-II	H-III
Importance Factor	I = 1.0	I = 1.25	I = 1.5

[a] Function shall be classified as follows:
- F-I Nonbuilding structures not classified as F-III.
- F-II Not applicable for nonbuilding structures.
- F-III Nonbuilding structures that are required for post-earthquake recovery or as emergency back-up facilities for Seismic Use Group III structures.

[b] Hazard shall be classified as follows:
- H-I Nonbuilding structures that are not assigned to H-II or H-III.
- H-II Nonbuilding structures that have a substantial public hazard due to contents or use as determined by the authority having jurisdiction.
- H-III Nonbuilding structures containing sufficient quantities of toxic or explosive substance deemed to be hazardous to the public as determined by the authority having jurisdiction.

14.2.2 Ground motion. Where a site-specific study is required by an approved standard or the authority having jurisdiction, the design ground motion shall be determined in accordance with Sec. 3.4.

If a longer recurrence interval is defined in the adopted reference or other approved standard for a nonbuilding structure (such as LNG tanks), the recurrence interval required in the standard shall be used.

14.2.3 Design basis. Nonbuilding structures shall be designed to have sufficient stiffness, strength, and ductility to resist the effects of seismic ground motions. Where adopted references or other approved standards establish specific seismic design criteria for nonbuilding structures, the design shall satisfy those criteria as amended in this chapter. When adopted references or other approved standards are not available, nonbuilding structures shall be designed in accordance with these *Provisions*.

Unless otherwise noted in this chapter, the effects on the nonbuilding structure due to gravity loads and seismic forces shall be combined in accordance with the factored load combinations as presented in ASCE 7 except that the seismic loads, E, shall be as defined in Sec. 4.2.2.1.

Where specifically required by these *Provisions*, the design seismic force on nonbuilding structure components sensitive to the effects of structural overstrength shall be as defined in Sec. 4.2.2.2. The system overstrength factor, Ω_o, shall be taken from Table 14.2-2.

14.2.4 Seismic-force-resisting system selection and limitations. The basic seismic-force-resisting system shall be selected as follows:

1. For nonbuilding structures similar to buildings, a system shall be selected from among the types indicated in Table 14.2-2 subject to the system limitations and height limits, based on Seismic Design Category, indicated in the table. The appropriate values of R, Ω_0, and C_d indicated in Table 14.2-2 shall be used in determining the base shear, element design forces, and design story drift as indicated in these *Provisions*. Design and detailing requirements shall comply with the sections referenced in table 14.2-2.

2. For nonbuilding structures not similar to buildings, a system shall be selected from among the types indicated in Table 14.2-3 subject to the system limitations and height limits, based on Seismic design Category indicated in the table. The appropriate values of R, Ω_0, and C_d indicated in Table 4.3-1 shall be used in determining the base shear, element design forces, and design story drift as indicated in these *Provisions*. Design and detailing requirements shall comply with the sections referenced in Table 14.2-3.

3, Where neither Table 14.2-2 nor Table 14.2-3 contains an appropriate entry, applicable strength and other design criteria shall be obtained from an adopted reference that is applicable to the specific type of nonbuilding structure. Design and detailing requirements shall comply with the adopted reference.

Where an approved standard provides a basis for the earthquake-resistant design of a particular type of nonbuilding structure, such a standard may be used subject to the following limitations:

1. The design ground motion shall be determined in accordance with Chapter 3.

2. The values for total lateral force and total base overturning moment used in design shall not be less than 80 percent of the base shear and overturning moment that would be obtained using Chapter 5 of these *Provisions*.

3. Where the approved standard defines acceptance criteria in terms of allowable stresses (as opposed to strengths), the design seismic forces shall be obtained from the *Provisions* and reduced by a factor of 1.4 for use with allowable stresses and allowable stress increases used in the approved standard are permitted.

Table 14.2-2 Design Coefficients and Factors for Nonbuilding Structures Similar to Buildings

Nonbuilding Structure Type	Required Detailing Provisions	R	Ω_0	C_d	System Limitations and Height Limits (ft) by Seismic Design Category[a]				
					B	C	D	E	F
Steel Storage Racks	Sec. 14.3.5	4	2	3.5	NL	NL	NL	NL	NL
Building frame systems:									
Special steel concentrically braced frames	AISC Seismic, Part I, Sec. 13	6	2	5	NL	NL	160	160	100
Ordinary steel concentrically braced frame									
With Building Structure Height Limits	AISC Seismic, Part I, Sec. 14	5	2	4.5	NL	NL	35[b]	35[b]	NP[b]
With Non-building Structure Height Limits	AISC Seismic, Part I, Sec. 14	3.5	2	3.5	NL	NL	160	160	100
Moment resisting frame systems:									
Special steel moment frames	AISC Seismic, Part I, Sec. 9	8	3	5.5	NL	NL	NL	NL	NL
Special reinforced concrete moment frames	Sec. 9.2.2.2 & ACI 318, Chapter 21	8	3	5.5	NL	NL	NL	NL	NL
Intermediate steel moment frames									
With Building Structure Height Limits	AISC Seismic, Part I, Sec. 10	4.5	3	4	NL	NL	35[c,d]	NP[c,d]	NP[c,d]
With Non-building Structure Height Limits	AISC Seismic, Part I, Sec. 10	2.5	2	2.5	NL	NL	160	160	100
Intermediate reinforced concrete moment frames									
With Building Structure Height Limits	9.2.2.3 and ACI 318, Chapter 21	5	3	4.5	NL	NL	NP	NP	NP
With Non-building Structure Height Limits	9.2.2.3 and ACI 318, Chapter 21	3.5	2.5	3	NL	NL	50	50	50
Ordinary moment frames of steel									
With Building Structure Height Limits	AISC Seismic, Part I, Sec. 10	3.5	3	3	NL	NL	NP[c,d]	NP[c,d]	NP[c,d]
With Non-building Structure Height Limits	AISC Seismic, Part I, Sec. 10	2.5	2	2.5	NL	NL	100	100	NP[c]
Ordinary reinforced concrete moment frames	Sec. 9.3.1 & ACI 318, Chapter 21	3	3	2.5	NL	NP	NP	NP	NP

[a] NL = no limit and NP = not permitted. If using metric units, 50 ft approximately equals 15 m.
Heights are measured from the base of the structure as defined in Sec. 14 1.3.
[b] Steel ordinary braced frames are permitted in pipe racks up to 65 feet (20 m).
[c] Steel ordinary moment frames and intermediate moment frames are permitted in pipe racks up to a height of 65 feet (20 m) where the moment joints of field connections are constructed of bolted end plates.
[d] Steel ordinary moment frames and intermediate moment frames are permitted in pipe racks up to a height of 35 ft (11 m).

Table 14.2-3 Design Coefficients and Factors for Nonbuilding Structures NOT Similar to Buildings

Nonbuilding Structure Type	Required Detailing Provisions	R	Ω_0	C_d	System Limitations and Height Limits (ft) by Seismic Design Category[a]				
					B	C	D	E	F
Elevated tanks, vessels, bins, or hoppers:	Sec. 14.4.7.9								
On symmetrically braced legs		3	2[b]	2.5	NL	NL	NL	160	100
On unbraced or asymmetrically braced legs		2	2[b]	2.5	NL	NL	NL	100	60
Single pedestal or skirt supported									
- welded steel		3	2[b]	2	NL	NL	NL	NL	NL
- prestressed or reinforced concrete[c]		3[b]	2[b]	2	NL	NL	NL	NL	NL
Horizontal, saddle supported welded steel vessels	Sec. 14.4.7.13	3	2[b]	2.5	NL	NL	NL	NL	NL
Tanks or vessels supported on structural towers similar to buildings	Sec. 14.3.2	3	2	2	NL	NL	NL	NL	NL
Flat bottom, ground supported tanks, or vessels:	Sec. 14.4.7								
Steel or fiber-reinforced plastic:									
Mechanically anchored		3	2[b]	2.5	NL	NL	NL	NL	NL
Self-anchored		2.5	2[b]	2	NL	NL	NL	NL	NL
Reinforced or prestressed concrete:									
with reinforced nonsliding base		2	2[b]	2	NL	NL	NL	NL	NL
with anchored flexible base		3.25	2[b]	2	NL	NL	NL	NL	NL
with unanchored and unconstrained flexible base		1.5	1.5[b]	1.5	NL	NL	NL	NL	NL
Other material		1.5	1.5[b]	1.5	NL	NL	NL	NL	NL
Cast-in-place concrete silos, stacks, and chimneys having walls continuous to the foundation	Sec. 14.4.3	3	1.75	3	NL	NL	NL	NL	NL
Reinforced masonry structures not similar to buildings	Chapter 11	3	2	2.5	NL	NL	NL	50	50
Plain masonry structures not similar to buildings	Chapter 11	1.25	2	1.5	NL	NL	50	50	50
Steel and reinforced concrete distributed mass cantilever structures not covered herein (including stacks, chimneys, silos, and skirt-supported vertical vessels that are not similar to buildings)	Adopted References	3	2	2.5	NL	NL	NL	NL	NL
Trussed towers (freestanding or guyed), guyed stacks and chimneys	Adopted References	3	2	2.5	NL	NL	NL	NL	NL
Cooling towers:	Adopted References								
Concrete or steel		3.5	1.75	3	NL	NL	NL	NL	NL
Wood frames		3.5	3	3	NL	NL	NL	50	50
Inverted pendulum type structures (except elevated tanks, vessels, bins and hoppers)	Adopted References	2	2	2	NL	NL	NL	NL	NL
Signs and billboards	Adopted References	3.5	1.75	3	NL	NL	NL	NL	NL
Self-supporting structures that are not similar to buildings and are not covered above or by approved standards	Adopted References	1.25	2	2.5	NL	NL	50	50	50

[a] NL = no limit and NP = not permitted. If using metric units, 50 ft approximately equals 15 m.
Heights are measured from the base of the structure as defined in Sec. 14 1.3.

[b] In the case of tanks and vessels, the overstrength factors, Ω_0, tabulated above apply only to connections, anchorages and other seismic-force-resisting tank *components* or *elements*, which shall be designed in accordance with the provisions of Sec. 14.4.7.2 and 14.4.7.4 (except that anchor bolts or anchor cables that are designed to yield shall be permitted to be designed using an overstrength value, Ω_0, = 1.0). The overstrength provisions of Sec. 4.2.2.2 and the, Ω_0, values tabulated above, do not apply to the design of walls, including interior walls of tanks and vessels.

[c] Detailing in accordance with Sec. 9.2.1.6 of these *Provisions* for special reinforced concrete shear walls is required, or *R* shall be taken as 2.

14.2.5 Structural analysis procedure selection. Structural analysis procedures for nonbuilding structures that are similar to buildings shall be selected in accordance with Sec. 4.4.1 of these *Provisions*.

Nonbuilding structures that are not similar to buildings shall be analyzed by using either the equivalent lateral force procedure in accordance with Sec. 5.2 of these Provisions, the response spectrum procedure in accordance with Sec. 5.3 of these *Provisions*, or the procedure prescribed in the specific adopted reference.

14.2.6 Seismic weight. The seismic weight, W, for nonbuilding structures shall include all dead loads as defined for structures in Sec. 5.2.1. For the purposes of calculating design seismic forces in nonbuilding structures, W also shall include all normal operating contents for items such as tanks, vessels, bins, hoppers, and piping. W shall include snow and ice loads where these loads constitute 25 percent or more of W or where required by the authority having jurisdiction based on local environmental conditions.

14.2.7 Rigid nonbuilding structures. Nonbuilding structures that have a fundamental period, T, less than 0.06 sec, including their anchorages, shall be designed for the base shear, V, obtained using Eq. 14.2-1 as follows:

$$V = 0.3 S_{DS} I W \tag{14.2-1}$$

where:

S_{DS} = the short period spectral response acceleration parameter, as determined in Sec. 3.3.3,

I = the importance factor, as determined from Table 14.2-1, and

W = the seismic weight.

In this case, the force shall be distributed with height in accordance with Sec. 5.2.3.

14.2.8 Minimum base shear. For nonbuilding systems that have an R value provided in Table 14.2-2, the minimum value specified in Sec. 5.2.1.1 shall be replaced by:

$$C_s = 0.03 \tag{14.2-2}$$

and the minimum value specified in Eq. 5.2-5 shall be replaced by:

$$C_s = \frac{0.8 S_1}{R/I} \tag{14.2-3}$$

Exceptions:

1. Nonbuilding systems that have an R value provided in Table 14.2-3 and are designed to an adopted reference as modified by these Provisions shall be subject to the minimum base shear values defined by Equations 5.2-4 and 5.2-5.
2. Minimum base shear requirements need not apply to the convective (sloshing) component of liquid in tanks.

14.2.9 Fundamental period. The fundamental period of the nonbuilding structure shall be determined using the structural properties and deformation characteristics of the resisting elements in a properly substantiated analysis, such as the method described in Sec. 5.3.2.

When adopted references or other approved standards are not available, the fundamental period T may be computed using the following formula:

$$T = 2\pi \sqrt{\frac{\sum_{i=1}^{n} w_i \delta_i^{\,2}}{g \sum_{i=1}^{n} f_i \delta_i}} \qquad (14.2\text{-}4)$$

The values of f_i represent any lateral force distribution in accordance with the principles of structural mechanics. The elastic deflections, δ_i, shall be calculated using the applied lateral forces, f_i.

Equations 5.2-6, 5.2-7 and 5.2-8 shall not be used for determining the period of a nonbuilding structure.

14.2.10 Vertical distribution of seismic forces. In addition to the methods prescribed in Chapter 5 of these *Provisions*, it shall be permitted to determine the vertical distribution of lateral seismic forces in accordance with an adopted reference or other standard that is approved by the authority having jurisdiction and is applicable to the specific type of nonbuilding structure.

14.2.11 Deformation requirements. The drift limits of Sec. 4.5.1 need not apply to nonbuilding structures if a rational analysis indicates they can be exceeded without adversely affecting structural stability or attached or interconnected components and elements (such as walkways and piping). P-delta effects shall be considered where critical to the function or stability of the structure.

Structures shall satisfy the separation requirements as determined in accordance with Sec. 4.5.1 unless specifically amended in this chapter.

14.2.12 Nonbuilding structure classification. Nonbuilding structures with structural systems that are designed and constructed in a manner similar to buildings and that have dynamic response similar to building structures shall be classified as "similar to buildings" and shall be designed in accordance with Sec. 14.3. All other nonbuilding structures shall be classified as "not similar to buildings" and shall be designed in accordance with Sec. 14.4.

14.3 NONBUILDING STRUCTURES SIMILAR TO BUILDINGS

Nonbuilding structures similar to buildings, as defined in Sec. 14.1.3, shall be designed in accordance with these *Provisions* as modified by this section and the specific adopted references.

14.3.1 Electrical power generating facilities. Electrical power generating facilities are power plants that generate electricity by steam turbines, combustion turbines, diesel generators, or similar turbo machinery. Such structures shall be designed in accordance with Sec. 14.2 of these *Provisions*.

14.3.2 Structural towers for tanks and vessels. Structural towers that support tanks and vessels shall be designed in accordance with Sec. 14.1.5. In addition, the following special considerations shall be included:

1. The distribution of the lateral base shear from the tank or vessel onto the supporting structure shall consider the relative stiffness of the tank and resisting structural elements.
2. The distribution of the vertical reactions from the tank or vessel onto the supporting structure shall consider the relative stiffness of the tank and resisting structural elements. Where the tank or vessel is supported on grillage beams, the calculated vertical reaction due to weight and overturning shall be increased at least 20 percent to account for nonuniform support. The grillage beam and vessel attachment shall be designed for this increased design value.
3. Calculation of the seismic displacements of the tank or vessel shall consider the deformation of the support structure where determining P-delta effects or evaluating required clearances to prevent pounding of the tank on the structure.

14.3.3 Piers and wharves. Piers and wharves are structures located in waterfront areas that project into a body of water. Two categories of these structures are:

a. Piers and wharves with general public occupancy, such as cruise ship terminals, retail or commercial offices, restaurants, fishing piers and other tourist attractions.

b. Piers and wharves where occupancy by the general public is not a consideration and economic considerations (on a regional basis, or for the owner) are a major design consideration, such as container wharves, marine oil terminals, bulk terminals, etc., or other structures whose primary function is to moor vessels and barges.

These structures shall conform to the building or building-like structural requirements of the Provisions or other rational criteria and methods of design and analysis. Any methods used for design of these structures should recognize the unique importance of liquefaction and soil failure collapse mechanisms, as well as consider all applicable marine loading combinations, such as mooring, berthing, wave and current. Structural detailing shall be carefully considered for the marine environment.

14.3.3.1 Additional seismic mass. Seismic forces on elements below the water level shall include the inertial force of the mass of the displaced water. The additional seismic mass equal to the mass of the displaced water shall be included as a lumped mass on the submerged element, and shall be added to the calculated seismic forces of the pier or wharf structure.

14.3.3.2 Soil effects. Seismic dynamic forces from the soil shall be determined by the registered design professional. The design shall account for the effects of liquefaction on piers and wharves, as appropriate.

14.3.4 Pipe racks. Pipe racks supported at the base shall be designed for the forces defined in Chapter 5 of these *Provisions*.

Displacements of the pipe rack shall be calculated using Eq. 5.2-15. The potential for interaction effects (pounding of the piping system) shall be considered based on these amplified displacements.

Piping systems, and their supports and attachments, shall be designed in accordance with Sec. 6.4.7. Friction resulting from gravity loads shall not be considered to provide resistance to seismic forces.

14.3.5 Steel storage racks. Steel storage racks supported below, at, or above grade shall be designed in accordance with this section.

14.3.5.1 Testing. Unless higher values of R are justified by test data, the seismic-force-resisting system shall be subject to the requirements and limitations of Sec. 14.2.4.

14.3.5.2 Importance factor. For storage racks in occupancies open to the general public, the importance factor, I, shall be taken as 1.5.

14.3.5.3 Operating weight. Steel storage racks shall be designed for each of the following conditions of operating weight, W.

1. Weight of the rack plus every storage level loaded to 67 percent of its rated load capacity.

2. Weight of the rack plus the highest storage level only loaded to 100 percent of its rated load capacity.

The design shall consider the actual height of the center of mass of each storage load component.

14.3.5.4 Vertical distribution of seismic forces. For all steel storage racks, the vertical distribution of seismic forces shall be as specified in Sec. 5.2.3 and in accordance with the following:

1. The base shear, V, of the steel storage rack shall be determined considering the loading conditions defined in Sec. 14.3.5.3.

2. The base of the structure shall be the floor supporting the steel storage rack. Each storage level of the rack shall be treated as a level of the structure, with heights h_i and h_x measured from the base of the structure.

3. The factor k may be taken as 1.0.

14.3.5.5 Seismic displacements. Steel storage rack installations shall accommodate the seismic displacement of the storage racks and their contents relative to all adjacent or attached components and elements. The assumed total relative displacement for storage racks shall not be less than 5 percent of the height above the base unless a smaller value is justified by test data or a properly substantiated analysis.

14.3.5.6 RMI storage racks. Steel storage racks designed in accordance with Sec. 2.7 of RMI shall be deemed to satisfy the seismic force and displacement requirements of these *Provisions* if all of the following conditions are met:

1. Where determining the value of C_a in Sec. 2.7.3 of RMI, the value of C_s is taken as equal to $S_{DS}/2.5$, the value of C_v is taken as equal to S_{D1}, and the value of I_p is taken equal to the importance factor, I, determined in accordance with Sec. 14.3.5.2;
2. The value of C_s in RMI is not taken less than $0.14S_{DS}$; and
3. For storage racks supported above grade, the value of C_s in RMI is not taken less than the value determined for F_p in accordance with Sec. 6.2.6 of these *Provisions* where R_p taken equal to R, a_p taken equal to 2.5, and I_p is taken equal to the importance factor, I, determined in accordance with Sec. 14.3.5.2.

14.4 NONBUILDING STRUCTURES NOT SIMILAR TO BUILDINGS

The following nonbuilding structures usually do not have lateral and vertical seismic-force-resisting-systems that are similar to buildings and shall be designed in accordance with these *Provisions* as modified by this section and the specific references.

14.4.1 General

14.4.1.1 Loads. Loads and load distributions that are less severe than those determined in accordance with these *Provisions* shall not be used.

14.4.1.2 Redundancy. The redundancy factor, ρ, shall be permitted to be taken as 1.

14.4.2 Earth retaining structures. This section applies to all earth retaining walls. The applied seismic forces shall be based on the recommendations in a geotechnical report prepared by a registered design professional in accordance with Sec. 7.5.1.

14.4.3 Stacks and chimneys. Stacks and chimneys are permitted to be either lined or unlined, and shall be constructed of concrete, steel, or masonry.

Steel stacks, concrete stacks, steel chimneys, concrete chimneys, and liners shall be designed to resist seismic lateral forces determined from a substantiated analysis using approved standards. Interaction of the stack or chimney with the liners shall be considered. A minimum separation shall be provided between the liner and chimney equal to C_d times the calculated differential lateral drift.

14.4.4 Amusement structures. Amusement structures are permanently fixed structures constructed primarily for the conveyance and entertainment of people. Such structures shall be designed to resist seismic lateral forces determined from a substantiated analysis using approved standards.

14.4.5 Special hydraulic structures. Special hydraulic structures are structures that are within liquid-containing structures and are exposed to liquids on both wall surfaces at the same head elevation under normal operating conditions. Under earthquake excitation, such structures are subjected to out-of-plane forces which arise due to differential hydrodynamic pressures. Special hydraulic structures include separation walls, baffle walls, weirs, and other similar structures.

Special hydraulic structures shall be designed for out-of-phase movement of the fluid. Unbalanced forces from the motion of the liquid must be applied simultaneously “in front of” and “behind” these elements.

Structures subject to hydrodynamic pressures induced by earthquakes shall be designed for rigid body and sloshing liquid forces and their own inertia force. The height of sloshing shall be determined and compared to the freeboard height of the structure.

Interior elements, such as baffles or roof supports, also shall be designed for the effects of unbalanced forces and sloshing.

14.4.6 Secondary containment systems. Secondary containment systems, such as impoundment dikes and walls, shall meet the requirements of the applicable standards for tanks and vessels and any additional requirements imposed by the authority having jurisdiction.

Secondary containment systems shall be designed to withstand the effects of a maximum considered earthquake when empty and a maximum considered earthquake when full, including all hydrodynamic forces.

Sloshing of the liquid within the secondary containment area shall be considered in determining the height of the impound. The freeboard provided shall not be less than the sloshing height, δ_s, determined using Eq. 14.4-9. For circular impoundment dikes, *D* shall be the diameter of the impoundment. For rectangular impoundment dikes, *D* shall be the longer horizontal plan dimension.

14.4.7 Tanks and vessels. This section applies to all tanks, vessels, bins, silos, and similar containers storing liquids, gases, or granular solids supported at the base (hereinafter referred to as “tanks and vessels”). Tanks and vessels covered herein include those constructed of reinforced concrete, prestressed concrete, steel, and fiber-reinforced plastic materials. The supports and attachments for tanks supported on elevated levels in buildings shall be designed in accordance with Chapter 6.

14.4.7.1 Design basis. Tanks and vessels storing liquids, gases, or granular solids shall satisfy the analysis and design requirements set forth in the applicable references as indicated in Table 14.1-1 and the additional requirements of these *Provisions* including the following:

1. Damping for the convective (sloshing) force component shall be taken as 0.5 percent unless otherwise define in an adopted reference or other approved standard.
2. Impulsive and convective components may be combined by taking the square root of the sum of the squares of the components.
3. Vertical earthquake effects shall be considered in accordance with the applicable approved standard. If the approved standard permits the user the option of including or excluding the vertical earthquake effects, to comply with these *Provisions*, they shall be included. For tanks and vessels not covered by an approved standard, the forces due to the vertical acceleration shall be defined as follows:

    a. Hydrodynamic *vertical and lateral* forces in tank walls: The increase in hydrostatic pressures due to the vertical excitation of the contained liquid shall correspond to an effective increase in density, γ_L, of the stored liquid equal to $0.2S_{DS}\ \gamma_L$.

    b. Hydrodynamic *hoop* forces in cylindrical tank walls: In a cylindrical tank wall, the *hoop* force per unit height, N_h, at level *y* from the base, associated with the vertical excitation of the contained liquid, shall be computed in accordance with Eq. 14.4-1

$$N_h = 0.2 S_{DS} \gamma_L \left(H_L - y \right) \left(D_i / 2 \right). \qquad (14.4\text{-}1)$$

where:

D_i = inside tank diameter (ft)

H_L = liquid height inside the tank (ft).

y = distance from base of the tank to level being investigated (ft).

γ_L = unit weight of stored liquid (lb/ft^3)

c. Vertical *inertia* forces in cylindrical and rectangular tank walls: Vertical *inertia* forces associated with the vertical acceleration of the structure itself shall be taken equal to $0.2S_{DS}W$.

14.4.7.2 Strength and ductility. Structural components and members that are part of the lateral support system shall be designed to provide the following:

1. Connections and attachments for anchorage and other seismic-force-resisting components shall be designed to develop the lesser of the yield strength of the anchor or Ω_0 times the calculated element design load.
2. Penetrations, manholes, and openings in shell components shall be designed to maintain the strength and stability of the shell to carry tensile and compressive membrane shell forces.
3. Support towers for tanks and vessels with irregular bracing, unbraced panels, asymmetric bracing, or concentrated masses shall be designed using the provisions of Sec. 4.3.2 for irregular structures. Support towers using chevron or eccentric braced framing shall satisfy the appropriate requirements of these *Provisions*. Support towers using tension only bracing shall be designed such that the full cross section of the tension element can yield during overload conditions.
4. Compression struts that resist the reaction forces from tension braces shall be designed to resist the lesser of the yield strength of the brace (A_gF_y), or Ω_0 times the calculated tension load in the brace.
5. The vessel stiffness relative to the support system (foundation, support tower, skirt, etc.) shall be considered in determining forces in the vessel, the resisting components, and the connections.
6. For concrete liquid-containing structures, system ductility and energy dissipation under unfactored loads shall not be allowed to be achieved by inelastic deformations to such a degree as to jeopardize the serviceability of the structure. Stiffness degradation and energy dissipation shall be allowed to be obtained either through limited microcracking, or by means of lateral-force resistance mechanisms that dissipate energy without damaging the structure.

14.4.7.3 Flexibility of piping attachments. Design of piping systems connected to tanks and vessels shall consider the potential movement of the connection points during earthquakes and provide sufficient flexibility to avoid release of the product by failure of the piping system. The piping system and supports shall be designed so as not to impart significant mechanical loading on the attachment to the tank or vessel shell. Local loads at piping connections shall be considered in the design of the tank or vessel shell. Mechanical devices which add flexibility, such as bellows, expansion joints, and other flexible apparatus, may be used where they are designed for seismic displacements and defined operating pressure.

Unless otherwise calculated, the minimum displacements in Table 14.4-1 shall be assumed. For attachment points located above the support or foundation elevation, the displacements in Table 14.4-1 shall be increased to account for drift of the tank or vessel.

Table 14.4-1 Minimum Design Displacements for Piping Attachments

Condition	Displacement (in.)
Mechanically-anchored tanks and vessels:	
Upward vertical displacement relative to support or foundation	1
Downward vertical displacement relative to support or foundation	0.5
Range of displacement (radial and tangential) relative to support or foundation:	0.5
Self-anchored tanks and vessels (at grade):	
Upward vertical displacement relative to support or foundation	

If designed in accordance with an adopted reference. Anchorage ratio less than or equal to 0.785 (indicates no uplift): Anchorage ratio greater than 0.785 (indicates uplift):	1 4
If designed for seismic loads in accordance with these *Provisions* but not covered by an adopted reference: For tanks and vessels with a diameter less than 40 ft: For tanks and vessels with a diameter equal to or greater than 40 ft:	8 12
Downward vertical displacement relative to support of foundation For tanks with a ringwall/mat foundation: For tanks with a berm foundation: Range of horizontal displacement (radial and tangential) relative to support or foundation	0.5 1 2

The anchorage ratio, J, for self-anchored tanks is defined *as:*

$$J = \frac{M_{rw}}{D^2\left(w_t + w_a\right)} \qquad (14.4\text{-}2)$$

Where:

$$w_t = \frac{W_s}{\pi D} + w_{rs}$$

w_{rs} = roof load acting on the shell in pounds per foot. Only permanent roof loads shall be included. Roof live load shall not be included.

w_a = weight of annular plate participating

M_{rw} = the ringwall overturning moment due to the seismic design loads

D = tank diameter

Anchorage Ratio

J anchorage ratio	**Criteria**
J < 0.785	No uplift under the design seismic overturning moment. The tank is self anchored.
0.785 < J <1.54	Tank is uplifting, but the tank is stable for the design load providing the shell compression requirements are satisfied. Tank is self-anchored.
J > 1.54	Tank is not stable and cannot be self-anchored for the design load. Modify annular plate if L < 0.035D is not controlling or add mechanical anchors.

Where the elastic deformations are calculated, the minimum design displacements for piping attachments shall be the calculated displacements at the point of attachment increased by the amplification factor C_d.

The values given in Table 14.4-1 do not include the influence of relative movements of the foundation and piping anchorage points due to foundation movements (such as settlement or seismic displacements). The effects of foundation movements shall be included in the design of the piping system design, including the determination of the mechanical loading on the tank or vessel consideration of the total displacement capacity of the mechanical devices intended to add flexibility.

14.4.7.4 Anchorage. Tanks and vessels at grade are permitted to be designed without anchorage where they meet the requirements for unanchored tanks in approved standards. Tanks and vessels supported above grade on structural towers or building structures shall be anchored to the supporting structure.

The following special detailing requirements shall apply to steel tank anchor bolts in seismic regions where S_{DS} is greater than 0.5, or where the structure is assigned to Seismic Use Group III.

1. Hooked anchor bolts (L- or J-shaped embedded bolts) or other anchorage systems based solely on bond or mechanical friction shall not be used where S_{DS} is greater than 0.33. Post-installed anchors may be used provided that testing validates their ability to develop the yield load in the anchor when subjected to cyclic loads in cracked concrete.
2. Where anchorage is required, the anchor embedment into the foundation shall be designed to develop the minimum specified yield strength of the anchor.

14.4.7.5 Ground-supported storage tanks for liquids

14.4.7.5.1 Seismic forces. Ground-supported, flat bottom tanks storing liquids shall be designed to resist the seismic forces calculated using one of the following procedures:

1. The base shear and overturning moment calculated in accordance with Sec. 14.2.7 of these *Provisions* assuming the tank and all its contents are a rigid mass system.
2. Tanks or vessels assigned to Seismic Use Group III or with a diameter greater than 20 ft shall be designed considering the hydrodynamic pressures of the liquid in determining the equivalent lateral forces and lateral force distribution in accordance with the appropriate references listed in Table 14.1-1 and Sec. 14.4.7 of these *Provisions*.
3. The force and displacement provisions of Sec 5.2 of these *Provisions*.

The design of tanks storing liquids shall consider the impulsive and convective (sloshing) effects and consequences on the tank, foundation, and attached elements. The impulsive component corresponds to the high frequency amplified response to the lateral ground motion of the tank roof, shell, and portion of the contents that moves in unison with the shell. The convective component corresponds to the low frequency amplified response of the contents in the fundamental sloshing mode. The following definitions shall apply:

T_c = natural period of the first (convective) mode of sloshing,

T_i = fundamental period of the tank structure and impulsive component of the contents,

T_v = natural period of vertical vibration of the liquid and tank structural system,

V_i = base shear due to impulsive component from the weight of tank and its contents,

V_c = base shear due to the convective component of the effective sloshing mass,

W_i = impulsive weight (impulsive component of liquid, roof and equipment, shell, bottom and internal components).

W_c = the portion of the liquid weight sloshing.

The seismic base shear is the combination of the impulsive and convective components:

$$V = \sqrt{V_i^2 + V_c^2} \tag{14.4-3}$$

where:

$$V_i = \frac{S_{ai}}{R} W_i \tag{14.4-4}$$

$$V_c = \frac{S_{ac}}{R_c} W_c \tag{14.4-5}$$

where

R_c = the force reduction factor for the convective force = 1.5

S_{ai} = the spectral acceleration, in terms of the acceleration due to gravity, including the site impulsive components at period T_i and assuming 5 percent damping.

For $T_i \le T_s$, $S_{ai} = S_{DS}$. (14.4-6)

For $T_i > T_s$, $S_{ai} = \dfrac{S_{D1}}{T_i}$ (14.4-7)

Note: Where an adopted reference or other approved standard is used in which the spectral acceleration for the tank shell and the impulsive component of the liquid is independent of T_i, S_{ai} shall be taken equal to S_{DS}, for all cases.

S_{ac} = the spectral acceleration of the sloshing liquid based on the sloshing period T_c and assuming 0.5 percent damping.

For $T_c \le 4.0$ sec, $S_{ac} = \dfrac{1.5 S_{D1}}{T_c} \le S_{DS}$ (14.4-8)

For $T_c > 4.0$ sec, $S_{ac} = \dfrac{6 S_{D1}}{T_c^2}$ (14.4-9)

The natural period of the first (convective) mode of sloshing shall be determined using Eq. 14.4-10 as follows:

$$T_c = 2\pi \sqrt{\frac{D}{3.68 g \tanh\left(\frac{3.68H}{D}\right)}} \tag{14.4-10}$$

where D = the tank diameter, H = liquid height, and g = the acceleration due to gravity.

The general design response spectra for ground-supported liquid storage tanks is shown in Figure 14.4-1.

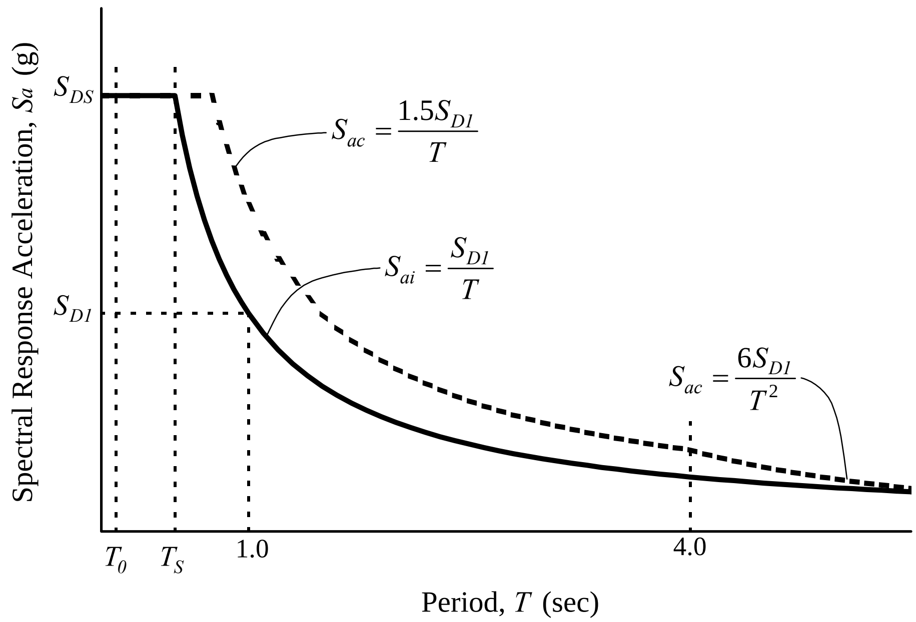

Figure 14.4-1 Design Response Spectra for Ground-supported Liquid Storage Tanks

14.4.7.5.2 Distribution of hydrodynamic and inertia forces. Unless otherwise required by the appropriate reference in Table 14.1-1, the method given ACI 350.3 may be used to determine the vertical and horizontal distribution of the hydrodynamic and inertia forces on the walls of circular and rectangular tanks.

14.4.7.5.3 Freeboard. Sloshing of the stored liquid shall be taken into account in the seismic design of tanks and vessels in accordance with the following provisions:

1. The *height of the sloshing wave*, δ_s, shall be computed using Eq. 14.4-11 as follows:

$$\delta_s = 0.5 D_i I S_{ac} \quad (14.4\text{-}11)$$

   For cylindrical tanks, D_i shall be the inside diameter of the tank; for rectangular tanks, the term D_i shall be replaced by the longer longitudinal plan dimension of the tank, L.

2. The *effects of sloshing* shall be accommodated by means of one of the following:
   - A minimum freeboard in accordance with Table 14.4-2.
   - A roof and supporting structure designed to contain the sloshing liquid in accordance with subsection 3 below.
   - For open-top tanks or vessels only, an overflow spillway around the tank or vessel perimeter.

3. If sloshing is restricted because the freeboard provided is less than the computed sloshing height, the roof in the vicinity of the roof-to-wall joint shall be permitted to be designed for an equivalent *hydrostatic* head equal to the computed sloshing height less the freeboard provided.
   In addition, the design of the tank shall take into account the fact that a portion of the confined convective (sloshing) mass becomes part of the impulsive mass in proportion to the degree of confinement.

Table 14.4-2 Minimum Required Freeboard [a]

Value of S_{DS}	Seismic Use Group		
	I	II	III
$S_{DS} < 0.167$	— [b]	— [b]	δ_s
$0.167 \leq S_{DS} < 0.33$	— [b]	— [b]	δ_s
$0.33 \leq S_{DS} < 0.50$	— [b]	$0.7\delta_s$	δ_s
$0.50 \leq S_{DS}$	— [b]	$0.7\delta_s$	δ_s

[a] The noted freeboard is required unless one of the following conditions is satisfied:

1. Secondary containment in accordance with Sec. 14.4.6 is provided to control the product spill.
2. The roof and supporting structure are designed to contain the sloshing liquid.

[b] No minimum freeboard is required.

14.4.7.5.4 Equipment and attached piping. Equipment, piping, and walkways or other appurtenances attached to the structure shall be designed to accommodate the displacements imposed by seismic forces. For piping attachments, see Sec. 14.4.7.3.

14.4.7.5.5 Internal components. The attachments of internal equipment and accessories that are attached to the primary liquid or pressure retaining shell or bottom, or provide structural support for major components (such as a column supporting the roof rafters) shall be designed for the lateral loads due to the sloshing liquid in addition to the inertial forces.

14.4.7.5.6 Sliding resistance. The transfer of the total lateral shear force between the tank or vessel and the subgrade shall be considered as follows:

1. For unanchored, flat-bottom steel tanks, the overall horizontal seismic shear force shall be resisted by friction between the tank bottom and the foundation or subgrade. Unanchored storage tanks must be designed such that sliding will not occur when the tank is full of stored product. The maximum calculated seismic base shear, V, shall not exceed $N \tan(30°)$.

   N shall be determined using the effective weight of the tank, roof, and contents, after reduction for vertical earthquake effects. Values of the friction factor lower than tan(30°) should be used if the condition at the bottom of the tank (such as a leak detection membrane beneath the bottom with a lower friction factor, smooth bottoms, etc.) is not consistent with such a friction value.

2. No additional lateral anchorage is required for anchored steel tanks designed in accordance with approved standards.
3. The lateral shear transfer behavior for special tank configurations (such as shovel bottoms, highly crowned tank bottoms, or tanks on grillage) can be unique and is beyond the scope of these *Provisions*.

14.4.7.5.7 Local shear transfer. Local transfer of the shear from the roof to the wall and for the wall of the tank into the base shall be considered. For cylindrical tanks and vessels, the peak local tangential shear per unit length shall be calculated using Eq. 14.4-12 as follows:

$$V_{max} = \frac{2V}{\pi D} \tag{14.4-12}$$

Shear transfer shall be accomplished as follows:

1. Tangential shear in flat-bottom steel tanks shall be transferred through the welded connection to the steel bottom. This transfer mechanism is deemed acceptable where S_{as} is less than 1.0 and the tank is designed in accordance with the approved standards.

2. For concrete tanks with a sliding base where the lateral shear is resisted by friction between the tank wall and the base, the friction coefficient shall not exceed tan(30 degrees).

3. In fixed-base or hinged-base concrete tanks, the total horizontal seismic base shear is transferred to the foundation by a combination of membrane (tangential) shear and radial shear. For anchored flexible-base concrete tanks, the majority of the base shear is resisted by membrane (tangential) shear through the anchoring system with only insignificant vertical bending in the wall. The connection between the wall and floor shall be designed to resist the maximum tangential shear.

14.4.7.5.8 Pressure stability. For steel tanks, the internal pressure from the stored product stiffens thin cylindrical shell structural elements subjected to membrane compression forces. This stiffening effect may be considered in resisting seismically induced compressive forces if permitted by the approved standard or the authority having jurisdiction.

14.4.7.5.9 Shell support. Steel tanks resting on concrete ring walls or slabs shall have a uniformly supported annulus under the shell. Uniform support shall be provided by one of the following methods:

1. Shimming and grouting the annulus,
2. Using fiberboard or other suitable padding,
3. Using butt-welded bottom or annular plates resting directly on the foundation, or
4. Using closely spaced shims (without structural grout) provided that the localized bearing loads are considered in the design of the tank wall and foundation so as to prevent local crippling and spalling.

Anchored tanks shall be shimmed and grouted. Local buckling of the steel shell for the peak compressive force due to operating loads and seismic overturning shall be considered.

14.4.7.5.10 Repair, alteration, or reconstruction. Repairs, modifications, or reconstruction (such as cut-down and re-erection) of a tank or vessel shall comply with industry standard practice and these *Provisions*. For welded steel tanks storing liquids, see API 653 and the adopted reference in Table 14.1-1. Tanks that are relocated shall be re-evaluated for the seismic loads for the new site and the requirements of new construction in accordance with the appropriate approved standard and these *Provisions*.

14.4.7.6 Water and water treatment tanks and vessels

14.4.7.6.1 Welded steel. Welded steel water storage tanks and vessels shall be designed in accordance with the seismic requirements of AWWA D100 except that the sloshing height shall be calculated in accordance with Sec 14.4.7.5.3 (rather than using Eq. 13-26 of AWWA D100) and design input forces shall be modified as follows:

1. The impulsive and convective components of the base shear for allowable stress design procedures shall be determined using the following equations, which shall be substituted into Eq. 13-4 and 13-8 of AWWA D100:

   For $T_s < T_c < 4.0$ sec, $V_i = \dfrac{S_{DS} I}{1.4R} W_i$ and $V_c = \dfrac{S_{DS} I}{1.4RT_c}$

   For $T_c \geq 4.0$ sec, $V_c = \dfrac{6S_{DS} I}{1.4R} \dfrac{T_s}{T_c^2} W_c$

2. In Eq. 13-4, 13-8, and 13-20 through 13-25 of AWWA D100, the following changes shall be made:

   $\dfrac{ZI}{R_w}$ shall be replaced by $\dfrac{S_{DS} I}{2.5(1.4R)}$, and

   the term S shall be replaced by the term B.

Where S_{DS} and T_S, are determined in accordance with Chapter 3, R is determined in accordance with Sec. 14.2.4, and B is determined as follows:

For $T_s < T_c < 4.0$ sec, $B = 1.11T_s$

For $T_c \geq 4.0$ sec, $B = 1.25T_s$

Thus, Eq. 13-4 of AWWA D100, for base shear at the bottom of the tank shell, becomes

$$V_{ACT} = \frac{18S_{DS}I}{2.5(1.4R)}\left[0.14\left(W_s + W_r + W_f + W_1\right) + BC_1W_2\right]$$

Alternatively,

For $T_s < T_c < 4.0$ sec, $V_{ACT} = \frac{S_{DS}I}{1.4R}\left[\left(W_s + W_r + W_f + W_1\right) + 1.5\frac{T_s}{T_c}W_2\right]$

For $T_s \geq 4.0$ sec, $V_{ACT} = \frac{S_{DS}I}{1.4R}\left[\left(W_s + W_r + W_f + W_1\right) + 6\frac{T_s}{T_c^2}W_2\right]$

Similarly, Eq. 13-8 of AWWA D100, for overturning moment applied to the bottom of the tank shell, becomes

$$M = \frac{18S_{DS}I}{2.5(1.4R)}\left[0.14\left(W_sX_s + W_rH_t + W_1X_1\right) + BC_1W_2X_2\right]$$

14.4.7.6.2 Bolted steel. Bolted steel water storage structures shall be designed in accordance with the seismic requirements of AWWA D103 except that the design input forces shall be modified in the same manner as shown in Sec 14.4.7.6.1 of these *Provisions*.

14.4.7.6.3 Reinforced and prestressed concrete. Reinforced and prestressed concrete tanks shall be designed in accordance with the seismic requirements of ACI 350.3 except that the design input forces shall be modified as follows:

1. For $T_i < T_0$ or $T_i > T_s$, the following terms shall be replaced by $\frac{S_aI}{1.4R}$:

   For shear and overturning moment equations of AWWA D110 and AWWA D115, $\frac{ZIC_1}{R_1}$, and

   For base shear and overturning moment equations of ACI 350.3, $\frac{ZISC_1}{R_i}$.

2. For $T_o \leq T_i \leq T_s$, $\frac{ZIC_i}{R_1}$ and $\frac{ZISC_i}{R_i}$ shall be replaced by $\frac{S_{DS}I}{1.4R}$.

3. For all values of T_c (or T_w), $\frac{ZIC_c}{R_c}$ and $\frac{ZISC_c}{R_c}$ shall be replaced by $\frac{6S_{D1}I}{T_c^2}$ or $\frac{6S_{DS}I}{T_c^2}T_s$.

Thus, for $T_o \leq T_i \leq T_s$,

Eq. 4-1 of AWWA D110 becomes $V_I = \frac{S_{DS}I}{1.4R}\left(W_s + W_R + W_I\right)$, and

Eq. 4-2 of AWWA D110 becomes $V_c = \frac{6S_{DS}I}{1.4R}\left(\frac{T_s}{T_c^2}\right)W_c$.

Where S_a, S_{D1}, S_{DS}, T_0, and T_s are determined in accordance with Chapter 3 of these *Provisions*.

14.4.7.7 Petrochemical and industrial tanks and vessels storing liquids

14.4.7.7.1 Welded steel. Welded steel petrochemical and industrial tanks and vessels storing liquids shall be designed in accordance with the seismic requirements of API 650 and API 620 except that the design input forces shall be modified as indicated in this section.

Where using the equations in Sec. E.3 of API 650, the following substitutions shall be made in the equation for overturning moment *M*:

For $T_o < T_i \leq T_s$ 4.0 sec, $M = S_{DS} I \left[0.24 \left(W_s X_s + W_t H_t + W_1 X_1 \right) + 0.80 C_2 T_s W_2 X_2 \right]$, and

$$C_2 = \frac{0.75S}{T_c} \text{ and } S = 1.0$$

For $T_c > 4.0$ sec, $M = S_{DS} I \left[0.24 \left(W_s X_s + W_t H_t + W_1 X_1 \right) + 0.71 C_2 T_s W_2 X_2 \right]$, and

$$C_2 = \frac{3.375S}{T_c^2} \text{ and } S = 1.0 .$$

Where S_{DS} and T_s are determined in accordance with Chapter 3 of these *Provisions*.

14.4.7.7.2 Bolted steel. Bolted steel tanks used for storage of production liquids are designed in accordance with API 12B, which covers the material, design, and erection requirements for vertical, cylindrical, above-ground, bolted tanks in nominal capacities of 100 to 10,000 barrels for production service. Unless required by the authority having jurisdiction, these temporary structures need not be designed for seismic loads. If design for seismic load is required, the loads may be adjusted for the temporary nature of the anticipated service life.

14.4.7.7.3 Reinforced and prestressed concrete. Reinforced concrete tanks for the storage of petrochemical and industrial liquids shall be designed in accordance with the force requirements of Sec. 14.4.7.6.3.

14.4.7.8 Ground-supported storage tanks for granular materials

14.4.7.8.1 Design considerations. In determining the effective mass and load paths, consideration shall be given to the intergranular behavior of the material as follows:

1. Increased lateral pressure (and the resulting hoop stress) due to loss of the intergranular friction of the material during the seismic shaking,
2. Increased hoop stresses resulting from temperature changes in the shell after the material has been compacted, and
3. Intergranular friction that can transfer seismic shear directly to the foundation.

14.4.7.8.2 Lateral force determination. The lateral forces for tanks and vessels storing granular materials at grade shall be determined using the requirements and accelerations for short period structures.

14.4.7.8.3 Force distribution to shell and foundation

14.4.7.8.3.1 Increased lateral pressure. The increase in lateral pressure on the tank wall shall be added to the static design lateral pressure but shall not be used in the determination of pressure stability effects on the axial buckling strength of the tank shell.

14.4.7.8.3.2 Effective mass. A portion of a stored granular mass will act with the shell (the effective mass). The effective mass is related to the physical characteristics of the product, the height-to-diameter (*H/D*) ratio of the tank and the intensity of the seismic event. The effective mass shall be used to determine the shear and overturning loads resisted by the tank.

14.4.7.8.3.3 Effective density. The effective density factor (that part of the total stored mass of product that is accelerated by the seismic event) shall be determined in accordance ACI 313.

14.4.7.8.3.4 Lateral sliding. For granular storage tanks that have a steel bottom and are supported such that friction at the bottom to foundation interface can resist lateral shear loads, no additional anchorage to prevent sliding is required. For tanks without steel bottoms (that is, where the material rests directly on the foundation), shear anchorage shall be provided to prevent sliding.

14.4.7.8.3.5 Combined anchorage systems. If separate anchorage systems are used to prevent overturning and sliding, the relative stiffness of the systems shall be considered in determining the load distribution.

14.4.7.8.4 Welded steel. Welded steel granular storage structures shall be designed for seismic forces determined in accordance with these *Provisions*. Component allowable stresses and materials shall be in accordance with AWWA D100, except that the allowable circumferential membrane stresses and material requirements in API 650 shall apply.

14.4.7.8.5 Bolted steel. Bolted steel granular storage structures shall be designed for seismic forces determined in accordance with these *Provisions*. Component allowable stresses and materials shall be in accordance with AWWA D103.

14.4.7.8.6 Reinforced and prestressed concrete. Reinforced and prestressed concrete structures for the storage of granular materials shall be designed for seismic forces determined in accordance with these *Provisions* and shall satisfy the requirements of ACI 313.

14.4.7.9 Elevated tanks and vessels for liquids and granular materials. This section applies to tanks, vessels, bins, and hoppers that are elevated above grade where the supporting tower is an integral part of the structure, or where the primary function of the tower is to support the tank or vessel. Tanks and vessels that are supported within buildings or are incidental to the primary function of the tower are considered mechanical equipment and shall be designed in accordance with Chapter 6 of these *Provisions*.

Elevated tanks shall be designed to satisfy the force and displacement requirements of the applicable approved standard, or these *Provisions*.

14.4.7.9.1 Effective mass. The design of the supporting tower or pedestal, anchorage, and foundation for seismic overturning shall assume the material stored is a rigid mass acting at the volumetric center of gravity. The effects of fluid-structure interaction may be considered in determining the forces, effective period, and mass centroids of the system if the following requirements are met:

1. The sloshing period, T_c is greater than $3T$ where T is the natural period of the tank (with the contents assumed to be rigid) and supporting structure.
2. The sloshing mechanism (percentage of convective mass and centroid) is determined for the specific configuration of the container by detailed fluid-structure interaction analysis or testing.
3. Soil-structure interaction in accordance with Sec. 5.6 may be included in determining T.

14.4.7.9.2 P-delta effects. The lateral drift of the elevated tank shall be considered as follows:

1. For evaluating the additional load in the support structure due to P-delta effects, the design drift shall be computed as the elastic lateral displacement at the center of gravity of the stored mass times the deflection amplification factor, C_d.
2. The base of the tank shall be assumed to be fixed rotationally and laterally.
3. Deflections due to bending, axial tension, or compression shall be considered. For pedestal tanks with a height-to-diameter ratio less than 5, shear deformations of the pedestal shall be considered.
4. The dead load effects of roof-mounted equipment or platforms shall be included in the analysis.

5. If constructed within the plumbness tolerances specified in the approved standard, initial tilt need not be considered in the P-delta analysis.

14.4.7.9.3 Transfer of lateral forces into support tower. For post-supported tanks and vessels that are cross-braced:

1. The bracing shall be installed in such a manner as to provide uniform resistance to the lateral load (such as pre-tensioning or tuning to attain equal sag).
2. The additional load in the brace due to the eccentricity between the post-to-tank attachment and the line of action of the bracing shall be included.
3. Eccentricity of compression strut lines of action with their attachment points shall be considered.
4. The connection of the post or leg with the foundation shall be designed to resist both the vertical and lateral resultant from the yield load in the bracing assuming the direction of the lateral load is oriented to produce the maximum lateral shear at the post-to-foundation interface. Where multiple rods are connected to the same location, the anchorage shall be designed to resist the concurrent tensile loads in the braces.

14.4.7.9.4 Evaluation of structures sensitive to buckling failure. Shell structures that support substantial loads may exhibit a primary mode of failure from localized or general buckling of the support pedestal or skirt during seismic loads. Such structures may include single pedestal water towers, skirt-supported process vessels, and similar single member towers. Where the structural assessment concludes that buckling of the support is the governing primary mode of failure, structures and components assigned to Seismic Use Group III shall be designed to resist the seismic forces as follows:

1. The seismic response coefficient for this evaluation shall be determined in accordance with Sec. 5.2.1.1 with *R/I* taken equal to 1.0. Soil-structure and fluid-structure interaction may be included when determining the structural response. Vertical or orthogonal combinations need not be considered.
2. The resistance of the structure or component shall be defined as the critical buckling resistance of the element with a factor of safety taken equal to 1.0.
3. The anchorage and foundation shall be designed to resist the load determined in item 1. The foundation shall be proportioned to provide a stability ratio of 1.2 for the overturning moment. The maximum toe pressure under the foundation shall not exceed the lesser of the ultimate bearing capacity or 3 times the allowable bearing capacity. All structural components and elements of the foundation shall be designed to resist the combined loads with a load factor of 1.0 on all loads, including dead load, live load, and earthquake load. Anchors shall be permitted to yield.

14.4.7.9.5 Welded steel. Welded steel elevated water storage structures shall be designed and detailed in accordance with the seismic requirements of AWWA D100 and these *Provisions* except that in using Eq. 13-1 and 13-3 of AWWA D100 S shall be taken equal to 1.0 and the term shall be replaced by the following:

For $T < T_s$, $\dfrac{S_{DS}I}{1.4R}$,

For $T_s \le T \le 4.0$ sec, $\dfrac{S_{D1}I}{T(1.4R)}$, and

For $T > 4.0$ sec, $\dfrac{S_{D1}I}{T^2(1.4R)}$.

14.4.7.9.5.1 Analysis procedures. The equivalent lateral force procedure may be used. A more rigorous analysis shall be permitted. Analysis of single pedestal structures shall be based on a fixed-base, single degree-of-freedom model. All mass, including the contents, shall be considered rigid unless the sloshing mechanism (percentage of convective mass and centroid) is determined for the specific configuration of the container by detailed fluid-structure interaction analysis or testing. Soil-structure interaction may be included.

14.4.7.9.5.2 Structure period. The fundamental period of vibration of the structure shall be established using the structural properties and deformational characteristics of the resisting elements in a substantiated analysis. The period used to calculate the seismic response coefficient shall not exceed 4.0 seconds. See AWWA D100 for guidance on computing the fundamental period of cross-braced structures.

14.4.7.9.6 Concrete pedestal (composite) tanks. Concrete pedestal (composite) elevated water storage structures shall be designed in accordance with the requirements of ACI 371 except that the design input forces shall be modified as follows:

1. In Eq. 4-8a of ACI 371,

   For $T_s \leq T \leq 4.0$ sec, $\frac{1.2C_v}{RT^{2/3}}$ shall be replaced by $\frac{S_{D1}I}{TR}$, and

   For T > 4.0 sec, $\frac{1.2C_v}{RT^{2/3}}$ shall be replaced by $\frac{4S_{D1}I}{T^2R}$.

2. In Eq. 4-8b of ACI 371, $\frac{2.5C_a}{R}$ shall be replaced by $\frac{S_{DS}I}{R}$.

3. In Eq. 4-9 of ACI 371, $0.5C_a$ shall be replaced by $0.2S_{DS}$.

14.4.7.9.6.1 Analysis procedures. The equivalent lateral force procedure may be used for all structures and shall be based on a fixed-base, single-degree-of-freedom model. All mass, including that of the contents, shall be considered rigid unless the sloshing mechanism (percentage of convective mass and centroid) is determined for the specific configuration of the container by detailed fluid-structure interaction analysis or testing. Soil-structure interaction may be included. A more rigorous analysis is permitted.

14.4.7.9.6.2 Structure period. The fundamental period of vibration of the structure shall be established using the uncracked structural properties and deformational characteristics of the resisting elements in a properly substantiated analysis. The period used to calculate the seismic response coefficient shall not exceed 2.5 seconds.

14.4.7.10 Boilers and pressure vessels. Supports and attachments for boilers and pressure vessels shall be designed to satisfy the requirements of Chapter 6 and the additional requirements of this section. Boilers and pressure vessels assigned to Seismic Use Group II or III shall be designed to satisfy the force and displacement requirements of Chapter 6.

14.4.7.10.1 ASME boilers and pressure vessels. Boilers and pressure vessels designed and constructed in accordance with ASME BPV shall be deemed to satisfy the seismic force and relative displacement requirements of these *Provisions* provided that the forces and displacements defined in Chapter 6 are used in lieu of the seismic forces and displacements defined in ASME BPV.

14.4.7.10.2 Attachments of internal equipment and refractory. Attachments to the pressure boundary for internal and external ancillary components (refractory, cyclones, trays, etc.) shall be designed to resist the seismic forces in these *Provisions* to safeguard against rupture of the pressure boundary. Alternatively, the element attached to the boiler or pressure vessel may be designed to fail prior to damaging the pressure boundary provided that the pressure boundary is not jeopardized as a consequence of the failure. For boilers or vessels containing liquids, the effect of sloshing on the internal equipment shall be considered if the equipment can damage the pressure boundary.

14.4.7.10.3 Coupling of vessel and support structure. Where the mass of the operating vessel or vessels supported is greater than 25 percent of the total mass of the combined system, the coupling of the masses shall be considered. Coupling with adjacent, connected structures such as multiple towers shall be considered if the structures are interconnected with elements that will transfer loads from one structure to the other.

14.4.7.10.4 Effective mass. Fluid-structure interaction (sloshing) shall be considered in determining the effective mass of the stored material provided that sufficient liquid surface exists for sloshing to occur and the sloshing period, T_c, is greater than $3T$. Changes to or variations in material density with pressure and temperature shall be considered.

14.4.7.10.5 Other boilers and pressure vessels. Boilers and pressure vessels that are assigned to Seismic Use Group III but are not designed and constructed in accordance with the requirements of ASME BPV shall satisfy the following requirements:

1. Provision shall be made to eliminate seismic impact for components vulnerable to impact, for components constructed of nonductile materials, and in cases where material ductility will be reduced due to service conditions (such as low temperature applications).
2. The design strength for seismic loads in combination with other service loads and appropriate environmental effects (such as corrosion) shall be based on the material properties indicated in Table 14.4-3.

Table 14.4-3 Design Material Properties

Material type	Minimum ratio of F_u/F_y	Design material strength	
		Vessel	Threaded Connection [a]
Ductile (such as steel, aluminum, or copper)	1.33 [b]	$0.9F_y$	$0.7F_y$
Semi-ductile	1.2 [c]	$0.7F_y$	$0.5F_y$
Nonductile (such as cast iron, ceramics, or fiberglass)	NA	$0.25F_u$	$0.20F_u$

[a] Threaded connection to vessel or support system.
[b] Minimum 20 percent elongation per the appropriate ASTM material specification.
[c] Minimum 15 percent elongation per the appropriate ASTM material specification.

14.4.7.10.6 Supports and attachments for boilers and pressure vessels. Supports for boilers and pressure vessels and attachments to the pressure boundary shall satisfy the following requirements:

1. Supports and attachments transferring seismic loads shall be constructed of ductile materials suitable for the intended application and environmental conditions.
2. Seismic anchorages embedded in concrete shall be ductile and detailed for cyclic loads.
3. Seismic supports and attachments to structures shall be designed and constructed so that the support or attachment remains ductile throughout the range of reversing seismic lateral loads and displacements.
4. In the design of vessel attachments, consideration shall be given to the potential effects on the vessel and the support due to uneven vertical reactions based on variations in relative stiffness of the support members, dissimilar details, non-uniform shimming, or irregular supports and uneven distribution of lateral forces based on the relative distribution of the resisting elements, the behavior of the connection details, and vessel shear distribution.

The requirements of Sec. 14.4.7.9.4 shall apply.

14.4.7.11 Liquid and gas spheres. Supports and attachments for liquid and gas spheres shall be designed to satisfy the requirements of Chapter 6 and the additional requirements of this section. Spheres assigned to Seismic Use Group II or III shall be designed to satisfy the force and displacement requirements of Chapter 6.

14.4.7.11.1 ASME spheres. Spheres designed and constructed in accordance with Division VIII of ASME BPV shall be deemed to satisfy the seismic force and relative displacement requirements of these *Provisions* provided that the forces and displacements defined in Chapter 6 are used in lieu of the seismic forces and displacements defined in ASME BPV.

14.4.7.11.2 Attachments of internal equipment and refractory. Attachments to the pressure or liquid boundary for internal and external ancillary components (refractory, cyclones, trays, etc.) shall be designed to resist the seismic forces in these *Provisions* to safeguard against rupture of the pressure boundary. Alternatively, the element attached to the sphere may be designed to fail prior to damaging the pressure or liquid boundary provided that the pressure boundary is not jeopardized as a consequence of the failure. For spheres containing liquids, the effect of sloshing on the internal equipment shall be considered if the equipment can damage the pressure boundary.

14.4.7.11.3 Effective mass. Fluid-structure interaction (sloshing) shall be considered in determining the effective mass of the stored material provided that sufficient liquid surface exists for sloshing to occur and the sloshing period, T_c, is greater than $3T$. Changes to or variations in fluid density shall be considered.

14.4.7.11.4 Post and rod supported. For post supported spheres that are cross-braced:

1. The requirements of Sec. 14.4.7.9.3 shall apply.
2. The stiffening effect (reduction in lateral drift) of pre-tensioning of the bracing shall be considered in determining the natural period.
3. The slenderness and local buckling of the posts shall be considered.
4. Local buckling of the sphere shell at the post attachment shall be considered.
5. For spheres storing liquids, bracing connections shall be designed and constructed to develop the minimum published yield strength of the brace. For spheres storing gas vapors only, bracing connections shall be designed for Ω_0 times the maximum design load in the brace. Lateral bracing connections directly attached to the pressure or liquid boundary are prohibited.

14.4.7.11.5 Skirt supported. For skirt supported spheres, the following requirements shall apply:

1. The requirements of Section 14.4.7.9.4 shall apply.
2. The local buckling of the skirt under compressive membrane forces due to axial load and bending moments shall be considered.
3. Penetrations of the skirt support (manholes, piping, etc.) shall be designed and constructed so as to maintain the strength of the skirt without penetrations.

14.4.7.12 Refrigerated gas liquid storage tanks and vessels. The seismic design of the tanks and facilities for the storage of liquefied hydrocarbons and refrigerated liquids is beyond the scope of this section. The design of such tanks is addressed in part by various product and industry standards. See Commentary Sec. 14.1.2.2.

> **Exception:** Low-pressure, welded steel storage tanks for liquefied hydrocarbon gas (such as LPG or butane) and refrigerated liquids (such as ammonia) may be designed in accordance with the requirements of Sec. 14.4.7.7 and API 620.

14.4.7.13 Horizontal, saddle-supported vessels for liquid or vapor storage. Horizontal vessels supported on saddles shall be designed to satisfy the force and displacement requirements of Chapter 6.

14.4.7.13.1 Effective mass. Changes to or variations in material density shall be considered. The design of the supports, saddles, anchorage, and foundation for seismic overturning shall assume the material stored is a rigid mass acting at the volumetric center of gravity.

14.4.7.13.2 Vessel design. Unless a more rigorous analysis is performed:

1. A horizontal vessel with a length-to-diameter ratio of 6 or more may be assumed to be a simply supported beam spanning between the saddles for the purposes of determining the natural period of vibration and global bending moment.
2. For horizontal vessels with a length-to-diameter ratio of less than 6, the effects of "deep beam shear" shall be considered where determining the fundamental period and stress distribution.
3. Local bending and buckling of the vessel shell at the saddle supports due to seismic load shall be considered. The stabilizing effects of internal pressure shall not be considered to increase the buckling resistance of the vessel shell.
4. If the vessel is a combination of liquid and gas storage, the vessel and supports shall be designed both with and without gas pressure acting (assume piping has ruptured and pressure does not exist).