UPCOMING CHANGES TO SEISMIC DESIGN CRITERIA - 2000

by

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Introduction

National design standards first began to include procedures for the design of liquid storage tanks to resist earthquakes in the 1970's. The basic design standards and codes for tanks focused on providing better details and structural resistance based on observed behavior and problems. This evolution in the design standards has reduced both the frequency and the severity of problems with liquid storage tanks when they are exposed to ground motion.

The goal of seismic design criteria for engineers and code writers is first and foremost the safety of the public. To accomplish this, the approach has often been directed at preventing collapse or catastrophic failure. The performance or serviceability of the structure exposed to after shocks, minimizing property damage, or surviving the "big one" has not been incorporated into today's building codes. Early methods, which are still in use today by most liquid storage tank standards, are based on a prescribed earthquake load measured against an allowable stress in the components of the structural system.

Since engineers first began to consider lateral loads from ground motion in the design of structures, the fundamental basis of the design load has changed very little. The methods for establishing the level of seismic ground motion and accelerations has continued to be defined into four basic zones that roughly approximated an event with a return interval of 475 years. As maps were developed, the boundaries were often skewed to fit local political or jurisdictional issues. New parameters to consider the influence of the type of soil, the importance of the structure to post-earthquake society, and the ductility of different types of structural systems and materials were added to the methods as knowledge increased. As a result of impending changes to seismic design criteria, structures in many areas of the country will have to be designed to withstand a much more severe seismic event. This is particularly true of structures east of the Rocky Mountains.

Several changes either have been made or will be incorporated into earthquake design standards such as the 1997 National Earthquake Hazard Reduction Program (NEHRP) Provisions, ASCE 7, and the upcoming International Building Code 2000, which is intended to replace UBC, SBC, and BOCA.

Owners and operators of liquid storage tanks should factor these changes into their facility upgrade and operational readiness planning. It is often practical and economical for existing tanks and vessels to be upgraded to these new seismic criteria in order to remain compliant with the governing building code. However, retrofits patterned after building-type structure solutions are expensive and often not suitable for tanks and vessels. A seismic retrofit of a storage tank should begin with a thorough evaluation of the existing structure, with particular attention to tank details that may be susceptible to damage in an earthquake. A structural engineer experienced in the behavior of tanks and knowledgeable in details used in tank construction should perform the design of the retrofit. Properly retrofitted, many tanks—whether of steel or concrete—can offer significant continued service life and not endanger public safety during a seismic event.

Defining the Seismic Hazard for Design

The goals of seismic criteria for the design and construction of structures in present day standards are to

- minimize the hazard to life,
- increase the expected performance of structures with a greater importance or hazard to the public,

- to improve the capability of structures essential for the welfare of the public after an earthquake.

Present standards do not explicitly limit the level of damage and repair costs or the suitability for continued service.

The definition of the seismic load considered by the proposed codes and standards is based on buildings, where most of the investigation and research has focused. The design loads for nonbuilding structures have traditionally been derived from buildings. The seismic load level is defined from the following major elements.

Level of Risk

The 1997 NEHRP Provisions are intended to serve as one of the source documents for use by groups developing model building codes and voluntary standards. The seismic provisions in the pending International Building Code 2000 are derived from the 1997 NEHRP Provisions, 97 UBC, SEAOC, and ASCE 7 publications. Prior seismic design requirements for most building and nonbuilding structures were based on a hazard defined with a 10% probability of exceedence (PE) in 50 years (a return internal of 475 years). Some nonbuilding structures such as nuclear facilities and refrigerated gas storage structures are designed for Safe Shutdown Earthquake with a much longer return period. During the development of the NEHRP Provisions, it was believed that the 10%PE was generally appropriate for defining seismic risk for sites in the western US. However, it is believed to be inadequate for many eastern US locations that historically have had fewer earthquakes with much longer return intervals. Consequently, the 1997 NEHRP Provisions adopted a 2% probability of exceedence in 50 years (a return period of approximately 2000 years). The USGS developed contour maps of the US based on 2%PE for short period and 1 second period accelerations using the latest attenuation models and known faults. These maps are included in NEHRP and proposed IBC 2000.

If the accelerations associated with the 2%PE are used directly for design, the seismic magnitudes would be about 150% of the 10%PE magnitudes in present design standards. To avoid increasing the magnitude of the seismic design accelerations, a factor of 2/3 was introduced to scale the mapped values to a design level that closely approximates the present codes.

In addition to the probabilistic based mapping, USGS and the 1997 NEHRP provisions also developed a deterministic approach for “near fault” zones. In several regions of the US where major faults are known to exist, the near fault models are used to define a rational design load.

Comparison of the old UBC type contour maps and the new NEHRP / IBC 2000 maps yield several distinct differences:

- The IBC maps do not use zones to define the ground accelerations.
- Many areas in the eastern US that were considered exempt from seismic design now have a seismic ground acceleration defined.
- The maps are independent of political jurisdictions (although that may changed during the code adoption process).
- In many regions, especially near faults, the mapped accelerations are steeply contoured and significantly higher than previous maps.
- The impulsive accelerations are typically larger than previous codes and standards (sometimes significantly larger).

Local soil and site influences

The influence of the soil characteristics continues to play a very significant role in determining the design accelerations. Data from recent earthquakes has been incorporated into the site factors of the NEHRP and ASCE 7 provisions. Comparison of design levels for older codes with the pending criteria often yields higher design values than expected, often due to the soil factors. A geotechnical evaluation and classification of the site is one of the most important pieces of information needed by the design professional, whether it is new construction or evaluating existing structures for modifications or upgrades.

The following table is an excerpt from the Final Draft of the proposed IBC 2000. It clearly illustrates the potential impact that soil considerations may have on determining the seismic design loads. If no soil information is available to support classification, Site D must be assumed.

TABLE 1615.1.2-1
VALUES OF SITE COEFFICIENT F_a AS A FUNCTION OF SITE CLASS AND MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIODS (S_s)

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIODS				
	$S_s \le 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \ge 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	a
F	Note a	Note a	Note a	Note a	Note a

NOTE: Use straight line interpolation for intermediate values of mapped spectral acceleration at short period, S_s.
* Site specific geotechnical investigation and dynamic site response analyses shall be performed to determine appropriate values.

TABLE 1615.1.2-2
VALUES OF SITE COEFFICIENT F_v AS A FUNCTION OF SITE CLASS AND MAPPED SPECTRAL RESPONSE ACCELERATION AT 1 SECOND PERIOD (S_1)

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT 1 SECOND PERIOD				
	$S_1 \le 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \ge 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	a
F	Note a	Note a	Note a	Note a	Note a

NOTE: Use straight line interpolation for intermediate values of mapped spectral acceleration at 1 second period, S_1.
Site-specific geotechnical investigation and dynamic site response analyses shall be performed to determine appropriate values.

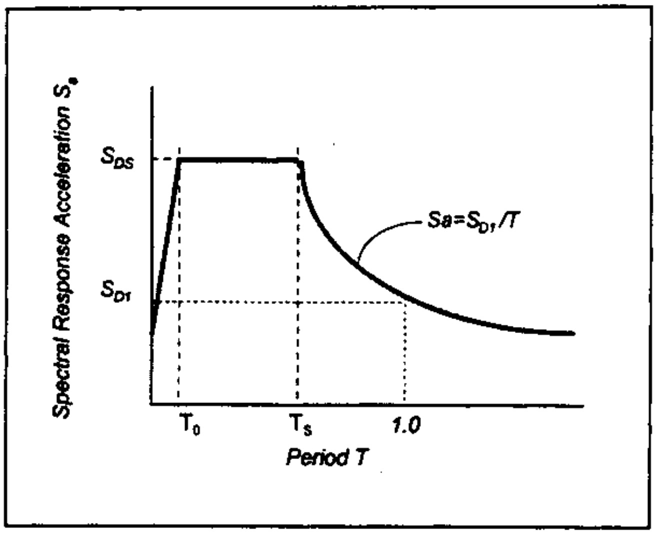


FIGURE 4.1.2.6 Design response spectrum.

System response

The design response spectra curve is also being defined in terms of the two acceleration values- S_{d1} and S_{DS}, which include modification factors for soil, F_v and F_a. The shape of the response curve is similar to the historically used curve. However, for tanks and vessels designed to AWWA or API standards, there may be significant differences in the magnitudes for the portion of the response spectra beyond Ts. The criteria in the AWWA D100 and API 650 standards is based on Ts =1, where the proposed criteria bases Ts on the ratio of Sds and Sd1. This has significant impact on the magnitude of the convective forces for some locations and tank configurations.

Minimum loads are also required in the proposed IBC 2000. For nonbuilding systems that have an R value provided, the minimum specified value shall be replaced by

$$C_s = 0.14S_{DS}I$$

Or,

$$C_s = 0.8S_1I/R$$

For tanks and vessels, the approved national standard loads are the minimum loads permitted.

Nonbuilding Structure Type	R	Ω_0	C_d	Structural System and Height Limits (ft)[c]			
				Seismic Design Category			
				A & B	C	D	E & F
Flat bottom, ground supported tanks, or vessels:							
Anchored (welded or bolted steel)	3	2	2-1/2	NL	NL	NL	NL
Unanchored (welded or bolted steel)	2-1/2	2	2	NL	NL	NL	NL
Reinforced or prestressed concrete:							
Tanks with reinforced nonsliding *base*	2	2	2	NL	NL	NL	NL
Tanks with anchored flexible *base*	3	2	2	NL	NL	NL	NL
Tanks with unanchored and unconstrained:							
Flexible *base*	1-1/2	1-1/2	1-1/2	NL	NL	NL	NL
Other material	1 -/2	1-1/2	1-1/2	NL	NL	NL	NL

Level of performance

Buildings are designed to protect occupants inside the structure whereas nonbuilding structures may need to be designed in a special manner because they pose a different sort of risk to public safety (e.g., they may contain very hazardous compounds or be essential components in critical lifeline systems); or, they may be of no risk at all to the public. For example, tanks and vessels may contain materials that are essential for lifeline functions following a seismic event (e.g., fire fighting, potable water), potentially harmful or hazardous to the environment or general health of the public, biologically lethal or toxic, or explosive or flammable (threat of consequential or secondary damage). For nonbuilding structures, an Importance Factor (I) is defined based on the material stored and the function of the structure. See below:

Importance Factor (*I*) and Seismic Use Group Classification for Nonbuilding Structures

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

H - I The stored product is biologically or environmentally benign; low fire or low physical hazard.

H - II The stored product is rated low explosion, moderate fire, or moderate physical hazard as determined by the authority having jurisdiction.

H - III The stored product is rated high or moderate explosion hazard, high fire hazard, or high physical hazard as determined by the authority having jurisdiction.

F - I *Nonbuilding structures* not classified as F - III.

F - II Not applicable.

F - III *Seismic use group III nonbuilding structures* or designated ancillary *nonbuilding structures* (such as communication towers, fuel storage tanks, cooling towers, or electrical substation *structures*) required for operation of *Seismic Use Group* III *structures*.

The most common damage to tanks observed during past earthquakes include:

- Buckling of the tank shell near the base due to excessive axial membrane forces. This buckling damage is usually evident as an “elephant foot” buckle a short distance above the base in large diameter tanks, or as diamond shaped buckles in the lower ring of tanks with an H/D or 1 or more. Buckling of the upper ring has also been observed in some tanks.
- Damage to the roof due to sloshing liquid impinging on the underside of the roof in tanks with insufficient freeboard.
- Failure of piping or other attachments that are overly restrained.
- Foundation failures.

Small diameter tanks and vessels are more susceptible to overturning and vertical buckling. As a general rule, the greater the ratio of H/D, the lower its resistance is to vertical buckling. When H/D > 2, the overturning begins to approach “rigid mass” behavior (the sloshing mass is small). Large diameter tanks may be governed by additional hydrodynamic hoop stresses in the middle regions of the shell.

The performance of floating roofs typically used in the petroleum industry during earthquakes has been good with damage usually confined to the rim seals, gage poles, and ladders. Similarly the performance of an open top with top wind girder stiffeners designed per API 650 has been good.

The following performance categories are being proposed for the 2000 NEHRP Provisions:

Proposed Performance Criteria NEHRP 2000

Category	Minimum post-earthquake performance
I	The structure shall be permitted to sustain localized damage, including minor leaks, provided (a) such damage remains localized and does not propagate; and (b) the resulting leakage does not pose a threat to the public or to adjoining Category I, II or III structures.
II	The structure shall be permitted to sustain minor damage, and its operational systems or components (valves and controls) shall be permitted to become inoperative, provided that (a) the structure retains its ability to contain 100% of its contents; and (b) the structure’s minor damage and the failure of its operational systems or components are not accompanied by, or lead to, leakage.
III	The structure shall be permitted to sustain minor damage provided that (a) it shall retain its ability to contain 100% of its contents without leakage; and (b) its operational systems or components shall remain fully operational.
IV	The structure shall be permitted to fail provided the resulting spill does not pose a threat to the public or to adjoining Category I, II, or III structures.

Piping flexibility is an important part of the leak tightness of the tank system. The following criteria from NEHRP are included in the proposed IBC 2000.

TABLE 14.7.3.5 Minimum **Displacements for Piping Attachments**

Anchored Tanks or Vessels	Displacements (inches)
Vertical *displacement* relative to support or foundation.	2
Horizontal (radial and tangential) relative to support or foundation.	0.5
Unanchored Tanks or Vessels (at grade)	
Vertical *displacement* relative to support or foundation. If designed to meet approved standard. If designed for seismic loads per these provisions but not covered by an approved standard. For tanks and vessels with a diameter <40 ft, horizontal (radial and tangential) relative to support or foundation.	 6 12 8

Strength and Ductility

Structural components and members that are part of the lateral support system (which includes the tank, anchorage and foundation) should be designed to provide the following (excerpt from NEHRP):

a. Connections and attachments for anchorage and other lateral force resisting components shall be designed to develop the strength of the connected member (e.g., minimum published yield strength, F_y in direct tension, plastic bending moment), or Ω_o times the calculated element design load.

b. Penetrations, manholes, and openings in shell components shall be designed to maintain the capacity and stability of the shell to carry tensile and compressive membrane shell forces.

c. Support towers for tanks and vessels with irregular bracing, unbraced panels, asymmetric bracing, or concentrated masses shall be designed using the provisions of 1997 NEHRP Sec. 5.2.3 for irregular structures. Support towers using chevron or eccentric braced framing shall comply with the requirements of 1997 NEHRP Sec. 5. Support towers using tension only bracing shall be designed such that the full cross section of the tension element can yield during overload conditions.

d. Compression struts that resist the reaction forces from tension braces shall be designed to resist the lesser of the yield load of the brace ($A_g F_y$), or Ω_0 times the calculated tension load in the brace.

e. 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.

f. For concrete liquid-containing structures, system ductility and energy dissipation under nonfactored loads shall not be allowed to be achieved by excursions into the inelastic range 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.

Additionally, "hooked anchor bolts" (L or J type bolts) or other anchorage systems based solely on bond or mechanical friction should not be used. They cannot usually develop the yield force in the bolt.

Freeboard is another important performance consideration of the performance of ground storage tanks in past earthquakes has indicated that sloshing of the contents can cause leakage and damage to the roof and internal components. While the effect of sloshing often involves only the cost and inconvenience of making repairs, not catastrophic failure, even this limited damage can be prevented or significantly mitigated when the following aspects are considered:

1. Effective masses and hydro-dynamic forces in the container.
2. Impulsive and pressure loads.
    a. Sloshing zone (i.e. the upper shell and edge of roof system).
    b. Internal supports (roof support columns, tray-supports, etc.).
    c. Equipment (distribution rings, access tubes, pump wells, risers, etc.).
3. Freeboard (depends on the sloshing wave height).

Tanks and vessels storing biologically or environmentally benign materials do not typically require freeboard to protect the public health and safety. However, providing freeboard in areas of frequent seismic occurrence for vessels normally operated at or near top capacity may lessen damage (and the cost of subsequent repairs) to the roof and upper container.

The estimate given in the NEHRP Provisions is based on a median response spectrum rather than on the one standard deviation response spectra. Estimates for the sloshing height contained in national standards are based on the one standard deviation spectra applied at a working stress level.

Aboveground Storage Tank Model

The design of tanks storing liquids usually considers 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.

Methods of seismic design of tanks, currently adopted by a number of industry standards have evolved from earlier analytical work by Jacobsen, Housner, Veletsos, Haroun, and others. The procedures used to design flat bottom storage tanks and liquid containers are based on the work of Housner and Wozniak and Mitchell (1978). The AWWA and API standards for tanks and vessels have specific requirements to safeguard against catastrophic failure of the primary structure based on observed behavior in seismic events since the 1930s.

These methods entail these fundamental steps:

1 The dynamic modeling of the structure and its contents. When a liquid-filled tank is subjected to a ground acceleration, the lower portion of the contained liquid, identified as the impulsive component of mass W_I, acts as if it were a solid mass rigidly attached to the tank wall.

2 Under the influence of the same ground acceleration, the upper portion of the contained liquid responds as if it were a solid liquid mass flexibly attached to the tank wall. This portion, which oscillates at its own natural frequency, is identified as the convective component W_c. The convective component oscillations are characterized by the phenomenon of sloshing whereby the liquid surface rises above the static level on one side of the tank, and drops below that level on the other.

3 The determination of the period of vibration of the tank structure and impulsive mass (the impulsive component); and the natural period of the sloshing or convective component. The impulsive period (the natural period of the tank components and the impulsive component of the liquid is typically in the 0.25 to 0.6 second range. Many methods are available for calculating the impulsive period. Many tank designers commonly use the Veletsos flexible shell method. (See: *Seismic Effects in Flexible Liquid Storage Tanks*, A.S. Veletsos). The convective period is typically 2.5 seconds or more for common tank configurations.

4 The selection of the design response spectrum. The response spectrum may be site-specific; or it may be constructed deterministically on the basis of seismic coefficients given in national codes and standards. Once the design response spectrum is constructed, the spectral accelerations corresponding to the periods are obtained and are used to calculate the dynamic forces.

In addition to the AWWA and API Standards, ACI Committee 350 has drafted a document, ACI 350.3, titled *"ACI Practice for the Seismic Design of Liquid-Containing Structures."* This document, which covers all types of concrete tanks (prestressed and non-prestressed, circular and rectilinear), is currently being revised to conform to the seismic risk guidelines of NEHRP 1997 and IBC 2000. This ACI *"Practice"* will serve as a practical, "how-to" - and yet rigorous - guide to supplement Chapter 21 (*"Special Provisions for Seismic Design"*) of ACI 350.

Changes Needed To National Design Standards

1. The trend in structural design is to load–resistance-factor (LRFD) concepts rather than the allowable stress (ASD) based methods. Unfortunately many nonbuilding structures are designed to national industry standard that continue to use ASD. Nonbuilding structures are categorized into those that are building-like, and those that are not building- like. Tanks and vessels obviously fall into the latter.
2. An evaluation of whether criteria based on buildings is the proper approach for tanks and vessels.
3. Evaluation of "R" factors.
4. Evaluation of "I" (importance factors) based on overall system performance criteria in lifeline systems.
5. Evaluation of past research to determine if the rigid tank methods should be replaced by more accurate, but complex methods for determining hydrodynamic pressures, anchorage and overturning.
6. Review of anchorage provisions.
7. Review of membrane shell resistance to axial load (i.e. buckling) provisions.
8. Require conformance with industry standards when a tank or vessel is repaired, modified or reconstructed (i.e. cut down and re-erect).

APPENDIX

Application of IBC and NEHRP to Tanks

Excerpt from Proposed NEHRP 2000 Provision

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

$$V = V_i + V_c$$

Where,
$$Vi = \frac{S_{ai} W_i}{R} \text{ and } Vc = \frac{S_{ac} W_c}{R}$$

S_{ai} = the spectral acceleration as a multiplier of gravity including the site impulsive components at period T_i and 5% damping

For $T_i < T_s$: $S_{ai} = S_{DS}$

For $T_i > T_s$: $S_{ai} = \frac{S_{D1}}{T_i}$

Note: When an approved national standard is used in which the spectral acceleration for the tank shell, and the impulsive component of the liquid is independent of Ti, then $S_{ai} = S_{DS}$.

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

For T_c < 4.0 sec, $S_{ac} = \frac{1.5 S_{D1}}{T_c}$

For T_c of 4.0 sec or greater, $S_{ac} = \frac{6 S_{D1}}{T_c^2}$

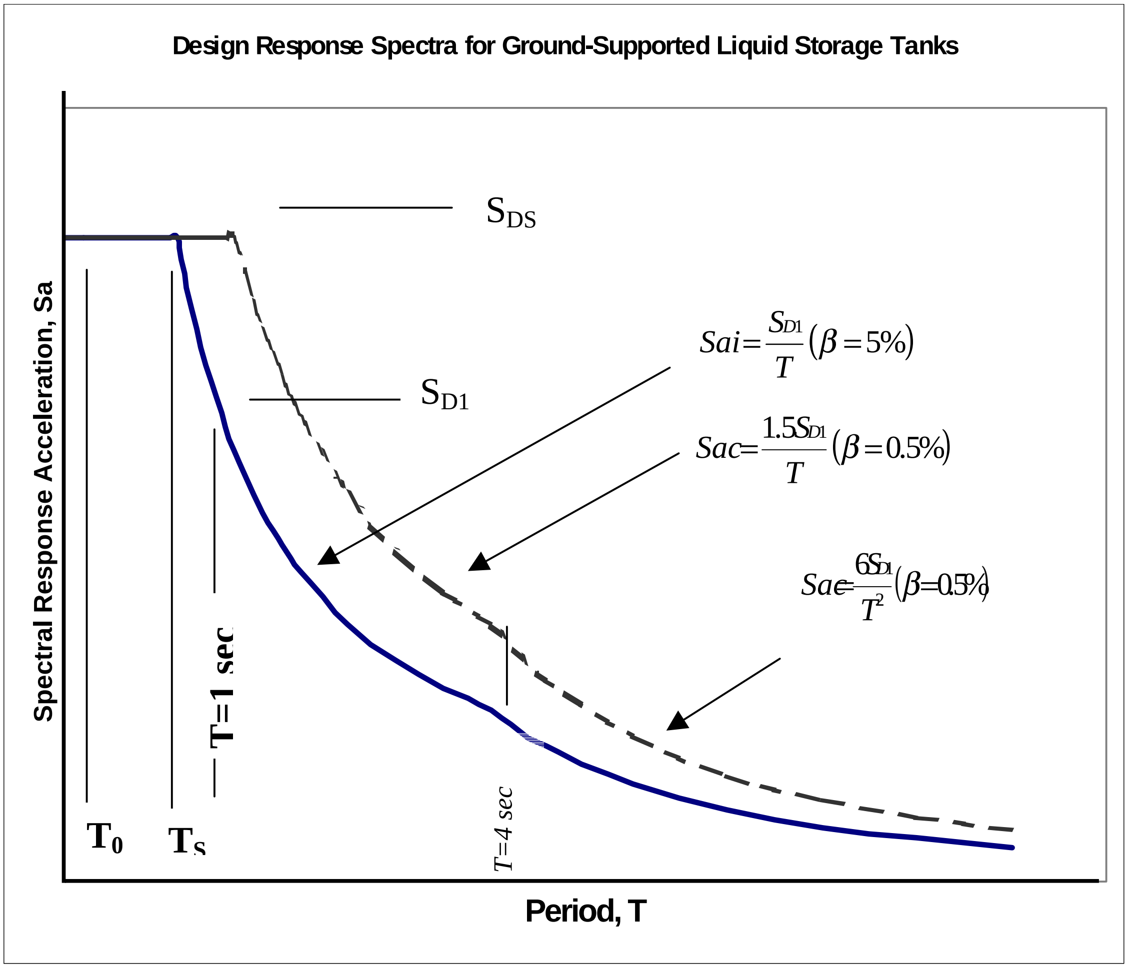
$$T_c = 2\pi \sqrt{\frac{D}{3.68g \tanh\left(\frac{3.68H}{D}\right)}}$$

where, D = the tank diameter in feet, H = liquid height (feet or meters) and g = acceleration due to gravity in consistent units.

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 general design response spectra for ground-supported liquid storage tanks is shown.



Distribution of Hydrodynamic and Inertia Forces: Unless otherwise required by the appropriate approved standard in Table 14.3, 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.

Freeboard: Sloshing of the liquid within the tank or vessel shall be considered in determining the freeboard required above the top capacity liquid level. A minimum freeboard shall be provided per Table 14.7.3.7.1.2. The height of the sloshing wave can be estimated by:

$$\delta_s = 0.50DIS_{ac}$$

Minimum Required Freeboard

Seismic Use Group		
I	**II**	**III**
See note a	*See note a*	δs *(see note c)*
See note a	*See note a*	δs *(see note c)*
See note a	$0.7\delta s$ *(see note b)*	δs *(see note c)*
See note a	$0.7\delta s$ *(see note b)*	δs *(see note c)*

a A freeboard of $0.7\delta_s$ is recommended for economic considerations but not required.

b A freeboard equal to $0.7\delta_s$ is required unless one of the following alternatives are provided:

1. Secondary containment is provided to control the product spill.
2. The roof and supporting *structure* are designed to contain the sloshing liquid.

c Freeboard equal to the calculated wave height, δ_s, is required unless one of the following alternatives are provided:

1. Secondary containment is provided to control the product spill.
2. The roof and supporting *structure* are designed to contain the sloshing liquid.

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 Section 14.7.3.5.

Internal Components: The *attachments* of internal equipment and accessories which are attached to the primary liquid or pressure retaining shell or bottom, or provide structural support for major *components* (e.g., a column supporting the roof rafters) shall be designed for the lateral loads due to the sloshing liquid in addition to the inertial forces. See Wozniak and Mitchell 1978.

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

a. 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:

$$V_s \leq V \tan 30^o$$

V shall be determined using the effective weight of the tank, roof and contents after reduction for coincident vertical earthquake. Lower values of the friction factor should be used if the design of bottom to supporting foundation does not justify the friction value above (e.g., leak detection membrane beneath the bottom with a lower friction factor, smooth bottoms, etc).

b. No additional lateral anchorage is required for anchored steel tanks designed in accordance with approved standards.

c. The lateral shear transfer behavior for special tank configurations (e.g., shovel bottoms, highly crowned tank bottoms, tanks on grillage) can be unique and are beyond the scope of these provisions.

Local shear transfer: Local transfer of the shear from the *roof* to the *wall* and 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 by:

$$V_{max} = \frac{2V}{\pi D}$$

a. Tangential shear in flat bottom steel tanks shall be transferred through the welded connection to the steel bottom. This transfer mechanism is deemed acceptable for steel tanks designed in accordance with the approved standards and $S_{as} < 1.0g$.

b. 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^o.

c. Fixed-*base* or hinged-*base* concrete tanks, transfer the horizontal seismic *base shear* is shared by membrane (tangential) shear and radial shear into the foundation. 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.

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 building official having jurisdiction.

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:

a. Shimming and grouting the annulus,

b. Using fiberboard or other suitable padding

c. Using butt-welded bottom or annular plates resting directly on the foundation,

d. Using closely spaced shims (without structural grout) provided that the localized bearing loads are considered in the tank wall and foundation 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.

Repair, Alteration or Reconstruction: Repairs, modifications, or reconstruction (i.e. cut down and re-erect) of a tank or vessel shall conform to industry standard practice and these Provisions. For welded steel tanks storing liquids, see API 653 and the approved national standard in Table 14.3. 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 national standard and these Provisions.

Water and Water Treatment Tanks and Vessels:

Welded Steel: Welded steel water storage tanks and vessels shall be designed in accordance with the seismic requirements of AWWA D100 except that the design input forces shall be modified as follows:

The impulsive and convective components of the base shear are defined by the following equations for allowable stress design procedures:

$$V_i = \frac{S_{DS} I}{1.4R} W_i$$

For $T_s < T_c < 4.0$ sec,

$$V_c = \frac{S_{DS} I}{1.4R} \frac{T_s}{T_c} W_c$$

For T_c of 4.0 sec or greater,

$$V_c = \frac{6 S_{DS} I}{1.4R} \frac{T_s}{T_c^2} W_c$$

a. Substitute the above parameters into Eqns (13-4) and (13-8) of AWWA D100. Substitute the expression $\frac{S_{DS}I}{2.5(1.4R)}.....for.....\frac{ZI}{R_w}$ and substitute the term "B" for the term "S" in these equations in AWWA D100,

where S_{DS} and T_S, are defined in Section 4.1.2.5
R is defined in Table 14.2.1.1
$B = 1.25\ T_S$, when T_C is in the range $T_S < T_C \leq 4.0$ secs.
$B = 1.11\ T_S$, when T_C is >4.0 secs

Thus, equation (13-4) for base shear at the bottom of the tank shell in AWWA D100 becomes

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

Alternatively,

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

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

Similarly, equation (13-8) for overturning moment applied to the bottom of the tank shell in AWWA D100 becomes

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

b. The hydrodynamic seismic hoop tensile stress is defined in Equation (13-20) through (13-25) in AWWA D100. When using these equations, make the following substitution directly into the equations.

$$\frac{S_{DS}I}{2.5(1.4R)}.....for.....\left[\frac{ZI}{R_w}\right]$$

Sloshing height shall be calculated per Sec 14.7.3.7.1.2 instead of (Eq 13-26) of AWWA D100.

14.7.3.8.2 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 shown in Sec 14.7.3.8.1 of these Provisions.

14.7.3.8.3 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:

a. For $T_I < T_o$, and $T_I > T_s$, :

Substitute the term $\frac{SaI}{1.4R}$,where S_a is defined in Section 4.1.2.6, subsections 1, 2, or 3 or (4.1.2.6-3), for the terms in the appropriate equations as shown below:

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

- for $\frac{ZISC_i}{R_i}$ in the base shear and overturning moment equations of ACI 350.3

b. For $T_o \le T_I \le T_s$, :

Substitute the term $\frac{S_{DS}I}{1.4R}$ for terms $\frac{ZIC_1}{R_1}$ and $\frac{ZISC_i}{R_i}$

c. For all values of T_C (or T_w):

$$\frac{ZIC_c}{R_c} \text{ and } \frac{ZISC_c}{R_c} \text{ are replaced by } \frac{6S_{D1}I}{Tc^2} ...or... \left[\frac{6S_{DS}I}{Tc^2}T_S\right]$$

Thus, for $T_o \le T_I \le T_s$, Eq. (4-1) of AWWA D110 becomes

$$V_I = \frac{S_{DS}I}{1.4R}(W_s + W_R + W_I)$$

and Eq. (4-2) becomes

$$V_C = \frac{6S_{DS}I}{1.4R}\left(\frac{T_s}{T_c^2}\right)W_C$$

S_a, S_{D1}, S_{DS}, T_0, and T_s are defined in Sect. 4.1.2.6 of these Provisions

Petrochemical and Industrial Tanks and Vessels Storing Liquids:

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 follows:

a. When using the equations in Section E.3 of API 650, substitute into the equation for overturning moment M (where S_{DS} and T_s are defined in Section 4.1.2.5 of these Provisions). Thus,

In the range $T_s < T_C \le 4.0$ sec

$$M = S_{DS}I\left[0.24(W_sX_s + W_tH_t + W_1X_1) + 0.80C_2T_sW_2X_2\right]$$

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

In the range $T_w > 4.0$ sec,

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

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

Bolted Steel: Bolted steel tanks used for storage of production liquids. API 12B covers the material, design and erection requirements for vertical, cylindrical, aboveground, bolted tanks in nominal capacities of 100 to 10,000 barrels for production service. Unless required by the building official 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.

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. 14.7.3.8.3.

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Elevated Tanks and Vessels for Liquids and Granular Materials:

General: 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 for the force and *displacement* requirements of the applicable approved standard, or Sec 14.2.

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:

a. The sloshing period, T_c is greater than 3T, where T = natural period of the tank with confined liquid (rigid mass) and supporting *structure*.

b. The sloshing mechanism (i.e. the 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 in determining T providing the provisions of Sec 2.5 are met.

***P*-Delta effects:** The lateral drift of the elevated tank shall be considered as follows:

a. The design drift, the elastic lateral *displacement* of the stored mass center of gravity shall be increased by the factor, C_d for evaluating the additional load in the support *structure*.

b. The *base* of the tank shall be assumed to be fixed rotationally and laterally

c. 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.

d. The *dead load* effects of roof mounted equipment or platforms shall be included in the analysis.

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

Transfer of Lateral Forces into Support Tower: For post supported tanks and vessels that are cross braced:

b. The bracing shall be installed in such a manner as to provide uniform resistance to the lateral load (e.g. pre-tensioning or tuning to attain equal sag).

c. 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.

d. Eccentricity of compression strut line of action (*elements* that resist the tensile pull from the bracing rods in the lateral force resisting systems) with their attachment points shall be considered.

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.

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 in Seismic Use Group III shall be designed to resist the seismic forces as follows:

a. The seismic response coefficient for this evaluation shall be per Sec 5.3.2.1 of these provisions with I/R set equal to 1.0. Soil-structure and fluid-structure interaction may be utilized in determining the structural response. Vertical or orthogonal combinations need not be considered.

b. The resistance of the structure or component shall be defined as the critical buckling resistance of the element; i.e. a factor of safety set equal to 1.0

c. The anchorage and foundation shall be designed to resist the load determined in (a). 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 ultimate bearing capacity or the lesser of 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.

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 the design input forces shall be modified by substituting the following terms for $\frac{ZIC}{R_w}$ into (Eqn 13-1) and (Eqn 13-3) of AWWA D100 and set the value for S =1.0.

$T \leq T_s$:	substitute the term $\frac{S_{DS}I}{1.4R}$
$T_s < T \leq 4.0$ sec:	substitute the term $\frac{S_{D1}I}{T(1.4R)}$
$T > 4.0$ sec.:	substitute the term $\frac{4S_{D1}I}{T^2(1.4R)}$

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 liquid, shall be considered rigid unless the sloshing mechanism (i.e. the 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.

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 sec. See AWWA D100 for guidance on computing the fundamental period of cross braced structures.

Concrete Pedestal (Composite) Tanks: Concrete pedestal (composite) elevated water storage *structures* shall be designed in accordance with the requirements of ACI 371 and except that the design input forces shall be modified as follows:

In equation 4-8a of ACI 371,

$T_s < T \leq 4.0$ sec: substitute the term $\dfrac{S_{D1}I}{TR}$ for $\dfrac{1.2C_v}{RT^{2/3}}$

$T > 4.0$ sec: substitute the term $\dfrac{4S_{D1}I}{T^2R}$ for $\dfrac{1.2C_v}{RT^{2/3}}$

In equation 4-8b of ACI 371,

substitute the term $\dfrac{S_{DS}I}{R}$ for $\dfrac{2.5C_a}{R}$

In equation 4-9 of ACI 371,

substitute the term $0.2S_{DS}$ for $0.5C_a$

Analysis Procedures: The equivalent lateral force procedures may be. A more rigorous analysis is permitted. 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 the liquid, shall be considered rigid unless the sloshing mechanism (i.e. the 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.

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 sec.