Table 15.7-1. Minimum Design Displacements for Piping Attachments.

Condition	Minimum Design Displacement, in. (mm)
Mechanically Anchored Tanks and Vessels	
Upward vertical displacement relative to support or foundation	1 (25.4)
Downward vertical displacement relative to support or foundation	0.5 (12.7)
Range of horizontal displacement (radial and tangential) relative to support or foundation	0.5 (12.7)
Self-Anchored Tanks or Vessels (at Grade)	
Upward vertical displacement relative to support or foundation:	
If designed in accordance with a reference document as modified by this standard:	
Anchorage ratio less than or equal to 0.785 (indicates no uplift)	1 (25.4)
Anchorage ratio greater than 0.785 (indicates uplift)	4 (101.1)
If designed for seismic loads in accordance with this standard but not covered by a reference document:	
For tanks and vessels with diameter less than 40 ft (12.2 m)	8 (202.2)
For tanks and vessels with diameter equal to or greater than 40 ft (12.2 m)	12 (0.305)
Downward vertical displacement relative to support or foundation:	
For tanks with a ringwall/mat foundation	0.5 (12.7)
For tanks with a berm foundation	1 (25.4)
Range of horizontal displacement (radial and tangential) relative to support or foundation	2 (50.8)

Table 15.7-2. Anchorage Ratio.

Anchorage Ratio, J	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, provided that the shell compression requirements are satisfied. The tank is self-anchored.
$J > 1.54$	Tank is not stable and shall be mechanically anchored for the design load.

The anchorage ratio, J, for self-anchored tanks shall comply with the criteria shown in Table 15.7-2 and is defined as

$$J = \frac{M_{rw}}{D^2(w_t + w_a)} \tag{15.7-2}$$

where

$$w_t = \frac{W_s}{\pi D} + w_r \tag{15.7-3}$$

w_r = Roof load acting on the shell [lb/ft (N/m)] of shell circumference. Only permanent roof loads shall be included. Roof live load shall not be included;
w_a = Maximum weight of the tank contents that may be used to resist the shell overturning moment [lb/ft (N/m)] of shell circumference (w_a usually consists of an annulus of liquid limited by the bending strength of the tank bottom or annular plate);
M_{rw} = Overturning moment applied at the bottom of the shell caused by the seismic design loads [ft-lb (N-m)] (also known as the ringwall moment);
D = Tank diameter, ft (m), [ft (m)]; and
W_s = Total weight of tank shell [lb (N)].

15.7.5 Anchorage Tanks and vessels at grade are permitted to be designed without anchorage where they meet the requirements for self-anchored tanks in reference documents. Tanks and vessels supported above grade on structural towers or building structures shall be anchored to the supporting structure.

For the anchorage of steel tanks and vessels with a diameter or width greater than 5 ft (1.5 m) or a height greater than 10 ft (3.0 m) in Seismic Design Category B, anchorage shall be designed in accordance with Section 15.4.9.

For the anchorage of steel tanks and vessels with a diameter or width greater than 5 ft (1.5 m) or a height greater than 10 ft (3.0 m) in Seismic Design Categories C, D, E, and F, all of the following special detailing requirements shall apply:

(a) Anchorage shall be in accordance with Section 15.4.9.1, whereby the anchor embedment into the concrete shall be designed to develop the steel strength of the anchor in tension in accordance with ACI 318 Section, 17.10.5.3 (a), as given by ACI 318, Equation (17.6.1.2), or shall be designed using anchor reinforcement in accordance with ACI 318, Section 17.4.2.9, to develop the steel strength of the anchor in tension per ACI 318, Equation (17.6.1.2).
(b) The minimum gauge length of anchor rod, which is the length over which its elongation can occur, shall be at least eight times the rod diameter.
(c) Post-installed anchors are permitted to be used in accordance with Section 15.4.9.3, provided the anchor embedment into the concrete is sufficient to develop the steel strength of the anchor rod in tension.
(d) Where the special detailing requirements of this section apply, the load combinations of Section 12.4.3 that include overstrength do not apply.

For steel tanks and vessels with a diameter or width less than or equal to 5 ft (1.5 m) and a height less than or equal space to 10 ft (3.0 m) in Seismic Design Categories C, D, E, and F, anchorage shall be in accordance with Section 15.4.9.

15.7.6 Ground-Supported Storage Tanks for Liquids

15.7.6.1 General Ground-supported, flat-bottom tanks storing liquids shall be designed to resist the seismic forces as follows:

(a) For tanks or vessels storing liquids with a diameter or width less than or equal to 5 ft (1.5 m), the base shear and overturning moment shall be calculated as if the tank and the entire contents act as an impulsive mass, using Equation (15.7-5). The convective mass shall be set equal to zero in Equation (15.7-6). The lateral force distribution shall be per API 650, API 620, AWWA D100, AWWA D110, AWWA D115, or ACI 350.3. The requirements of Section 15.7, including Section 15.7.6.2, shall apply.

(b) Tanks or vessels storing liquids with a diameter or width greater than 5 ft (1.5 m) shall be designed to consider the hydrodynamic pressures of the liquid in determining the equivalent lateral forces and lateral force distribution per the applicable reference documents listed in Chapter 23. The requirements of Section 15.7 including 15.7.6.2 shall apply.

15.7.6.2 Design Basis The design of tanks storing liquids shall consider the impulsive and convective (sloshing) effects and their 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, the shell, and the 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. Damping for the convective component shall be 0.5% for the sloshing liquid unless otherwise defined by the reference document. The following definitions shall apply:

D_i = Inside diameter of tank or vessel;
H_L = Design liquid height inside the tank or vessel;
L = Inside length of a rectangular tank, parallel to the direction of the earthquake force being investigated;
N_h = Hydrodynamic hoop force per unit height in the wall of a cylindrical tank or vessel;
T_c = Natural period of the first (convective) mode of sloshing;
T_i = Fundamental period of the tank structure and impulsive component of the content;
V_i = Base shear caused by impulsive component from weight of tank and contents;
V_c = Base shear caused by the convective component of the effective sloshing mass;
y = Distance from base of the tank to level being investigated; and
γ_L = Unit weight of stored liquid.

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

$$V = V_i + V_c \tag{15.7-4}$$

where

$$V_i = \frac{S_{ai} W_i}{\left(\frac{R}{I_e}\right)} \tag{15.7-5}$$

and

$$V_c = \frac{S_{ac} I_e}{1.5} W_c \tag{15.7-6}$$

where

W_i = Impulsive weight (impulsive component of liquid, roof and equipment, shell, bottom, and internal elements);
W_c = Portion of the liquid weight sloshing; and
S_{ai} = Spectral acceleration as a multiplier of gravity, including the site impulsive components at period T_i and 5% damping. For $T_i \le T_s$,

$$S_{ai} = S_{DS} \tag{15.7-7}$$

For $T_s < T_i \le T_L$,

$$S_{ai} = \frac{S_{D1}}{T_i} \tag{15.7-8}$$

For $T_i > T_L$,

$$S_{ai} = \frac{S_{D1} T_L}{T_i^2} \tag{15.7-9}$$

NOTES:

1. Where a reference document is used in which the spectral acceleration for the tank shell and the impulsive component of the liquid are independent of T_i, then $S_{ai} = S_{DS}$.
2. S_{ai} determined from Equations (15.7-8) and (15.7-9) shall not be less than the minimum values required in Section 15.4.1,
Item 2, multiplied by R/I_e.
3. Impulsive and convective seismic forces for tanks are permitted to be combined using the SRSS method in lieu of the direct sum method shown in Section 15.7.6 and its related subsections.

S_{ac} = Spectral acceleration of the sloshing liquid (convective component), based on the sloshing period T_c and 0.5% damping.

For $T_c \le T_L$,

$$S_{ac} = \frac{1.5 S_{D1}}{T_c} \le S_{DS} \tag{15.7-10}$$

For $T_c > T_L$,

$$S_{ac} = \frac{1.5 S_{D1} T_L}{T_c^2} \tag{15.7-11}$$

EXCEPTIONS:

1. Where the design spectral acceleration parameter, S_a, determined in accordance with either Section 11.4.5.1 or Chapter 21 is available, the value of S_{ai} determined by Equation (15.7-7), (15.7-8), or (15.7-9) is permitted to be taken as the value of S_a at the period T_i. Where the period T_i is less than the period at which S_a is maximum, the maximum value of S_a shall be used. The value of S_{ai} shall not be less than the minimum values required in Section 15.4.1, Item 2, multiplied by R/I_e. When Exception 1 is invoked, the value of S_{ac} must be determined using Exception 2.
2. Where the design spectral acceleration parameter, S_a, determined in accordance with either Section 11.4.5.1 or Chapter 21 is available, the value of S_{ac} determined by Equation (15.7-10) or (15.7-11) is permitted to be taken as 1.5 times the value of S_a at the period T_c. The value of 1.5 S_{ac} need not exceed the maximum value of S_a. When Exception 2 is invoked, the value of S_{ai} must be determined using Exception 1.
3. For $T_c > 4$ s, S_{ac} is permitted to be determined by a site-specific study using one or more of the following methods: (a) the procedures in Chapter 21, provided such procedures, which rely on ground-motion attenuation equations for computing response spectra, cover the natural period band containing T_c; (b) ground-motion simulation methods that use seismological models of fault rupture and wave

propagation; and (c) analysis of representative strong-motion accelerogram data with reliable long-period content extending to periods greater than T_c. Site-specific values of S_{ac} shall be based on one-standard-deviation determinations. However, in no case shall the value of S_{ac} be taken as less than the value determined in accordance with Equation (15.7-11) using 50% of the mapped value of T_L from Chapter 22.

The 80% limit on S_a required by Sections 21.3 and 21.4 shall not apply to the determination of site-specific values of S_{ac}, which satisfy the requirements of this exception. In determining the value of S_{ac}, the value of T_L shall not be less than 4 s, where

$$T_c = 2\pi\sqrt{\frac{D}{3.68\ g\tanh\left(\frac{3.68\ H}{D}\right)}} \qquad (15.7\text{-}12)$$

where

D = Tank diameter, ft (m), [ft (m)],
H = Liquid height, ft (m), [ft (m)], and
g = Acceleration caused by gravity in consistent units.

15.7.6.2.1 Distribution of Hydrodynamic and Inertial Forces Unless otherwise required by the appropriate reference document listed in Chapter 23, the method given in ACI 350.3 is permitted to be used to determine the vertical and horizontal distribution of the hydrodynamic and inertial forces on the walls of circular and rectangular tanks.

15.7.6.2.2 Sloshing Sloshing of the stored liquid shall be taken into account in the seismic design of tanks and vessels in accordance with the following requirements:

(a) The height of the sloshing liquid, δ_s, above the product design height shall be computed using Equation (15.7-13):

$$\delta_s = 0.42 D_i I_e S_{ac} \qquad (15.7\text{-}13)$$

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

(b) For tanks in Risk Category IV, the Importance Factor, I_e, used for freeboard determination only, shall be taken as 1.0.

(c) For tanks in Risk Categories I, II, and III, the value of T_L used for freeboard determination is permitted to be set equal to 4 s. The value of the Importance Factor, I_e, used for freeboard determination for tanks in Risk Categories I, II, and III shall be determined from Table 1.5-1.

(d) The effects of sloshing shall be accommodated by means of one of the following:
1. A minimum freeboard in accordance with Table 15.7-3,
2. A roof and supporting structure designed to contain the sloshing liquid in accordance with Subsection (e),
3. Secondary containment is provided to control the product spill, or
4. For open-top tanks or vessels only, an overflow spillway around the tank or vessel perimeter.

EXCEPTION: No minimum freeboard is required for open-top tanks where the following conditions are met:
1. Contained fluid is not toxic, explosive, or highly toxic and has been approved by the Authority Having Jurisdiction as acceptable for product spill.
2. Site-specific product spill prevention, control, and countermeasure plan (SPCC) has been developed and approved by the Authority Having Jurisdiction to properly handle resulting spill. The SPCC shall account for proper site drainage, infiltration, foundation scour, and protection of adjacent facilities from sloshing spill.

(e) If the sloshing is restricted because the freeboard is less than the computed sloshing height, then the roof and supporting structure shall be designed for an equivalent hydrostatic head equal to the computed sloshing height less the freeboard. Also, the design of the tank shall use the confined portion of the convective (sloshing) mass as an additional impulsive mass.

Table 15.7-3. Minimum Required Freeboard.

Value of S_{DS}	Risk Category I or II	Risk Category III	Risk Category IV
$S_{DS} < 0.33g$	Not required	Not required	δ_s
$S_{DS} \geq 0.33g$	Not required	$0.7\delta_s$	δ_s

15.7.6.2.3 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 15.7.4.

15.7.6.2.4 Internal Elements The attachments of internal equipment and accessories that are attached to the primary liquid or pressure retaining shell or bottom or that provide structural support for major elements (e.g., a column supporting the roof rafters) shall be designed for the lateral loads caused by the sloshing liquid, in addition to the inertial forces, by a substantiated analysis method.

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

(a) For flat-bottom steel tanks, the overall horizontal seismic shear force is permitted to be resisted by friction between the tank bottom and the foundation or subgrade. Storage tanks shall be designed such that sliding does not occur where the tank is full of stored product. The maximum calculated seismic base shear, V, shall not exceed

$$V < W \tan 30° \qquad (15.7\text{-}14)$$

(b) W shall be determined using the effective seismic weight of the tank, roof, and contents after reduction for coincident vertical earthquake. Lower values of the friction factor shall be used if the design of the tank bottom to supporting foundation does not justify the friction value given by Equation (15.7-14) (e.g., leak detection membrane beneath the bottom with a lower friction factor, smooth bottoms, etc.). Alternatively, the friction factor is permitted to be determined by testing in accordance with Section 11.1.4.

(c) No additional lateral anchorage is required for steel tanks designed in accordance with reference documents.