the finished top of the concrete bottom. Concrete shall be reinforced and designed in accordance with ACI 318. Additional reinforcing steel shall be installed around the base-setting ring, as required, to control shrinkage and resist horizontal loads, in accordance with the construction drawings (Sec. 1.2).

## Sec. 13.5 Foundation Design Details

13.5.1 *Height above ground.* The tops of the concrete foundations shall be a minimum of 6 in. (150 mm) above the adjacent grade, unless otherwise specified.

13.5.2 *Minimum depth of foundations.* The extreme frost penetration depths in Figure 1 shall be the minimum depth of foundation below the finished grade. However, the minimum depth below finished grade shall not be less than 12 in. (300 mm). Foundation depth shall be increased in localities where soil or other factors are favorable to deep frost penetration and may be reduced for foundations resting on rock. Consult local records for the extreme frost penetration in the circled area of Figure 1. Uplift or soil-bearing requirements may dictate greater depths.

13.5.3 *Size of top.* The tops of foundations shall project at least 3 in. (76 mm) beyond the tank sidewall, or greater if required by design. In base-setting

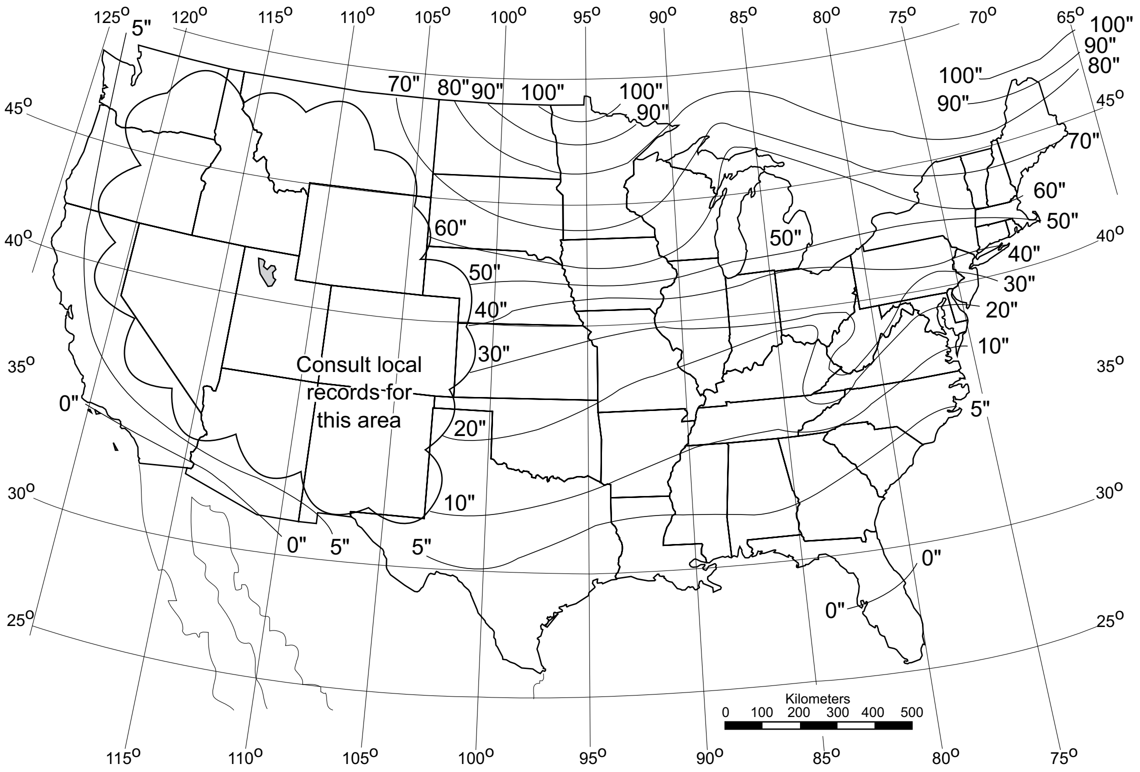


**Figure 1** Extreme frost penetration—inches (based on state averages)

ring applications, the top of the foundation should project a minimum of 8 in. (200 mm) beyond the tank sidewall, or greater if required by design. When anchor bolts are used, the foundations shall project 9 in. (230 mm) beyond the tank sidewall, or greater as required by anchor bolt design (Sec. 5.9). The top corners of the foundation shall be either neatly rounded or finished with a suitable bevel.

13.5.4 *Deep foundations.* If a deep foundation is required using piles, caissons, piers, etc., the type of supports, depth below existing grade, and design capacities for all loads and load combinations—including live, dead, weight of soil above the footing, wind, and seismic—shall be specified.

## Sec. 13.6 Concrete Design, Materials, and Construction

The design of the concrete foundations, the specifications for the cement and aggregate, and the mixing and placing of the aggregate shall be in accordance with ACI 318, except as may be modified in this section and the following subsections. Concrete work shall conform to all requirements of ACI 301, unless otherwise specified.

13.6.1 *Tolerances on concrete foundations.* Ringwalls and slabs, after grouting or before placing the cane-fiber joint filler, shall be level within ±⅛ in. (±3 mm) in any 30-ft (9-m) circumference under the shell. The levelness on the circumference shall not vary by more than ±¼ in. (±6 mm) from an established plane. The tolerance on poured concrete before grouting shall be ±1 in. (±25 mm).

13.6.2 *Finish.* The top portions of foundations, to a level 6 in. (150 mm) below the proposed ground level, shall be finished to a smooth form finish in compliance with ACI 301. The top corners of the foundation shall be either neatly rounded or finished with a suitable bevel. Any small holes may be troweled over with mortar as soon as possible after the forms are removed.

13.6.3 *Tolerances on anchor bolts.* Anchor bolt location, projection, and embedment tolerance shall be ±¼ in. (±6 mm). Anchor bolt plumbness tolerance shall be ±3° from vertical.

13.6.4 *Tolerances on base-setting rings.* Base-setting rings shall be level ±1⁄16 in. (±1.6 mm) and concentric ±¼ in. (±6 mm). It is extremely important that the base-setting ring be assembled and installed in strict accordance with these tolerances and the tank manufacturer's instructions.

## Sec. 13.7 Backfill

For tanks with ringwall foundation, all topsoil, organic material, and undesirable material within the ringwall shall be removed and replaced with a

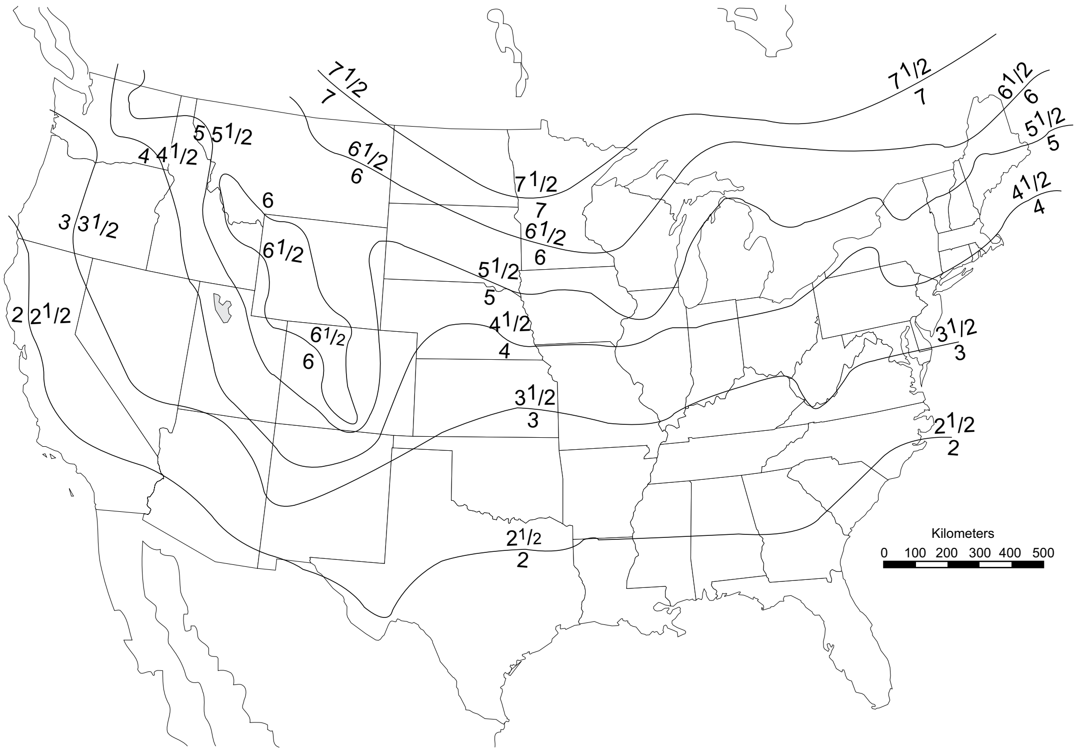


**Figure 2** Recommended depth of pipe cover—feet above top of pipe

controlled, load-bearing backfill. The natural soils and load-bearing backfill within the ringwall shall be capable of supporting the tank bottom without general or localized settlement that may damage the tank.

13.7.1 *Material and compaction.* Load-bearing backfill shall be suitable nonfrozen material placed and compacted in uniform horizontal lifts to the degree of compaction required by the foundation design. The water load and ringwall height shall be considered in determining the required degree of compaction.

13.7.2 *Pipe cover.* Pipe cover shall be provided in compliance with Figure 2 unless local conditions dictate that more or less cover should be used.

## SECTION 14: SEISMIC DESIGN

### Sec. 14.1 General

14.1.1 *Scope.* The design earthquake ground motion in this standard is derived from ASCE 7 and is based on a maximum considered earthquake ground motion defined as the motion due to an event with a 2 percent probability of exceedance within a 50-year period (recurrence interval of approximately 2,500 years). Application of these provisions, as written, is deemed to meet the intent and requirements of ASCE 7. Techniques for applying these provisions where regulatory requirements differ from ASCE 7 are provided in the commentary.

Tanks located where $S_1$ (Sec. 14.2.2) is less than or equal to 0.04 and $S_S$ (Sec. 14.2.2) is less than or equal to 0.15 need not be designed for seismic forces. Where design for seismic forces is required by this standard, the design earthquake ground motion shall be determined using the general procedure (Sec. 14.2.6) or, when specified or required by this standard, the site-specific procedure (Sec. 14.2.7). Seismic design forces are reduced to service-level forces by the use of strength-level to service-level factor $\lambda_E$ (refer to Sec. 14.2.8).

Alternative procedures that account for the effects of soil-structure interaction for mechanically anchored tanks are permitted in Sec. 14.2.9 and must meet specific criteria.

14.1.2 *Definitions.*

1. Active fault. A fault with an average historic slip rate of at least 1 mm per year and geologic evidence of seismic activity within Holocene time (i.e., past 11,000 years).

2. Characteristic earthquake. An earthquake assessed for an active fault having a magnitude equal to the best estimate of the maximum magnitude capable of occurring on the fault, but not less than the largest magnitude that has occurred historically on the fault.

3. Convective component. The convective component represents the sloshing portion of the contents and is characterized by a long natural period.

4. Impulsive component. The impulsive component represents the portion of the contents that moves in unison with the shell.

5. Mechanical-anchoring. Utilizing anchor bolts or base-setting ring to anchor the tank to the foundation.

6. Risk-adjusted maximum considered earthquake ($MCE_R$). The most severe earthquake considered by ASCE 7 determined for the orientation that results in the largest maximum response to horizontal ground motions and with adjustment for targeted risk.

7. Self-anchoring. Utilizing the self-weight of the tank and contents to resist overturning forces.

**Table 2 Seismic importance factor $I_E$**

| Risk Category* | Seismic Importance Factor $I_E$ |
|---|---|
| II | 1.00 |
| III | 1.25 |
| IV | 1.50 |

*Risk Category I was deleted. Refer to Sec. 5.2.1 for definitions of risk categories.

## Sec. 14.2 Design Earthquake Ground Motion

14.2.1 *Seismic importance factor $I_E$.* The seismic importance factor $I_E$ is based on the risk category (Sec. 5.2.1) and shall be in accordance with Table 2.

14.2.2 *Mapped acceleration parameters.* Mapped risk-adjusted maximum considered earthquake ($MCE_R$) spectral response accelerations, 5 percent damped, at 0.2-s period $S_S$ and 1-s period $S_1$ shall be obtained from ASCE 7, Figures 22-1 through 22-6.

14.2.3 *Site class.* Site class accounts for the effect of local soil conditions on the ground motion and shall be based on the types of soil present and their engineering properties. The types of soil present and their engineering properties shall be established by a geotechnical investigation. The site shall be classified in accordance with ASCE 7 chapter 20. Site Class D shall be used when the soil properties are not known in sufficient detail to determine the site class, provided Site Class E or F soils are not present at the site.

A site response analysis that complies with Sec. 14.2.7 is required for sites classified as Site Class F, except as follows. For structures having fundamental periods of vibration equal to or less than 0.5 s, a site response analysis is not required to determine spectral accelerations for liquefiable soils. Rather, a site class is permitted to be determined in accordance with ASCE 7, Chapter 20, and the corresponding values of $F_a$ and $F_v$ determined in accordance with Sec. 14.2.4.

14.2.4 *Site coefficients $F_a$ and $F_v$.* Short-period site coefficient $F_a$ and long-period site coefficient $F_v$ are used to modify mapped spectral response accelerations for 0.2-s and 1-s periods, respectively, for site classes other than B. Site coefficients $F_a$ and $F_v$ shall be in accordance with Tables 3 and 4, respectively.

14.2.5 *Response modification factors $R_i$ and $R_c$.* The response modification factor accounts for damping, overstrength, and the ductility inherent in the tank at displacements great enough to surpass initial yield and approaching the ultimate load displacement of the tank. The response modification factor applied to the

**Table 3 Short-period site coefficient $F_a$**

| Site Class | Mapped Spectral Response Acceleration at 5 Percent Damping and 0.2-s Period* | | | | |
|---|---|---|---|---|---|
| | $S_S \leq 0.25$ | $S_S = 0.5$ | $S_S = 0.75$ | $S_S = 1.0$ | $S_S \geq 1.25$ |
| 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 | 0.9 |
| F | † | † | † | † | † |

* Use straight-line interpolation for intermediate values of $S_S$.
† Site-specific evaluation and procedure (Sec. 14.2.7) are required.

**Table 4 Long-period site coefficient $F_v$**

| Site Class | Mapped Spectral Response Acceleration at 5 Percent Damping and 1-s Period* | | | | |
|---|---|---|---|---|---|
| | $S_1 \leq 0.1$ | $S_1 = 0.2$ | $S_1 = 0.3$ | $S_1 = 0.4$ | $S_1 \geq 0.5$ |
| 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 | 2.4 |
| F | † | † | † | † | † |

* Use straight-line interpolation for intermediate values of $S_1$.
† Site-specific evaluation and procedure (Sec. 14.2.7) are required.

**Table 5 Response modification factors $R_i$ and $R_c$**

| Tank Type | Response Modification Factor | |
|---|---|---|
| | $R_i$ (impulsive component) | $R_c$ (convective component) |
| Mechanically-anchored | 3.0 | 1.5 |
| Self-anchored | 2.5 | 1.5 |

impulsive component $R_i$ and the response modification factor applied to the convective component $R_c$ shall be in accordance with Table 5.

14.2.6 *Design response spectra—general procedure.*

14.2.6.1 General. The general procedure is based on the mapped $MCE_R$ spectral response accelerations from Sec. 14.2.2 for an event with a 2 percent probability of exceedance within a 50-yr period.

14.2.6.2 MCE$_R$ spectral response acceleration. Mapped MCE$_R$ spectral response accelerations from Sec. 14.2.2 shall be adjusted for site class using the following equations.

$$S_{MS} = F_a S_S \quad \text{(Eq 14-1)}$$

$$S_{M1} = F_v S_1 \quad \text{(Eq 14-2)}$$

where:

$S_{MS}$ = MCE$_R$ spectral response acceleration, 5 percent damped, at 0.2-s period and adjusted for site class effects, stated as a multiple (decimal) of $g$

$S_{M1}$ = MCE$_R$ spectral response acceleration, 5 percent damped, at 1-s period and adjusted for site class effects, stated as a multiple (decimal) of $g$

$S_S$ = mapped MCE$_R$ spectral response acceleration, 5 percent damped, at 0.2-s period for Site Class B from Sec. 14.2.2, stated as a multiple (decimal) of $g$

$S_1$ = mapped MCE$_R$ spectral response acceleration, 5 percent damped, at 1-s period for Site Class B from Sec. 14.2.2, stated as a multiple (decimal) of $g$

$F_a$ = short-period site coefficient from Table 3

$F_v$ = long-period site coefficient from Table 4

$g$ = acceleration caused by gravity in ft/s$^2$ (m/s$^2$)

14.2.6.3 Design response spectra. Design response spectra for impulsive and convective components shall be based on design earthquake spectral response accelerations, 5 percent damped, at 0.2-s period $S_{DS}$ and 1-s period $S_{D1}$.

$$S_{DS} = US_{MS} \quad \text{(Eq 14-3)}$$

$$S_{D1} = US_{M1} \quad \text{(Eq 14-4)}$$

where:

$S_{DS}$ = design earthquake spectral response acceleration, 5 percent damped, at 0.2-s period, stated as a multiple (decimal) of $g$

$S_{D1}$ = design earthquake spectral response acceleration, 5 percent damped, at 1-s period, stated as a multiple (decimal) of $g$

$U$ = scaling factor to scale the $MCE_R$ spectral response acceleration to the design earthquake spectral response acceleration

= ⅔

The other symbols have been previously defined in this section.

14.2.6.3.1 Design response spectrum for impulsive components. The design response spectrum for impulsive components shall be based on 5 percent damping and the following equations:

For $0 \le T_i \le T_S$: $$S_{ai} = S_{DS} \quad \text{(Eq 14-5)}$$

For $T_S < T_i \le T_L$: $$S_{ai} = \frac{S_{D1}}{T_i} \le S_{DS} \quad \text{(Eq 14-6)}$$

For $T_i > T_L$: $$S_{ai} = \frac{T_L S_{D1}}{T_i^2} \quad \text{(Eq 14-7)}$$

where:

$S_{ai}$ = design spectral response acceleration for impulsive components, 5 percent damped, at the natural period of the structure $T_i$, stated as a multiple (decimal) of $g$.

$T_i$ = natural period of the structure, in seconds

$T_L$ = region-dependent transition period for longer-period ground motion, in seconds, from ASCE 7, Figures 22-12 through 22-16

$T_S$ = $\frac{S_{D1}}{S_{DS}}$

The other symbols have been previously defined in this section.

14.2.6.3.2 Design response spectrum for the convective component. The design response spectrum for the convective component shall be based on 0.5 percent damping and the following equations:

For $T_c \le T_L$: $$S_{ac} = \frac{K S_{D1}}{T_c} \le S_{DS} \quad \text{(Eq 14-8)}$$

For $T_c > T_L$: $$S_{ac} = \frac{KT_L S_{D1}}{T_c^2}$$ (Eq 14-9)

where:

$S_{ac}$ = design spectral response acceleration for the convective component, 0.5 percent damped, at the first mode sloshing wave period $T_c$, stated as a multiple (decimal) of $g$

$K$ = damping scaling factor

= 1.5 to convert spectrum from 5 percent damping to 0.5 percent damping

$T_c$ = first mode sloshing wave period in seconds

The other symbols have been previously defined in this section.

14.2.7 *Design response spectra—site-specific procedure.*

14.2.7.1 General. The site-specific procedure only applies when specified or required by this standard. The site-specific procedure is required if the tank is located on Site Class F soils. When the site-specific procedure is specified or required by this standard, the site-specific evaluation geotechnical investigation and dynamic site response analyses shall be in accordance with Sec. 3.4 of FEMA 450.

14.2.7.2 Probabilistic $MCE_R$ ground motion. The probabilistic $MCE_R$ ground motion shall be represented by a 5 percent damped acceleration response spectrum having a 2 percent probability of exceedance within a 50-yr period. The probabilistic $MCE_R$ spectral response acceleration at any period $S_{aM}$ shall be taken from that spectrum.

14.2.7.3 Deterministic $MCE_R$ ground motion. The deterministic $MCE_R$ ground motion shall be based on the dynamic site response analyses and shall be taken as 150 percent of the median 5 percent damped spectral response accelerations $S_{aM}$ at all periods resulting from a characteristic earthquake on any known active fault within the region. The deterministic $MCE_R$ ground motion response spectrum shall not be less than the corresponding ordinates of the response spectrum determined in Sec. 14.2.7.4.

14.2.7.4 Deterministic lower limit on $MCE_R$ ground motion. The deterministic lower limit for maximum considered earthquake ground motion is defined by the response spectrum shown in Figure 3. Site coefficients $F_a$ and $F_v$ used to determine the deterministic limit shall be based on mapped spectral response accelerations at 0.2-s period $S_S$ equal to 1.5$g$ and 1-s period $S_1$ equal to 0.6$g$.

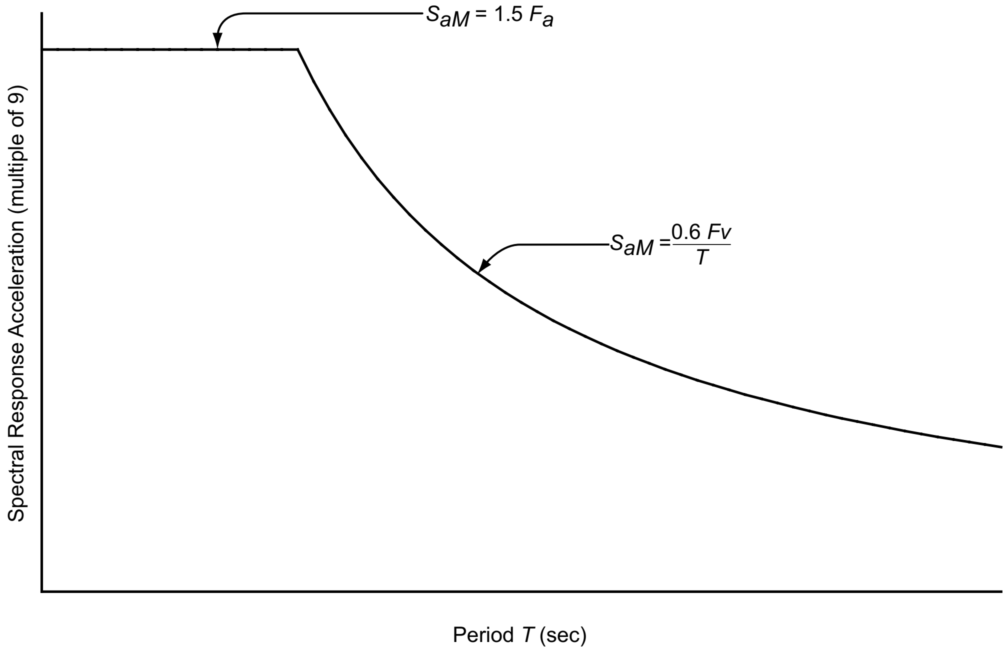


**Figure 3** Deterministic lower limit for maximum considered earthquake ground motion

14.2.7.5 Site-specific $MCE_R$ ground motion. The site-specific $MCE_R$ spectral response acceleration at any period $S_{aM}$ shall be taken as the lesser of the spectral response accelerations from the probabilistic maximum $MCE_R$ ground motion (Sec. 14.2.7.2) and the deterministic $MCE_R$ ground motion (Sec. 14.2.7.3).

14.2.7.6 Design response spectrum.

14.2.7.6.1 Design response spectrum for impulsive components. The design response spectrum for impulsive components $S_{ai}$ shall be based on 5 percent damping and Eq 14-10 except as noted. The design spectral response acceleration by Eq 14-10 shall not be less than 80 percent of the design spectral response acceleration by the general procedure (Sec. 14.2.6). For sites classified as Site Class F requiring site-specific evaluations, the design spectral response acceleration at any period shall not be less than 80 percent of the design spectral response acceleration for Site Class E by the general procedure (Sec. 14.2.6).

$$S_{ai} = US_{aM} \qquad \text{(Eq 14-10)}$$

where:

$S_{aM}$ = $MCE_R$ spectral response acceleration, stated as a multiple (decimal) of $g$

The other symbols have been previously defined in this section.

For tanks with $H$ (distance from bottom of shell to MOL) to $D$ (tank diameter) ratios equal to or less than 0.8, the design spectral response acceleration by Eq 14-10 may be limited to $(W_T / W_i)(\tan 30°)$ when the tanks are:

1. Self-anchored.
2. Mechanically anchored and are not otherwise prevented from sliding laterally at least 1 in. See Sec. 14.3.2.1 and Sec. 14.3.2.2.1 for definitions of $W_T$ and $W_i$.

14.2.7.6.2 Design response spectrum for the convective component. The design response spectrum for the convective component shall be based on 0.5 percent damping and Eq 14-11. The design spectral response acceleration by Eq 14-11 shall not be less than 80 percent of the design spectral response acceleration by the general procedure (Sec. 14.2.6).

$$S_{ac} = UKS_{aM} \quad \text{(Eq 14-11)}$$

The symbols have been previously defined in this section.

Alternatively, the design spectral response acceleration for the convective component $S_{ac}$ may be taken from a 0.5 percent damped site-specific response spectrum based on the requirements of Sec. 14.2.7, except that the damping scaling factor $K$ shall be set equal to 1.0.

14.2.8 *Horizontal design accelerations.*

14.2.8.1 For the general procedure, the impulsive design acceleration $A_i$ is independent of $T_i$ and $S_{ai}$ shall be taken as $S_{DS}$. For the site-specific procedure, the impulsive design acceleration $A_i$ shall be based on the design spectral response acceleration, 5 percent damped, $S_{ai}$ for the natural period of the shell-fluid system. The convective design acceleration $A_c$ shall be based on the spectral response acceleration, 0.5 percent damped, $S_{ac}$ at the first mode sloshing wave period $T_c$. The first mode sloshing wave period shall be determined in accordance with Sec. 14.3.1. The design spectral response accelerations for impulsive and convective components shall be taken from design spectra determined by the general procedure (Sec. 14.2.6) or, when specified or required, the site-specific procedure (Sec. 14.2.7). The impulsive and convective design accelerations shall be determined by the following equations:

$$A_i = \frac{\lambda_E S_{ai} I_E}{R_i} \geq \frac{0.36 S_1 I_E}{R_i} \quad \text{(Eq 14-12)}$$