T_I = natural period of tank in impulsive mode, in sec, Sec. 4.3.1(4)
T_S = S_{DI} / S_{DS}, in sec, Section 4.
T_V = natural period of vibration of vertical liquid motion, in sec, Sec. 4.5.1
$\ddot{u}_V$ = vertical acceleration, in g, Sec. 4.5.1
V_C = base shear at the bottom of the tank shell caused by convective force, in lb (N), Sec. 4.3.1(1)
V_I = base shear at the bottom of the tank shell caused by impulsive forces, in lb (N), Sec. 4.3.1(1)
V_T = total base shear at the bottom of the tank shell, in lb (N), Sec. 4.3.1(1)
W_C = weight of effective mass of tank contents that moves with the tank shell in convective mode, in lb (N), Sec. 4.3.1(7)
W_I = weight of effective mass of tank contents that moves in unison with the tank shell in impulsive mode, in lb (N), Sec. 4.3.1(7)
W_R = total weight of the tank roof, plus a portion of snow or other roof live load, in lb (N)
W_S = total weight of the tank wall (shell), in lb (N)
W_T = the total weight of tank contents, in lb (N), Sec. 4.3.1(7)
w = width of elastomeric bearing pad in radial direction, in in. (mm)
w_t = weight of the tank, in lb/ft (N/m) of shell circumference, Sec. 4.4.5
X_C = height from the bottom of the tank shell to the centroid of W_C, in ft (m), Sec. 4.3.1(8)
X'_C = height from the bottom of the tank foundation to the centroid of W_C, in ft (m), Sec. 4.9.3
X_I = height from the bottom of the tank shell to the centroid of W_I, in ft (m), Sec. 4.3.1(8)
X'_I = height from the bottom of the tank foundation to the centroid of W_I, in ft (m), Sec. 4.9.3
X_S = height from bottom of tank shell to center of gravity of the tank shell, in ft (m), Sec. 4.3.1(2)
α = angle of cable or strand with horizontal, in degrees
β = damping ratio, in percent, Sec. 4.3.3
γ = unit weight of water, 62.4 lb/ft^3 (9,802 N/m^3)
μ = coefficient of friction, Sec. 4.7
ω_I = circular frequency of the impulsive mode of vibration, in rad/sec, Eq 4-12 and Eq 4-13
ε = effective mass coefficient, Eq 4-24
ρ_c = mass density of concrete, 4.66 lb·s^2/ft^4 (2.40 kN·s^2/m^4)

η_c = modification ratio to account for the influence of damping on the spectral amplification, Sec. 4.3.3

Ω_o = overstrength factor as defined in Table 3

Sec. 4.2 Seismic Joint Types

4.2.1 *Wall-base joint types.* For purposes of seismic design, externally wrapped, prestressed concrete water-storage tanks currently in use can be classified into tanks with the following three types of joints between the wall and the foundation:

1. Reinforced nonsliding base. Tanks with a substantially fixed joint between the wall and the foundation (Figure 4A) that are tied to the footing and floor by adequate steel reinforcement.

2. Anchored flexible base. Tanks with an anchored flexible joint between the wall and the foundation. Anchorage is achieved by diagonal-restraint strand cables embedded in the wall and in the footing, as shown in Figure 4B, which resist tangential movements but permit only limited radial movements of the wall.

3. Unanchored and uncontained flexible base. Tanks with an unanchored and uncontained flexible joint between the wall and the foundation; flexibility is achieved by an elastomeric bearing pad (Figure 4C).

NOTE: Tanks with hinged bases or unanchored and containing flexible bases, while used in the past, are no longer used in current practice in wire- and strand-wound tank construction.

4.2.2 *Applicability of base joint types.* Tanks located in seismic locations where $S_{DS} \geq 0.50$ shall use a Sec. 4.2.1, Figure 4A- or Figure 4B-type joint that anchors the wall to the foundation to prevent or restrict wall displacement during a seismic event. The fixed-base joint described in Sec. 4.2.1(1), Figure 4A, has been used in seismic locations where $S_{DS} \geq 0.50$ primarily in tanks of 2.0 mil gal (7.57 ML) capacity or smaller, whereas the radially freed but anchored flexible base joint described in Sec. 4.2.1(2), Figure 4B, has been used in tanks of all sizes. The fixed base is not recommended for tanks larger than 2.0 MG (7.57 ML) in locations where $S_{DS} \geq 0.50$ without full consideration and adequate reinforcement to counteract the base shear and vertical bending moments induced in the wall and its interaction with the footing and floor slab.

4.2.3 *Wall-to-roof joint connection.* Any of the above categories of tanks may have, at the wall-to-roof connection, a joint that is substantially fixed, has flexible or rigid ties, or that has no ties (elastomeric pad only). A joint with an

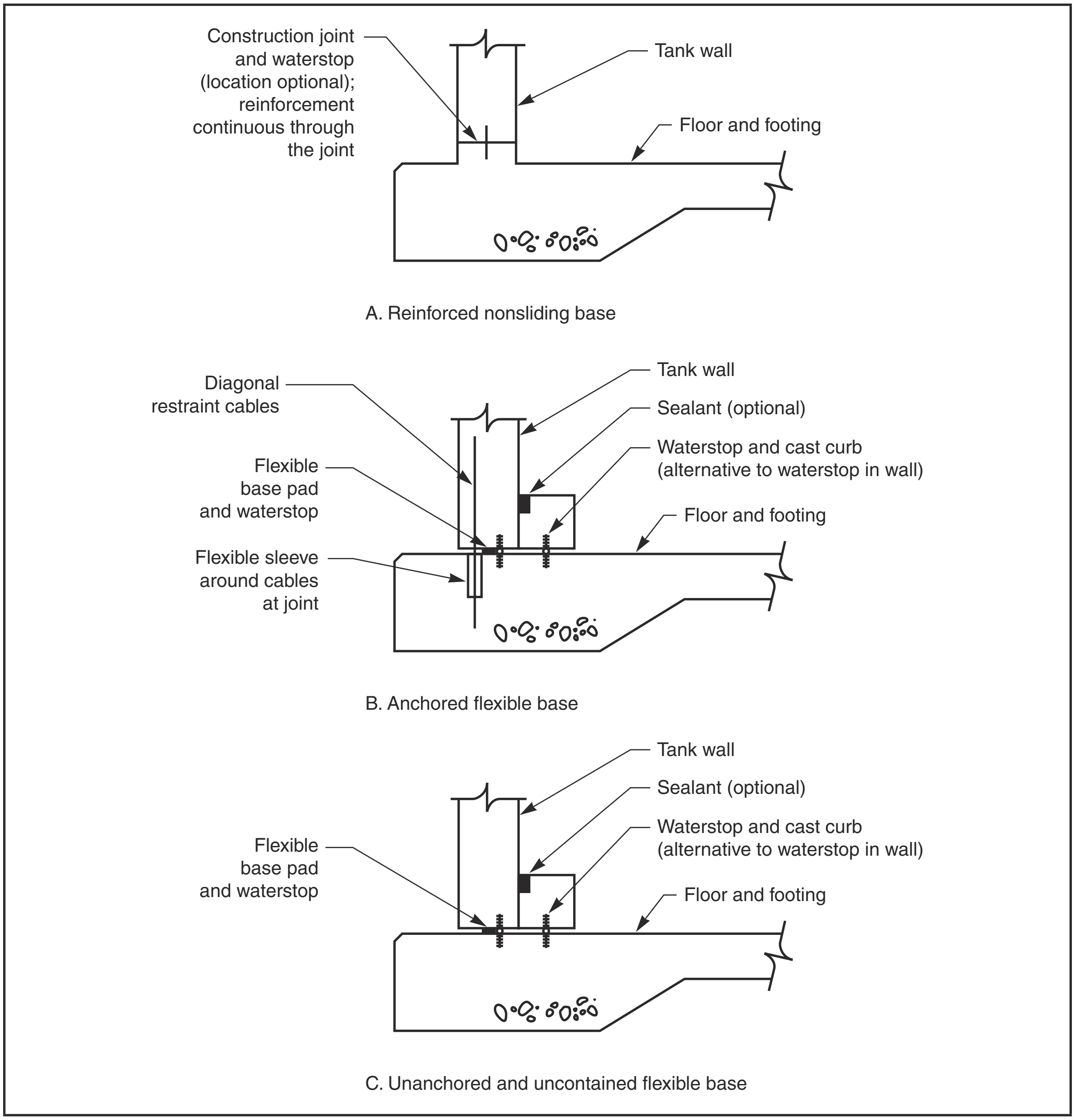

Figure 4 Types of joints used between the wall and its foundation

elastomeric pad and without ties shall be contained to preclude excessive lateral displacement between the roof and the wall. The tank design shall have provisions that prevent the upward displacement of the roof with respect to the wall caused by the height of the sloshing wave and vertical accelerations (see Sec. 4.10).

Sec. 4.3 Seismic Design Loads

4.3.1 *Effective-mass procedure for determining base shear and overturning moment as a result of seismic effects.* The effective-mass procedure considers the following two response modes of the tank and its contents: (1) the impulsive mode, which is the high-frequency amplified response to lateral ground motion of the tank shell and roof together with that portion of the liquid contents that moves in unison with the shell, and (2) the convective mode, which is the low-frequency amplified response of a portion of the liquid contents in the fundamental sloshing mode. The design requires the determination of the hydrodynamic mass associated with each mode and the lateral force and overturning moment applied to the shell resulting from the response of the masses to lateral ground motion. Because the two different response modes are not maximized at the same time, the root mean square can be used for combining forces and moments resulting from the two response modes.

1. The lateral or horizontal base shear caused by seismic forces applied at the bottom of the tank wall shall be determined by Eq 4-1, 4-2, and 4-3.

$$V_I = \frac{IC_I}{1.4\ R_I}(\varepsilon W_S + W_R + W_I) \tag{Eq 4-1}$$

$$V_C = \frac{IC_C}{R_C} W_C \tag{Eq 4-2}$$

$$V_T = \sqrt{V_I{}^2 + V_C{}^2} \tag{Eq 4-3}$$

In the case of a Figure 4A base, the wall design shall provide for 100 percent of the base shear V_T to be transferred tangentially. In addition to providing for 100 percent of the base shear, provide for the maximum radial base shear from the direction of the earthquake, along with the corresponding vertical bending moments and hoop forces, according to Sec. 4.5.3.

In the case of a Figure 4B base with diagonal restraint cables between the footing and the wall, the wall design shall provide for 100 percent of the base shear V_T to be transferred tangentially. In addition, for a Figure 4B base, the maximum hoop forces from the direction of the earthquake shall also be provided for according to Sec. 4.5.3.

2. The overturning moment caused by seismic forces applied at the bottom of the tank wall shall be determined by Eq 4-4, 4-5, and 4-6.

$$M_I = \frac{IC_I}{1.4\ R_I}(\varepsilon W_S X_S + W_R H_T + W_I X_I) \tag{Eq 4-4}$$

$$M_C = \frac{IC_C}{R_C} W_C X_C \tag{Eq 4-5}$$

$$M_T = \sqrt{M_I{}^2 + M_C{}^2} \tag{Eq 4-6}$$

3. The seismic response impulsive coefficient C_I is determined from Eq 4-7 or Eq 4-8.

For $T_I \leq T_S$

$$C_I = S_{DS} \tag{Eq 4-7}$$

For $T_I > T_S$

$$C_I = \frac{S_{D1}}{T_I} \leq S_{DS} \tag{Eq 4-8}$$

Where

$$T_S = \frac{S_{D1}}{S_{DS}} \tag{Eq 4-9}$$

$$S_{DS} = \frac{2}{3} S_S F_a \tag{Eq 4-10}$$

$$S_{D1} = \frac{2}{3} S_1 F_v \tag{Eq 4-11}$$

The notation S_S and S_1 are the mapped spectral response accelerations at short and 1-sec periods, respectively, and shall be obtained from the seismic ground motion maps in Figures 22-1 through 22-14 of ASCE 7-05, chapter 22, and F_a and F_v are the site coefficients and shall be obtained from Tables 11.4-1 and 11.4-2, respectively, of ASCE 7-05, in conjunction with Table 4 of this standard.

4. The tank's natural period T_I may be determined by a rational analysis that considers the weight of the tank wall and roof and the effective weight W_I of the tank contents. For tanks with a nonsliding base (Figure 4A), T_I may be determined from Eq 4-12. For tanks with anchored flexible bases (Figure 4B) and tanks with unanchored and uncontained flexible bases (Figure 4C), T_I may be determined from Eq 4-16 and C_w can be obtained from Figure 5 or by Eq 4-15.

$$T_I = \frac{2\pi}{\omega_I} \leq 0.3 \text{ sec} \tag{Eq 4-12}$$

$$\omega_I = C_L \times \frac{12}{H} \times \sqrt{\frac{E_C}{\rho_c}} \tag{Eq 4-13}$$

$$\omega_I = C_L \times \frac{1}{H} \times \sqrt{\frac{E_C}{1{,}000\rho_c}} \quad \text{(in SI system)}$$

$$C_L = C_W \times 10 \times \sqrt{\frac{t_w}{12r}} \tag{Eq 4-14}$$

Table 4 Soil site class definitions

Site Class	Soil Profile Name	Average Properties in Top 100 ft: Soil shear wave velocity, V_s (ft/s)	Standard penetration resistance, N	Soil undrained shear strength S_u (psf)
A	Hard rock	$V_s > 5{,}000$	N/A	N/A
B	Rock	$2{,}500 < V_s \le 5{,}000$	N/A	N/A
C	Very dense soil and soft rock	$1{,}200 < V_s \le 2{,}500$	$N > 50$	$S_u \ge 2{,}000$
D	Stiff soil profile	$600 \le V_s \le 1{,}200$	$15 \le N \le 50$	$1{,}000 \le S_u \le 2{,}000$
E	Soft soil profile	$V_s < 600$	$N < 15$	$S_u < 1{,}000$
		Any profile with more than 10 ft of soil having the following characteristics: 1. Plasticity index > 20 2. Moisture content, MC > 40% 3. Undrained shear strength $S_u < 500$ psf		
F	—	Any profile containing soils having one or more of the following characteristics: 1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. 2. Peats and/or highly organic clays ($H_{soil} > 10$ ft of peat and/or highly organic clay) 3. Very high plasticity ($H_{soil} > 25$ ft with plasticity index PI > 75) 4. Very thick soft/medium stiff clays ($H_{soil} > 120$ ft)		

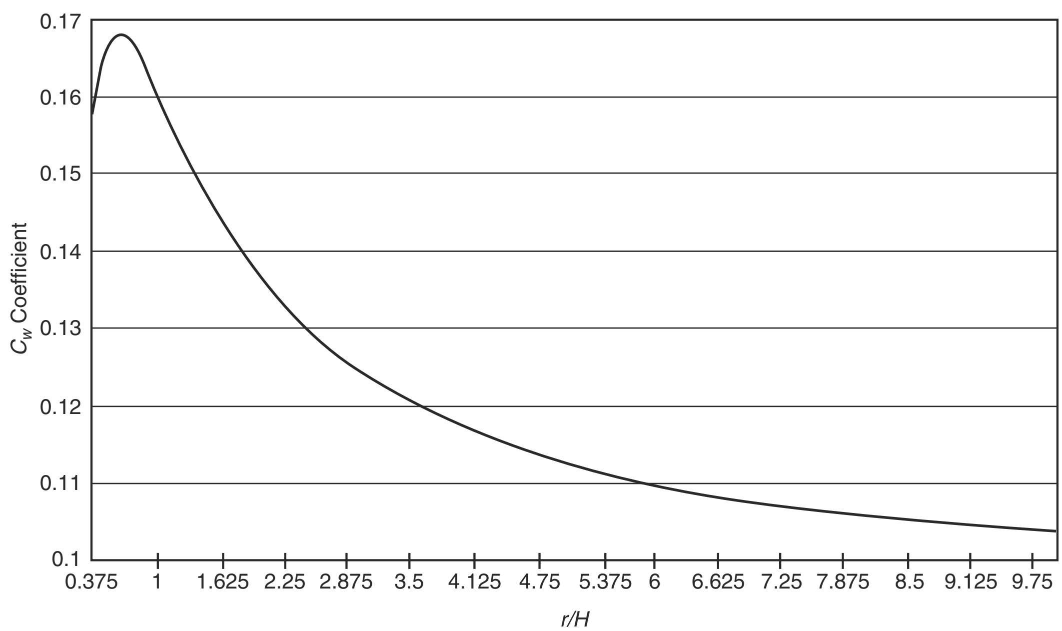

Figure 5 Curve for obtaining factor C_w for the ratio r/H

$$C_L = C_W \times 10 \times \sqrt{\frac{t_w}{1{,}000r}} \text{ (in SI system)}$$

$$C_W = 9.375 \times 10^{-2} + 0.1020(H/r) - 2.585 \times 10^{-2}(H/r)^2 - 1.566 \times 10^{-2}(H/r)^3 + 7.919 \times 10^{-3}(H/r)^4 - 9.956 \times 10^{-4}(H/r)^5 \quad \text{(Eq 4-15)}$$

$$T_I = \sqrt{\frac{4\pi(W_S + W_R + W_I)}{grk}} \leq 1.25 \text{ sec} \quad \text{(Eq 4-16)}$$

5. For tanks with a Figure 4B base, the spring stiffness k is determined from Eq 4-17. In Eq 4-17 and Eq 4-18, for a tank with a continuous bearing pad, the ratio L_p/S_p =1.0. For a tank with a series of bearing pads, for example, having lengths of 6 in. (150 mm) spaced at 12 in. (300 mm) on center, L_p/S_p =0.5.

$$k = 144 \left[\frac{(AE)\cos^2\alpha}{L_c S_c} + \frac{2GwLp}{tS_p}\right] \quad \text{(Eq 4-17)}$$

$$k = \left[\frac{(AE)\cos^2\alpha}{L_c S_c} + \frac{2GwLp}{tS_p}\right] \text{ (in SI system)}$$

For tanks with a Figure 4C base, k is determined from Eq 4-18.

$$k = 144 \frac{2GwL_p}{tS_p} \quad \text{(Eq 4-18)}$$

$$k = \frac{2GwL_p}{tS_p} \text{ (in SI System)}$$

Note: Eq 4-17 and Eq 4-18 were derived without including the effects of the flexibility of the tank shell and the wall-to-roof connection. These effects may be important under some circumstances.

6. The seismic response convective coefficient C_C is determined from Eq 4-19 or Eq 4-20.

For $T_c \leq \frac{1.6}{T_S}$ sec

$$C_C = \frac{1.5\, S_{D1}}{T_C} \leq 1.5\, S_{DS} \quad \text{(Eq 4-19)}$$

For $T_c > \frac{1.6}{T_S}$ sec

$$C_C = \frac{6(0.4)S_{DS}}{T_C{}^2} = \frac{2.4\, S_{DS}}{T_C{}^2} \quad \text{(Eq 4-20)}$$

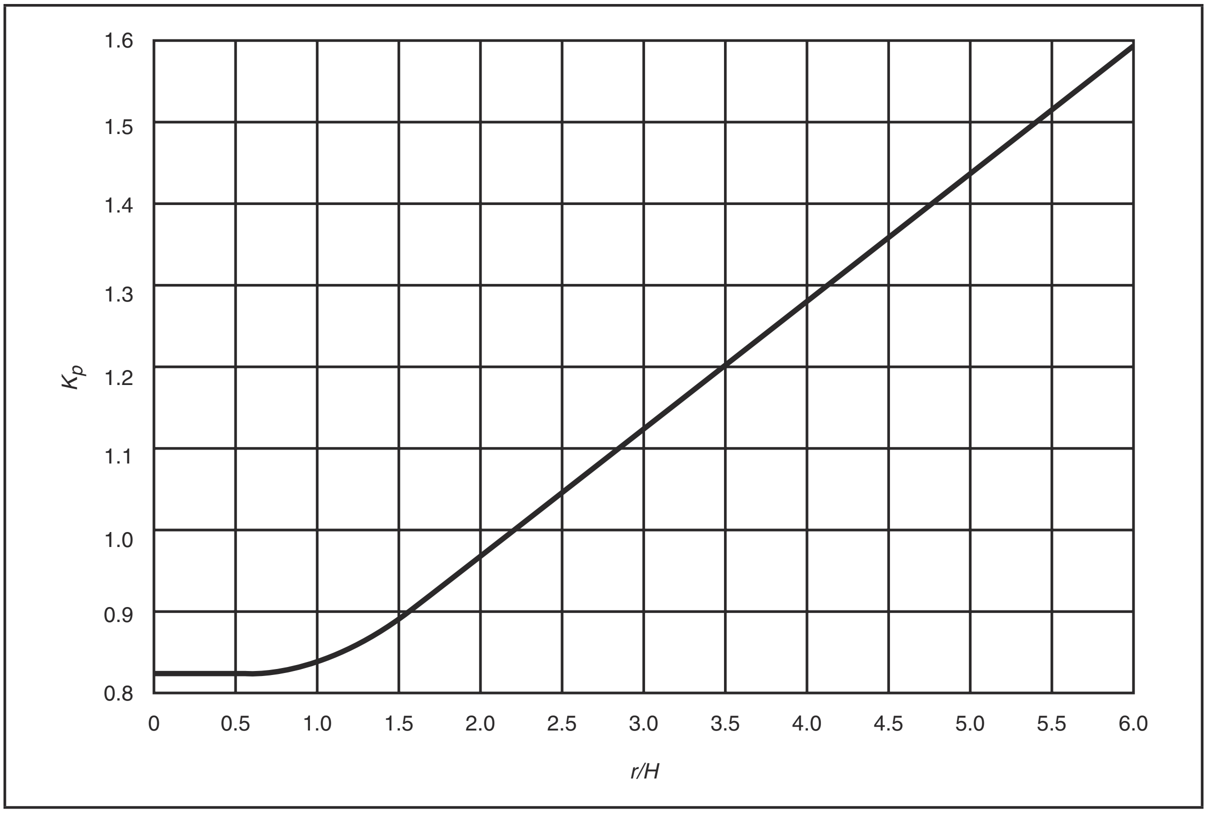

Figure 6 Curve for obtaining factor K_p for the ratio r/H

Factor 1.5 in Eq 4-19 represents the approximate ratio of the spectral amplification based on 0.5 percent damping to that based on 5 percent damping. The value $0.4S_{DS}$ in Eq 4-20 is an approximation of the effective peak ground acceleration (at time $T=0$) reduced by a factor of ⅔.

The first-mode sloshing wave period T_C is determined from Eq 4-21 or Eq 4-22, and K_p is obtained from Figure 6.

$$T_C = K_p\sqrt{r} \quad \text{(Eq 4-21)}$$

$$T_C = K_p\sqrt{\frac{r}{0.3048}} \text{ (in SI system)}$$

or

$$T_C = \sqrt{\frac{r}{1.5\tanh\left(\sqrt{3.375}\,\frac{H}{r}\right)}} \quad \text{(Eq 4-22)}$$

$$T_C = \sqrt{\frac{r}{1.5(0.3048\tanh\left(\sqrt{3.375}\,\frac{H}{r}\right)}} \text{ (in SI system)}$$

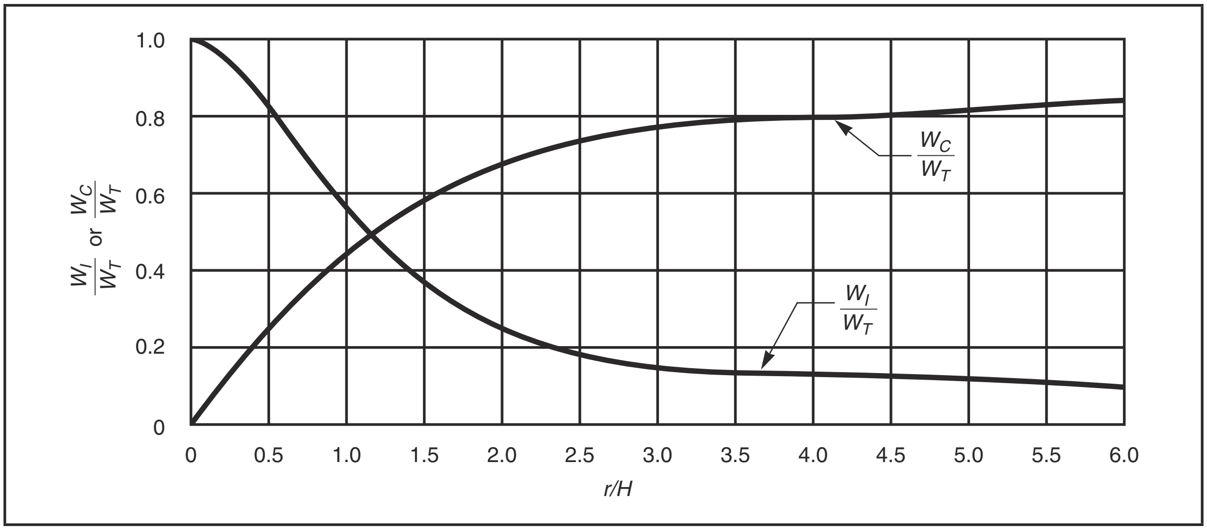

Figure 7 Curves for obtaining factors W_I/W_T and W_C/W_T for the ratio r/H

7. Effective mass of tank contents. The weight of the tank contents that moves in unison with the tank shell in the impulsive mode W_I and the weight of the tank contents that move with the tank wall in the convective mode, W_C, may be determined by multiplying W_T by the ratio W_I/W_T and W_C/W_T, respectively, obtained from Figure 7 for the ratio r/H of the tank, or from Eq 4-25 and Eq 4-26.

The total weight of the tank contents W_T is determined from Eq 4-23. The ratio of the equivalent (or generalized) dynamic mass ε of the tank shell to its actual total mass shall be determined from Eq 4-24.

$$W_T = \gamma \pi r^2 H \qquad \text{(Eq 4-23)}$$

For a Figure 4A base,

$$\varepsilon = [0.0151 \left(\frac{D}{H}\right)^2 - 0.1908 \left(\frac{D}{H}\right) + 1.021] \leq 1.0 \qquad \text{(Eq 4-24)}$$

For a Figure 4B and 4C base, ε =1.0

$$\frac{W_I}{W_T} = \frac{\tanh\left(\sqrt{3}\frac{r}{H}\right)}{\sqrt{3}\frac{r}{H}} \qquad \text{(Eq 4-25)}$$

$$\frac{W_C}{W_T} = \frac{\sqrt{3.375}\ r \tanh\left(\sqrt{3.375}\ H/r\right)}{4H} \qquad \text{(Eq 4-26)}$$

8. The heights X_I and X_C from the bottom of the tank shell to the centroids of the lateral seismic forces applied to W_I and W_C may be determined by multiplying

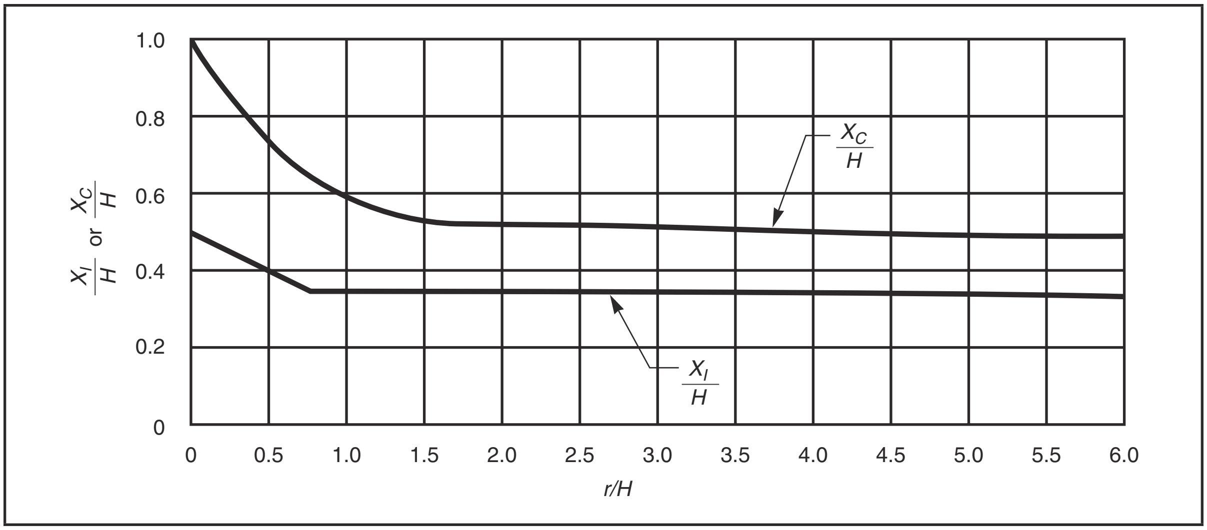

Figure 8 Curves for obtaining factors X_I/H and X_C/H for the ratio r/H

H by the ratios X_I/H and X_C/H, respectively, obtained from Figure 8 for the ratio r/H or from Eq 4-27 and 4-28.

When $r/H \le 0.6667$, then

$$\frac{X_I}{H} = \left[0.50 - 0.1875\left(\frac{r}{H}\right)\right] \qquad \text{(Eq 4-27)}$$

When $r/H > 0.6667$, then

$$\frac{X_I}{H} = 0.375$$

For all values of r/H,

$$\frac{X_C}{H} = 1 - \left[\frac{\cosh\left(\sqrt{3.375}\ H/r\right) - 1}{\left(\sqrt{3.375}\ H/r\right)\sinh\left(\sqrt{3.375}\ H/r\right)}\right] \qquad \text{(Eq 4-28)}$$

9. The curves in Figure 6 and Figure 7 are based on equations in chapter 6 and appendix F of *Nuclear Reactors and Earthquakes* (US Nuclear Regulatory Commission 1963). Alternatively, W_I, W_C, X_I, and X_C may be determined by other analytical procedures based on the dynamic characteristics of the tank.

4.3.2 *Application of site-specific response spectrum.* Where site-specific procedures are used, the maximum considered earthquake spectral response accelerations S_{aM} and S_{cM} shall be determined in accordance with Sec. 4.3.5 and shall not be less than the probabilistic maximum earthquake spectral response acceleration as defined in Sec. 4.3.3 and/or the deterministic maximum spectral response accelerations as defined in Sec. 4.3.4.