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Seismic design of liquid-containing concrete structures per ACI Standard 350.3

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ABSTRACT: The new ACI Code 350-01/350.R-01, *"Code Requirements for Environmental Engineering Concrete Structures"*, has greatly expanded the seismic design provisions of the previous edition, ACI 350-89, in two ways: (1) through the adoption of Chapter 21 of ACI 318 in ACI 350 ("Special Provisions for Seismic Design"*),* and (2) the drafting of detailed seismic analysis guidelines in a separate Standard, ACI 350.3/350.3R *("Seismic Design of Liquid-Containing Structures").*

As a result of this approach, the two documents, ACI Standard 350.3/350.3R and Chapter 21 of ACI 350, fill a real need for the profession. They equip the practicing engineer with a practical and reliable tool for analyzing and designing liquid-containing concrete structures of all types (circular and rectangular, prestressed and non-prestressed) to resist earthquakes.

1 INTRODUCTION

The seismic design provisions of the previous (1989) edition of ACI 350 were very limited in scope. The five paragraphs of Section 2.9.4 provided only a general description of the fundamental principles, while referring to two other documents for further guidance.

The industry standards offering detailed guidelines for the seismic design of circular concrete tanks have been: AWWA D110 for prestressed, wire-wrapped tanks (since 1986); and AWWA D115 for prestressed concrete tanks stressed with tendons (since 1995). The national model building codes and standards, and specifically IBC, UBC, SBC, BOCA and ASCE-7, have either refrained from covering the seismic design of liquid-containing structures, or have provided only simple, static-force equations for calculating base shears.

ACI 350.3 covers all types of concrete tanks (prestressed and non-prestressed, circular and rectilinear). This new ACI Standard presents a practical, "how-to" - and yet rigorous - guide to supplement Chapter 21 of ACI 350; and equips the practicing engineer with a comprehensive, practical and reliable tool for analyzing and designing liquid-containing concrete structures of all types to resist earthquakes.

2 DYNAMIC MODELING

Methods of seismic analysis of tanks, currently adopted by a number of industry standards, have evolved from earlier analytical work [Jacobsen 1949, Housner 1956, 1963a and 1963b, Haroun 1984, 1985, 1994, Veletsos 1974 and 1997]. Of these, the best known is Housner's pioneering work as published in the early 1960's in the Atomic Energy Commission's (now NRC) "*Technical Information Document (TID) 7024*".

ACI 350.3 utilizes the above references, particularly the Housner method. This method essentially assumes that hydrodynamic effects due to seismic loading can be evaluated approximately as the sum of the following two parts:

1. The impulsive part, which represents the portion of the stored liquid that moves in unison with the structure and,
2. The convective part, which represents the effect of the sloshing action of the liquid.

Figure 1a shows the typical schematic of a rectangular tank with length L, width B, liquid height $H_{L.}$ Figure 1b It represents the dynamic model of a typical tank (circular or rectangular), in which the impulsive portion of W_L (W_I) is assumed to be rigidly attached to the tank wall at height h_I, while the convective portion (W_C) is attached to the structure by springs of finite stiffness and damping at height h_C. For concrete tanks with relatively thick, rigid walls and roof, this results in a two degree-of-freedom system The impulsive and the convective components have periods associated with them that are generally far apart. The total approximate response of the system can be estimated by the square-root-of-the-sum-of-the-squares (SRSS) combination of the responses of the two components.

2.1 Period of Vibration

The equations for determining the periods T_I and T_C of rectangular and circular liquid-containing structures having different base conditions are given below. However, it is permitted to use any other rational methods that include a reasonable distribution of mass and stiffness characteristics for determining the natural period of the structure.

As most concrete tanks are relatively rigid, T_I may be taken as 0.3s or less for the preliminary and approximate design calculations. It is recommended that for flexible base tanks, T_I should not exceed 1s for anchored and unanchored contained tanks and 2 s for unanchored uncontained tanks. The purpose of these recommended limits is to prevent excessive deformations.

2.1.1 Rectangular Tanks

The following general equation can be used for determining the impulsive period of a rectangular tank:

$$T_I = 2p\sqrt{\frac{W_T}{gK}}$$

For fixed base, free top rectangular tank walls with a minimum length-to-height ratio $B/H_W \geq 2$, K is given as follows:

$$K = \frac{E_c}{4\times 10^6}\left(\frac{t_w}{h}\right)^3$$

$$W_T = W_W + W_R + W_I$$

where h = mean height at which the inertia force of the tank and its contents is assumed to act, (m); t_w = wall thickness (mm); E_c = modulus elasticity of concrete (Mpa); g = acceleration due to gravity (9.81 m/s^2); W_W = weight of tank wall; W_R = weight of roof; and W_I = weight of impulsive component, [all in (kN)].

The period associated with the convective component (T_C) can be determined as follows:

$$T_C = \frac{2\pi}{\lambda}\sqrt{L}$$

where L = length of rectangular wall (parallel to the action of the earthquake) (m); and factor $2p/l$ is a function of the ratio L/H_L, and can be obtained from ACI 350.3-01, Figure 9.5.

2.1.2 Circular Tanks

(a) Non-sliding Base (Types 1.1, 1.2, 2.1 and 2.2 from ACI 350.3). The following general procedure can be used for determining the impulsive period of fixed or hinged base circular tanks with or without prestressing:

$$T_I = \frac{2\pi}{\omega_I}$$

$$w_I = C_L \frac{1}{H_L}\sqrt{\frac{10^3\ E_C}{r_C}}$$

$$C_L = C_W\sqrt{\frac{t_w}{10R}}$$

r_c = mass density of concrete (2.4 $kN\text{-}sec^2/m^2$), t_w = wall thickness (mm); H_L = maximum liquid depth (m); and R = radius of tank (m). C_W for different D/H_L ratios is given in ACI 350.3-01, Figure 9.10.

(b) Sliding Base (Type 2.3 from ACI 350.3). The following general method can be used to determine the impulsive period T_I of flexible (sliding)-base circular prestressed tanks:

$$T_I = \sqrt{\frac{8pW_T}{gDk_a}}$$

where $W_T = W_W + W_R + W_I$

$$k_a = 144\left[\frac{A_S E_S \cos^2 q}{L_S S_b} + \frac{2G_p w_p L_p}{t_p S_p}\right]$$

For anchored flexible tanks

$$k_a = 144\left[\frac{2G_p w_p L_p}{t_p S_p}\right]$$

For unanchored flexible tanks

where, A_s = cross-sectional area of base cable/strand (mm^2); E_s = modulus of elasticity of cable/strand (MPa); q = angle of cable/strand with horizontal; L_s = effective length of cable/strand taken as sleeve length plus 35 times the diameter (mm); S_b= spacing between cable sets (mm); S_p = spacing of elastomeric pads (mm); G_p = shear modulus of elastomeric pads (MPa); t_p = thickness of elastomeric bearing pad (mm); L_p = length of individual elastomeric pad (mm); and w_p = width of elastomeric pad in radial direction (mm). Note that, for flexible-base tanks (Type 2.3), ACI 350.3 sets an upper limit of 1.25 s on the period T_I.

The convective period $T_C = \frac{2\pi}{\lambda}\sqrt{D}$

where D = tank diameter (m); and factor $2p/l$ for a given D/H_L ratio can be obtained from ACI 350.3-01, Figure 9.9.

3 STEP-WISE DESIGN PROCEDURE

The provisions of ACI 350.3-01 are geared for and compatible with UBC 1994. Note that ACI 350-01 refers to ACI 318-95 for most of its design provisions and load combinations. Section 21.2.1.7 of ACI 350-01 indicates that the environmental durability factor *(S)* defined in 9.2.8 need not be applied to load combinations that include earthquake effects.

3.1 Lateral Forces

The inertia, impulsive and convective forces to be applied on the walls of rectangular and circular tanks can be determined as follows:

Wall Inertia $P_W = ZIC_I \frac{W_W}{R_{WI}}$, Roof Inertia $P_R = ZIC_I \frac{W_R}{R_{WI}}$

Impulsive $P_I = ZIC_I \frac{W_I}{R_{WI}}$, Convective $P_C = ZIC_C \frac{W_C}{R_{WC}}$

where Z = seismic zone factor from UBC 1994, Table 16-I, or ACI 350.3-01, Table 4(a); I = importance factor; R_{WI} and R_{WC} are response modification factors (Table 1); W_W, W_R, W_I and W_C, respectively, represent the wall and roof weights, and the weights of the impulsive and convective components of the liquid [all in kN]. The impulsive weight W_I and convective weight W_C are expressed as fractions of the total weight of the contained liquid, W_L, according to Figure 2. A similar figure is given in ACI 350.3-01 for circular tanks.

C_I and C_C are period-dependent spectral amplification factors determined as shown below.

Impulsive factor C_I, per UBC 1994 and ACI 350.3-01:

$$C_I = 2.75 \text{ for } T_I \le T_S \qquad C_I = \frac{1.25S}{T_I^{2/3}} \text{ for } T_I > T_S$$

For soil type 1 (soil profile coefficient S_1), T_S can be conservatively taken as 0.3s. For other soil types, T_S can more accurately be determined from the design spectrum given in UBC 1994, Figure 16-3.

Convective factor C_C:

Per UBC 1994, $C_C = C = \frac{1.25S}{T_C^{2/3}}$

Per ACI 350.3, $C_C = \frac{6S}{T_C^2}$ (for $T_C \geq 2.4$ s)

3.2 Total Base Shear

$$V_I = \frac{ZIC_I}{R_{WI}}\left(W_W + W_R + W_I\right) = (P_W + P_R + P_I) \qquad \text{Impulsive}$$

$$V_C = \frac{ZIC_C}{R_{WC}}\left(W_C\right) = P_C \qquad \text{Convective}$$

Total base shear $V_T = \sqrt{V_I^2 + V_C^2}$

3.3 Total Overturning Moment

$$M_I = (P_W h_W + P_R h_R + P_I h_I) \qquad \text{Impulsive}$$

$$M_C = P_C h_C \qquad \text{Convective}$$

Total overturning moment $M_T = \sqrt{M_I^2 + M_C^2}$

where h_W and h_R are the distances from the base of the tank to the centers of gravity of the wall and roof respectively; and h_I and h_C are the heights at which the impulsive and convective lateral forces are assumed to act. Charts to determine h_I and h_C are given in ACI 350.3-01, Figure 9.3 for rectangular tanks and Figure 9.7 for circular.

3.4 Response Spectrum Method

The lateral forces on the tank can also be determined from a design response spectrum such as the one given in UBC 1994, Figure 16-3, in which a_0 represents the specified ground acceleration expressed as a fraction of the acceleration due to gravity, g. The design base shear is determined using this spectrum as follows:

$$V_I = \frac{a_I}{R_{WI}}\left(W_W + W_R + W_I\right)I \qquad \text{Impulsive}$$

$$V_C = \frac{a_C}{R_{WC}}\left(W_C\right)I \qquad \text{Convective}$$

Total base shear $V_T = \sqrt{V_I^2 + V_C^2}$

where a_I and a_C are the impulsive and convective *spectral* accelerations, respectively, corresponding to the impulsive and convective periods T_I and T_C in the design response spectrum, ($a_I = C_I{}' a_0$ and $a_C = C_C{}' a_0$).

4 COMPARATIVE BASE SHEARS - EXAMPLE

The example [Munshi, 2002] illustrates the use of the ACI 350.3 provisions in conjunction with UBC 1994, and also extends the concepts of these provisions to UBC 1997 and IBC 2000. The base shears derived on the basis of UBC 1994 and UBC 1997 are quite comparable [664 kN and 627 kN respectively, (Table 2 below)]. On the other hand, when computed solely in accordance with ACI 350.3-01, the base shear increases to 726 kN – which, incidentally, compares well to the 713.0 kN derived from the simplified, rigid-structure provisions of UBC 1997. This increase is primarily due to the reduction in the response modification factor, R_W , for the convective component, from $R_W = 2.75$ to $R_{WC} = 1.0$. The base shear computed per IBC 2000 is 611 kN.

5 CONCLUDING REMARKS

The new ACI Code 350-01/350.R-01, *"Code Requirements for Environmental Engineering Concrete Structures,"* has greatly expanded the seismic design provisions of the previous edition, ACI 350-89, in two ways: (1) through the adoption of Chapter 21 of ACI 318 *(*"Special Provisions for Seismic Design"), and (2) through the drafting of detailed seismic analysis guidelines in a separate Standard, ACI 350.3-01/350.3R-01 *("Seismic Design of Liquid-Containing Concrete Structures").* These two documents fill a real need for the profession in that they equip the practicing engineer with a practical and reliable tool for analyzing and designing liquid-containing concrete structures for earthquake forces. It should be noted, however, that the current ACI 350.3-01 provisions are compatible only with UBC 1994 based on service-level earthquake design. See reference 20 for design of tanks according to the UBC 1997 and IBC 2000.

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Table 1 - Response Modification Factor, R_w [Table 4(d), ACI 350.3-01]

Type of Structure	**R_{wi}**		**R_{wc}**
	On or Above Grade	**Buried(1)**	
(a) Anchored, flexible-base tanks	4.5	4.5(2)	1.0
(b) Fixed or hinged-base tanks	2.75	4.0	1.0
(c) Unanchored, contained or uncontained tanks(3)	2.0	2.75	1.0
(d) Elevated Tanks	3.0	--	1.0

(1) Buried tank is defined as a tank whose maximum water surface is at or below ground level.

(2) $R_{wi} = 4.5$ is the maximum R_{wi} value permitted.

(3) *Unanchored, uncontained tanks shall not be built in Zone 2B or higher.*

Table 2 – Comparison of results based on UBC 1994, ACI 350.3 and UBC 1997

Computed Base Shears, kN					
Base Shear	UBC 1994/ACI 350.3-01			UBC 1997	
	(1)	(2)	(3)	(4)	(5)
V_I	658	658	----	625	----
V_C	92	308	----	53	----
V_T	664	726	463	627	713

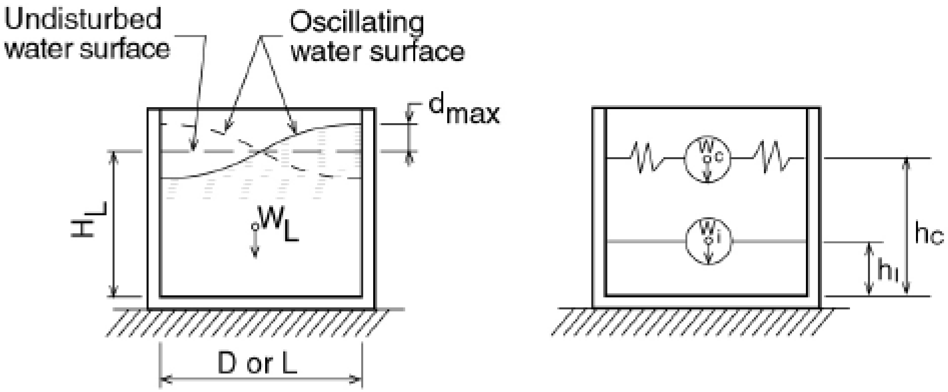
(1) Using UBC 1994 with $R_{WI} = R_{WC} = R_W = 2.75$, and $C_I = C_C = C = 1.25S/T_C^{2/3}$

(2) Using ACI 350.3-01 with R_{WI} and R_{WC} per Table 1; and $C_C = 6S/T_C^2$

(3) Using the rigid-structure equation of UBC 1994, Section 1632.3, Eq. (32-1)

(4) Using the Static Force Procedure of UBC 1997, Section 1630.2

(5) Using the rigid-structure equation of UBC 1997, Section 1634.3, Eq. (34-1)



(a) FLUID MOTION IN TANK

(b) DYNAMIC MODEL FOR RIGID WALL TANK

Fig. 1 -- Dynamic model of tank

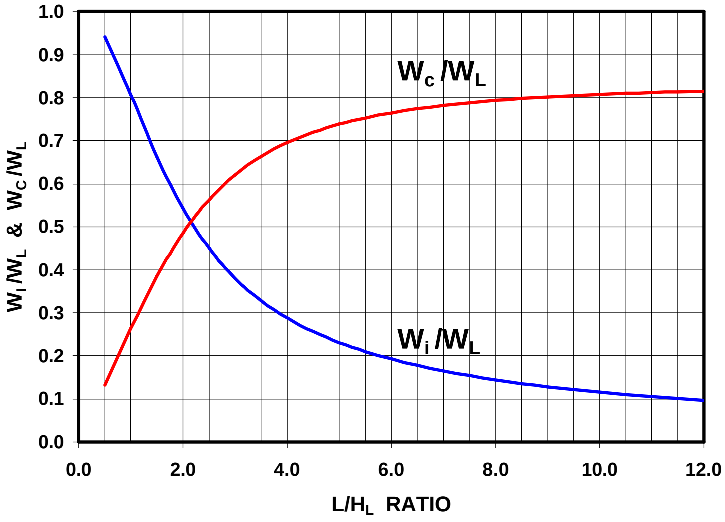


Fig. 2 -- Chart for computing impulsive and convective weights