Review of Seismic Codes on Liquid-Containing Tanks

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Liquid storage tanks generally possess lower energy-dissipating capacity than conventional buildings. During lateral seismic excitation, tanks are subjected to hydrodynamic forces. These two aspects are recognized by most seismic codes on liquid storage tanks and, accordingly, provisions specify higher seismic forces than buildings and require modeling of hydrodynamic forces in analysis. In this paper, provisions of ten seismic codes on tanks are reviewed and compared. This review has revealed that there are significant differences among these codes on design seismic forces for various types of tanks. Reasons for these differences are critically examined and the need for a unified approach for seismic design of tanks is highlighted.
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INTRODUCTION

Liquid-containing tanks are used in water distribution systems and in industries for storing toxic and flammable liquids. These tanks are mainly of two types: ground-supported tanks and elevated tanks. Ground-supported tanks are generally of reinforced concrete (RC), prestressed concrete (PSC), or steel. In elevated tanks, the container is supported on a structural tower, which could be in the form of a RC shaft or RC/steel frame. The large-scale damage to tanks during the 1960 Chilean earthquake initiated extensive research on seismic analysis of tanks. Since then, codes of practice have undergone significant changes. The performance of tanks during the 1964 Alaska earthquake (Hanson 1973), the 1979 Imperial County (California) earthquake (Gates 1980), the 1983 Coalinga (California) earthquake (Manos and Clough 1985), and the 1994 Northridge (California) earthquake (Hall 1995) have also helped in identifying and improving deficiencies in codes of practices. Recently, Rai (2002) studied the performance of elevated tanks during the 2002 Bhuj (India) earthquake and correlated it to the inadequacies in the prevailing practice.

Seismic analysis of liquid-containing tanks differs from buildings in two ways: first, during seismic excitation, liquid inside the tank exerts hydrodynamic force on tank walls and base. Second, liquid-containing tanks are generally less ductile and have low redundancy as compared to buildings. Traditionally, hydrodynamic forces in a tank-liquid system are evaluated using mechanical analog in the form of spring-mass system, which

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Table 1. Details of reviewed codes and standards

Code/Standard	Type of tanks considered[1]	Seismic force level[2]	Provisions on convective mode
2006 IBC & ASCE 7	1,2,3,4	SD	Yes
Eurocode 8 (1998)	1,2,3,4	SD	Yes
NZSEE	1,2,3,4	SD	Yes
ACI 350.3 (2001)	1,3	ASD	Yes
ACI 371 (1998)	3	SD	No
AWWA D-100 (2005)	2,3,4	ASD	Yes[3]
AWWA D-110 (1995)	1	ASD	Yes
AWWA D-115 (1995)	1	ASD	Yes
API 650 (2005)	2	ASD	Yes

[1] 1=Ground-supported RC/PSC tanks; 2=ground-supported steel tanks; 3=elevated tanks on shaft-type tower 4=elevated tanks on frame-type tower
[2] SD=strength design level; ASD=allowable stress design level
[3] Provisions on convective mode are given for ground-supported tanks only.

simulate the impulsive and convective mode of vibration of a tank-fluid system (Housner 1963; Veletsos and Yang 1977). Due to low ductility and redundancy, lateral design seismic forces for tanks are usually higher than that for buildings with "equivalent" dynamic characteristics, which is achieved by specifying lower values of response modification factor or its equivalent factor. Since tanks have higher utility and damage consequences, codes specify a higher importance factor for liquid-containing tanks, which further increases design seismic forces for tanks.

Though the aforementioned general features are retained by various codes of practices, their implementation strategy is rather varied leading to significantly different design forces in some cases. In this paper, ten such documents are reviewed and significant differences in their provisions are brought out to help develop a unified seismic design approach. The focus of the paper is primarily on the provisions related to design seismic forces and modeling for the seismic analysis of the tank-liquid system.

BRIEF DESCRIPTION OF REVIEWED CODES AND STANDARDS

Table 1 lists various codes and standards reviewed in this paper. Among these, 2006 IBC, Eurocode 8, and NZSEE are national codes, and ACI 350.3, ACI 371, AWWA D-100, AWWA D-110, AWWA D-115, and API 650 are standards from American industries, namely, American Concrete Institute (ACI), American Water Works Association (AWWA), and American Petroleum Institute (API). For the sake of brevity, standards from AWWA will be denoted as D-100, D-110, and D-115. For such structures, the 2006 IBC refers to ASCE 7 (2005), which has two sets of provisions: the first is its own provisions on design seismic forces and analysis, whereas the second consists of modified expressions for design seismic forces given in other standards from American industries (AWWA, API, and ACI). This modification was necessary so that the seismic hazard parameters as contained in ASCE 7/ 2006 IBC are referred by all such standards, which originally referred to 1994 and 1997 UBC. However, API 650 and D-100 have already adopted ASCE 7 parameters, hence in ASCE 7 there are no modifications for API 650 and D-100. Recommendations for the New Zealand Society for Earthquake Engineering (NZSEE 1986) were originally developed by Priestley et al., and were modified by Whittaker and Jury (2000) to incorporate the changes in the primary New Zealand code for design loading, NZS 4203 (1992).

Various types of tanks considered in these codes and standards can be broadly put into the following four categories:

(1) ground-supported RC/PSC tanks
(2) ground-supported steel tanks
(3) elevated tanks on shaft-type tower
(4) elevated tanks on frame-type tower

Details on the types of tanks considered in each of the documents are also given in Table 1. ASCE 7, Eurocode 8, and NZSEE deal with all four categories of tanks. Standards from other American industries deal with only those tanks that are used in that particular industry. Some of the documents specify design seismic force at strength design level, and others specify at working stress design level (Table 1). In strength design, factored loads are used and they correspond to ultimate level. Provisions on the evaluation of convective mode seismic forces are given in all the documents except ACI 371.

PROVISIONS ON DESIGN SEISMIC FORCE

Lateral design seismic forces for liquid-containing tanks include impulsive (V_i) and convective (V_c) components. The impulsive component is expressed as $V_i=(C_s)_i W_i$, where $(C_s)_i$ is the impulsive base shear coefficient and W_i is the seismic weight of the impulsive component. Likewise, the convective component is given by $V_c=(C_s)_c W_c$. Expressions for the base shear coefficient of impulsive $(C_s)_i$ and connective $(C_s)_c$ components from ASCE 7, Eurocode 8, and NZSEE are given in Table 2. Corresponding expressions from ACI, AWWA, and API standards are given in Tables 3 and 4, along with the modified expressions of ASCE 7. Various terms used in these expressions are also described in these tables. Base shear coefficient is typically specified in terms of design acceleration spectrum, seismic zone factor, soil factor, importance factor, response modification factor, and damping factor. In the next section, various quantities involved in the expressions for base shear coefficient from various codes/standards are reviewed and compared.

VARIATION OF BASE SHEAR COEFFICIENT WITH TIME PERIOD

Variation of base shear coefficient with natural period can typically be divided into three time period ranges: acceleration-sensitive (or short-period) range, velocity-sensitive range, and displacement-sensitive (or long-period) range. In most of the codes, impulsive and convective mode base shear coefficients have a different type of variation with natural period and therefore they are discussed separately.

Table 2. Base shear coefficient from 2006 IBC/ASCE 7, Eurocode 8, and NZSEE

Code	Expression for base shear coefficient	
2006 IBC /ASCE 7	For impulsive mode $(C_s)_i = \frac{S_{DS} I}{R}$ for $T_i \leq T_s$ $= \frac{S_{D1} I}{R T_i}$ for $T_s < T_i \leq T_L$ $= \frac{S_{D1} I T_L}{R T_i^2}$ for $T_i > T_L$ $\geq 0.5 S_1$	For convective mode $(C_s)_c = \frac{S_{D1} I}{T_c}$ for $T_c \leq T_L$ $\leq S_{DS} I$ $= \frac{S_{D1} I T_L}{T_c^2}$ for $T_c > T_L$
	I is importance factor; R is response modification factor; T_i is natural period of impulsive mode; T_c is natural period of convective mode; S_{DS} and S_{D1} are design spectra response coefficients; $T_s = S_{D1}/S_{DS}$; T_L is transition period for long-period range; and S_1 is mapped maximum considered earthquake spectral response acceleration at a period of 1 s.	
Eurocode 8	For impulsive mode $(C_s)_i = \gamma_I S_e$ or $\gamma_I S_d$	For convective mode $(C_s)_i = \gamma_I S_e$
	where S_e is elastic spectrum and S_d is design spectrum; γ_I is importance factor.	
	$S_e = \alpha S \left[1 + \frac{T}{T_B (2.5\eta - 1)} \right] 0 \leq T < T_B$ $= 2.5 \alpha S \eta \; T_B \leq T < T_c$ $= 2.5 \alpha S \eta \left(\frac{T_c}{T} \right) T_c \leq T < 3$ $= 7.5 \alpha S \eta \left(\frac{T_c}{T^2} \right) 3 \leq T$ $\eta = \left(\frac{7}{2 + \zeta} \right)^{0.5}$	$S_d = \alpha S \left[1 + \frac{T}{T_B} \left(\frac{2.5}{q} - 1 \right) \right] 0 \leq T < T_B$ $= 2.5 \alpha \frac{S}{q} \; T_B \leq T < T_c$ $= 2.5 \alpha \frac{S}{q} \left(\frac{T_c}{T} \right)^{2/3} \geq 0.2 \alpha T_c \leq T < 3$ $= 39 \alpha \frac{S}{q} \left(\frac{T_c^{2/3}}{T^{5/3}} \right) \geq 0.2 \alpha 3 \leq T$
	α is peak ground acceleration factor; S is soil factor; η is damping factor; ξ is viscous damping ratio; q is behavior factor; T is natural period; and T_B and T_c are periods at which constant-acceleration and constant-velocity range begin, respectively.	
NZSEE	For impulsive and convective mode $(C_s)_i = C_h(T,1) S_p R Z L_u C_f(\mu, \xi)$	
	$C_h(T,1)$ is basic seismic hazard coefficient; T is natural period; S_p is performance factor; R is risk factor; Z is zone factor; L_u is limit state factor; and $C_f(\mu, \xi)$ is correction factor that depends on ductility factor, μ, and damping factor, ξ.	

Table 3. Impulsive mode base shear coefficient from American industry standards

Standard	Original expression from standard	Modified expression from ASCE 7
ACI 350.3	$(C_s)_i = \dfrac{2.75ZI}{R_{wi}}$ for $T_i \leq 0.31$ s $= \dfrac{1.25ZIS}{R_w T_i^{2/3}}$ for $T_i > 0.31$ s $< \dfrac{2.75ZI}{R_{wi}}$	$(C_s)_i = \dfrac{\left(0.6\dfrac{S_{Ds}}{T_0}T_i + 0.4S_{DS}\right)I}{1.4R}$ for $0 < T_i < T_s$ $= \dfrac{S_{DS}I}{1.4R}$ for $T_0 \leq T_i < T_s$ $= \dfrac{S_{D1}I}{1.4RT_i}$ for $T_s \leq T_i \leq T_L$ $= \dfrac{S_{D1}IT_L}{RT_i^2}$ for $T_i > T_L$
D-110	$(C_s)_i = \dfrac{1.25ZIS}{R_i T_i^{2/3}} \leq \dfrac{2.75ZI}{R_i}$	Same as ACI 350.3
D-115	$(C_s)_i = \dfrac{1.25ZIS}{R_w T_i^{2/3}} \leq \dfrac{2.75ZI}{R_w}$	Same as ACI 350.3
API 650	$(C_s)_i = \dfrac{S_{DS}I}{R_{wi}}$ ≥ 0.007 or $0.5S_1(I/R_{wi})$	No modification
D-100	$(C_s)_i = \dfrac{S_{DS}I}{1.4R_i}$ for $0 \leq T_i \leq T_s$ $= \dfrac{S_{D1}I}{1.4R_iT_i}$ for $T_s < T_i \leq T_L$ $= \dfrac{S_{D1}IT_L}{1.4R_iT_i^2}$ for $T_i > T_L$ $\geq 0.36S_1I/R_i$	No modification
ACI 371	$(C_s)_i = \dfrac{1.2C_V}{RT_i^{2/3}}$ $\leq \dfrac{2.5C_a}{R}$ $\geq 0.5C_a$	$(C_s)_i = \dfrac{S_{D1}I}{RT_i}$ for $T_s < T_i < 2.5$ s $\leq \dfrac{S_{DS}I}{R}$ and $\geq 0.2S_{DS}$

Note: Z is zone factor; S is soil factor; I is importance factor; R, R_i, R_w, and R_{wi} are response modification factor; S_{DS} and S_{D1} are design spectra response coefficients; S_1 is mapped maximum considered earthquake spectral response acceleration at a period of 1 s; C_a and C_v, are seismic acceleration coefficients; T_i is natural period of impulsive mode; T_o=0.2S_{DS}/S_{D1}; T_s=S_{D1}/S_{DS}; and T_L is transition period for long-period range.

Table 4. Convective mode base shear coefficient from American industry standards

Standard	Original expression from standard	Modified expression from ASCE 7
ACI 350.3	$(C_s)_c = \frac{1.875ZIS}{T_c^{2/3}} < 2.75ZI$ for $T_c < 2.4$ s $= \frac{6ZIS}{T_c^2}$ for $T_c \geq 2.4$ s	$(C_s)_c = \frac{1.5S_{D1}IT_L}{T_c^2}$ for all values of T_c
D-110	$(C_s)_c = \frac{4ZIS}{R_c T_c^2}$	Same as ACI 350.3
D-115	$(C_s)_c = \frac{ZIS}{R_w T_c}$	Same as ACI 350.3
API 650	$(C_s)_c = \frac{1.5S_{D1}I}{T_c R_{wc}}$ for $T_c \leq T_L$ $= \frac{1.5S_{D1}IT_L}{T_c^2 R_{wc}}$ for $T_c > T_L$ $\leq (C_s)_i$	No modification
D-100	$(C_s)_c = \frac{1.5S_{D1}I}{1.4T_c R_c}$ for $T_c \leq T_L$ $\leq S_{DS}I/(1.4R_c)$ $= \frac{1.5S_{D1}IT_L}{1.4T_c^2 R_c}$ for $T_c > T_L$	No modification
ACI 371	No Provision	No Provision

Note: Z is zone factor; S is soil factor; I is importance factor; R_c, R_c, and R_w are response modification factor; S_{DS} and S_{D1} are design spectra response coefficients; $T_s = S_{D1}/S_{DS}$; T_c is natural period of convective mode; and T_L is transition period for long-period range.

Impulsive Mode

Natural period of the impulsive mode (T_i) for ground-supported RC/PSC tanks, which may have a flexible base, is expected to remain in the acceleration-sensitive or velocity-sensitive range, and therefore, in ACI 350.3, D-110, and D-115, the impulsive base shear coefficient is specified in these ranges only. In these standards, the base shear coefficient has a constant value in the acceleration-sensitive range and beyond this range it has $1/T_i^{2/3}$ variation (Table 3), which has been changed to $1/T_i$ in ASCE 7 modified expressions for $T_s < T_i \leq T_L$, and for $T_i > T_L$ it has $1/T_i^2$ variation. Here T_L is transition

Table 5. Basic seismic hazard coefficient, $C_h(T,1)$, for flexible soil (NZS 4203)

Period, T in s	0.0 to 0.60	0.70	0.80	0.90	1.0	1.5	2.0	2.5	3.00	4.00
$C_h\ (T,1)$	1.0	0.94	0.88	0.81	0.75	0.52	0.38	0.30	0.25	0.19

period for long-period or constant displacement range. ASCE 7 provides contour maps for values of T_L in various regions of America. These contour maps are given for T_L =4, 6, 8, 12, and 16 s.

Natural period of the impulsive mode for ground-supported steel tanks is expected to remain in the acceleration-sensitive range, and therefore API 650 specifies a constant value of the base shear coefficient, which is independent of time period. The value of the base shear coefficient shall not be less than 0.007 for tanks on hard or stiff soil and shall not be less than $0.5S_1I/R_{wi}$ for tanks on very soft soils.

Impulsive base shear coefficients given in ASCE 7, D-100, and Eurocode 8 are applicable to ground-supported as well as elevated tanks. Since elevated tanks can have quite large time period for the impulsive mode, ASCE 7, D-100, and Eurocode 8 have specifically prescribed variation of the impulsive base shear coefficient in the displacement-sensitive range also. In ASCE 7, the impulsive base shear coefficient has a constant value in the acceleration-sensitive range and has $1/T_i$ variation in the velocity-sensitive range, and in the displacement-sensitive range it has $1/T_i^2$ variation. There is a lower limit $(0.5S_1)$ on base shear coefficient, however, which ensures a minimum level of design force. This lower limit of ASCE 7 is quite higher than the lower limit specified by D-100 $(0.36S_1I/R_i)$.

In Eurocode 8, two types of spectra, namely, the *elastic spectrum* and the *design spectrum*, are mentioned (see Table 2). In the acceleration-sensitive range, both the spectra have a rising part from zero periods to T_B, at which constant-acceleration range begins and continues up to T_c. In the velocity-sensitive range, which begins at T_c, the elastic spectrum has $1/T_i$ variation, whereas the design spectrum has $1/T_i^{2/3}$ variation. In the displacement-sensitive range, which begins at 3 s, the elastic spectrum has $1/T_i^2$ variation, whereas the design spectrum has $1/T_i^{5/3}$ variation. The elastic spectrum does not have any lower limit, but the design spectrum has a lower limit due to which the base shear coefficient is a constant value in the long-period range (Table 2). This lower limit is similar to one given in ASCE 7 and D-100. ACI 371 also specifies such a lower limit for elevated tanks on pedestal tower and the modified expression of ASCE 7 retains this lower limit (Table 3). In NZSEE, variation of the base shear coefficient with time period is governed by the basic seismic hazard coefficient $C_h(T,1)$, which is taken from NZS 4203 (1992). The basic seismic hazard coefficient corresponds to the elastic design level, i.e., ductility factor μ=1.0. In NZS 4203, values of $C_h(T,1)$ for different time period$T$ are given in tabular form and they depend on soil type. Values of $C_h(T,1)$ for flexible soil are reproduced in Table 5, wherein it is seen that in the short-period range, $C_h(T,1)$ has constant value.

Convective Mode

The natural period of convective mode (T_c) is usually more than 2 s and can be as high as 10 s. Thus, for convective mode, variation of the base shear coefficient in the velocity- and displacement-sensitive range is of relevance. Significant differences exist among various codes in specified variation of the convective base shear coefficient with time period. ASCE 7, D-100, and API 650 put an upper limit on the convective base shear coefficient, whereas ACI 350.3, D-110, and D-115 do not have such upper limit (Table 4). The upper limit specified in API 650 is quite different and lower than that specified in ASCE 7 and D-100. In ASCE 7, ACI 350.3, D-100, and API 650, the displacement-sensitive range is well demarcated from the velocity-sensitive range. The displacement-sensitive range begins at 2.4 s in ACI 350.3 (Table 4), whereas in ASCE 7, D-100, and API 450 it begins at T_L, whose values varies from 4 to 16 s, depending on the location. In these standards, base shear coefficient has $1/T_c^2$ variation in displacement-sensitive range. In velocity-sensitive range, convective base shear coefficient varies as $1/T_c^{2/3}$ in ACI 350.3, whereas in ASCE 7, D-100, and API 650, it has $1/T_c$ variation. D-110 and D-115 do not explicitly specify the beginning of the displacement-sensitive range. Moreover, D-110 specifies $1/T_c^2$ variation for all values of T_c, whereas D-115 specifies $1/T_c$ variation for all values of T_c (Table 4). Notwithstanding the differences in the convective base shear coefficients of ACI 350.3, D-110, and D-115, the modified expression of ASCE 7 is the same for these standards (Table 4).

In Eurocode 8 and NZSEE, variation of the base shear coefficient with time period in convective and impulsive modes is the same. It may be recalled here that NZSEE uses the basic seismic hazard coefficient $C_h(T, 1)$ given in NZS 4203, whose values are given for a maximum period of 4 s only (Table 5), which may be too low for certain shallow containers.

RESPONSE MODIFICATION FACTOR

In seismic codes, design seismic forces are reduced by a certain amount depending on the ductility, overstrength, and redundancy of the structure or depending on its energy-absorbing capacity. In ASCE 7, this reduction is achieved with the help of the response modification factor R; Eurocode 8 uses the behavior factor q; and NZSEE uses the correction factor C_f, which is a function of ductility factor μ and damping ratio ξ. Standards from American industries use a factor similar to the response modification factor of ASCE 7; however, D-110 and D-115 refer to it as a structure coefficient.

Significant differences are seen in the strategies followed by different codes to reduce elastic design seismic force. The first major difference pertains to classification of tanks depending on their energy-absorbing capacity. Some codes and standards give a detailed classification of tanks and specify the value of the response modification factor for each type of tank. For example, three types of ground-supported RC and PSC tanks and two types of ground-supported steel tanks are described in ASCE 7 and other American standards. Details of these tanks and their response modification factors are given in Table 6. NZSEE also suggests classification for tanks, which is given in Table 7 along with the corresponding values of ductility factor μ, damping ratio ξ, and correc-

Table 6. Type of tanks and response modification factors from American standards

Type of base	Response modification factor							
	Ground-supported RC/PSC tanks							
	ASCE 7		ACI 350.3		D-110		D-115	
	Impl.	Conv.	Impl.	Conv.	Impl.	Conv.	Impl.	Conv.
Anchored flexible	3.0	1.5	4.5	1.0	4.5	1.0	2.5	2.5
Reinforced nonsliding	2.0	1.5	2.75	1.0	2.75	1.0	3.0	3.0
Unanchored and contained flexible	—	—	2.0	1.0	—	—	3.0	3.0
Unanchored and uncontained flexible	1.5	1.5	2.0	1.0	2.0	1.0	1.0	1.0
	Ground-supported steel tanks							
	ASCE 7		D-100		API 650			
Mechanically anchored	3.0	1.5	3.0	1.5	4.0	2.0		
Self anchored	2.5	1.5	2.5	1.5	3.5	2.0		
	Elevated tanks							
	ASCE 7		ACI 350.3		ACI 371		D-100	
RC pedestal	2.0	1.5	3.0	1.0	2.0	*a*	3.0[1]	1.5[1]
Braced/ unbraced legs	3.0	1.5	—	—	—	—	3.0	1.5

a = No provision
[1] For steel pedestal

tion factor C_f. It may be noted that NZSEE gives a detailed classification for ground-supported steel tanks but does not give such a classification for RC/PSC tanks. It is intriguing to note that Eurocode 8 does not suggest any classification for ground-supported tanks. It mentions that elastic design forces (i.e., $q = 1$) shall be used for all types of ground-supported tanks unless better energy-dissipating capacity is demonstrated by proper analysis.

Values of the response modification factor from D-115 are quite different than those from ACI 350.3 and D-110 (Table 6). Moreover, D-115 uses the response modification factor for the convective mode, which is not the case with ACI 350.3 and D-110. D-115 specifies different values of the response modification factor for unanchored contained and unanchored uncontained bases; however, ACI 350.3 specifies the same values for these two base conditions.

The values of the response modification factor from ACI 350.3, D-110, and API 650 are about 1.4 times higher than that of ASCE 7 (Table 6). This difference is due to the fact that ASCE 7 specifies seismic design forces at the strength design level, whereas ACI 350.3, D-110, and API 650 are at the allowable stress design level. In this context it is interesting to note that D-100 also specifies seismic design forces at the allowable

Table 7. Types of tanks, ductility factor μ, damping ratio ξ, and correction factor C_f, from NZ-SEE (Whittaker and Jury 2000)

Type of Tank	μ	ξ(%)		C_f	
Steel Tanks on Grade		Impl.**	Conv.	Impl.	Conv.
Elastically supported	1.25	2	0.5	0.83	0.92
Unanchored tank designed for uplift (elephant foot shell buckling may occur under seismic overload)	2.0[a]	2	0.5	0.54	0.58
Unanchored tank designed for uplift and elastic (diamond shaped) shell buckling mode	1.25	2	0.5	0.83	0.92
Anchored with nonductile hold-down bolts	1.25	2	0.5	0.83	0.92
Anchored with ductile tension yielding hold-down bolts	3.0[b]	2	0.5	0.41	0.43
Ductile skirt pedestal	3.0[b]	2	0.5	0.41	0.43
On concrete base pad designed for rocking	2.0[b]	2	0.5	0.54	0.58
Concrete Tanks on Grade					
Reinforced concrete	1.25	5	0.5	0.72	0.92
Prestressed concrete	1.0	5	0.5	1.0	1.75
Elevated Tanks	*		0.5		

[a] Check that elastic buckling does not occur before elephant foot.
[b] Capacity design check required to protect against other forms of failure.
* As appropriate for support structure. Capacity design approach shall be used to protect elevated tanks against failure while yielding occurs in the chosen support system
** Damping ratio ξ depends on soil type and aspect ratio of tank. Values given here are for soil with shear-wave velocity of 500 m/s and height to radius ratio of 2.0.

stress design level; however, it uses a factor of 1.4 to convert seismic design forces from strength design level to allowable stress design level. Hence the values of the response modification factor in D-100 are the same as those in ASCE 7. In the case of elevated tanks, the response modification factor depends on the structural form of the supporting tower. Different response modification factors are suggested in ASCE 7 for tanks supported on pedestal towers and frame-type towers. However, NZSEE does not give any specific description of a supporting tower, and it merely states that the ductility factor applicable to a supporting tower shall be used (Table 7). Similarly, Eurocode 8 suggests elastic design forces (i.e., $q=1$) for all elevated tank types except for tanks with low risk and simple types of support structures, for which $q=2$ can be used. D-100 has specified a response modification factor of 3.0 for elevated tanks on frame-type towers and pedestal towers. It is to be noted that the pedestal tower referred to in D-100 is of steel plates, whereas ASCE 7, ACI 350.3, and ACI 371 refer to the RC pedestal tower.

Another major difference among various codes is regarding the use of the response modification factor for convective forces. ACI 350.3, D-110, and Eurocode 8 explicitly mention that the response modification factor shall not be used for the convective mode, thereby implying that no reduction due to the energy-dissipating capacity is available. ASCE 7, D-100, and API 650 allow limited reduction in convective mode forces by specifying lower values of the response modification factor for the convective mode. ASCE 7 and D-100 specify a response modification factor of 1.5 and API 650 suggests a response modification factor of 2.0. Moreover, in these standards, the response modification factor for the convective mode is the same for all types of tanks. On the other hand, D-115 and NZSEE allow large reduction in convective forces by specifying the same response modification factor (or its equivalent factor) used for impulsive forces. Thus in D-115 and NZSEE the response modification factor for the convective mode is different for different types of tanks.

DAMPING IN IMPULSIVE AND CONVECTIVE MODES

All codes prescribe 0.5% damping for the convective mode, whereas for the impulsive mode they have different values, depending on the type of the tank, construction material, etc. ASCE 7 uses 5% damping for impulsive modes in all types of tanks and this results in a design spectrum that is 1.5 times lower than the 0.5% damped spectrum in the velocity sensitive range. Eurocode 8 specifies 5% damping for the impulsive mode of RC and PSC tanks and 2% damping for steel tanks and its effect is included in the damping factor, η. Thus the convective spectrum (η=0.5%) is 1.7 times the impulsive spectrum (η=5%) in Eurocode 8.

NZSEE specifies 0.5% damping for the convective mode in all types of tanks, and for the impulsive mode of ground-supported tanks, it suggests damping values that depend on tank material, aspect ratio of tank geometry, and foundation soil shear wave velocity. However, for elevated tanks, NZSEE does not suggest any specific value for the impulsive mode, and it mentions that the damping value appropriate for the supporting tower of an elevated tank shall be used. In NZSEE, the effect of damping on the correction factor C_f depends on the ductility factor μ (Table 7).

ACI 350.3, which deals with RC/PSC tanks, has 5% damping for the impulsive mode and 0.5% damping for the convective mode. Further, in the velocity-sensitive range, the 0.5% spectrum is 1.5 times higher than the 5% spectrum. D-110 and D-115, which deal with PSC tanks, suggest 5% damping for the impulsive mode and 0.5% damping for the convective mode. API 650 and D-100, which deals with steel tanks, specify 5% damping for the impulsive mode and 0.5% damping for the convective mode, and the 0.5% spectrum is 1.5 times higher than the 5% spectrum in the velocity-sensitive range. It is to be noted that in D-110 and D-115, the impulsive and convective base shear coefficients have a different variation with natural period.

IMPORTANCE FACTOR

The importance factor depends on the utility of tank and damage consequences. In ASCE 7, tanks are classified in three categories (I=1.5, 1.25, and 1.0), which depend on functional requirements and hazards due to leakage of their content. In Eurocode 8, tanks are assigned three protection levels depending on the type of liquid stored. Each protection level is further assigned three classes of reliability depending on risk to life and environmental, economical, and social consequences. Thus there are nine values of the importance factor, ranging from 0.8 to 1.6. NZSEE uses a risk factor whose values range from 0.5 to 1.6, depending on whether consequences of failure are negligible, slight, moderate, or extreme, which are arrived at by considering risk to life, environment, community utility, and value of adjoining properties.

ACI 350.3, D-100, and API 650 also classify tanks in three categories with importance factors of 1.5, 1.25, and 1.0, respectively. ACI 350.3 mentions that a value greater than 1.5 may be used for tanks containing hazardous materials, depending on engineering judgment to account for the possibility of an earthquake greater than the design earthquake. D-110 and D-115 group tanks in two categories with importance factors of 1.25 and 1.0, respectively.

COMPARISON OF BASE SHEAR COEFFICIENTS FROM VARIOUS CODES

As discussed above, among various codes, significant qualitative and quantitative differences exist in the parameters associated with base shear coefficients. These differences lead to large variations in the values of base shear coefficients across these codes, as shown in Figures 1–3. Impulsive and convective mode base shear coefficients are compared separately at strength design level, for which prescribed values in American industry standards (except ACI 371) at working stress level were multiplied by a factor of 1.4. For this comparison, several parameters corresponding to a similar seismic hazard level are chosen from various codes and are given in Table 8. The soil categories chosen from various codes represent medium to stiff soil, representing approximately similar shear-wave velocity. In ASCE 7, the value of transition period T_L is taken as 4 s.

GROUND-SUPPORTED RC/PSC TANKS

In Figure 1, a comparison for ground-supported RC/PSC tanks with three types of base conditions is presented. Unlike American standards, impulsive base shear coefficients from NZSEE and Eurocode 8 have higher values as they either permit very little inelastic behavior or none. Among American codes, impulsive base shear coefficients of D-115 are different from those from ACI 350.3, D-110, and ASCE 7 (Figure 1) because of its very different values of response modification factor (Table 6). The lower-bound limit on the impulsive base shear coefficient from ASCE 7 is quite high.

In NZSEE, for PSC tanks, the value of the correction factor C_f for convective mode is 1.75 compared to 0.92 for RC tanks (Table 6), and hence PSC tanks have a significantly higher convective base shear coefficient than RC tanks. Further, convective base shear coefficient values from ACI 350.3 are quite higher than those from D-110 and ASCE 7.

Comparison of base shear coefficient from American industry standards and corresponding modified expressions from ASCE 7 is given in Table 9. This comparison is presented at selected values of time periods for impulsive and convective modes. ASCE 7 modifications suggest the same values of base shear coefficients for ACI 350.3, D-110, and D-115. The modified values match well with ACI 350.3 values for ground-supported RC/PSC tanks on flexible base and for elevated tanks on shaft support.

GROUND-SUPPORTED STEEL TANKS

Comparison of the base shear coefficient is presented in Figure 2 for ground-supported steel tanks with anchored and unanchored bases. The impulsive base shear coefficient from Eurocode 8 is on the higher side, since it is specified at the elastic level.

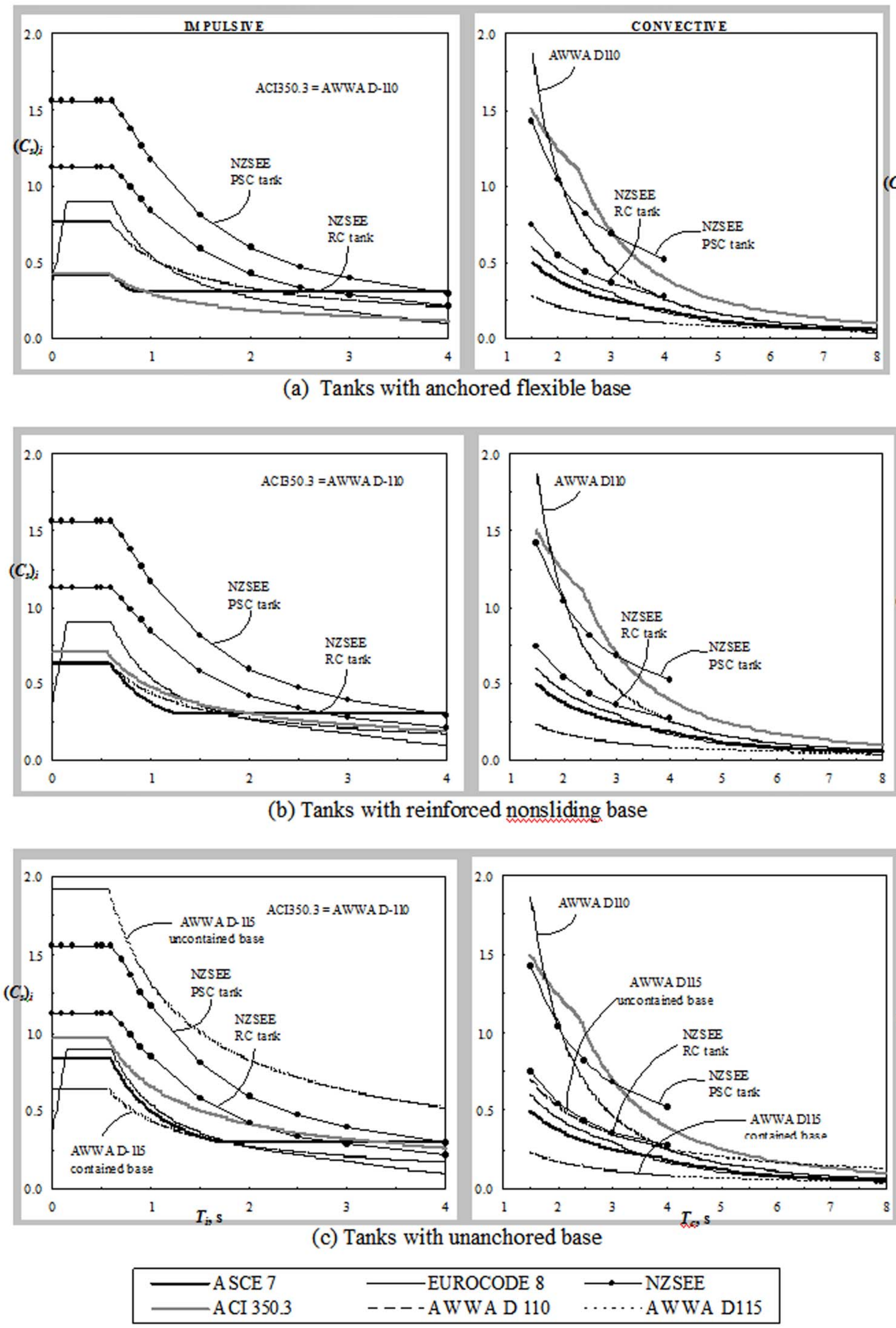

Figure 1. Base shear coefficient for RC/PSC tanks.

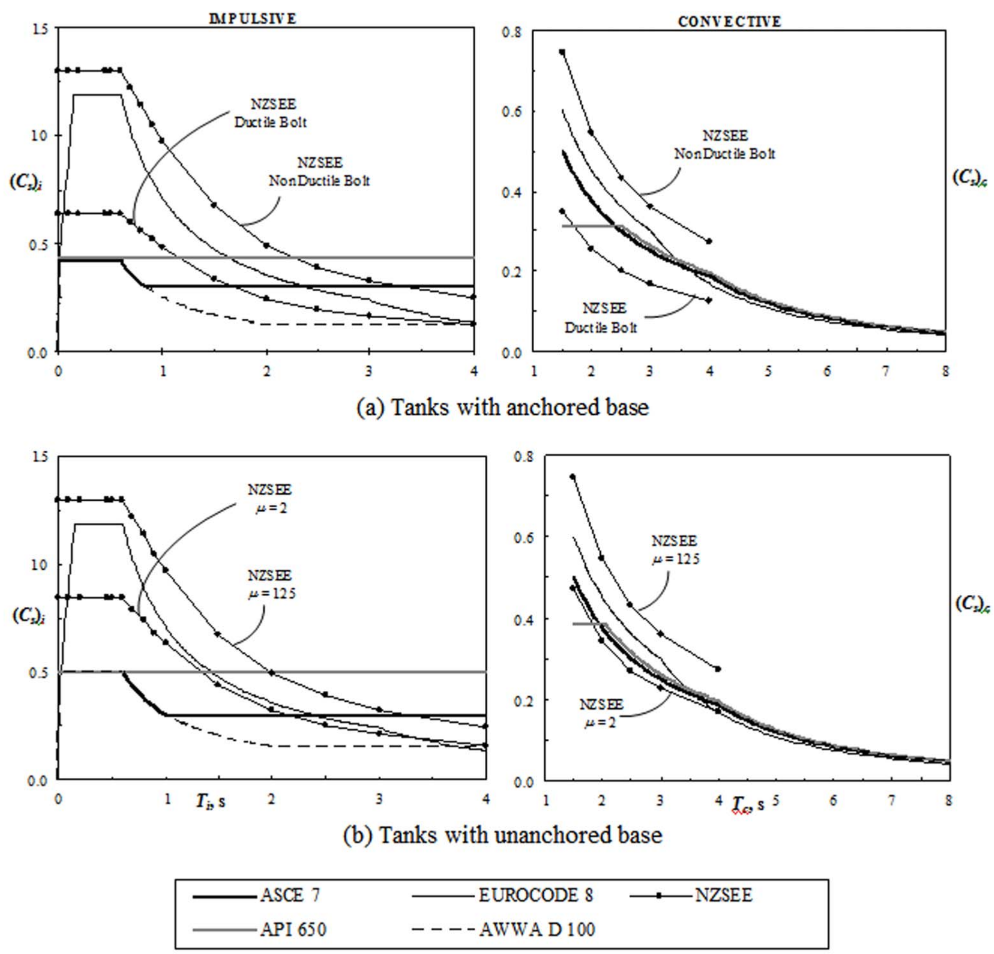

Figure 2. Base shear coefficient for ground-supported steel tanks.

For tanks with ductile anchored bolts, NZSEE suggests a very high ductility factor, hence its impulsive base shear coefficient is less than that for anchored tanks with non-ductile bolts (Figure 2a). In API 650, due to a lower value of upper limit, the convective base shear coefficient remains constant for natural periods less than 2 s. On the other hand, in ASCE 7 and D-100 this upper limit is quite high and its effect is not seen for natural periods greater than 1.5 s (Figure 2).

Since API 650 and D-100 have already adopted parameters from ASCE 7, there are no modifications in ASCE 7 for these standards. Hence, in Table 9, there is no comparison between API 650, D-100, and modified expressions of ASCE 7.

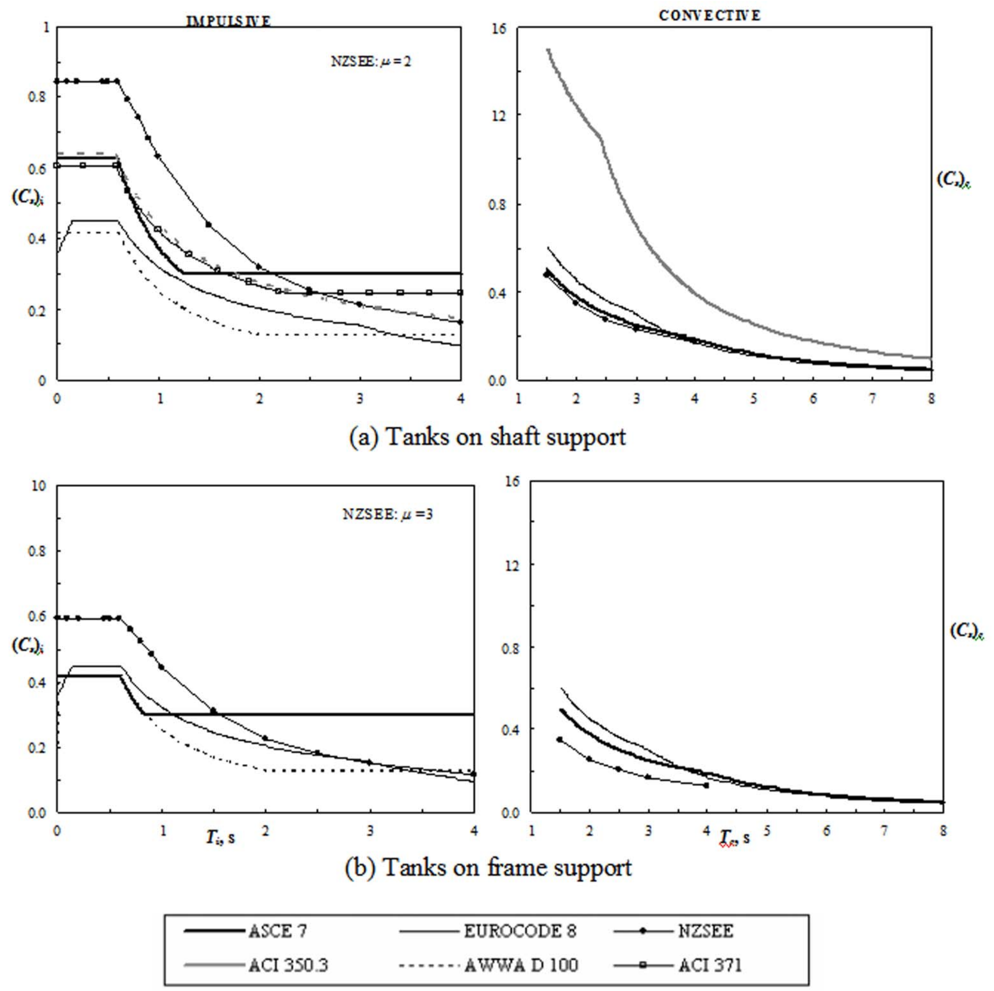

Figure 3. Base shear coefficient for elevated tanks.

ELEVATED TANKS

In Figure 3, comparison of the base shear coefficient for elevated tanks on a frame-type tower and a RC shaft–type tower is presented. Since NZSEE does not give explicit values of the ductility factor for elevated tanks, a ductility factor $\mu=3.0$ for the frame-type tower and $\mu=2.0$ for RC shaft–type tower is assumed for comparison purposes. In Eurocode 8, impulsive base shear coefficients for both the elevated tanks correspond to behavior factor $q=2$. The convective base shear coefficient from ACI 350.3 is quite a bit higher. Base shear coefficients per the modified expressions of ASCE 7 match well with those obtained from ACI 350.3, ACI 371, and D-100 (Table 9).

Table 8. Parameters from various codes and standards

Code/Standard	Values of various parameters
ASCE 7, D-100, and API 650	S_S=1.5, S_1=0.6, F_a=1.0, F_V=1.5, Site Class D, I=1.25, S_{DS}=2/3F_aS_S, S_{D1}=2/3F_VS_1, T_L=4 s
Eurocode 8	α=0.3, S=1, γ=1.2, T_B=0.15, T_C=0.6, q=2, sub soil class B
NZSEE	Z=1.2, S_p=1.0, R=1.3, L_u=1, site category C
ACI 350.3, D-110, and D-115	Z=0.4, I=1.25, S=1.5, Soil type C
ACI 371	C_a=0.44, C_v=0.64, Soil type D

PROVISIONS ON ANALYSIS OF TANKS

Codes and standards also give provisions for analysis of the tank liquid system. These provisions deal with modeling of the tank-liquid system, rules for combining impulsive and convective responses, hydrodynamic pressure on wall, sloshing wave height, and so on. Some important provisions on analysis aspects are reviewed and compared in this section.

MODELING OF TANK LIQUID SYSTEM

All the codes and standards suggest modeling the tank-liquid system using mechanical analogs, wherein liquid mass is divided into impulsive and convective masses. The impulsive liquid mass vibrates along with the tank wall and the convective liquid mass vibrates relative to the tank wall and undergoes sloshing motion. Liquid in the lower portion mostly contributes to impulsive mass and liquid in the upper portion undergoes sloshing motion. Housner (1963) has given details on impulsive and convective masses. In the literature, two types of mechanical analogs are available for obtaining impulsive and convective masses. The first one is for tanks with rigid walls, which represents the tank-liquid system as a two-mass model (Housner 1963; Veletsos and Yang 1977). The second one is for tanks with flexible walls, which represents the tank-liquid system as a three-mass model (Haroun and Housner 1981; Veletsos 1984). In the three-mass model, the effect of wall flexibility is included while evaluating impulsive and convective masses. Except for NZSEE, all other codes use a rigid tank model for all types of tanks. NZSEE uses a rigid tank model for RC tanks, and a flexible tank model for steel tanks. The effect of wall flexibility on impulsive and convective mass has been studied by Veletsos (1984), and it is shown that wall flexibility becomes important only for very slender and thin tanks. Moreover, those codes, which use the rigid tank model, do include the effect of wall flexibility in the evaluation of impulsive mode time period. Thus wall flexibility is neglected only in the evaluation of impulsive and convective masses, but is included in the evaluation of time period.

It is important to point out that the mechanical analog is a combination of impulsive and convective responses. ASCE 7, and Eurocode 8 use the absolute summation rule, whereas ACI 350.3, D-110, D-115, D-100, API 650, and NZSEE use the SRSS rule. The absolute summation rule in Eurocode 8 is taken from Malhotra et al. (2000); however,

Table 9. Comparison of base shear coefficient obtained from original expressions of various American industry standards with their modified expressions given in ASCE 7[1]

		Impulsive base shear coeff.					Convective base shear coeff.				
Time period (s)		0.0	0.2	0.5	0.8	1.0	2.0	3.0	4.0	5.0	6.0
Ground-supported RC/PSC tanks; flexible base											
ACI 350.3	Original	0.43	0.43	0.43	0.39	0.29	1.24	0.70	0.39	0.25	0.18
D-110	Original	0.43	0.43	0.43	0.39	0.29	1.05	0.47	0.26	0.17	0.12
D-115	Original	0.77	0.77	0.77	0.61	0.53	0.21	0.14	0.11	0.08	0.07
Modified[2]	0.17	0.42	0.42	0.31	0.25	1.60	0.70	0.39	0.25	0.18	
Ground-supported RC/PSC tanks; reinforced nonsliding base											
ACI 350.3	Original	0.70	0.70	0.70	0.55	0.48			*Same as flexible base*		
D-110	Original	0.70	0.70	0.70	0.55	0.48			*Same as flexible base*		
D-115	Original	0.64	0.64	0.64	0.51	0.44	0.18	0.12	0.09	0.07	0.06
	Modified[2]	0.25	0.63	0.63	0.47	0.38			*Same as flexible base*		
Ground-supported RC/PSC tanks; unanchored, uncontained base											
ACI 350.3	Original	0.96	0.96	0.96	0.76	0.66			*Same as flexible base*		
D-110	Original	0.96	0.96	0.96	0.76	0.66			*Same as flexible base*		
D-115	Original	1.93	1.93	1.93	1.52	1.31	0.53	0.35	0.26	0.21	0.18
	Modified[2]	0.33	0.83	0.83	0.62	0.50			*Same as flexible base*		
Elevated tanks on shaft support											
ACI 350.3	Original	0.64	0.64	0.64	0.51	0.44	1.24	0.70	0.39	0.25	0.18
	Modified	0.25	0.63	0.63	0.47	0.38	1.6	0.70	0.39	0.25	0.18
ACI 371	Original	0.61	0.61	0.61	0.49	0.42	—	—	—	—	—
	Modified	0.63	0.63	0.63	0.49	0.42	—	—	—	—	—

[1] In ASCE 7, the value of T_L is taken as 4 s.
[2] common for ACI 350.3, D-110, and D-115

recently Malhotra (2004) has also used the SRSS rule. Though ASCE 7 suggests use of the absolute summation rule, it also mentions that the SRSS rule may also be used.

HYDRODYNAMIC PRESSURE ON TANK WALL AND BASE

Stresses in the tank wall depend on distribution of hydrodynamic pressure along its height. Distribution of impulsive and convective hydrodynamic pressure along wall height, which is curvilinear, is described in NZSEE and Eurocode 8, and is based on the work of Housner (1963). Simplified linear pressure distribution is also described in NZSEE and ACI 350.3. Expressions for hydrodynamic pressure on the tank base are given in NZSEE only; however, the effect of hydrodynamic pressure on a tank base in obtaining overturning moment is included in all the codes. ASCE 7 does not specify hydrodynamic pressure distribution on wall and base; however, as mentioned earlier, for different types of tanks, it suggests using the provisions of respective industry standards.

SLOSHING WAVE HEIGHT

The sloshing component of liquid mass undergoes vertical displacement and it is necessary to provide suitable freeboard to prevent spilling of liquid and possible damage to the tank roof. All the codes except D-115 and ACI 371 give explicit expressions to evaluate maximum sloshing wave height. ACI 350.3 and D-110 give the sloshing wave height as $(C_s)_c R_o$, where $(C_s)_c$ is the convective mode base shear coefficient and R_o is the radius of the tank. Eurocode 8 suggests wave height as $0.84(C_s)_c R_o$. NZSEE recommends that the contribution of the higher sloshing mode shall be considered while evaluating the sloshing wave height. However, if only the first sloshing mode is considered, then the sloshing height is given as $0.84(C_s)_c R_o$. ASCE 7 and API 650 suggest the sloshing wave height as $(C_s)_c R_o R_{wc}$ and D-100 suggests $(C_s)cR_0(1.4R_{wc})$, where R_{wc} is the response modification factor for the convective mode. In ASCE 7, D-100, and API 650, the upper limit on the convective base shear coefficient is not applicable for obtaining the sloshing wave height. For determining the sloshing wave height in tanks under low seismic user group, D-100 and API 650 suggest setting the value of the transition period T_L as 4 s. Though D-115 does not give any explicit expression for sloshing wave height, it mentions that the sloshing wave height shall be evaluated per Housner (1963). A comparison of the sloshing wave height from various codes and standards is shown in Table 10. Like the convective base shear coefficient, ACI 350.3 also overestimates the sloshing wave height. In NZSEE, for different types of tanks, different values of the response modification factor are used in the expression for the convective base shear coefficient. Hence one gets different sloshing wave heights in different types of tanks when using NZSEE, whereas in other codes, sloshing wave height remains the same for all types of tanks.

Based on the sloshing wave height, Malhotra (2005) has proposed a simplified method of estimating the additional design forces for tank roof and walls, when sufficient freeboard is not provided.

SOIL STRUCTURE INTERACTION

Provisions on soil structure interaction are given in ASCE 7, NZSEE, and Eurocode 8. Soil flexibility enhances the impulsive time period, and radiation damping of the soil

Table 10. Comparison of sloshing wave height from various codes and standards

T(s)	Sloshing wave height/radius of tank								
	ASCE 7	Eurocode 8	NZSEE[1]	NZSEE[2]	NZSEE[3]	ACI 350.3	D-110	D-100	API 650
2	0.56	0.38	0.46	0.87	0.21	0.88	0.75	0.56	0.56
4	0.28	0.14	0.23	0.43	0.107	0.28	0.19	0.28	0.28
6	0.125	0.063	—	—	—	0.125	0.083	0.125	0.125
8	0.07	0.035	—	—	—	0.07	0.047	0.07	0.07

[1] RC tanks and unanchored steel tanks
[2] PSC tanks
[3] Anchored steel tanks with ductile bolts

increases the total damping of the structure. Expressions for the impulsive time period including soil flexibility are given in ASCE 7, NZSEE, and Eurocode 8, along with expressions for the equivalent damping of a tank including the radial damping of soil, which are taken from Veletsos (1984).

CONCLUDING REMARKS

Recognizing that liquid-containing tanks possess low ductility and redundancy, all the codes discussed in this paper suggest higher design seismic force for tanks by specifying lower values of the response modification factor or its equivalent factor in comparison to the building system. There are substantial differences, however, in the manner and extent to which design seismic forces are increased in various codes. American codes and standards provide a detailed classification of tanks and are assigned a different value of the response modification factor. In contrast, Eurocode 8 and NZSEE do not have such detailed classification, although NZSEE has given classification for ground-supported steel tanks. Due to this basic difference in the strategy, there is a large variation in the values of impulsive and convective base shear coefficients from Eurocode 8, NZSEE, and American standards (Figures 1–3).

Interestingly, there are some appreciable differences among American standards also. Convective base shear forces from ACI 350.3 are quite a bit higher than those given in other American standards. The lower limit on the impulsive base shear coefficient specified in ASCE 7 ($0.5S_1$) is quite different and is higher than that specified in D-100 ($0.36S_1I/R_i$) and API 650 ($0.5S_1I/R_{wi}$). Moreover, there is no such lower limit in ACI 350.3. For convective base shear, ASCE 7, D-100, and API 650 specify an upper limit, which is not present in ACI 350.3, D-110, and D-115. Moreover, this upper limit is on the lower side in API 650 in comparison to that of ASCE 7 and D-100. For elevated tanks, which can have a large time period in the impulsive mode, D-100, and ACI 371 have given a lower limit on the value of the impulsive base shear coefficient. Such a lower limit does not exist for elevated tanks in ACI 350.3. For the convective base shear coefficient, in ACI 350.3, the displacement-sensitive range begins at 2.4 s, whereas in ASCE 7, D-100, and API 650, it begins the transition period T_L, whose values vary from 4 to 16 s, depending on the location of the site. ACI 350.3 and D-110 have identical expressions for the impulsive base shear coefficient, but for the convective base shear they have quite different expressions.

Provisions of D-115, which deals with ground-supported PSC tanks, are singularly different from those of D-110 and ACI 350.3. These differences are in the values of the response modification factor, nature of the variation of convective base shear coefficient with time period, and presence of the response modification factor in the expression for convective base shear. Provisions of D-115 need a critical revision so as to make them consistent with other American standards.

D-100 and API 650 specify design seismic forces in terms of the ground-motion parameters of ASCE 7. However, other standards from American industry (ACI 350.3, D-110, D-115, and ACI 371) specify design seismic forces in terms of the ground-motion parameters of 1994 and 1997 UBC. For these standards, ASCE 7 suggests modified expressions for design seismic forces in terms of its own ground motion parameters, without changing the basic design philosophy of these standards. A critical review of these modifications has revealed the following:

- For ground-supported RC/PSC tanks, ASCE 7 modifications bring base shear coefficients of ACI 350.3, D-110, and D-115 at the same level. The ASCE 7 modifications match well with the original values of ACI 350.3.
- For the convective base shear coefficient, ACI 350.3 values are on the higher side, and in ASCE 7 modifications these higher values are retained. It seems that ASCE 7 modifications should reduce its values by a factor of 1.4, so as to be consistent with other provisions of ASCE 7.

Among other differences in various codes, it is noted that some codes continue to specify design forces at the allowable stress design level, whereas others have upgraded themselves to strength design level. In some codes (ACI 350.3, D-110, Eurocode 8), the response modification factor is not used for the convective mode; however, NZSEE and D-115 use the same response modification factor as that of the impulsive mode. On the other hand, ASCE 7, D-100, and API 650 use a lower value of response modification factor for the convective mode.

Differences also exist in the provisions on the analysis of the tank-liquid system. NZSEE uses different mechanical analogs for tanks with rigid and flexible walls. All other codes use the rigid tank model for all types of tanks. However, in these codes, design acceleration corresponding to the impulsive mode time period is used, which depends on wall flexibility. ASCE 7 and Eurocode 8 use the absolute summation rule, whereas ACI 350.3, D-110, D-115, D-100, API 650, and NZSEE use the SRSS rule to combine impulsive and convective responses. However, ASCE 7 states that SRSS rule may also be used to combine impulsive and convective responses. Expressions for hydrodynamic pressure distribution on the tank wall are provided in NZSEE, Eurocode 8, and ACI 350.3. Except for NZSEE, no code has given expressions for hydrodynamic pressure distribution on the tank base. However, the effect of hydrodynamic pressure on the base in the evaluation of overturning moment is considered in all the codes. Provisions on soil-structure interaction are provided in ASCE 7, NZSEE, and Eurocode 8 only.

The present study has revealed significant differences in the seismic provisions of various codes and standards on tanks, particularly with regard to design seismic forces. There is an urgent need to evolve a unified approach for the classification of tanks and the assigning of response modification factor for different types of tanks. Such a unified approach will also help in ironing out other differences addressed in this study.

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