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Comparison between Different Seismic Design Criteria for Tanks

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ABSTRACT

It is well recognized that liquid storage tanks possess low ductility and energy absorbing capacity as compared to the conventional buildings. Accordingly, various design codes provide higher level of design seismic forces for tanks. In this article, provisions of IBC 2000, Euro code 8, and NZSEE guidelines are reviewed to assess the severity of design seismic forces for tanks than those for buildings. It is seen that, depending on the type of tank, design seismic force for tanks can be to 7 times higher than that for buildings. Based on the comparison of provisions in these documents, various similarities, discrepancies and limitations are found in their provisions.

مقارنة معايرة التصاميم الزلزالية للخزانات

الخلاصة:

تعتبر خزانات السوائل ذات مرونة اقل بامتصاص الطاقة حيث تفرض الكودات التصميمية تصميم زلزالي اكبر للخزانات وفي هذة المقالة تناقش شروط الكود IBC 2000, EUR Cod 8, NZSEE guidelines التي توضح قدر من الحدة في تصميم الخزانات حيث يوضح ان التصميم الزلزالي اكبر بنسبة (٧) مرات من البنايات وذلك بالاعتماد على التشابهات و الاختلافات و الحدود للكودات.

INTRODUCTION

Seismic safety of liquid storage tanks is of considerable importance. Water storage tanks should remain functional in the post earthquake period to ensure potable water supply to earthquake-affected regions and to cater the need for firefighting. Industrial liquid containing tanks may contain highly toxic and inflammable liquids and these tanks should not loose their contents during the earthquake. Liquid storage tanks are mainly of types: ground supported tanks and elevated tanks. Elevated tanks are mainly used for water supply schemes and they could be supported on RCC shaft, RCC or steel frame, or masonry pedestal. Following two aspects came to forefront:

(a) Due consideration should be given to sloshing effects of liquid and flexibility of container wall while evaluating the seismic forces on tanks.

(b) It is recognized that tanks are less ductile and have low energy absorbing capacity and redundancy compared to the conventional building systems.

Studies focused on the first aspect resulted in the development of mechanical of tank which represented tank-fluid system in a more realistic fashion. Many investigations followed along this

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line to further refine these mechanical models to include effects of flexibility of soil and base uplifting of unanchored tanks. Further studies have provided more simplifications to these mechanical models. Most of the design codes use these mechanical models to represent dynamics of tank-fluid system, which are applicable to ground supported as well as elevated tanks.

The second aspect which is related to low ductility and redundancy in tanks as compared to the conventional buildings has been dealt with in a rather empirical manner. Lateral seismic coefficient for tanks is generally taken higher than for the buildings.

Most of the design codes do follow this approach and assign higher design seismic action for tanks as compared to buildings. How high this design action should be, is perhaps decided on ad-hoc basis or based on past experiences, however, it is influenced by type of tank, supporting sub grade, type of anchorage to tank etc. Basically it depends on how good ductility and energy absorbing capacity a particular type of tank can provide. For elevated tanks, ductility, redundancy and energy absorbing capacity are mainly governed by the supporting structure, which could be in the form of a RCC shaft, RCC frame, Steel frame or even masonry pedestal.

This article presents an assessment of design seismic force for tanks and design seismic force for buildings as mentioned in the following documents:

(a) International Building Code IBC 2000.
(b) Euro Code 8 (1998).
(c) New Zealand NZSEE guidelines and NZS 4203:1992.

IBC 2000

International Building Code (IBC) 2000 does provide provisions for certain types of non-building structures which include tanks. For buildings, the seismic base shear is given by V = Cs W, where, W is the effective seismic weight. Seismic response coefficient or base shear coefficient, Cs should be minimum of the following two values $C_s=S_{Ds}/(R/I)$ or $Cs=S_{Ds1}/(R/I)$ T, where S_{DS} and S_{D1} are the design spectral response accelerations at short periods and 1 second period, respectively; I is importance factor; R is response modification factor and T is the fundamental time period of building. The minimum value of C_s should not be less than 0.044 SDS I. IBC suggests a value of R = 8.0 for buildings with ductile frames. For most of the buildings, importance factor, I = 1.0. Figure (1) shows the variation of base shear coefficient, Cs = (V/W) with time period. The values of SDS and SD1 are taken as 1.0 and 0.6 respectively, which correspond to SD = 1.5, Fa = 1.0, S1 = 0.6 and Fv = 1.5 with site class D.

For tanks, due to low ductility and redundancy, low values of R are specified. Table 1 gives details of various types of tanks mentioned in IBC along with their R values. Four values of R are specified, i.e. R = 1.5, 2.0, 2.5 and 3.0. For most of the tanks the value of importance factor I will be I =1.25. However, for tanks containing highly toxic materials, importance factor could be I =1.5. The expression for base shear of tank is same as that for building with suitable values of R and I. For tanks, the minimum value of C_s should not be less than 0.14 S_{DSI} as against 0.044 S_{DSI} for buildings. For ground-supported tanks (i.e., at-grade tanks), IBC suggests to include the effects of sloshing.

Similarly, for elevated tanks (i.e., above-grade tanks), IBC states that when sloshing mode period of the stored liquid is within 70 percent to 150 percent of the fundamental period of the supporting structure, the effects of sloshing shall be included in the design of tank and supporting structure. However, IBC 2000 does not provide any particular details on evaluation of sloshing or convective mode forces. Thus, the values of R specified for tanks can be considered only for impulsive modes. The variation of base shear coefficient (BSC) for tanks, with time period is also shown in Figure 1. It is seen from this figure that depending on the type of tank, base shear coefficient is 3 to 7 times higher than that of a ductile building. The ratio of base shear coefficient of tank and building, (BSC_{tank}/BSC_{bldg}), plotted in Figure 2, directly indicates how severe design base shear for tank is with respect to a ductile building (R = 8.0). The effect of response reduction factor of tank is seen up to 2 sec. For time period greater than 3 sec, all types of tank have same base shear coefficient, which is about four times that for a ductile building.

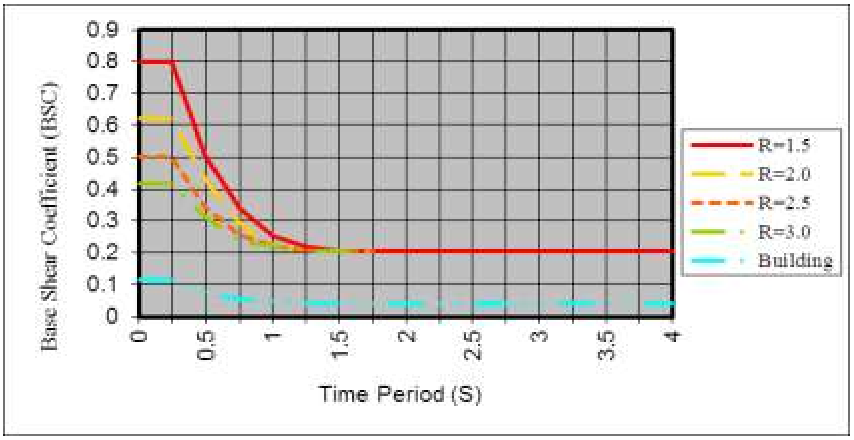

Figure 1: Variation of base shear coefficient with natural period; IBC 2000 (SD =1.5, S1 = 0.6, F_a =1.0, F_v = 1.5, Class D site).

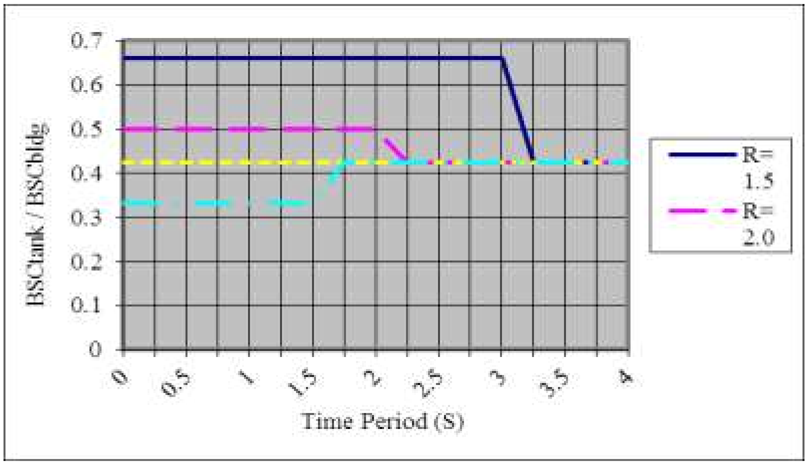

Figure 2: Ratio of tank and building base shear coefficient (IBC 2000).

EUROCODE 8 (1998)

Five parts of Eurocode 8 (1998) cover provisions for seismic design of various types of civil engineering structures. Part-4 of Eurocode 8 deals with tanks, silos and pipelines. This code describes in detail about dynamic modeling of convective and impulsive components, and also discusses other aspects like base uplifting of unanchored tanks, soil-structure interaction etc. The seismic action is specified in terms of response spectrum. In this code, behavior factor, q, accounts for energy dissipation capacity of the structure, mainly through ductile behavior and other mechanisms. For elastic structures, q = 1.0 and for structures with good energy dissipation capacity, q = 5.0. Eurocode 8 specifies two types of response spectrum, first one is elastic spectrum, S_e (T), (for q =1.0) and second is spectrum for linear analysis, S_d(T), (for q > 1.0). For tanks on ground, elastic spectrum is to be used, i.e., behavior factor, q = 1.0. For buildings with ductile frames, behavior factor q can be as high as q = 5.0, and spectrum for linear analysis is used. Seismic base shear for building is given by $V = \gamma_I S_d(T) W$, where, γ_I is the importance factor and $S_d(T)$ is the spectrum acceleration at time period T. Expression for base shear of tank is same as that of building, except that instead of spectrum for linear analysis $S_d(T)$, elastic spectrum $S_e(T)$ is to be used. The expressions for elastic spectrum and spectrum for linear analysis are given in Table 1. A closer look at these expressions reveals that *elastic* spectrum depends on damping correction factor η, whereas, spectrum for linear analysis does not depend on η. Further, it can be seen that there is a lower bound limit on values of spectrum for linear analysis in long period range. There is no such lower bound limit on elastic spectrum. It may be noted that Eurocode 8 provides indicative values of behavior factor, q and various parameters defining shape of spectrum. However, there is no indication on maximum value of design ground acceleration, a_g, which corresponds to a reference return period of 475 years. It mentions that National Authorities of the member countries should arrive at suitable values of a_g for various seismic zones. In the present study, value of $a_g = 0.3g$ (i.e., $\alpha = 0.3$) is assumed. Figure 15 shows variation of base shear coefficient with time period for ductile building (q= 5.0) and impulsive mode of tank. These results correspond to S =1.0, $\beta = 2.5$, $\eta= 1.0$, $K_1 =1.0$, $K_2 =2.0$, $K_{d1} =2/3$, $K_{d2} =5/3$, $T_B =0.15$, $T_C =0.6$ $T_D = 3.0$ and $\alpha = 0.3$. For buildings, $\gamma_I =1.0$ and $\gamma_I =1.2$ for tanks with high risk to life, and large environmental, economic and social consequences. Sub soil class B is considered which is similar to site class D of IBC 2000. In Figure 3, base shear coefficient for convective mode with 0.5% damping is also shown. It is to be noted that for buildings, i.e., when spectrum for linear analysis is used, there is a lower bound limit on spectrum values however for elastic spectrum no such limit is specified. Further, it is important to note that shapes of $S_e(T)$ and $S_d(T)$ are also different beyond $T = T_B$. Elastic spectrum, $S_e(T)$ reduces much faster with time period than spectrum for linear analysis, $S_d(T)$. Hence, for higher time periods (T>0.6 s), the difference between base shear of tank and building is reduced considerably. This is clearly seen from Figure 4, wherein ratio BSC_{tank} / BSC_{bldg} is plotted. Eurocode 8 specifies only one value of q (= 1.0) for ground-supported tanks. Neither it mentions about different types of ground-supported tanks nor does it give specific values of q for different types of ground-supported tanks. However, it states that if adequately demonstrated, inelastic response (i.e., q > 1) can be considered. For elevated tanks also, Eurocode 8 does not give very specific values of q. It mentions that supporting structure may be designed to respond beyond the yield level, thereby allowing energy dissipation in it. Elevated tanks with simple support and which have little risk to life, negligible environmental and social consequences due to failure, will have the value of q = 2.0. For elevated tanks under higher risk category, the selected value of q should be properly substantiated and proper ductility be provided through ductile design of supporting structure. For convective mode, in all types of tanks, the value of behavior factor, q =1.0 and damping value, $\xi = 0.5\%$ is suggested. For this value of ξ, the damping correction factor η is 1.673. As a result of this, 'elastic spectrum' corresponding to convective mode (0.5% damping) turns out to be 1.673 times higher than that for impulsive mode (5% damping).

Table 1: Elastic spectrum $S_e(T)$ and Spectrum for linear analysis S_d (T) of Eurocode 8

$S_e(T)=\alpha\, s[1+(T/T_B)(\eta\beta_0-1)]$	$0\le T< T_B$	$S_d(T)=\alpha\, s[1+(T/T_B)(\beta_0/q -1)]$	$0\le T< T_B$
$= \alpha\, s\, \eta\, \beta_0$	$T_B \le T< T_C$	$= \alpha\, s\, \beta_0 /q$	$T_B \le T< T_C$
$= \alpha\, s\, \eta\, \beta_0 [T_C/T]^{K1}$	$T_C \le T< T_D$	$= \alpha\, s\, \beta_0 /q[T_C/T]^{Kd1}$ $(\ge 0.2\, \alpha)$	$T_C \le T< T_D$
$=\alpha\, s\, \eta\, \beta_0 [T_C/T]^{K1}[T_C/T]^{K2}$	$T_D\le T$		

	$=\alpha\ s\ \eta\ \beta_0\ [T_C/T]^{Kd1}[T_C/T]^{Kd2}$ $(\geq 0.2\ \alpha)\ T_D \leq T$
Where: $\alpha = a_g/g$; a_g=design ground acceleration; β0=Spectral acceleration amplification factor for 5% viscous damping; S = Soil parameter; η=Damping correction factor. η = 1.0 for 5% damping. For any other damping ξ, the value of $\eta = \{7/\ (2+\xi)\}^{0.5;}$ K1, K2, Kd1, Kd2 = Exponents which influence the shape of spectrum. Values of these exponents depend on soil condition. Their values for different soil conditions are given in Tables 4.1 and 4.2 of Eurocode 8 – Part 4; TB, TC = Limits of the constant spectral acceleration branch; TD = Value defining beginning of the constant displacement range of the spectrum	

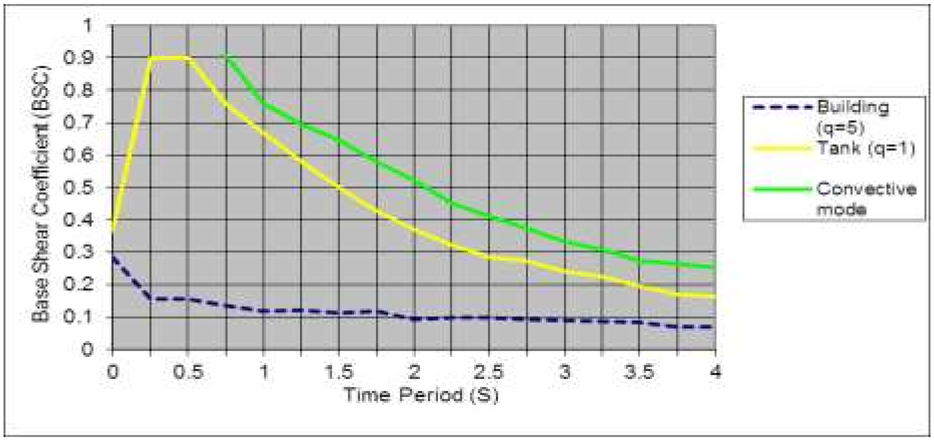

Figure 3: Variation of base shear coefficient with time period as per Eurocode 8 (S =1.0, β = 2.5, η= 1.0, K_1 =1.0, K_2 =2.0, K_{d1} =2/3, K_{d2} =5/3, T_B =0.1, T_C =0.4 T_D = 3.0, γ_I =1.0 for building and γ_I =1.3 for tank).

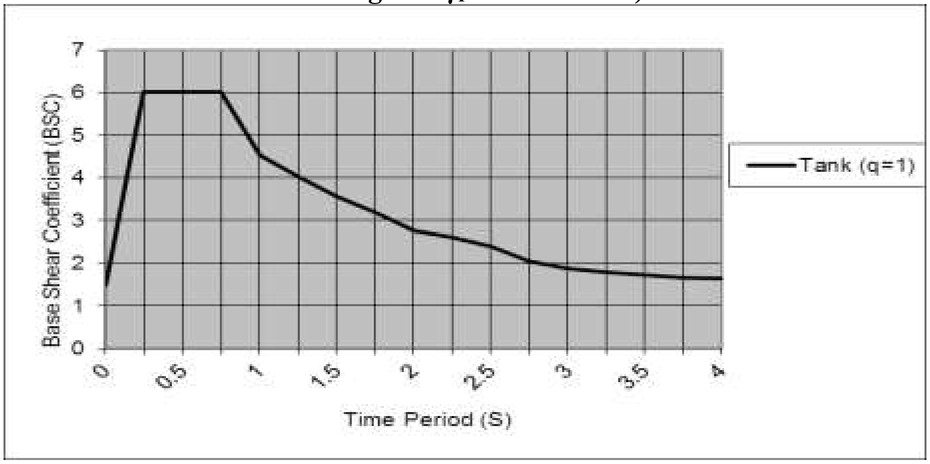

Figure 4: Ratio of base shear coefficient of tank impulsive mode and building (Eurocode8)

NZSEE GUIDELINES AND NZS 4203:1992

In New Zealand, seismic design of liquid storage tanks follow NZSEE's document (Priestley, et. al., 1986). A study group of NZSEE is presently revising this document to bring it in line with the NZS 4203:1992, the New Zealand loading code for buildings. Details of the proposed seismic loading are given by Whittaker and Jury (2000). This section discusses the proposed seismic loading along with the seismic loading provisions for building in

NZS4302:1992. As per NZS 4203:1992, seismic base shear for building is given by V = CW, where, lateral force coefficient or base shear coefficient, C is given by

$$C = C_h(T, \mu)\ S_p\ R\ Z\ L_u \geq 0.03 \qquad (1)$$

Where

$C_h(T, \mu)$ = Basic seismic hazard coefficient which accounts for different soil conditions, ductility factor μ and natural period T of building,
S_p = Structural performance factor. For buildings $S_p = 0.67$
R = Risk factor. For ordinary buildings R =1.0
Z = Zone factor as per seismic map
L_u = Limit state factor for ultimate limit state. $L_u = 1.0$

NZS 4203:1992 has provided tabulated values of $C_h(T, \mu)$ for three different soil conditions, eight different values of μ (from $\mu = 1.0$ to 10.0) and values of time period T from T = 0.0 to 4.0 sec. For buildings with ductile frames the value of μ could vary from $\mu = 6$ to10. As per Whittaker and Jury (2000), seismic base shear for tanks is V=CW,

Where

$$C = C_h(T, 1)\ S_p\ R\ Z\ Lu\ )\ C_f(\mu, \xi) \qquad (2)$$

Eq.(2) differs from Eq.(1) in two ways: First, basic seismic hazard coefficient, $C_h(T,1)$ corresponds to μ =1.0, i.e., purely elastic spectrum is used and secondly, an additional factor, $C_f(\mu,\xi)$ termed as correction factor is included. This correction factor accounts for ductility and level of damping. For tanks, performance factor S_p=1.0 is recommended as opposed to 0.67 for buildings.

Value of risk factor, R for tanks is arrived at by considering four aspects, namely, risk to number of persons, risk to environment, and community significance of the tank and value of adjacent property. Value of R can vary from 0.5 to 1.6 depending on the risk associated with the tank and a tank with serious risk has R = 1.3. The value of damping depends on material of tank shell and supporting soil. Whittaker and Jury (2000) have provided values of ductility factor, μ for different types of tanks, which are shown in Table 2. Similarly, damping level, ξ for different types of concrete and steel tanks are also provided. Further, provisions are made for increasing the damping values of tank depending on flexibility of supporting soil, i.e., to consider radiation damping in soil. For different values of ductility factor, μ and damping level, ξ, values of correction factor C_f (μ, ξ) are provided as shown in Table 3. For three different values of C_f, namely, C_f=0.72, 0.54 and 0.38, variation of base shear coefficient with time period is plotted in Figure 5. These results are for the most severe zone (Z =1.2) and site subsoil category (C), i.e., flexible and deep soil condition, which is similar to site class D of IBC 2000. Also plotted in this figure is the variation of base shear coefficient for a building with μ = 6.0. It would be appropriate to note that variation of $C_h(T,6)$ and $C_h(T,1)$ with time period is of different nature. This gets reflected in the variation of base shear coefficient of tanks and building with time period. For T > 0.6s, reduction in $C_h(T,1)$ with time period is slower than corresponding reduction in $C_h(T,6)$. This implies that elastic spectrum (C_h (T,1)) is more flatter than inelastic spectrum ($C_h(T,6)$). Moreover values of C_h (T, 1) and C_h (T, 6) at various time periods do not have a constant ratio. From the ratio of BSC_{tank} / BSC_{bldg} shown in Figure 5, it is seen that the ratio of base shear coefficients increases at around T= 0.6s, then remains almost constant up to T=3.0s and for T>3.0s it starts decreasing. The increase is due to the fact that values of C_h(T, 6) (i.e. for building) and C_h(T, 1) (i.e., for tank) are not in same proportion for values of T from 0.6-3.0s. The decrease in ratio of base shear for higher value of T (i.e., T > 3.0s) is due to the fact that there is a lower bound on value of C (i.e., C can't be less than 0.03) for buildings, but for tanks (i.e., elastic case of μ =1.0) there is no such lower bound limit. For elevated tanks, Whittaker and Jury (2000) do not provide specific information on ductility factor, μ. However, it mentions that for elevated tanks, ductility factor as appropriate for support structure should be considered. This may imply that if supporting structure is quite ductile then value of μ can be as high as for buildings (i.e., μ = 6 to 10). At the same time it should be noted that in Table 3, values of response modification factor, C_f is given only for maximum value of μ = 4.0, i.e., for values of μ greater than 4.0, response modification factor is not available. Whittaker and Jury (2000) have specified 0.5% damping for convective mode. Thus, in Table 9, values of Cf(μ,ξ) corresponding to ξ = 0.5, can be used for convective mode. These values of Cf(μ,ξ) change with ductility factor, μ, implying that convective mode base shear will vary with ductility of tank.

Table 2: Different types of tanks with their ductility factor, μ (Whittaker and Jury (2000))

Type of Tank	M
Steel Tanks on Grade	
Elastically supported	1.25
Unanchored tank designed for uplift *(elephant foot shell buckling may occur under seismic overload)*	2.001
Unanchored tank designed for uplift and elastic *(diamond shaped)* shell buckling mode	1.25
Anchored with non-ductile holding down bolts	1.25
Anchored with ductile tension yielding holding down bolts	
Ductile skirt pedestal	3.00^2
On concrete base pad designed for rocking	3.00^2
	2.00^2
Concrete Tanks on Grade	
Reinforced Concrete	1.25
Prestressed Concrete	1.00
Tanks of other materials on Grade	
Timber	1.00
Non-ductile materials (eg. Fiberglass)	1.00
Ductile materials and failure mechanisms	3.00
Elevated Tanks	As appropriate for support structure 3
Notes: 1. Check that elastic buckling does not occur before elephant foot 2. Capacity design check required to protect against other forms of failure 3. Capacity design approach shall be used to protect elevated tanks against failure while yielding occurs in the chosen support system	

Table 3: Correction factor, C_f (Whittaker and Jury (2000)).

Ductility factor, μ	**Damping level, ξ (%)**						
	0.5	**1.0**	**2.0**	**5.0**	**10.0**	**15.0**	**20.0**
1.0	1.75	1.57	1.33	1.00	0.80	0.71	0.67
1.25	0.92	0.88	0.83	0.72	0.62	0.58	0.55
1.5	0.75	0.72	0.68	0.61	0.54	0.51	0.48
2.0	0.58	0.56	0.54	0.48	0.44	0.42	0.40
2.5	0.49	0.48	0.46	0.42	0.38	0.36	0.35

3.0	0.43	0.43	0.41	0.38	0.35	0.33	0.32
4.0	0.36	0.36	0.35	0.33	0.30	0.29	0.28

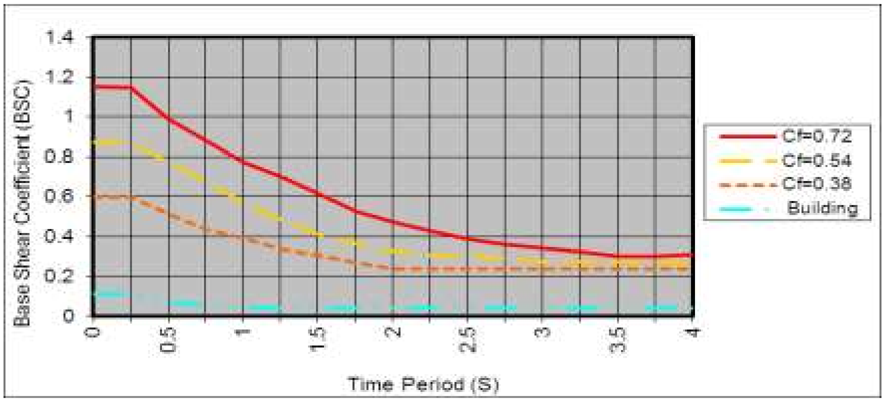

Figure 5: Variation of base shear coefficient with time period (NZSEE Guidelines) (Sp = 0.67 , R = 1.0 for building, Sp = 1.0 R =1.3 for tank, Z =1.2, Lu =1.0).

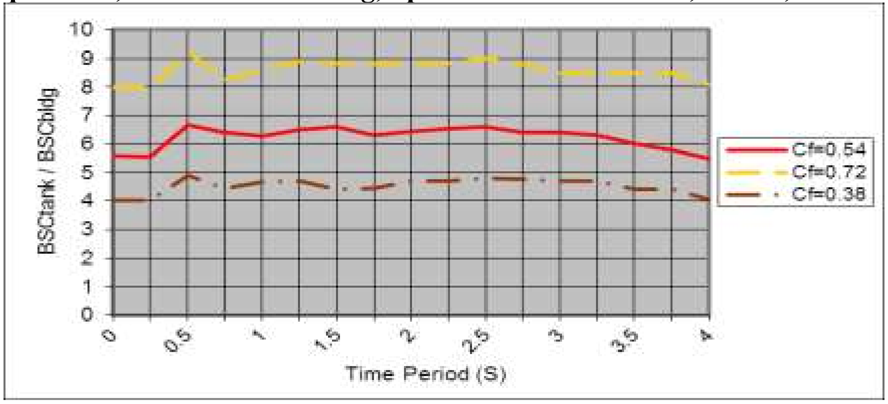

Figure 6: Ratio of base shear coefficient of tank and building (NZSEE Guidelines).

Comparison of Design Forces From Various Codes

In the previous sections provisions related to base shear coefficients for tanks as given in various codes, standards and guidelines are described. It will be interesting to compare base shear coefficients obtained from these documents. Before comparing the results for tanks, a comparison of base shear coefficient for a ductile building is shown in Figure 5. In this figure, base shear coefficients of building (BSC_{bldg}), obtained from IBC 2000, Eurocode 8 and NZS 4203:1992 are shown. These results correspond to the most severe zone of each code. It is seen that in the short period range (i.e., T=0.1-0.6s), results from Eurocode 8 and NZS 4203 match well. In this short period range, IBC 2000 results are on lower side by about 15%. Further, all the three codes have different shape of spectra in constant-velocity range (i.e., T>0.6s). Moreover, magnitude of the lower bound limit on spectra is also seen to be different in these codes. To obtain similar comparison for tanks, first of all, for a particular type of tank, all the relevant parameters (such as R, q, C_f) from different codes will have to be identified. It is seen that most of the codes consider ground supported unanchored concrete water tank as a low ductility tank or a tank with low energy absorbing capacity. For such a tank the relevant parameters will be as shown in Table 4. In Figure 8, comparison of base shear coefficient for this tank (BSC_{tank}) obtained from different codes is shown. From Figure 7 it is seen that in the short period range (T<0.6s), Eurocode 8 results are 10% higher and NZSEE results are 35% higher than the one obtained from IBC2000. Further, it can also be seen that except for IBC 2000, no other code has lower bound limit on base shear coefficient in long period range. Comparison of ratio of base shear coefficient of tank and building (BSC_{tank}/BSC_{bldg}) is shown in Figure 8. Here, base shear coefficient of tank from a particular code is divided by corresponding base shear coefficient of a ductile building. It is seen that from T=0.1-0.6s, this ratio is constant for all the codes. This constant value is 6 for Eurocode 8 and for IBC and NZSEE it is 6.7 and 7.3 respectively. The decrease in the value of this ratio for T>0.6s for the case of Eurocode 8, is due to difference in shapes of spectrum used for tank and building. Another factor contributing to this decrease, particularly in higher period range, is absence of lower bound limit on spectral values for tanks. For the case of IBC 2000, due to lower bound limit on spectral values for tanks, the ratio of tank to building shear does not fall below the value of 4, even in long period range.

Results similar to one presented in Figure 6, can be obtained for a high ductility tank, i.e., a tank with high energy absorbing capacity. For such a tank, various parameters of different codes are given in Table 5. These parameters can as well be applicable to some of the elevated tanks. For Eurocode 8, value of q = 2 is considered, which is suggested for a low risk category elevated tank with simple type of supporting structure. Results on ratio of base shear coefficient of tank to building, (BSC_{tank} / BSC_{bldg}), are shown in Figure 9. It is seen that maximum value of this ratio is about 3 to 4 in all the codes, as against a value of 6 to 7 for low ductility tanks. This implies that design base shear for a low ductility tank is double that of a high ductility tank. Variation in the ratio of base shear of tank and building, in the higher time period range is seen in Figure 10 also, which is due to reasons discussed earlier.

Table 4: Parameters for a low ductility tank

Code	Parameters
IBC 2000	R = 3
Eurocode 8	q = 2.0, γ_I = 1.2
NZSEE guidelines	S_p = 1.0, μ = 1.25, ξ = 5%, Cf = 0.72

Table 5: Parameters for a high ductility tank

Code	Parameters
IBC 2000	R = 1.5
Eurocode 8	q = 1.0, γ_I = 1.2
NZSEE guidelines	S_p = 1.0, μ = 3.0, ξ = 5%, Cf = 0.38

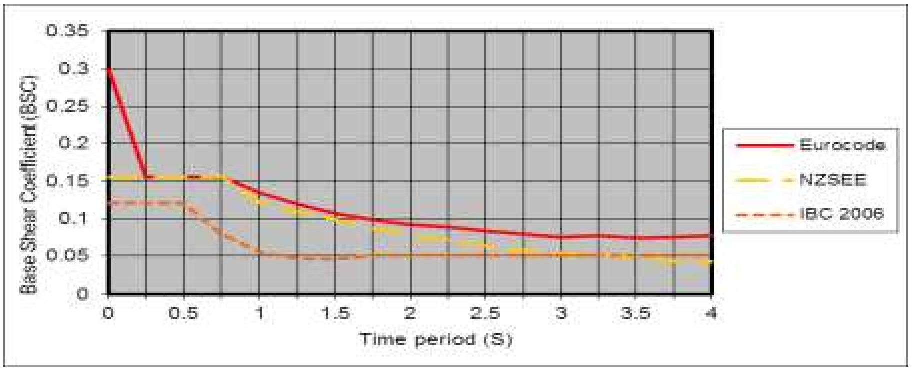

Figure 7: Comparison of base shear coefficient for ductile building obtained from various codes. Most severe zone in each code is considered.

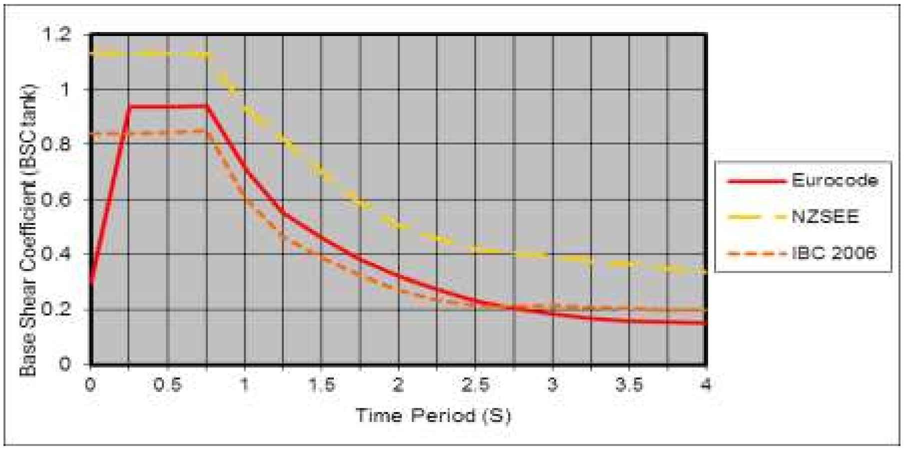

Figure 8: Comparison of base shear coefficient for ground supported unanchored concrete water tank obtained from various codes. Most severe zone in each code is considered.

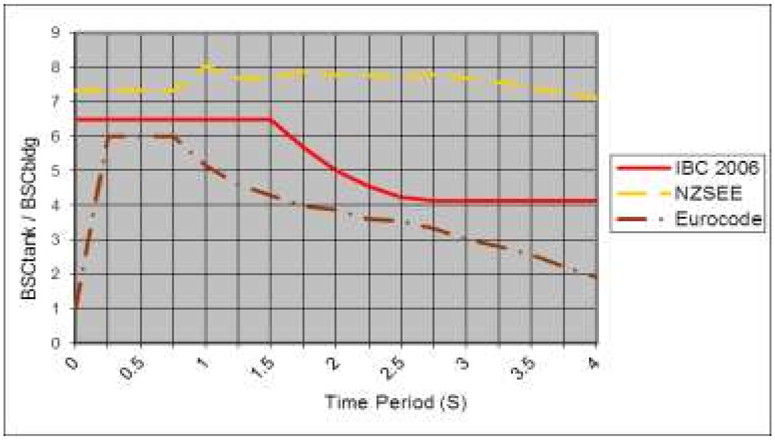

Figure 9: Comparison of ratio of base shear coefficients of tank and building from various codes (Low ductility tank).

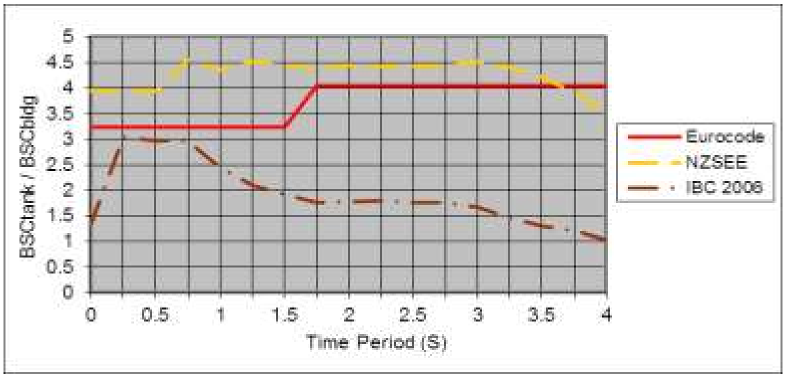

Figure 10: Comparison of ratio of base shear coefficient of tank and building from various codes (High ductility tank).

Discussion

Due to low ductility and energy absorbing capacity, liquid storage tanks are generally designed for higher seismic forces as compared to conventional buildings. In this article, provisions of various codes on design seismic forces for tanks are reviewed.

It is found that there is considerable variation in the types of tanks described in various codes. For example, ground supported tanks described in IBC 2000and NZSEE guidelines are having different types of base conditions. Eurocode 8 does not provide any details about base supports of ground-supported tanks. Less information is available on energy absorbing capacity of different types of supporting towers of elevated tanks. Less frequent use of elevated tanks in these countries may be one reason for low emphasis on elevated tanks in these codes.

All the codes, consider impulsive and convective modes of vibration in the seismic analysis of ground-supported tanks. The level of design seismic force for a particular tank obviously depends on its ductility and energy absorbing capacity. It is observed that for a tank with low ductility, impulsive base shear coefficient (ratio of lateral force to weight) is 6 to 7 times higher than the base shear coefficient of a ductile building; and for a high ductility tank this value is 3 to 4 in all the codes (Figures 7 and 7). However, this is so only for tanks with short time period (i.e., T<0.6s). Beyond this short period range, there is considerable difference in the values of BSC_{tank}/BSC_{bldg}. For example, at T=1.5s, for a tank with low ductility, the value of BSC_{tank}/BSC_{bldg}, as per NZSEE guideline is 8.2 and as per IBC 2000 and Eurocode 8 this value is 6.7 and 4.4, respectively. Thus, Eurocode 8 results are on lower side by almost 50%. In fact, beyond T=0.6s, as per Eurocode 8, the value of BSC_{tank}/BSC_{bldg}, decreases continuously, which is due to two reasons. First, in Eurocode 8, elastic spectrum (used for tank) has much faster reduction with time period than spectrum for linear analysis (used for buildings) in the constant-velocity range. Secondly, unlike for buildings, there is no lower bound limit on spectrum used for tanks.

In NZSEE guidelines [i.e., NZS 4230:1992 and Whittaker and Jury (2000)] the elastic spectrum (used for tanks) reduction with time period is slower than inelastic spectrum (used for buildings). Due to this reason, the NZSEE results in Figure 7, show a slight increase in the value of BSC_{tank}/BSC_{bldg} at T=0.6s. In IBC 2000, spectra used for tank and building, have same shape in constant velocity range. Further, IBC 2000 specifies, lower bound limits on spectral values for buildings as well as tanks. Hence, as per IBC 2000, values of BSC_{tank}/BSC_{bldg} , do not fall below four even in the long period range. This, as explained earlier, leads to loss of severity of tanks shear in long period range as compared to that of buildings (Figures 7 and 8).

While considering the convective base shear, all the codes suggest a damping value of 0.5%. However, in the evaluation of convective base shear coefficient, considerable differences are seen in the provisions of various codes. Firstly, Eurocode 8, convective base shear coefficient does not depend on response reduction factor. However, NZSEE guidelines (i.e. Whittaker and Jury (2000)), convective base shear coefficient depends on response reduction factor.

For the elevated tanks, Eurocode 8 and NZSEE guidelines recommend consideration of convective mode. At the same time, IBC 2000 suggests that convective mode need not be considered if certain conditions on weight of water and time period of convective mode are met with.

As far as liquid storage tanks are concerned. The elevated tanks are quite commonly used in public water distribution systems and a large number of them are in use. These tanks have various types of support structures, like, RC braced frame, steel frame, RC shaft, and even masonry pedestal. Ground supported tanks are used mainly by petroleum and other industrial installations.

CONCLUSIONS

Following conclusions are drawn from the comparative assessment of provisions of different codes on seismic design of liquid storage tanks:

1) There is no uniformity in types of tanks described in various documents. Most of the codes put emphasis on ground-supported tanks and very limited information is available on elevated tanks.

2) All the documents suggest consideration of convective and impulsive components in seismic analysis of tanks.

3) For a particular type of tank with short period (less than 0.6s), ratio of base shear of tank and building is almost same in all the codes. This ratio is 6 to 7 for low ductility tanks and 3 to 4 for high ductility tanks. However, for tanks with time period greater than 0.6s, there is a large variation in the values of this ratio obtained from different codes. For example, at time period of 1.5 sec, value of this ratio from Eurocode 8 is almost 50% less than the one obtained from NZSEE guidelines. This is attributed to the use of spectra of different shapes for buildings and tanks.

4) Unlike for buildings, most of the documents do not provide lower bound limit on spectral values for tanks. This results in decrease in the ratio of base shear of tank and building, in long period range. This effectively results in reduction in severity of tank base shear as compared to building base shear.

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