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Review of Code Provisions on Seismic Analysis of Liquid Storage Tanks

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Abstract

In the first part of this paper (Jaiswal, et. al., 2003), provisions from various international codes on design seismic forces for liquid storage tanks were reviewed. This paper reviews provisions related with the analysis and modeling aspects. These aspects include mechanical analogue of tank, time period of lateral and vertical mode of vibration, hydrodynamic pressure distribution, sloshing wave height, soil-structure interaction etc. The codes reviewed are: ACI 350.3, AWWA standards, API 650, NZSEE guidelines and Eurocode 8. It is noted that all the codes use mechanical analogues to evaluate hydrodynamic forces, particularly due to lateral base excitation. The provisions on inclusion of effect of vertical excitation are not covered in all codes. Provisions of soil-structure interaction, buried tanks, flexibility of piping are either not addressed or are given in only qualitative terms. A brief description on limitations in Indian code is also presented.

1. INTRODUCTION

In the first part of this paper (Jaiswal et. al., 2003) provisions on design seismic forces for liquid storage tanks from various international codes were reviewed. In this paper, provisions related with the analysis and modeling of tanks are being considered. Seismic analysis of liquid storage tanks requires special considerations. These special considerations account for the hydrodynamic forces exerted by the fluid on tank wall. Knowledge of these hydrodynamic forces is essential in the seismic design of tanks. Evaluation of hydrodynamic forces requires suitable modeling and dynamic analysis of tank-liquid system, which is rather complex. However, availability of mechanical models (analogues) of tanks has considerably simplified the analysis. These mechanical models, convert the tank-liquid system into an equivalent spring-mass system. Design codes use these mechanical models to evaluate seismic response of tanks. While using such an approach, various other parameters also get associated with the analysis. Some of these parameters are: Pressure distribution on tank wall due to lateral and vertical base excitation, time period of tank in lateral and vertical mode, effect of soil-structure interaction and maximum sloshing wave height. Design Codes have provisions with varying degree of details to suitably evaluate these parameters.

In this paper, provisions given in various codes on seismic analysis of tanks are reviewed. Codes considered are: ACI 350.3, AWWA D-100, AWWA D-110, API 650, Eurocode 8 and NZSEE guidelines. The review will in particular focus on following aspects:

i) Mechanical model and its parameters
ii) Hydrodynamic pressure due to lateral and vertical excitation
iii) Time period of tank in lateral and vertical mode
iv) Effect of soil flexibility

2. REVIEW OF CODAL PROVISIONS

Provisions given in ACI 350.3, AWWA D-100, AWWA D-110, API 650, Eurocode 8 and NZSEE guidelines will be reviewed. It may be noted that some of these codes deal with only specific types of tanks. Table 1 provides details of types of tanks considered in each of these codes. It is seen that ground supported tanks are either fixed at base or rest on flexible base. The type of flexible base used and its description varies from code to code.

2.1 Mechanical models

As explained earlier, a mechanical model replaces the tank-liquid system by a spring-mass system, which considerably simplifies the evaluation of hydrodynamic forces. In these mechanical models it is recognized that vibrating fluid inside the container has two components, one that moves in unison with the tank (called impulsive component) and another one which undergoes sloshing motion (called convective component). Figure 1 schematically demonstrates such a mechanical model. Various quantities associated with a mechanical model are: impulsive mass (M_i), convective mass (M_c), height of impulsive mass (h_i), height of convective mass (h_c) and convective mode time period (Tc). It may be noted that heights h_i and h_c are used when base pressure is not considered. If base pressure is included then corresponding heights are denoted by h'_i and h'_c respectively.

Historically, mechanical models were first developed for tanks with rigid walls. Housner (1963) was perhaps the first to propose such a mechanical model for circular and rectangular rigid tanks (Figure 1). Wozniak and Mitchell (1978) have generalized the Housner's model for short and slender tanks. Veletsos and Yang (1977) have used a different approach to arrive at a similar type of mechanical model for circular rigid tanks. Subsequently, Haroun and Housner (1981) and Veletsos (1984) have developed mechanical models for flexible tanks. Malhotra et. al. (2000) have further simplified the flexible tank model of Veletsos (1984). In Figure 3a to 3d a comparison of various parameters of rigid and flexible tank models is shown. In these figures, results obtained from Wozniak and Mitchell (1978) and Veletsos and Yang (1977) (i.e. rigid tank models) are plotted along with those of Malhotra et. al. (2000) (i.e. flexible tank model). It is seen that there is no significant difference in the results obtained from rigid and flexible tank models. Veletsos (1984) has also made similar observation while comparing the rigid and flexible tank models.

Various codes use one or the other mechanical models described above. ACI 350.3, AWWA D-100, AWWA D-110 and API 650 use mechanical model of Housner (1963) with modifications of Wozniak and Mitchell (1978). AWWA D-100 and API 650 deal with circular steel tanks, which are flexible tanks. However, since there is no appreciable difference in the parameters of mechanical models of rigid and flexible tank models, these codes evaluate parameters of impulsive and convective modes from rigid tank models. ACI 350.3 also mentions parameters of mechanical model for rectangular tanks.

NZSEE guidelines (Priestley et. al. (1986)) use mechanical model of Veletsos and Yang (1977) for rigid circular tanks and that of Haroun and Housner (1981) for flexible tanks. For rigid rectangular tanks, it suggests use of rigid circular tank model wherein, radius is replaced by half length of tank. It states that in most cases, such an approximation for rectangular tanks is expected to give base shears within 15% of values from more exact theory. For flexible rectangular tanks, it suggests the same procedure as that of rigid rectangular tanks. This document also suggests procedure for evaluating impulsive and mechanical mass of horizontal circular cylindrical tanks, which is based on work of Wrner and Sundquist (1949).

Eurocode 8 mentions mechanical model of Veletsos and Yang (1977) as an acceptable procedure for rigid circular tanks. For flexible circular tanks, models of Veletsos (1984) and Haroun and Housner (1981) are described along with the procedure of Malhotra et. al. (2000). For rigid rectangular tanks it suggests model of Housner (1963). The procedure given in NZSEE guidelines is also described in Eurocode 8 for evaluating impulsive and convective mass of horizontal circular tank.

An important point while using a mechanical model pertains to combination rule used for adding the impulsive and convective forces. Except Eurocode 8, all the codes suggest SRSS (square root of sum of square) rule to combine impulsive and convective forces. Eurocode 8 suggests use of absolute summation rule. For evaluating the impulsive force, mass of tank wall and roof is also considered along with impulsive fluid mass. ACI 350.3 and Eurocode 8 suggest a reduction factor to suitably reduce the mass of tank wall. Such a reduction factor was suggested by Veletsos (1984) to compensate the conservativeness in the evaluation of impulsive force.

2.2 Time period of impulsive mode

Impulsive mode refers to lateral mode of tank-liquid system. Lateral seismic force on tank depends on the impulsive mode time period. Time period of tank-fluid system depends on the flexibility of support also. Table 2 gives details of the expressions used in various codes to evaluate the impulsive mode time period.

For fixed base circular tanks, ACI 350.3 uses formula given by Veletsos (1984), whereas NZSEE guidelines have adopted the formula from Haroun and Housner (1981). Eurocode 8 has followed the expression given by Sakai et. al. (1984). Eurocode 8 also gives the expression suggested by Malhotra et. al. (2000) for evaluation of impulsive mode time period. AWWA D-100 and API 650 prescribe a constant value of design spectral acceleration and hence impulsive time period is not needed in these codes. AWWA D-110 and D-115 do not give explicit expression for evaluation of impulsive time period of fixed base circular tanks, however, they specify an upper limit of 0.3 sec on their time period.

It may be noted that in the expression from ACI 350.3, mass density of tank wall is used. Whereas, in the expressions from NZSEE guidelines and Eurocode 8, mass density of fluid is used. In this context, it may be mentioned that time period of tank-fluid system depends on mass of wall as well as fluid. However, recognizing the fact that mass of the wall is usually quite small as compared to fluid mass, certain approximations are made and mass of the wall is neglected. This point has been explained by Haroun and Housner (1981) and also by Veletsos (1984). Since ACI 350.3 deals with concrete tanks, wherein mass of tank may not always be very small compared to fluid mass, the expression in terms of mass density of wall is retained. Whereas, NZSEE guidelines and Eurocode 8 have converted the expression in terms of liquid mass density.

Since the expressions from NZSEE guidelines and Eurocode 8 are in terms of identical parameters, a comparison of results obtained from them can be made. For this purpose, expressions from NZSEE and Eurocode 8 are recast in a common form as shown in Table 3. In this table expression given by Malhotra et. al. (2000) is also included. It may be recalled here that Eurocode 8 has also described the procedure suggested by Malhotra et. al. (2000). In figure 4, variation of impulsive time period coefficient, C_i , with h/R is plotted. It is seen that results obtained from these expressions match reasonably well.

For circular tanks resting on flexible base, the expressions for impulsive time period given in ACI 350.3 and AWWA D-110 are identical. No other code has provision for flexibly supported circular tanks. It may be noted that when on flexible supports, tanks are considered as rigid mass, and stiffness is contributed by the supports. Rectangular tanks with fixed base are considered in ACI 350.3, NZSEE guidelines and Eurocode 8 which provide identical expression for their impulsive time period. Rectangular tanks resting on flexible base are not described in any of the codes.

2.3 Hydrodynamic pressure distribution due to lateral excitation

Stresses in the tank wall depend on distribution of hydrodynamic pressure along the wall height. Housner (1963) had derived the expressions for distribution of hydrodynamic pressure on a rigid tank wall due to lateral base excitation. Impulsive as well as convective components of hydrodynamic pressure were considered. Veletsos (1984) has also obtained the distribution of hydrodynamic pressure on rigid as well as flexible wall. It may be mentioned that flexibility of tank wall does not influence the convective hydrostatic pressure. However, it does affects the impulsive hydrodynamic pressure distribution, particularly for the slender tanks. Evaluation of impulsive pressure distribution in flexible tanks is quite involved and can be done only through iterative procedures (Veletsos, 1984).

Expressions for distribution of impulsive and connective hydrodynamic pressure from various codes are given in Table 4. All the codes use pressure distribution of rigid tanks. AWWA D-100 and D-103 provide expressions of Housner (1963) to obtain distribution of impulsive and convective hydrodynamic pressure. AWWA D-110 and D-115 has also suggested use of Housner's approach. ACI 350.3 has provided equivalent linear distribution of impulsive and convective hydrodynamic pressure. This linear distribution is taken from NZS 3206 (1986). NZSEE guidelines and Eurocode 8 use approach of Veletsos (1984) to get hydrodynamic pressure distribution in circular tanks. Expressions for hydrodynamic pressure distribution in rectangular tanks are provided in ACI 350.3. NZSEE guidelines also have provisions for evaluation of hydrodynamic pressure in rectangular tanks. NZSEE guidelines have provision for hydrodynamic pressure on base of tank also.

2.4 Response to vertical base excitation

Under the influence of vertical excitation, liquid exerts axisymmetric hydrodynamic pressure on tank wall. Knowledge of this pressure is essential in properly assessing the safety and strength of tank wall against buckling. In all the codes effect of vertical acceleration is considered only for circular tanks, and there are no provisions on rectangular tanks. Response to vertical excitation is mainly governed by the time period of fundamental breathing mode or axisymmetric mode of vibration of tank-liquid system. It may be noted that this mode is for the case of circular tanks only. Expression for exact time period of axisymmetric mode of a circular tank is quite involved. However, considering certain approximations like, mass of tank wall is quite small as compared to fluid mass, some simple closed form expressions have been given by Veletsos (1984) and Haroun and Tayel (1985).

Other than API 650, all codes do have provisions to consider tank response under vertical excitation. Expressions for time period of vertical mode (axisymmetric breathing mode), from various codes are given in Table 5. These expressions refer to circular tanks only. Eurocode 8 has used expression from Haroun and Tayel (1985). ACI 350.3 and AWWA D-110 suggest simpler expression. Luft (1984) has described that such a simpler formula is good approximation for tall tanks. NZSEE guidelines have used formula given by Veletsos (1984), wherein values of coefficient K_v are given in graphical form. A comparison of variation of time period of vertical mode with h/R as obtained from ACI 350.3, NZSEE guidelines and Eurocode 8 is shown in Figure 5. It is noted that as per simplified formula of ACI 350.3, time period is independent of h/R and results of ACI 350.3 match well with those of Eurocode 8 for tall tanks. Further it is noted that NZSEE results are on higher side for tanks with large values of thickness to radius ratio(t/R). It may be noted that there is no information about breathing mode time period of rectangular tanks.

Distribution of hydrodynamic pressure due to vertical excitation also gets influenced by wall flexibility. For tanks with rigid wall, it is linearly distributed i.e. hydrodynamic pressure is distributed same as hydrostatic pressure. From the expressions given in Table 6, it is seen that ACI 350.3 and NZSEE guidelines use linear pressure distribution for flexible tanks, i.e. effect of wall flexibility on distribution is not considered. This approach was suggested by Veletsos (1984). Eurocode 8 however, has incorporated the effect of wall flexibility on distribution of hydrodynamic pressure. For flexible tanks, total pressure is sum of rigid component and a flexible component. AWWA D-

100 & D-103 consider the response due to vertical acceleration in empirical fashion. It suggests that maximum value of hydrodynamic pressure should not be less than 75% of that due to lateral excitation. Similar empirical approximation is given in AWWA D-110 &D-115, wherein for different zones, maximum value of hydrodynamic pressure due to vertical excitation is given in terms of hydrodynamic pressure due to lateral excitation. With this type of empirical approach, AWWA Standards do not require information on time period of breathing mode.

2.5 Sloshing wave height

The sloshing component of liquid mass undergoes vertical displacement and it is necessary to provide suitable free board to prevent spilling of liquid. All the codes, except API 650, give explicit expressions to evaluate maximum sloshing wave height. These expressions are given in Table 7. Further, it may be mentioned that NZSEE guidelines considers contribution of higher sloshing modes also. ACI 350.3 and Eurocode 8 suggest higher of wave height.

2.6 Soil structure interaction

Provisions for consideration of soil-structure interaction are provided only in NZSEE guidelines and Eurocode 8. First provision pertains to influence of soil flexibility on time period of tank. Expressions for time period of lateral and vertical mode of tank, including the effect of soil flexibility are provided. These expressions are taken from Veletsos (1984). Secondly, inclusion of soil also increases the damping of the structure. Expressions are also provided for equivalent damping of tank-fluid-soil system.

2.7 Other provisions

Apart from the major issues discussed in previous sections, these codes have also provided provisions on some other aspects though with varying degree of details. All the codes mention that piping attached to tanks should have sufficient flexibility to not to induce large stresses at the joints between the tank and pipe. No quantitative specification is provided on flexibility of piping. However, Eurocode 8 mentions that minimum value of imposed relative displacement between the tank and the first anchoring point of piping can be assumed as $\Delta = \gamma_I \, x \, d_g/500$; where, x is the distance between the anchoring point and the point of connection with the tank; d_g is the maximum soil displacement; and γ_I is the importance factor.

ACI 350.3 and NZSEE guidelines mention about buried or underground tanks. ACI 350.3 suggests use of higher values of response reduction factor for buried tanks. This implies that design earthquake forces for buried tanks will be lower than those for above ground tanks. ACI 350.3 has not given any specific guideline for evaluating dynamic earth pressure. NZSEE guideline provides expressions for evaluating soil pressure, which varies linearly along the wall height.

Anchorage requirements for ground supported tanks and other complications involved in unanchored tanks are described in NZSEE guidelines and Eurocode 8.

For elevated tanks, AWWA D-100 suggests that convective mode need not be considered. However, ACI 350.3, NZSEE guideline and Eurocode 8 recommend consideration of convective mode. It may be noted that for elevated tanks, the impulsive mode is governed by the flexibility of supporting tower. NZSEE guidelines suggest that for elevated tanks also, impulsive and convective modes can be treated independently. Other codes have explicitly not stated such an approach for elevated tanks.

3. PROVISIONS OF IS CODES

Indian Standard IS:1893-1984 provides guidelines for earthquake resistant design of several types of structures including liquid storage tanks. This standard is under revision and in the revised form it has been divided into five parts. First part IS:1893(Part 1): 2002, which deals with the general guidelines and provisions for buildings has already been published. Second part, yet to be published, will deal with the provisions for liquid storage tanks. IS 1893-1984 has provisions for elevated tanks only, it does not have any provision for ground supported tanks. In the analysis of elevated tanks, the sloshing or convective component is not considered. These limitations in the provisions of IS 1893-1984 have been discussed by Jain and Medhekar (1993a, 1993b). They have also suggested a set of modifications to be incorporated in the provisions of IS 1893-1984, on seismic analysis of tanks. Their suggestions were mainly focused on inclusion of convective component in the analysis of tanks. They suggested separate mechanical models for rigid and flexible tanks. Model of Haroun and Housner (19841) is used for flexible tank and approach of Veletsos and Yang (1984) is used for rigid tank. Impulsive mass calculation suggested by Jain and Medhekar (1993a, 1993b) is along similar lines as that of NZSEE guidelines (Priestley, 1986). Jain and Medhekar (1993a, 1993b) did not provide any suggestion on response due to vertical excitation. Sloshing wave height expression is also not included.

4. DISCUSSION

Presence of hydrodynamic forces requires special considerations in the seismic analysis of liquid storage tanks. Invariably all the codes use mechanical models (analogues) to evaluate hydrodynamic forces. These mechanical models evaluate impulsive and convective masses, time period of impulsive and convective modes of vibrations, hydrodynamic pressure distribution and sloshing wave height. It is noted that separate mechanical models are available for tanks with rigid and flexible walls. Rigid tank models are much simpler than flexible tank models. As far as evaluation of impulsive and convective mass is concerned, there is no significant difference in the values obtained from rigid and flexible tank models (Figures 3a to 3d). Recognizing this fact, all the American codes, viz. ACI 350.3,API 650, AWWA D-100, D-110 use rigid tank models to evaluate impulsive and convective mass in all types of tanks. Time period of tank-fluid system, for which close form expressions are available, depends on tank flexibility. Such an approach makes these American codes much simpler as compared to Eurocode 8 and NZSEE guidelines. In Eurocode 8 and NZSEE guidelines, separate mechanical models are used for obtaining impulsive mass of rigid and flexible tanks. However, Eurocode 8 does mention about procedure of Malhotra et. al. (2000), which is common for tanks with rigid and flexible tanks.

It is also interesting to note that API 650 and AWWA D-100 which deal with ground supported circular steel tanks, recommend a constant value of design spectral acceleration for all types of tanks. Hence in these codes there is no need to evaluate time period of tank.

The type of base on which tank is resting influences the time period of tank. Some of the codes deal with tanks with different types of base supports. For example, ACI 350.3, AWWA D-100 and AWWA D-110 mention about anchored, unanchored, flexible and unconstrained type of base supports. Whereas, API 650, Eurocode 8 and NZSEE guidelines do not describe such base supports. Similarly it is noted that rectangular tanks are considered only in ACI 350.3, NZSEE guidelines and Eurocode 8.

Provisions on response to vertical base excitation have been given with varying degree of details. All the AWWA codes, specify the maximum value of hydrodynamic pressure due to vertical excitation in term of fraction of those due to lateral excitation. However, ACI 350.3, Eurocode 8 and NZSEE guidelines provide more rational approach for evaluating hydrodynamic pressure due to vertical excitation. They suggest evaluation of time period of breathing mode of vibration (axisymmetric mode), based on which design acceleration value can be obtained. Distribution of hydrodynamic pressure along the tank height is also provided in these codes. It is noted that Eurocode 8 has provisions to consider the influence of wall flexibility on hydrodynamic pressure due to vertical excitation. API 650 does not have any provisions to consider effect of vertical base excitation.

Except API 650, all codes have provisions to evaluate maximum sloshing wave height. NZSEE guidelines suggest consideration of higher convective mode while evaluating sloshing wave heights. All other codes consider only first sloshing mode. Eurocode 8 and ACI 350.3 mention higher values of sloshing wave height (Table 7).

As far as elevated tanks are concerned, AWWA D-100 does not recommend consideration of convective mode in the analysis of elevated tanks. However, ACI 350.3, Eurocode 8 and NZSEE guidelines do recommend consideration of convective mode in the analysis of elevated tanks. It may be mentioned here that ACI 371 which exclusively deals pedestal supported elevated tanks also mentions that convective mode need not be considered if fluid weight is more than 80% of total weight of tank. NZSEE guidelines also suggest that for elevated tanks, impulsive mode, which is largely governed by the flexibility of supporting tower, and convective mode can be treated independently.

Indian code IS 1893-1984 is quite ill equipped to provide any suitable seismic analysis of liquid storage tank. It has no provision for tanks resting on ground. The provision on elevated tank also does not considered convective mode of vibration. Recognizing these limitations Jain and Medhekar (1993a, 1993b) have given a set of suggestion to modify IS1893-1984. They have largely followed the approach of NZSEE guidelines and have suggested use of separate mechanical models for rigid and flexible tanks. Further, Jain and Medhekar (1993a, 1993b) have not given any provision for response due to vertical excitation. Expression for sloshing wave height is also not given by them. The review presented in this paper will be helpful in further improving the suggestions of Jain and Medhekar (1993a, 1993b).

5. CONCLUDING REMARKS

Review of various codes revealed that ACI 350.3 which is the most recent code, is quite comprehensive and simple to use. In this code parameters of mechanical model are evaluated using rigid tank model. The flexibility of tank is considered in the evaluation of impulsive time period. In contrast to this, Eurocode 8 and NZSEE guidelines use separate models to find parameters of rigid and flexible tanks. Such an approach makes these codes more cumbersome to use, without achieving any significant improvements in the values of parameters. Effect of vertical ground acceleration is considered in various codes with varying degree of details. In AWWA codes, hydrodynamic pressure due to vertical acceleration is taken as a fraction of that due to lateral acceleration. ACI 350.3, Eurocode 8 and NZSEE guidelines suggest more rational approach to obtain hydrodynamic pressure due to vertical acceleration, which is evaluated based on time period of breathing mode of vibration. All the codes suggest, quite similar expressions for evaluating maximum sloshing wave height.

For Indian code IS 1893, the provisions for seismic analysis of tanks suggested by Jain and Medhekar (1994a, 1994b), need to be modified. These modifications are particularly needed to include simplified mechanical models for flexible tanks, to include the effect of vertical acceleration, and to include simple expressions for sloshing wave height.

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References

ACI 350.3, 2001, “Seismic design of liquid containing concrete structures”, An American Concrete Institute Standard.

ACI 371, 1998, “Guide for the analysis, design and construction of concrete pedestal water towers”, An American Concrete Institute Standard.

API 650, 1998, “Welded storage tanks for oil storage”, American Petroleum Institute Standard, Washington D. C.

AWWA D-100, 1996, “Welded steel tanks for water storage”, American Water Works Association, Colorado

AWWA D-103, 1997, “Factory-coated bolted steel tanks for water storage”, American Water Works Association, Colorado

AWWA D-110, 1995, “Wire- and strand-wound circular, prestressed concrete water tanks”, American Water Works Association, Colorado

AWWA D-115, 1995, “Circular prestressed concrete water tanks with circumferential tendons”, American Water Works Association, Colorado

Eurocode 8, 1998, "Design provisions for earthquake resistance of structures, Part 1- General rules and Part 4 – Silos, tanks and pipelines", European committee for Standardization, Brussels.

FEMA 368, 2000, "NEHRP recommended provisions for seismic regulations for new buildings and other structures", Building seismic safety council, National Institute of Building Sciences.

Haroun,M.A. and Housner,G.W., 1981, "Seismic design of liquid storage tanks", Journal of Technical Councils of ASCE, Vol. 107, No. TC1, 191-207.

Haroun,M.A. and Tayel,M.A., 1985, "Axisymmetrical vibrations of tanks-Numerical", Journal of Engineering Mechanics, ASCE, Vol. 111, No. 3, 329-345.

Housner,G.W., 1963b, "Dynamic analysis of fluids in containers subjected to acceleration", Nuclear Reactors and Earthquakes, Report No. TID 7024, U. S. Atomic energy Commission, Washington D.C.

IBC 2000, International Building Code International Code Council, 2000, Falls Church, Virginia.

Jain,S.K., and Medhekar,P.S., 1993a, "Proposed provisions for aseismic design of liquid storage tanks: Part I – Codal provisions", Journal of Structural Engineering, Vol. 20, No. 3, 119-128.

Jain,S.K., and Medhekar,P.S., 1993b, "Proposed provisions for aseismic design of liquid storage tanks: Part II – Commentary and examples", Journal of Structural Engineering, Vol. 20, No. 4, 167-175.

JaiswalO.R., Rai,D.C., and Jain,S.K., 2003, "Codal provisions on seismic design forces for liquid storage tanks: A review", Under review.

Luft R W, 1984, "Vertical accelerations in prestressed concrete tanks", Journal of Structural Engineering, ASCE, Vol. 110, No. 4, 706-714.

Malhotra,P.K., Wenk,T., and Wieland,M., 2000, "Simple procedure for seismic analysis of liquid storage tanks", Structural Engineering, IABSE, Vol. 10, No.3, 197-201

NZS 3106, 1986, "Code of practice for concrete structures for the storage of liquids", Standards Association of New Zealand, Wellington.

Priestley,M.J.N.,*et.al.,* 1986, "Seismic design of storage tanks", Recommendations of a study group of the New Zealand National Society for Earthquake Engineering.

Sakai,F., Ogawa,H. and Isoe,A., 1984, "Horizontal, vertical and rocking fluid elastic response and design of cylindrical liquid storage tanks", Proc. of 8th World conference on Earthquake Engineering, San Francisco, Calif. Vol. V, 263-270.

VeletsosA.S., and Young, 1977, "Earthquake response of liquid storage tanks", Proc. of 2nd Engg. Mechanics specialty conf. ASCE Raleigh, 1977, 1-24.

Veletsos,A.S., 1984, "Seismic response and design of liquid storage tanks", Guidelines for Seismic design of oil & gas pipelines system, ASCE, NY, 255-370.

Veletsos,A.S., and Shivakumar, 1997, "Tanks containing liquids or solids", In Computer Analysis and Design of Earthquake Resistant Structures: A

Handbook, Eds.Beskos,D.E. and Anagnastoppoulos, Computational Mechanics Publication, 725-774

Werner,P.W., and Sundquist,K.J., 1949, "On hydrodynamic earthquake effects", Transactions of American Geophysical Union, Vol. 30, No 5.

Wozniak,R.S. and Mitchell,W.W., 1978, "Basis of seismic design provisions for welded steel oil storage tanks", American Petroleum Institute 43rd midyear meeting, session on Advances in Storage Tank Design, Toronto, Canada.

Table 1: Types of tanks considered in various codes

Code	Types of tanks
ACI 350.3	• Ground supported circular and rectangular concrete tanks with fixed and flexible base. • Pedestal supported elevated tanks.
AWWA D-100 & D-103	• Ground supported steel tanks with fixed and flexible base. • Elevated steel tanks with braced frame and pedestal type supporting tower.
AWWA D-110 & D-115	• Ground supported prestressed concrete tanks with fixed and flexible base.
API 650	• Ground supported steel petroleum tanks (Types of base support are not described).
NZSEE Guidelines	• Ground supported circular and rectangular tanks with fixed and flexible base. • Elevated tanks.
Eurocode 8	• Ground supported circular and rectangular tanks with fixed base. • Elevated tanks.

Table 2: Expressions for impulsive time period given in various codes

Type of tank	**Reference**	**Expression**
Circular tanks with fixed base	ACI 350.3	$T_i = \frac{0.628h\sqrt{\rho_c / E}}{C_w \sqrt{t/R}}$; C_w is a coefficient given as function of h/R in graphical form.
	AWWA D-100 and D-103	Impulsive natural period is not required in the analysis.
	AWWA D-110 and D-115	Expression not given. However, natural period should not be less than 0.3s.
	API 650	Expression is not required in the analysis.
	NZSEE Guidelines	$T_i = \frac{5.61\pi h\sqrt{\rho / E}}{K_h}$; K_h is function of h/R and t/R to be obtained from given graphs.
	Eurocode 8	$T_i = \frac{2R}{C_i}\sqrt{\frac{\rho h}{Et}}$; $C_i = 0.01675(h/R)^2 - 0.15(h/R) + 0.46$
Circular tanks with flexible base	ACI 350.3	$T_i = \sqrt{\frac{8\pi(W_w + W_R + W_i)}{gDk_p}}$
	AWWA D-100 and D-103	Impulsive time period is not required in the analysis.
	AWWA D-110 and D-115	$T_i = \sqrt{\frac{8\pi(W_w + W_R + W_i)}{gDk}}$; T_i >1.0 sec for tanks with anchored flexible base; T_i >2.0 for tanks with unanchored unconstrained flexible base.
	API 650	No expressions are given
	NZSEE	
	Eurocode 8	
Rectangular tanks with fixed base.	ACI 350.3	$T_i = 2\pi\sqrt{(W_i + W_w)/(gk)}$; k = flexural stiffness of tank wall
	AWWA D-100 and D-103	No expressions are given
	AWWA D-110 and D-115	
	API 650	
	NZSEE	$T_i = 2\pi\sqrt{d/g}$; d = deflection of wall due to a uniformly distributed load of magnitude q = m_f g/4Bh
	Eurocode 8	

ρ_c = mass density of wall, ρ = mass density of fluid, E = Modulus of elasticity of tank wall, t = thickness of wall, R = radius of tank, D = diameter of tank, W_W = Weight of wall; W_R= Weight of roof; W_i = Weight of impulsive fluid; k_p = flexibility of base pad. m_f =Impulsive mass of fluid; B=Length of rectangular tank; h=Height of fluid; g=Acceleration due to gravity.

Table 3: Recast expressions for fundamental time period of fixed-base flexible circular tank

Reference	Expression for the fundamental natural period (S) $\text{Ti} = C_i \dfrac{H\sqrt{\rho}}{\sqrt{E}\sqrt{t/R}}$
Eurocode 8	$C_i = \dfrac{2}{\sqrt{h/R}\left[0.46 - 0.15h/R + 0.017(h/R)^2\right]}$
NZSEE Guidelines	$C_i = \dfrac{5.6\pi\sqrt{t/R}}{K_h}$; Values of K_h are given in graphical form for various values of h/R and t/R
Malhotra (2000)	Values of C_i are given in tabular form as a function of h/R

ρ = mass density of fluid; E = Young's modulus of tank material; t = thickness of tank shell; R = radius of tank

Table 4: Expressions for distribution of hydrodynamic pressure due to lateral excitation given in various codes

<table>
<tr><th colspan="2">Distribution of hydrodynamic pressure due to lateral excitation</th></tr>
<tr><td colspan="2">**ACI 350.3**</td></tr>
<tr><td>• Circular tanks:
Impulsive pressure
$P_i = 0.58A_i\gamma\tanh(1.732R/h)\begin{bmatrix}4h-6h_i-\\(6h-12h_i)y/h\end{bmatrix}$
Convective pressure
$P_c = 0.4A_c\gamma(R/h)^2\tanh(1.732h/R)$
$\left[4h-6h_i-(6h-12h_i)y/h\right]$
y=Liquid level at which wall is investigated measured from base</td><td>• Rectangular tanks:
Impulsive pressure
$P_i = 0.58A_i\gamma\tanh(1.732L/h)\left[\begin{matrix}4h-6h\\(6h-12\end{matrix}\right.$
Convective pressure
$P_c = 0.132A_c\gamma(L/h)^2\tanh(1.732h/L)$
$\left[4h-6h_i-(6h-12h_i)y/h\right]$
y =Liquid level at which wall is investigated measured from base</td></tr>
<tr><td>**AWWA D-100 & D-103**
Impulsive pressure
For h/R ≤1.5
$P_i = 42.8A_i\gamma h\tanh(1.732R/h)\begin{bmatrix}y/h-\\0.5(y/h)^2\end{bmatrix}$
for y/R < 1.5
$= 26.4A_i\gamma h(R/h)$ for y/R > 1.5
For h/R > 1.5
$P_i = 52.6A_i\gamma h(R/h)\begin{bmatrix}y/(1.5R)-\\0.5\{y/(1.5R)\}^2\end{bmatrix}$
y =Liquid level at which wall is investigated measured from top surface.</td><td>Convective pressure
$P_c = 132.4A_c\gamma h(R/h)\dfrac{\cosh\left(\dfrac{1.84(h-}{R}\right.}{\cosh(1.84h/R}$
y =Liquid level at which wall is investigated
measured from top surface.</td></tr>
<tr><td colspan="2">**AWWA D-110 & D-115**
Expressions for distribution of pressure are not given, however, it is mentioned that this distribution should be as per Housner (1963).</td></tr>
<tr><td colspan="2">**API 650**
Distribution of hydrodynamic pressure is not considered.</td></tr>
<tr><td colspan="2">**NZSEE Guidelines**
Explicit expressions are not given, however graphically distribution of hydrodynamic pressure is shown. These graphs are given for circular as well as rectangular tanks. Distribution for circular tank is taken from Veletsos (1984).</td></tr>
<tr><td colspan="2">**Eurocode 8**
Expressions from Veletsos (1984) are given.</td></tr>
</table>

A_i = Impulsive acceleration; A_c=Convective acceleration;γ = Specific weight of fluid;
h = Design depth of stored liquid; R=Radius of tank; h_i = Height of impulsive lateral force;
h_c= Height of convective lateral force ; L = Half the length of rectangular tank.

Table 5: Expressions for time period of vertical mode given in various codes

Code	**Time period of vertical mode**
ACI 350.3	$T_v = \left(\frac{2}{\sqrt{t/R}}\right)\left(\pi h\sqrt{\frac{\rho}{E}}\right)$
AWWA D-100 & D-103	Evaluation of vertical time period is not described.
AWWA D-110 & D-115	$T_v = \left(\frac{2}{\sqrt{t/R}}\right)\left(\pi h\sqrt{\frac{\rho}{E}}\right)$
API 650	Evaluation of vertical time period is not described.
NZSEE Guidelines	$T_v = \left(\frac{5.61\pi h}{K_V}\sqrt{\frac{\rho}{E}}\right)$ K_v is given in graphical form as a function of h/R and t/R
Eurocode 8	$T_v = \left(\sqrt{\frac{8(1-\nu^2)I_0(\lambda)}{\pi(t/R)(h/R)I_1(\lambda)}}\right)\pi h\sqrt{\frac{\rho}{E}}$; Io, I_1 are respectively modified Bessel's functions of order 0 and 1; $\lambda = (\pi R/2h)$.

t = Average wall thickness ; R =Radius of tank; E =Modulus of elasticity of material;
ρ = Specific weight of liquid.

Table 6: Expressions for distribution of hydrodynamic pressure due to lateral excitation given in various codes

Code	**Distribution of hydrodynamic pressure due to vertical excitation**
ACI 350.3	$P_v = A_i\gamma hb(1-y/h)$ b = ratio of vertical and horizontal acceleration, b should not be less than 2/3.
AWWA D-100 and D-103	Distribution is not described. It is mentioned that maximum value of hydrodynamic pressure due to vertical excitation should not be less than 3/4th of horizontal excitation.
AWWA D-110 and D-115	Distribution is not described. Lower bound limit on value of maximum hydrodynamic pressure due to vertical excitation is described. This limit is in terms of values of pressure due to horizontal excitation.
API 650	Distribution is not described.
NZSEE Guidelines	$P_v = A_i\gamma h(1-y/h)$
Eurocode 8	For rigid tanks: $P_v = A_i\gamma h(1-y/h)$ For flexible tanks: $P_v = A_i\gamma h(1-y/h) + 0.815A_i\gamma h\cos\left(\frac{\pi}{2}[1-y/h]\right)f(h/R)$ f(h/R) = 1.078 + 0.274 ln(y/h) for 0.8 < h/R < 4.0 = 1.0 for h/R < 0.8

y =Liquid level at which wall is investigated measured from base ;h =Height of liquid surface;
γ=Specific weight of liquid; A_i = Impulsive acceleration.

Table 7: Expressions for maximum sloshing wave height given in various codes

Code	Sloshing wave height
ACI 350.3	A_cR
AWWA D-100 & D-103	0.84 A_cR
AWWA D-110 & D-115	A_cR
API 650	Not mentioned
NZSEE Guidelines	0.84 A_cR (Considering only first mode)
Eurocode 8	$0.84A_cR$

A_c = Convective acceleration; R = Radius of tank

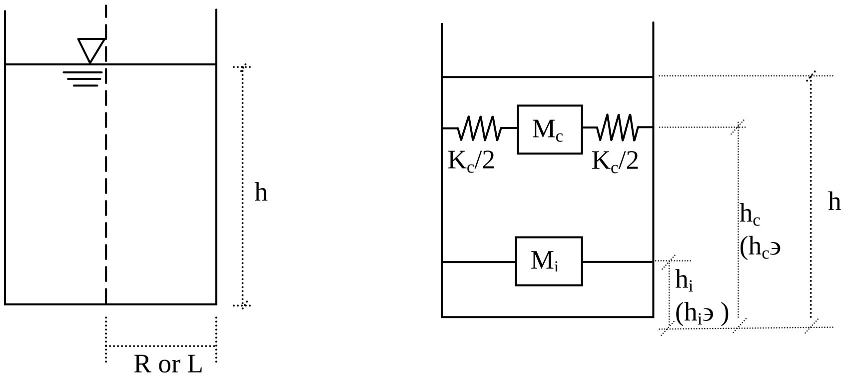


Figure 1: Description of tank dimensions and mechanical model

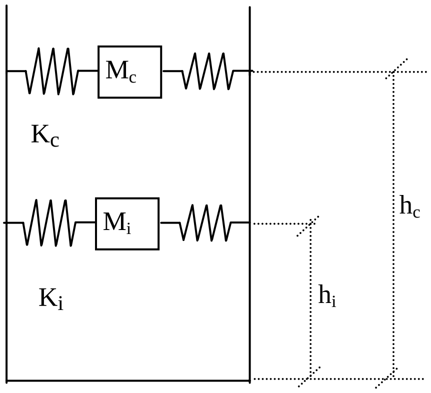
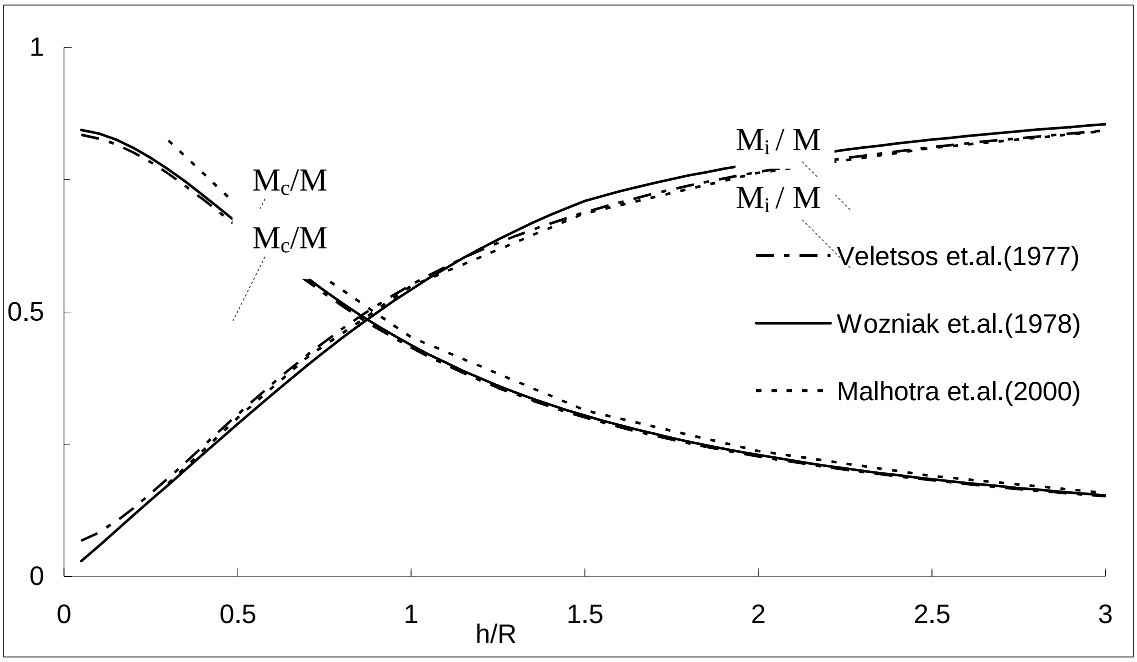
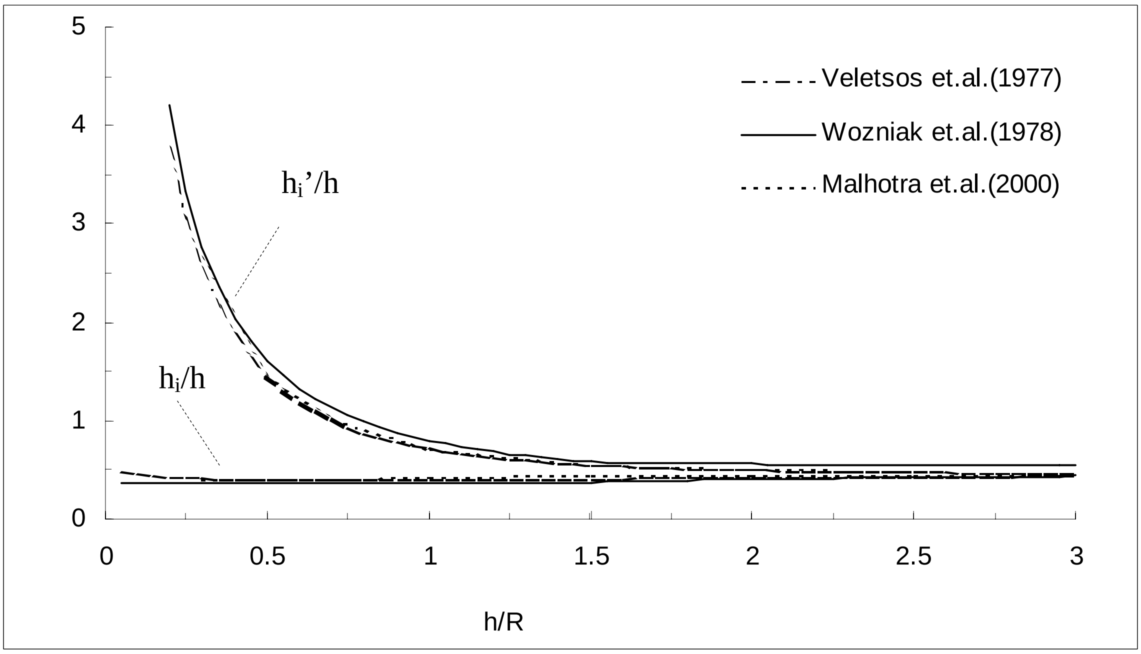


Figure 2: Mechanical models for flexible circular tanks (Malhotra et. al., 2000)

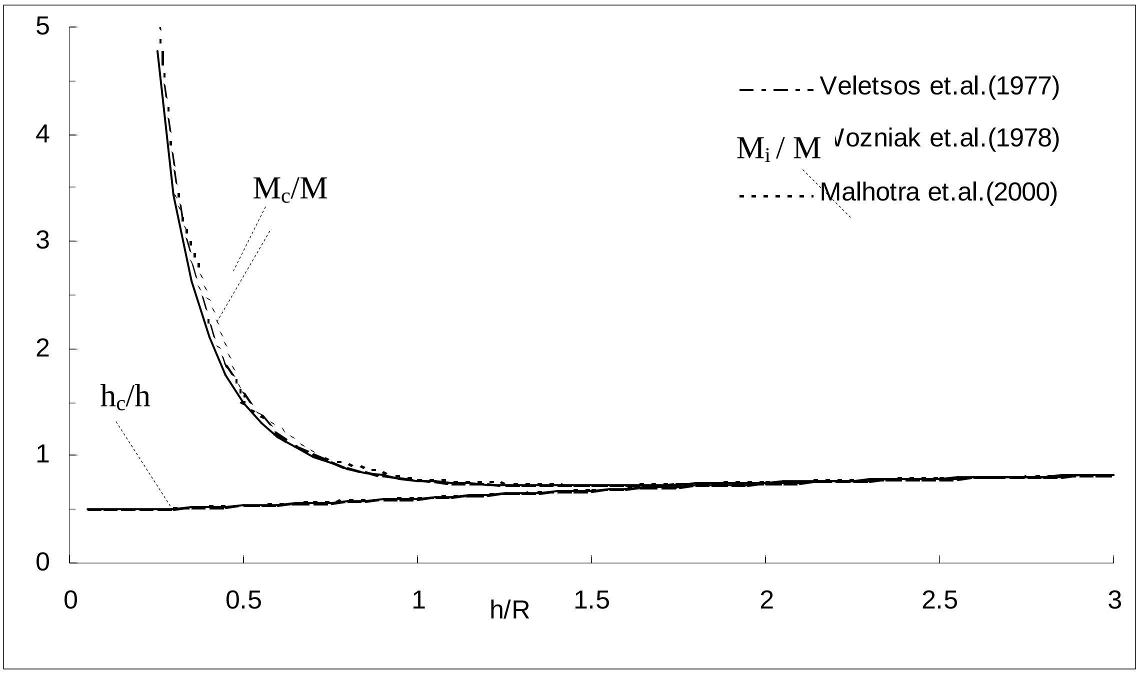


(a)

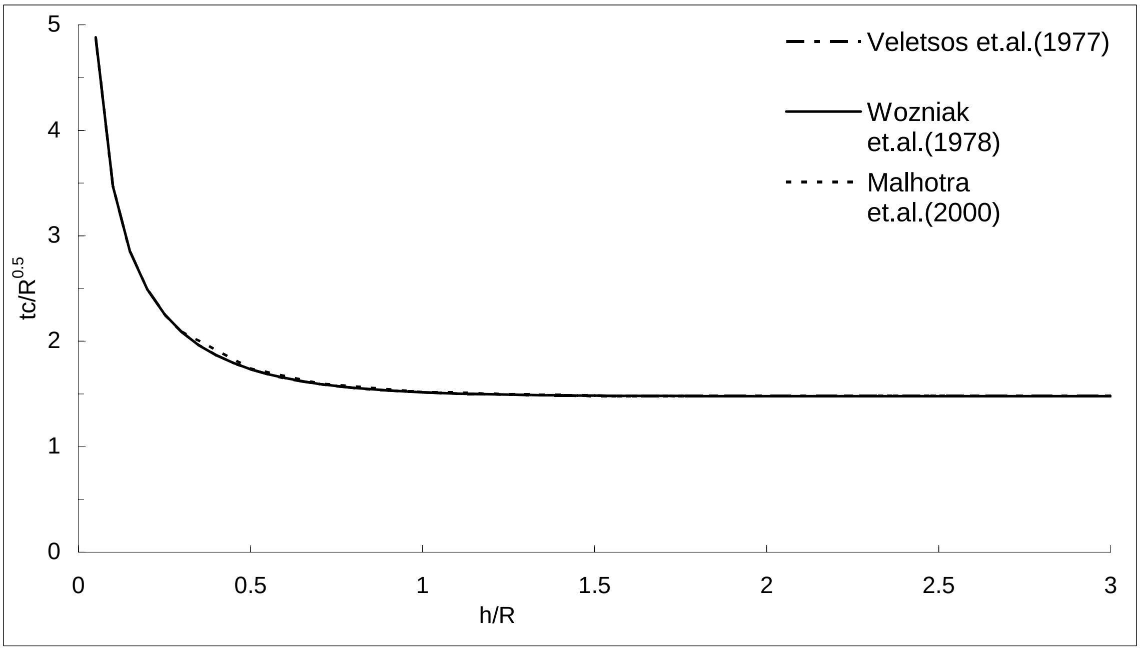


(b)

Figure 3: Comparison of (a) impulsive and convective masses, and (b) impulsive heights



(c)



(d)

Figure 3: Continued… Comparison of (c) convective heights, and (d) convective time period

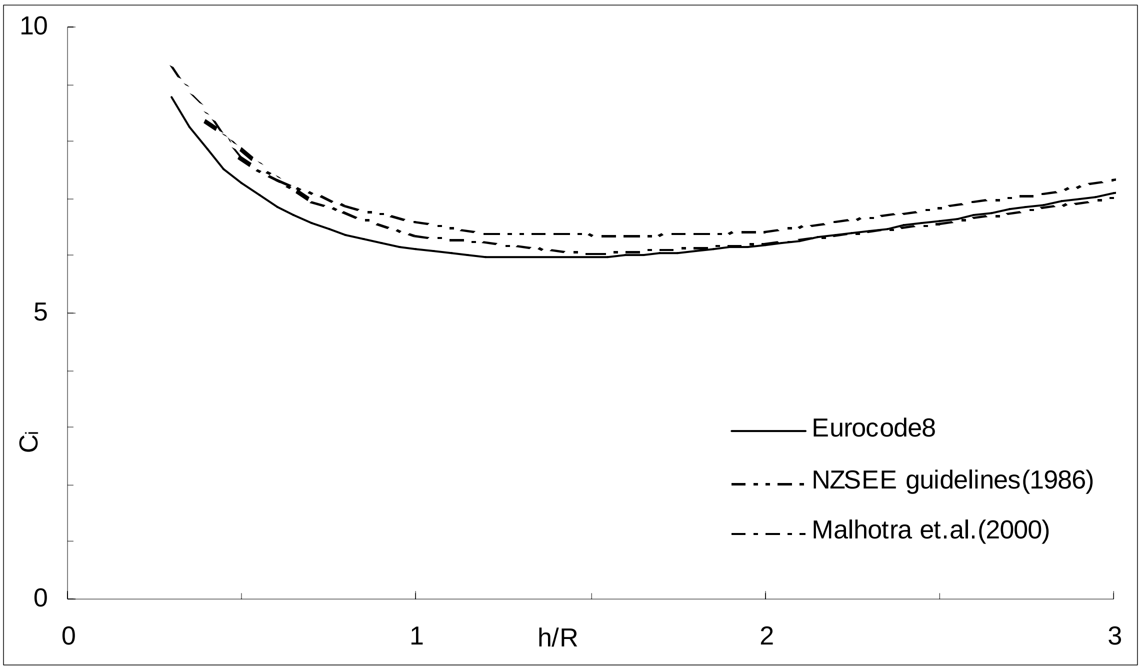


Figure 4: Comparison of lateral time period coefficient

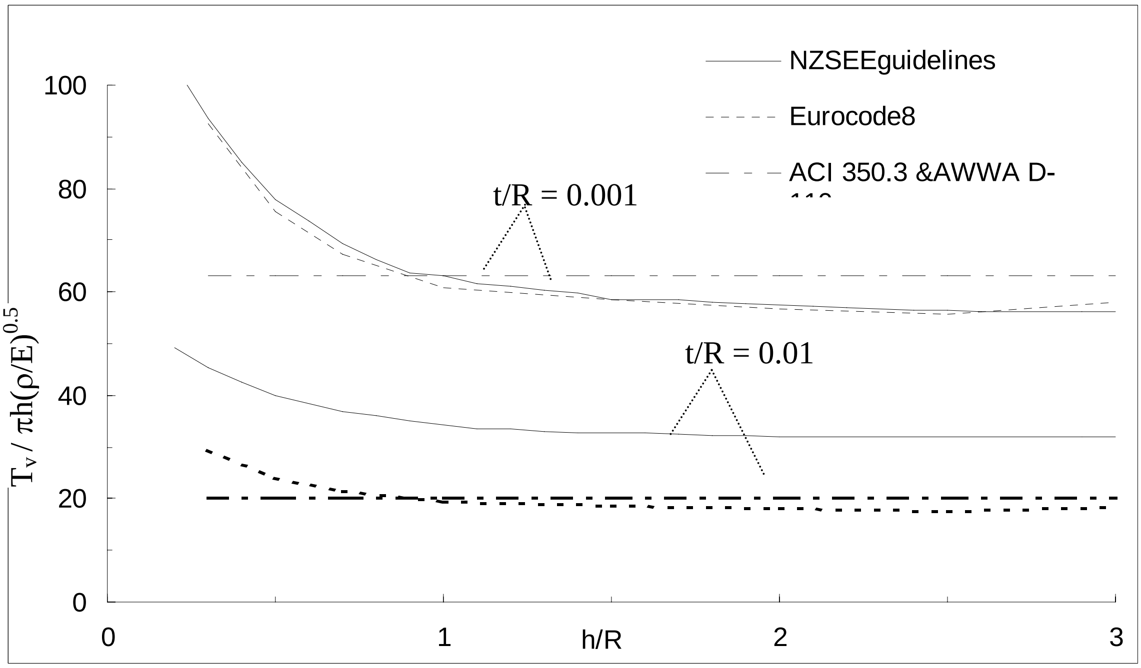


Figure 5: Comparison of vertical time period coefficient