Seismic Design of Elevated Slurry Storage Tanks for AS/NZS 1170

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Abstract

Australia's structural design actions standard, AS/NZS 1170, has been written with an emphasis on the requirements for new buildings and building-like structures. Consequently, the Australian earthquake actions section, AS1170.4, considers many non-building structures, including tanks containing liquid, to be outside its scope. A variety of elevated steel tanks are common in industrial and mining applications, so an engineer in Australia must look elsewhere for seismic design guidance.

An alternative design code commonly referred to is API 650, "Welded Steel Tanks for Oil Storage". This code refers to ASCE 7 for methodology but explicitly excludes elevated tanks when evaluating seismicity. It also assumes a homogenous liquid, but process tanks can contain mixtures of liquids, slurries and solids.

The American ASCE 7 code, "Minimum Design Loads for Buildings and Other Structures" has seismic design actions for many non-building structures, including elevated storage tanks. Fluid properties and tank shapes are not restricted.

This paper will present a methodology for applying AS1170.4 seismic parameters to ASCE 7 for seismic design of elevated slurry storage tanks. The seismic loads calculated are for limit states design and are therefore compatible for load combinations to AS/NZS 1170.0.

Keywords: elevated tank, thickener, ASCE 7, liquid storage, slurry, sloshing

1. INTRODUCTION

Outotec Pty Ltd designs mining and industrial thickeners for Australia and overseas. A common tank design is a cylindrical steel shell with a truncated conical bottom elevated above ground on steel columns. An example of a typical thickener tank installation is shown in Figure 1.

Figure 1: Typical thickener tank installation

Existing elevated thickener tanks vary in diameter from 4m to 50m and can carry up to 10 million litres with slurry mass greater than 15,000 tonnes. So even in relatively low seismic zones, a thorough understanding of the seismic behaviour of these tanks is warranted to economise on structure weight and provide realistic footing design.

Clients are often unaware of the exclusion of tanks containing liquid in AS 1170.4 (2007). For smaller tanks or those that are relatively tall and slender (high aspect ratio), the sloshing behaviour of the liquid has a small effect and can be ignored. The conservative approach of treating the liquid as a lumped mass is an acceptable method by many international codes. But with large, low aspect ratio tanks this lumped mass approach can give base shears up to 5 times greater than when the sloshing behaviour of the liquid is considered.

This paper will present a methodology for seismic design of elevated slurry storage tanks. Although originally derived for thickener tanks, the approach is applicable for any elevated tank application where the liquid has a free surface. A static analysis approach is used, therefore, the tank height should not exceed 25 m otherwise a dynamic analysis may be required as detailed in AS 1170.4.

2. CODE SELECTION

API 650 is the most well known code for steel liquid storage tanks in the minerals processing industry. The principles of seismic design specified in Appendix E of this code could be applied to elevated tanks with some minor changes. However, the appendix explicitly excludes elevated tanks from its scope. API 620, “Design and Construction of Large, Welded, Low-Pressure Storage Tanks”, covers some aspects of elevated tank design but again excludes them from the seismic design section.

The American Water Works Association standard AWWA D-100, “Welded Steel Tanks for Water Storage” is a very good standard for smaller elevated tanks and is often used in Australia. However, the design guidelines are oriented toward typical water tower configurations and have very conservative limitations on stresses and convective response. This is due to two considerations; firstly, water towers have a very high importance in post-earthquake activities; secondly, the structure and sloshing natural periods can be quite similar. Therefore, only a 25% reduction in base shear is allowed due to liquid sloshing. The limitations in this code are considered too restrictive for large tank design.

One of the most internationally respected storage tank guidelines comes from a 1986 study group of the New Zealand National Society for Earthquake Engineering entitled “Seismic Design of Storage Tanks”. It has been referenced in the loading codes for several countries including Eurocode 8. It would be an obvious choice except for its age. The principles within are still broadly applicable; however it has been acknowledged that for large steel storage tanks it is overly conservative since it assumes absolutely no yield or damage under the design earthquake. It’s currently being updated and will be republished sometime in 2008.

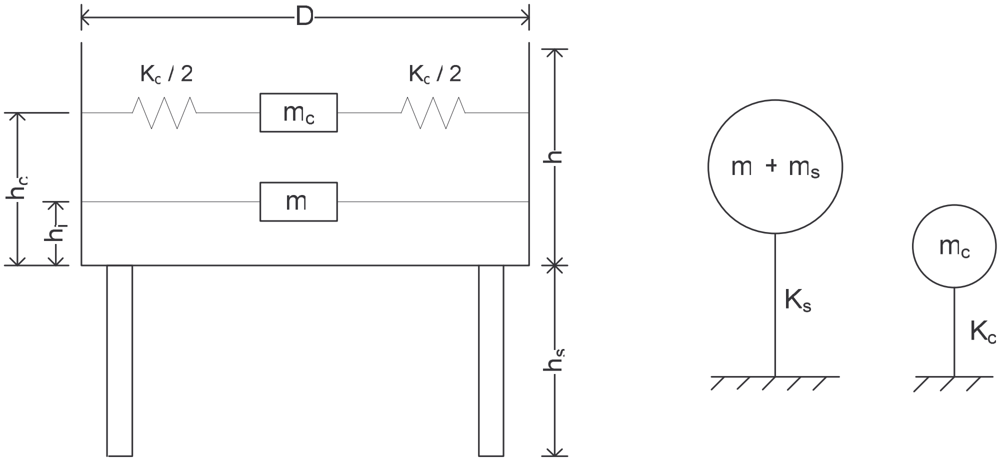
A recently published report (October 2007) from the Indian Institute of Technology Kanpur entitled “Guidelines for Seismic Design of Liquid Storage Tanks” presents a very clear and thorough review of the topic, and it appears it will become a standard in the Indian loading code. Its relative obscurity in Australia excluded it from selection but the author would like to acknowledge it as an excellent reference.

The American loading code, ASCE 7 (2005), was the final selection for several important reasons. The code allowed for the seismic design of elevated liquid storage tanks of varying shape and contents (with a properly substantiated analysis) and the methodology was the same as that for API 650. Any client or consultant familiar with API 650 could easily audit the design without requiring other documents or standards. ASCE 7 allows elevated tank designs up to 50 m in height as long as P-delta effects are fully considered. Thickeners are typically less than 20 m tall.

3. HYDRODYNAMICS OF LIQUIDS IN AN ELEVATED TANK

When a tank containing liquid is subjected to lateral earthquake ground motion, the liquid exerts impulsive and convective hydrodynamic pressure on the tank wall in addition to the hydrostatic pressure. The impulsive component is the liquid mass in the lower region of the tank that moves in unison with the tank structure at a relatively short period (under 1 second). The convective component in the upper region undergoes a sloshing motion with a period that can exceed 10 seconds.

In order to quantify these effects, tanks can be idealised as spring-mass models. The impulsive liquid mass (m_i) is rigidly connected to the structure while the convective liquid mass (m_c) is attached with springs. The model for an elevated tank as presented in Priestley et al. (1986) and the Australian Earthquake Engineering Manual (1993) is shown in Figure 2a.



(a) Spring Mass Model of Elevated Tank

(b) Simplified Uncoupled System

Figure 2: Two mass idealisation for an elevated tank

An equivalent uncoupled system is shown in Figure 2b in which the mass and lateral stiffness of the structure are represented by m_s and K_s respectively. This was proposed by Housner (1963) and is valid as long as the impulsive and convective time periods are well separated. In effect, the sloshing motion is unaffected by the structure motion unless the structure has a relatively long period (tall inverted pendulum structures such as water towers are an example). Priestley et al. (1986) recommended a ratio of at least 2.5 for this assumption to be valid. ASCE 7 uses a ratio of 3. This assumption simplifies the design process, especially in regards to damping. ASCE 7 uses a damping of 5% for structures and 0.5% for sloshing liquid. With a two degree of freedom system there may exist non-proportional damping.

The spring mass model parameters depend on tank geometry and were originally derived by Housner (1963). The formulas for circular tanks are now commonly found in references such as API 650 and ACI 350.3. Figure 3 shows a plot of impulsive and convective mass ratios versus aspect ratio for circular tanks.

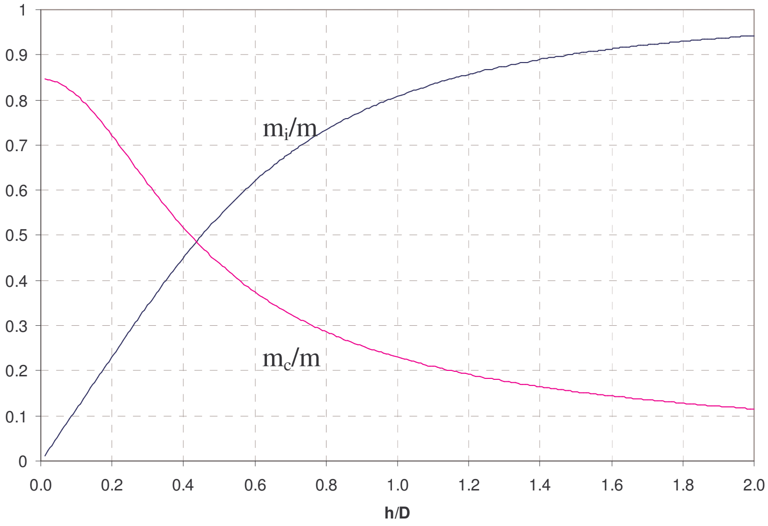


Figure 3: Impulsive and convective mass ratios for circular tanks

The convective component can range from 85% to 10%. It should be noted that the sum of impulsive mass (m_i) and convective mass (m_c) will not always equal the total mass of liquid (m). This difference is attributed to assumptions and approximations made in the derivation of these quantities. One approximation is the use of only one sloshing mode; other sloshing modes typically contribute less than 5%.

4. IMPULSIVE & CONVECTIVE NATURAL PERIODS

The impulsive period of an elevated tank must be calculated from the combined mass of the structure and the impulsive mass of the fluid acting at a height $h_i + h_s$ from Figure 2a. In theory, this can be done by adding non-structural mass to an FEA model of a tank and using a natural frequency solver. But in practice, an FEA model of a steel tank with thin plate thicknesses will generate dozens of wall flexure mode shapes unrelated to lateral seismic excitation. An easy way around this is to use the simple vibration formula:

$$T_i = 2\pi\sqrt{\frac{m_i + m_s}{K_s}} \tag{1}$$

where m_s = mass of structure (kg)
m_i = mass of impulsive liquid (kg)
K_s = lateral stiffness of structure (N/m)

The lateral stiffness of the structure is the required horizontal force applied at the impulsive action height ($h_i + h_s$) that causes a corresponding unit displacement.

For tall water tower type structures, the mass of the structure should only be the container weight and one-third mass of the staging (Sameer and Jain, 1994). For squat structures such as thickeners this makes little difference to the final result.

For most thickeners it's found that the impulsive natural period is quite short (less than 0.5 seconds). Hence, for initial design checks a period of 0.2 seconds can be used to give the highest response spectrum value (this is done in API 650).

The convective time period for a circular tank is given by:

$$T_c = 2\pi\sqrt{\frac{m_c}{K_c}} \qquad \text{where} \quad K_c = 0.836\frac{mg}{h}\tanh^2\left(3.68\frac{h}{D}\right) \tag{2}$$

5. SLURRY DYNAMICS

A thickener contains a fluid that increases in density and viscosity with depth, with a distinctive phase shift from liquid to slurry. International codes on liquid storage tanks assume a homogenous liquid.

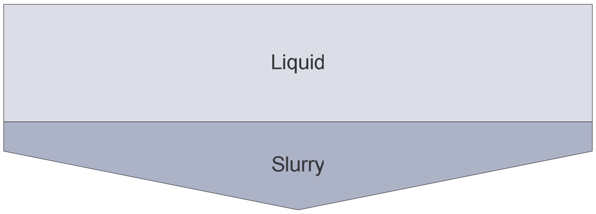


Figure 4: Phase shift in thickeners

Priestley et al. (1986) have shown that the effect of viscosity on spring mass model parameters is minimal. Furnace oil with viscosity 2000 times higher than water was shown to exhibit similar dynamic behaviour. So any viscosity changes can be ignored.

However, the slurry or paste produced by a thickener lies somewhere between a liquid and a solid. The behaviour of tanks with saturated solids is poorly understood, but it is known that granular solids on their own have limited convective response. A conservative approach is to treat the slurry as an impulsive body below a certain depth in the thickener.

Spring mass model parameters for varying liquid density have been derived (for example Shivakumar, 1995). These are recommended for tanks with a linear or exponential density gradient. In a thickener, it's found that the density gradient is small by comparison to the phase shift that occurs. Therefore, the single density parameters are used for the liquid contents of the tank.

6. TANK GEOMETRY

Spring mass model parameters are most readily available for cylindrical and square tanks. There are no universally accepted parameters for other shapes such as truncated conical tanks. Eurocode 8 (1998) has suggested that an equivalent circular tank approach be used.

Since some or all of the slurry in the conical section of a thickener tank will be treated as impulsive as per the previous section, any error involved in using an equivalent circular tank is reduced.

7. ASCE 7 SEISMIC PARAMETERS

The response spectrum used in ASCE 7 is shown in Figure 5:

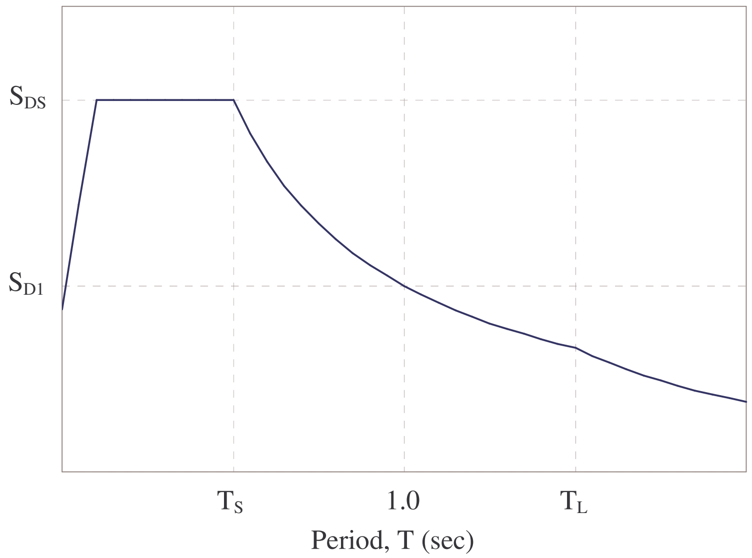


Figure 5: ASCE 7 design response spectrum

By adjusting the parameters S_{DS}, S_{D1} and T_L, this spectrum can match the exact spectra specified in AS 1170.4. This conversion is obtained from the following formulas and Table 1:

$$S_{DS} = k_p Z C_h(0) \qquad S_{D1} = k_p Z C_h(1) \tag{3}$$

where k_p = probability factor from AS 1170.4
Z = hazard factor from AS 1170.4

Table 1: Spectral shape factors from AS 1170.4 and long period transition period (T_L)

Site Sub-Soil Class	$C_h(0)$	$C_h(1)$	T_L (seconds)
A_e – Strong Rock	2.35	0.70	1.5
B_e – Rock	2.94	0.88	1.5
C_e – Shallow Soil	3.68	1.25	1.5
D_e – Deep or Soft Soil	3.68	1.98	1.5
E_e – Very Soft Soil	3.68	3.08	1.5

The response modification coefficient for the structure, R_i (analogous to structural ductility factor, μ) is given in Table 2 for elevated tanks and ground-supported tanks for comparison:

Table 2: Response modification coefficient from ASCE 7 for elevated and ground-supported tanks

Structure Type	R_i
Elevated tank on symmetrically braced legs	3
Elevated tank on unbraced or asymmetric braced legs	2
Single pedestal or skirt supported welded steel	2
Single pedestal or skirt supported welded steel with special detailing	3
Ground-supported mechanically anchored	3
Ground-supported self-anchored	2.5

An elevated thickener tank has symmetrically braced legs and falls into the first category with a R_i value of 3. It's interesting to note that this value is the same as that for a ground-supported mechanically anchored tank. An elevated steel tank primarily dissipates seismic energy through the flexure of the support structure while an on-ground tank dissipates energy through the movement of the foundation. It's found that for these 2 cases the values are roughly equal.

AS 1170.4 gives a structural ductility factor of 2 for elevated tanks, which agrees with the ASCE 7 values when the braced and unbraced structure types are grouped into one category.

This R_i value is for the impulsive mode of the structure. The convective mode response modification coefficient, R_c, is assigned a lower value since the sloshing energy is only dissipated through flexure of the tank wall and small amounts of viscous damping. Thus in ASCE 7, R_c is taken as 1.5 and convective damping is taken as 0.5%. The design response spectrum is multiplied by 1.5 to convert from 5% to 0.5% damping.

8. STATIC ANALYSIS

Impulsive and convective base shears are given by:

$$V_i = \frac{S_a(T_i)m_i g}{R_i} \qquad V_c = 1.5\frac{S_a(T_c)m_c g}{R_c} \tag{4}$$

$$\begin{aligned} S_a(T) &= S_{DS} && \text{for } T \le T_s \\ S_a(T) &= \frac{S_{D1}}{T} && \text{for } T_s < T \le T_L \\ S_a(T) &= \frac{S_{D1}T_L}{T^2} && \text{for } T > T_L \end{aligned}$$

These are combined to give the total base shear by the square root of sum of squares (SRSS) rule:

$$V = \sqrt{V_i^2 + V_c^2} \tag{5}$$

Most international codes including API 650 use the SRSS rule to combine responses.

This paper is too short to present all of the formulas for a full analysis but those for hydrodynamic pressure and sloshing wave height can be found in API 650 while the p-delta design requirements are given in ASCE 7.

There is an infrequent scenario with thickeners whereby a process upset or equipment abuse can cause the entire thickener to fill with aggregated solids with a high specific gravity. The tank walls are designed to resist this hydrostatic condition and by consequence, the hydrodynamic seismic loads typically do not govern the design.

9. EXAMPLE 36 m DIAMETER THICKENER

A 36 m diameter thickener may have a sidewall of 2.8 m, a floor slope of 1:6, and a minimum ground clearance of 1.5 m at the centre. If the thickener produces slurry of SG 2.0 the contents mass will be 5,750 tonnes during normal operation. A hazard factor of Z=0.2 and a site sub-soil class D_e are considered for this example.

The bottom cone contents are treated as impulsive solids; therefore the upper cylinder can be split into impulsive and convective components based on the standard circular formulas. For this h/D ratio of

0.078, 82% of the cylindrical contents will slosh with a period of 11.9 seconds. It's clear from this example that for low aspect ratio tanks very little of the convective component will contribute to the total base shear.

The impulsive period of the tank is calculated to be 0.36 seconds from an FEA model. This yields a total base shear of 6,832 kN or 11.8% g. This is considered to be a conservative and reasonable result for these seismic conditions.

Conversely, if the whole tank contents are treated as a lumped mass, the tank period increases to 0.52 seconds but the base shear also increases to 14,200 kN or 24.5% g. At the other extreme, if the entire tank contents are considered liquid, base shear drops to 3,057 kN or 5.3%.

Its important to note that at this height to diameter ratio, we're at the extreme left of the mass ratios shown in Figure 3. The formulas can be less accurate in this region as the impulsive mass ratio approaches zero so it's recommended to always use a minimum of 15% impulsive mass to maintain a conservative result.

10. CONCLUSION

This paper has presented a method for calculating seismic loads for elevated slurry storage tanks in Australia. The ASCE 7 loading code was chosen as it covers the scope limitations of AS 1170.4. Guidelines for implementation were given.

For large diameter, low aspect ratio tanks such as thickeners, assumptions about the slurry properties can change the seismic loads dramatically. A conservative approach is recommended.

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