COMPARISON BETWEEN STANDARDS FOR SEISMIC DESIGN OF LIQUID STORAGE TANKS WITH RESPECT TO SOIL-FOUNDATION-STRUCTURE INTERACTION AND UPLIFT

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SUMMARY

Field evidence has established that strong earthquakes can cause severe damage or even collapse of liquid storage tanks. Many tanks worldwide are built near the coast on soft soils of marginal quality. Because of the difference in stiffness between the tank (rigid), foundation (rigid) and the soil (flexible), soil-foundation-structure interaction (SFSI) has an important effect on the seismic response, often causing an elongation of the period of the impulsive mode. This elongation is likely to produce a significant change in the seismic response of the tank and will affect the loading on the structure. An issue not well understood, in the case of unanchored tanks, is uplift of the tank base that usually occurs under anything more than moderate dynamic loading. This paper presents a comparison of the loads obtained using "Appendix E of API STANDARD 650" of the American Petroleum Institute and the "Seismic Design of Storage Tanks" produced by the New Zealand Society for Earthquake Engineering. The seismic response assessed using both codes is presented for a range of tanks incorporating a range of the most relevant parameters in design. The results obtained from the analyses showed that both standards provide similar base shear and overturning moment; however, the results given for the anchorage requirement and uplift are different.

INTRODUCTION

Liquid storage tanks have enormous importance for communities in earthquake prone regions. These facilities are the source of supply for essential lifelines such as potable water, fuel and sewage disposal. For this reason, it is important that these structures remain in an operational status after an earthquake. However, evidence in the literature [1-3] has demonstrated that large earthquakes may cause severe damage to storage tanks or even collapse in some cases (Figure 1). This brings a twofold effect: a) economic loss due to tank and pipe damage and b) people from zones affected by the earthquake cannot access the basic supplies of potable water and energy after the seismic event. Many studies have been carried out to research the dynamic behaviour of storage tanks [4-6] largely as a result of item b) above. A number of codes of practice and design guides have been developed.

Two of the most widely used standards (perhaps worldwide) for the seismic design of liquid storage tanks are Appendix E of API Standard 650 (API 650) of the American Petroleum Institute and the "Seismic Design of Storage Tanks" (often known as Red Book) of the New Zealand Society for Earthquake Engineering. Both standards for seismic design are based mainly in the spring-mounted mass analogy proposed by [4]. This analogy is shown in Figure 2(a) and is derived from the solution of the hydrodynamic equations that describe the behaviour of liquid inside a container [4, 7]. The figure indicates that liquid storage tanks behave mainly in two vibration modes [5, 6]. The portion of the liquid contents which moves as if fixed to the tank shell is known as the impulsive mass. The portion of the content which moves independently of the tank shell and develops a sloshing motion is called the convective mass.

The predominant mode of liquid storage tanks during an earthquake is the impulsive mode [8, 9] and its period is very short, generally a few tenths of a second. In many cases, tanks are built on soft normally consolidated soils (typical in coastal zones), increasing the risk of damage in earthquake prone countries such as New Zealand. Because of these two factors, i.e. a very stiff structure and very flexible foundation soil, the soil-foundation-structure interaction (SFSI) has an important effect on the seismic response and may lengthen the period of the impulsive mode significantly. This elongation is likely to produce a change in the seismic response of the tank from that if the tank was sited on an infinitely stiff foundation, as some studies portray. The effect of SFSI is considered in "Appendix E of API STANDARD 650" of American Petroleum Institute (API 650) and also the "Seismic Design of Storage Tanks". Whereas the Red Book [20] includes in its design methodology SFSI analysis for all cases, API 650 considers SFSI only for storage tanks mechanically anchored. In this way, API 650 excludes SFSI effects for unanchored tanks i.e. tanks simply placed on a granular platform. Both standards deem that SFSI always reduces the base shear and the overturning moment on liquid storage tanks. However [8] concludes that this assertion is not always true. The reduction or increase in seismic loading will depend on the specific seismic event and the characteristics of the tank and foundation soil of the site.

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Figure 1: Total collapse of storage tanks in the Darfield earthquake (2010) (Courtesy of Timbertanks).

A phenomenon that has not received much attention is uplift of the base of the tank. Uplift is the physical separation of the tank base from the foundation or supporting soil. The seismic response of anchored tanks has been widely researched unlike the case of unanchored tanks [10]. The standards yield a conservative design for unanchored tanks because they consider that the uplift of the tank base plate is harmful by producing significant loading on the tank shell. Furthermore, as was already mentioned above, SFSI is not considered by API 650 for unanchored tanks, i.e., when in reality base plate uplift occurs this is not incorporated in the design as a SFSI factor. Contrary to the lack of including base plate uplift effects, a theoretical study developed by [11] showed that including uplift could reduce the base shear and the base moment on tanks. In the specific case of an unanchored tank described by [11] the overturning moment and base shear were reduced by more than 70% from that of the equivalent fully anchored tank, i.e. a tank that cannot develop uplift during an earthquake. This reduction is directly due to the uplift developed by an unanchored tank.

Another important difference between both standards is the way that they deal with the flexibility of the tank walls. A number of studies [12-14] have investigated the effect of the wall flexibility on the liquid motion. In this way, it has been possible to identify other more refined impulsive modes of vibration incorporating the wall flexibility. These modes, of which there is an infinite number, are called cosnθ-type modes. However, just the first cosnθ-type mode, i.e. n = 1, is relevant in seismic response due to the significant energy in earthquake motions at periods that match the fundamental period of this type of mode [12]. The Red Book takes into account this wall flexibility and proposes a design method that includes two impulsive modes for flexible tanks. The Red Book defines that flexible tanks are tanks with a height to radius ratio larger than 1. The two modes considered by the Red Book are the rigid impulsive mode, ignoring wall flexibility, and the flexible impulsive mode. The model used by the Red Book is shown in Figure 2(b). The proportion between the impulsive masses (i.e. between flexible and rigid) for flexible tanks depends exclusively on the liquid height to radius ratio (known as the aspect ratio) and therefore, the magnitude of the effect of wall flexibility on the seismic behaviour of tanks varies according to the aspect ratio.

The first flexible impulsive mode has a longer period of vibration than the rigid impulsive mode , depending on the design earthquake considered. This elongation could produce a change in the seismic response of the tank (similar effect to the case of considering lengthening of the impulsive period). API 650 considers one impulsive mode. The model used is shown in Figure 2(a). To the authors the standard is not clear in explaining the distinction between rigid tanks and flexible tanks. However, [5] explains that the calculation of the period of the impulsive mode is complex for rigid tanks and, for flexible tanks is even more so. For this reason [5] consider the seismic forces acting on the impulsive mass to be independent of the impulsive period. Despite the research carried out since [5], 26 years, API 650 adopts the same procedure to compute the forces acting on the impulsive mass, i.e., despite the fact that the design guide contains an equation to compute the period of the impulsive mode, the impulsive forces are treated as independent of the period. The objective of this work is to establish the degree of compatibility of liquid storage tank designed according to the Red Book and API 650.

METHOD OF ANALYSIS

A comparison between API 650 and the Red Book for cylindrical steel tanks is presented in this section. As was mentioned above, both standards for seismic design are based mainly on the spring-mounted masses analogy proposed by [4]. Subsequently, both codes have incorporated in their procedures results from more recent investigations such as [6 and 12] and, in this way have kept pace with developments. However, this process of remaining current has brought with it differences in the way the two design guides deal with some aspects. This research focuses on these differences and compares the results given by both standards. The equations to compute the parameters required for the design are obtained directly from the design guides.

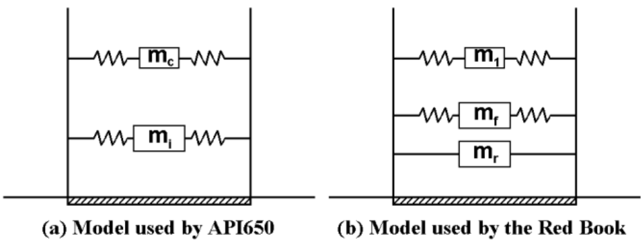

Figure 2: Spring-mounted mass analogy for storage tanks.

According to the Red Book procedure, the period of vibration of the first impulsive (tank + liquid) horizontal mode, T_f, with no incorporation of SFSI, is given by:

$$T_f = \frac{5.61 \cdot \pi \cdot H}{k_h} \cdot \sqrt{\frac{\gamma_l}{E \cdot g}} \qquad (1)$$

where H = liquid height;
k_h = period coefficient which depends on the liquid height to radius ratio;
γ_l = unit weight of the liquid;
E = Young's modulus for tank material = shear stiffness number; and
g = gravitational attraction.

To include the effect of SFSI, the Red Book provides an expression (equation 2 below) for the period of vibration, $\check{T}_f$, to modify the fixed base period (equation 1) to account for foundation flexibility:

$$\check{T}_f = T_f \cdot \sqrt{1 + \frac{K_f}{K_x} \cdot \left[1 + \frac{K_x \cdot h_f^2}{K_\theta}\right]} \qquad (2)$$

The second impulsive mode of the tank-foundation system is given by the following equation:

$$\check{T}_0 = 2\pi \cdot \sqrt{\frac{m_r + m_b}{K_x} + \frac{m_r \cdot h_r^2}{K_\theta}} \qquad (3)$$

where m_r = rigid impulsive mass;
m_b = mass of the base;
h_f = height of the flexible impulsive mass;
h_r = height of the rigid impulsive mass;
K_f = effective stiffness of the tank-liquid system;
K_x = the horizontal translational stiffness; and
K_θ = rocking stiffness of the foundation.

$\check{T}_f$ and $\check{T}_0$ are the periods of vibration including SFSI for the first two impulsive modes of flexible tanks. The former period is the period of the flexible impulsive mass, m_f and the latter one is the period of the rigid impulsive mass m_r. As described above a tank is considered rigid or flexible depending exclusively on its height to radius ratio. In the case of a rigid tank there is just one impulsive mode, the rigid impulsive mode, and the Red Book allows the use of equation (3) to compute the period of this mode.

On the other hand, API 650 does not recognise two impulsive modes (rigid wall and flexible wall) and thus gives one expression to compute a unique impulsive period. This expression is:

$$T_I = \frac{C_i \cdot H}{\sqrt{\frac{2 \cdot t_u}{D}}} \cdot \frac{\sqrt{\rho}}{\sqrt{E}} \qquad (4)$$

where C_i = coefficient for determining the impulsive period of the tank system;
t_u = equivalent uniform thickness of tank shell;
D = tank diameter; and
ρ = liquid density.

Note that the equations (1) and (4) are equivalents. Both give the first impulsive period of the system placed on a rigid base. For instance, consider a height to radius ratio of 2 and a shell thickness to radius ratio of 0.002. In this case the equations (1) and (4) give the expressions shown below respectively:

$$T_f = 141 \cdot H \cdot \sqrt{\frac{\rho}{E}} \qquad (5)$$

$$T_I = 139 \cdot H \cdot \sqrt{\frac{\rho}{E}} \qquad (6)$$

This comparison confirms that API 650 considers that all the impulsive mass is concentrated in one mode of vibration and this corresponds to the first impulsive tank-liquid horizontal mode given by the Red Book.

Considering the convective (sloshing) mode the period of vibration of the ith convective mode given by the Red Book is:

$$T_i = \frac{2 \cdot \pi \cdot \sqrt{\frac{R}{g}}}{\sqrt{\lambda_i \cdot \tanh\left(\lambda_i \cdot \frac{H}{R}\right)}} \qquad (7)$$

where R = radius of the tank; and
λ_i = 1.841, 5.331, 8.536, ... for i = 1, 2, 3, ... respectively for the mode number.

The expression given by API 650 to compute the first convective or sloshing period of vibration is:

$$T_c = 1.8 \cdot K_s \cdot \sqrt{D} \qquad (8)$$

where

$$K_s = \frac{0.578}{\sqrt{\tanh\left(\frac{3.68 \cdot H}{D}\right)}} \qquad (9)$$

In equation (8), D is the nominal diameter of the tank in metres.

As in the case of the impulsive period, equations (7) and (8) are equivalents.

To compute the impulsive and convective masses and their eccentricities above the base the procedure of the Red Book follows the charts proposed by [6]. Masses and their heights depend exclusively on the liquid height to radius ratio.

On the other hand, API 650 bases its procedure on the expressions given by [5] modified from the original work of [4]. The equations given by API 650 are:

Impulsive mass:

For D/H ≥ 1.333

$$W_i = \frac{\tanh\left(0.866 \cdot \frac{D}{H}\right)}{0.866 \cdot \frac{D}{H}} \cdot W_p \qquad (10)$$

For D/H < 1.333

$$W_i = \left(1.0 - 0.218 \cdot \frac{D}{H}\right) \cdot W_p \qquad (11)$$

Convective mass:

$$W_c = 0.230 \cdot \frac{D}{H} \cdot \tanh\left(\frac{3.67 \cdot H}{D}\right) \cdot W_p \qquad (12)$$

Height of the impulsive mass:

For D/H ≥ 1.333

$$X_i = 0.375 \cdot H \quad (13)$$

For D/H < 1.333

$$X_i = \left(0.5 - 0.094 \cdot \frac{D}{H}\right) \cdot H \quad (14)$$

Height of the convective mass:

$$X_c = \left(1.0 - \frac{\cosh\left(\frac{3.67 \cdot H}{D}\right) - 1}{\frac{3.67 \cdot H}{D} \cdot \sinh\left(\frac{3.67 \cdot H}{D}\right)}\right) \cdot H \quad (15)$$

where W_p = total mass of the content;
W_i = impulsive mass of the content;
W_c = convective mass of the content;
X_i = height of the impulsive mass; and
X_c = height of the convective mass.

The situation is further complicated by the fact that the Red Book is a Load and Resistance Factor Design (LRFD) standard and API 650 is an Allowable Stress Design (ASD) standard. To allow compatible comparison between the standards, the load factors for all the loads in the Red Book procedure are set equal to 1. The comparison is done in terms of the loads affecting the tank. In this way, only values such as overturning moment or base shear are important and, therefore, comparisons in terms of resistance or allowable stresses are not included.

API 650 uses the spectrum from [15] to compute the seismic loads. To obtain the seismic loads and allow a valid comparison between both standards, API 650 and the Red Book, the design spectra according to [16] are used. The values of ductility, damping, correction factors and the impulsive and convective seismic coefficients are obtained from section 3 of the Red Book. As was mentioned above, the procedure presented in API 650 is independent of the period of the impulsive mode of vibration. However, to make the comparison compatible, the impulsive period given by equation (4) will be used to compute the impulsive forces from the spectrum given by [16].

Effect of the foundation soil on earthquake response

The first effect to be considered is that of the subsoil on the seismic response of unanchored liquid storage tanks. The seismic response of a single steel cylindrical tank placed on sites with soils of four different shear wave velocities is presented. The sites are classified into four different site categories according to [16] based on the shear wave velocity and depth. The dimensions of the tank analysed are: diameter of 12 m, height of liquid of 6 m and wall thickness of 12 mm. The site categories and shear wave velocities are shown in Table 1. The periods of the impulsive and convective modes of vibration and the uplift computed by both standards are also included in Table 1. The base shear and overturning moments for each case are shown in Figure 3.

In Table 1 it is clear that the period of the impulsive mode does not vary with different site categories when using API 650. This occurs because API 650 does not implement SFSI for unanchored tanks. However, in spite of the fact that the impulsive period remains constant, Figure 3 shows that both the base shear and the overturning moment vary depending on the type of foundation soil as described by the site category. The reason of this variation is that for different types of soil, different spectra of design were applied from [16], i.e., for each site category the design spectrum is different. It is also noticeable in Table 1 that the impulsive period computed by the Red Book procedure converges to the value computed by API 650 as the soil becomes stiffer, i.e., the impulsive period becomes closer to the impulsive period of a tank placed on a rigid base. Table 1 shows that, according to API 650, there is not uplift for this level of overturning moment. However, the Red Book gives a value of uplift of approximately 10 mm for all site categories. Furthermore, the Red Book procedure yields higher values of base shear and overturning moment for all site categories. Convective periods computed by both codes match accurately because both design guides consider that this mode is not affected by SFSI [17].

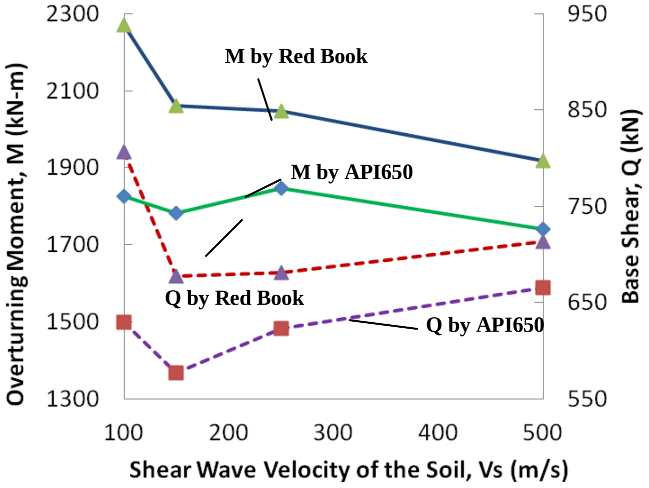

Figure 3: ***Comparison of base shear and overturning moment for different soils.***

Effect of the height to radius ratio

Another important characteristic of liquid storage tanks is the aspect ratio i.e. the height to radius ratio. The proportion of the impulsive and convective masses and their equivalent heights depend exclusively on this ratio [4-6]. For this reason the aspect ratio has a very significant influence on the seismic response of liquid storage tanks. The results carried out using both codes for a tank with a diameter of 6 m, wall thickness of 6 mm, base plate thickness of 5 mm and the shear wave velocity of the foundation soil of 400 m/s, corresponding to a category B site in [16], are shown in Table 2 and Figure 4. The comparison is performed for 6 different aspect ratios.

The Red Book considers two impulsive modes for flexible tanks. Table 1 shows that for height to radius ratios higher than 1.0 the tanks, according to the Red Book procedure, are classified as flexible and therefore two impulsive periods are computed.

The Red Book procedure does not require anchorage for any case analysed here whereas anchorage is required by API 650 for the two largest height to radius ratios. The criteria used by both codes, to decide if anchorage is required, are based on different investigations [5,18] and this can explain the different results obtained, shown in Table 2, concerning the anchorage requirements.

The procedure given by the Red Book is based on the work carried out by [18]. This investigation establishes two limits for rigid bodies to avoid overturning. The parameters that are limited to avoid overturning are the peak ground acceleration and the peak ground velocity. The first one is responsible for

Table 1: Seismic response for four different types of soil

		NZSEE (2009) Red Book			API 650 (2007)		
Vs (m/s)	**Soil NZS 1170.5**	**$\check{T}_f$ (s) eq. (2)**	**T_I (s) eq. (7)**	**Uplift (mm)**	**T_I (s) eq. (4)**	**T_c (s) eq. (8)**	**Uplift (mm)**
100	E	0.185	3.71	9	0.060	3.70	Assumed 0
150	D	0.132	3.71	10	0.060	3.70	Assumed 0
250	C	0.093	3.71	10	0.060	3.70	Assumed 0
500	B	0.070	3.71	11	0.060	3.70	Assumed 0

inducing rocking and the second one is responsible for providing energy to overturn the tank. Because storage tanks are not rigid bodies, the criterion of the peak ground acceleration, as applied for rigid bodies, is changed to the value of peak response acceleration. These two limits must be exceeded simultaneously to require anchorage for a tank. The first criterion is evaluated by a static equilibrium of moments acting on the tank. In this equilibrium the tank is considered a rigid body. The second criterion is obtained by limiting directly the peak ground velocity according to value given by [18].

On the other hand, the procedure given by API 650 is based on the work of [5]. The equilibrium of forces to compute the overturning resistance presented in their work is based on small deflection theory. Equilibrium is considered for a limited length of the base plate, unlike the Red Book that considers the entire tank and its content in the equilibrium of moments. Only the portion of the contents on this limited length and the weight of the shell are considered to resist the overturning moment. The diverse nature of the procedures of both codes, is expected to lead to the anchorage requirements of both codes being inconsistent.

With respect to uplift, Table 2 shows this to be very sensitive to the aspect ratio when using the Red Book procedure. On the other hand, application of API 650 results in no variation in uplift with a variation in soil stiffness. This can be explained by the equation provided by API 650 to compute uplift. Equation (16) gives an approximation of the tank uplift according to API 650.

$$y_u = \frac{12.10 \cdot F_y \cdot L^2}{t_b} \qquad (16)$$

where y_u = the tank uplift;
F_y = minimum specified yield strength of bottom annulus;
L = required minimum width of the bottom annulus; and
t_b = thickness of the tank bottom.

In the parameters involved in equation (16), the seismic forces do not appear directly but they have an influence in the computation of the dimensions of the tank such as L and t_b. For this reason, uplift is indirectly related to the seismic forces acting on the tank. However, in this analysis some ratios remained constant. One such ratio is the ratio of wall thickness to bottom thickness. This ratio has an influence on the values of the parameters L and t_b and, for this reason, y_u does not vary with aspect ratio.

Comparing the values of uplift given by both design guides it is very evident that they are not similar. This can be explained by the very different procedure adopted by the two codes to compute uplift. As was mentioned above, API 650 bases its procedure on the tank dimensions whereas the Red Book provides an equation that is based on a quasi-static equilibrium of forces and moments acting on the tank.

For the soil stiffnesses considered, both design guides produce very similar values of base shear and overturning moment. This suggests that there is certain concordance between both standards in the computation of seismic forces when this parameter is varied.

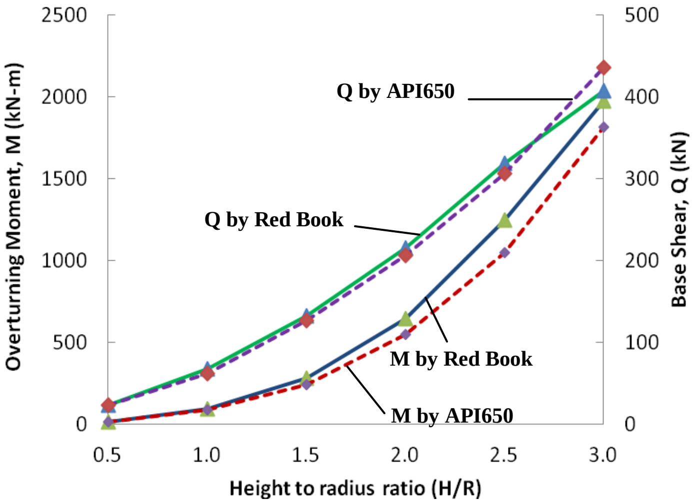

Figure 4: ***Comparison of base shear and overturning moment for different aspect ratios.***

Effect of the tank radius

In addition to the aspect ratio, the tank radius itself has an influence on SFSI. For this reason, it is expected that for a given aspect ratio and soil properties, the seismic response of storage tanks varies according to the tank radius. In Table 3 and Figure 5 the results of the analyses performed for four different tank radii are shown. The height to radius ratio is 1 for all cases and the shear wave velocity of the foundation soil is 150 m/s.

Table 3 illustrates that the uplift computed by the Red Book procedure is not very sensitive to the value of the tank radius. For a four fold increase in radius the uplift increases by 27%. On the other hand, the results obtained from API 650 show that uplift does not occur in any of the cases analysed. The reason of this disparity was explained above.

As in the case of a variable aspect ratio, the values of base shear and overturning moment computed by both standards closely match for all the radii analysed, with the values given by the Red Book being slightly higher than those given by API 650.

Table 2: Seismic response for different aspect ratios

					NZSEE (2009) Red Book					API 650 (2007)	
H/R	**H (m)**	$\check{T}_f$ **(s) eq. (2)**	$\check{T}_0$ **(s) eq. (3)**	T_I **(s) eq. (7)**	**Tank**	**Anchorage**	**Uplift (mm)**	T_I **(s) eq. (4)**	T_c **(s) eq. (8)**	**Anchorage**	**Uplift (mm)**
0.5	1.5	0.012	-	3.01	Rigid	not required	0	0.018	2.99	no required	Assumed 0
1.0	3.0	0.037	-	2.63	Rigid	not required	0	0.03	2.61	no required	Assumed 0
1.5	4.5	0.053	0.012	2.57	Flexible	not required	6	0.043	2.56	no required	31
2.0	6.0	0.072	0.015	2.56	Flexible	not required	8	0.058	2.55	no required	31
2.5	7.5	0.093	0.021	2.56	Flexible	not required	19	0.077	2.55	required	31
3.0	9.0	0.120	0.028	2.56	Flexible	not required	33	0.099	2.55	required	31

Table 3: Seismic response for tanks of different radii

	NZSEE (2009) Red Book				API 650 (2007)		
R (m)	T_f **(s) eq. (1)**	$\check{T}_f$ **(s) eq. (2)**	T_I **(s) eq. (7)**	**Uplift (mm)**	T_I **(s) eq. (4)**	T_c **(s) eq. (8)**	**Uplift (mm)**
3	0.031	0.057	2.63	11	0.03	2.61	Assumed 0
6	0.061	0.117	3.71	12	0.06	3.7	Assumed 0
9	0.092	0.177	4.55	14	0.09	4.53	Assumed 0
12	0.123	0.237	5.25	14	0.12	5.23	Assumed 0

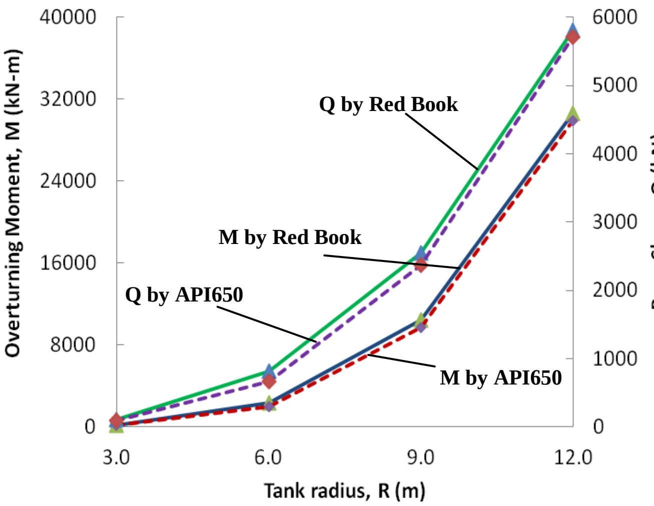

Figure 5: ***Comparison of base shear and overturning moment for different tank radii.***

CONCLUSIONS

A comparison between two of the most widely used design codes for storage tanks has been presented. This comparison has been performed in terms of the seismic response of unanchored storage tanks, i.e. base shear, overturning moment and uplift. The most significant parameters were varied to evaluate their importance in seismic response.

The type (and depth) of subsoil has an influence in the seismic response mainly because, depending on the site soil profile, the surface response (magnitude and frequency) changes. In the case of the Red Book, the influence on the period of the impulsive mode does not have much importance on the seismic response because the elongation in the impulsive period, in most of the cases, results in the period being still on or near the plateau of the design spectrum.

The results obtained from the aspect ratio analyses, in terms of base shear and overturning moment, show that both codes match for all the height to radius ratios analysed. The same is true when the parameter that is varied is the tank radius.

With respect to the requirement of anchorage, the two codes give different results. The different anchorage criteria used by the codes are the reason of this disparity. API 650 is more refined because the procedure limits the uplift length of the base plate whereas the Red Book considers a global equilibrium of moments acting on the tank.

In all the analysis performed the results obtained for uplift by the two codes are significantly different. The reason can be explained by the substantially different way that each code computes uplift. According to the results given by the Red Book, the parameter that has most influence on tank uplift is the aspect ratio.

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