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Seismic Assessment of Steel Chemical Storage Tanks.

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ABSTRACT

Water supply is one the crucial lifeline systems. The seismic safety of critical water facilities is a pivotal issue in urban earthquake hazard mitigation. This project conducts the seismic assessment of two typical steel chemical storage tanks (one in Zhitan and one in Changxing water purification plants) of Taipei Water Department. The assessment criteria follow Taiwan Building Seismic Design Code (2011; design response spectra), JWWA Guideline to and Explanation of Seismic Construction Method of Water Supply Facilities (2009; water pipe bridges) and API 650 Welded Steel Tanks for Oil Storage (11th ed., 2012, Appendix E: Seismic Design of Storage Tanks; steel tanks). Major findings include: Tank No. 2 of Zhitan and Tank No. 6 of Changxing do not have sufficient anchorage; also, the later doesn't have enough freeboard while at its highest content level. Accordingly, measures to enhance their seismic integrity or secure their seismic safety have been advised.

Keywords: Water facilities, Seismic assessment, Steel chemical storage tanks, API 650

INTRODUCTION

The steel chemical storage tanks selected for study under this project are No. 2 tank of Zhitan and No. 6 tank of Changxing water purification plant. They are the largest tanks of respective plant with capacity of 300 Tons and the heights are 7.7 meters and 9.2 meters and for accommodating PAC and NaOH respectively. The chemicals (liquid) posed remarkable weight, and any damage of the tanks could result detrimental effects to the purification quality. A rational approach to assess the seismic safety of such tanks is greatly needed..

SEISMIC ASSESSMENT PROCEDURE OF STEEL CHEMICAL STORAGE TANKS

For the design of these hazardous liquid storage tanks, "Appendix E: Seismic Design of Storage Tanks" in API 650 Welded Steel Tanks for Oil Storage (API, 2007) is most applied. Theoretically, it considers two response modes of a tank and its contents: impulsive and convective (Housner, 1963). This procedure applies to anchored steel tanks, which are the most commonly used variety, and is of high seismic concern in Taiwan. It is also incorporated with the ground motion specified in Taiwan Building Seismic Design Code (Construction and Planning Agency Ministry of the Interior,R.O.C., 2011).

API 650 classifies tanks into three Seismic User Groups (SUGs). **SUG III** tanks are those that provide service to facilities essential to the life and health of the public, or those that contain hazardous substances, to which it is greatly important to prevent public exposure. **SUG II** tanks are those that provide direct services to major facilities, or which store materials that may pose a public hazard and lack secondary controls. The rest belong to **SUG I** tanks.

In this study, a seismic assessment procedure for steel liquid storage tanks is given, as depicted in **Fig. 1**.

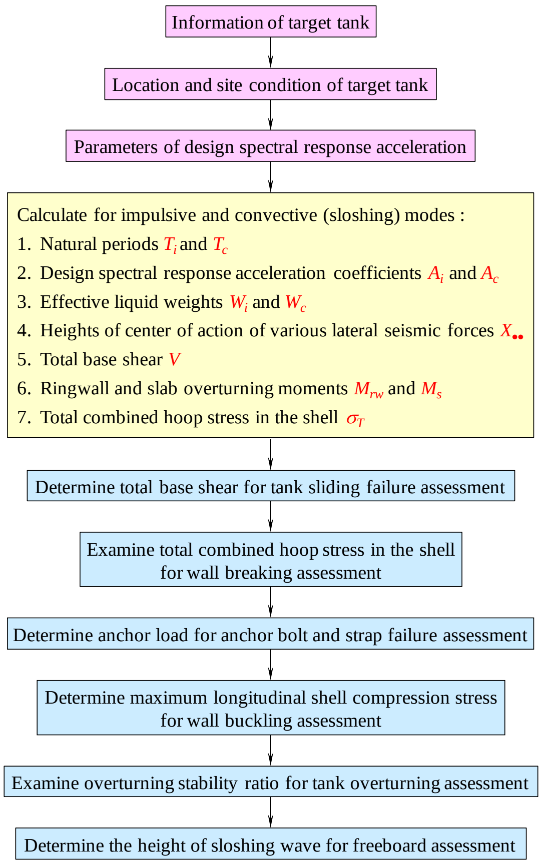
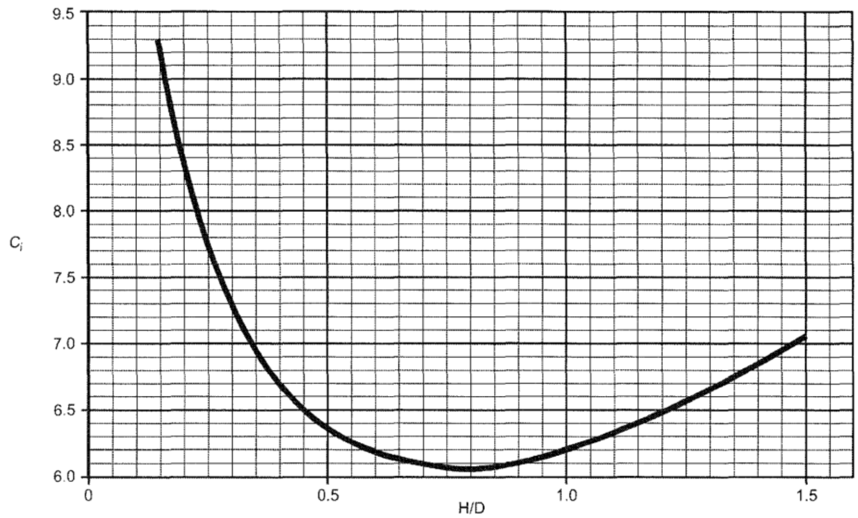


Fig. 1 Seismic assessment procedure for steel liquid storage tanks following API 650, App. E requirements.

1. Determine T_i (s) and T_c (s), the natural periods of vibration for impulsive and convective (sloshing) modes of behavior of the liquid.

$$T_i = \frac{1}{\sqrt{2000}} \cdot \left(\frac{C_i H}{\sqrt{\frac{t_u}{D}}} \right) \cdot \sqrt{\frac{\rho}{E}} \qquad T_c = 2\pi \cdot \sqrt{\frac{D}{3.68g \cdot \tanh\left(\frac{3.68H}{D}\right)}}$$

where the coefficient C_i is a function of H/D depicted in the following chart.



2. **Determine A_i (g) and A_c (g), the impulsive and convective design spectral response acceleration coefficients.**

$$A_i = \left(\frac{I}{R_{wi}}\right) \cdot S_{aD}(T_i) \qquad A_c = K \cdot \left(\frac{I}{R_{wc}}\right) \cdot S_{aD}(T_c)$$

where I is set by Seismic User Group (SUG), and $K = 1.5$ unless otherwise specified. The values of force reduction coefficients R_{wi} and R_{wc} for the impulsive and convective modes using allowable stress design methods are 4 and 2, respectively, for mechanically-anchored tanks.

3. **Determine V (N), the total base shear, from W_i (N) and W_c (N), the effective impulsive and convective portions of the liquid weight, respectively. Examine the possibility of tank sliding.**

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

where

$$\begin{cases} V_i = A_i(W_s + W_r + W_f + W_i) \\ V_c = A_c W_c \end{cases} \quad W_i = \begin{cases} \dfrac{\tanh\left(0.866\dfrac{D}{H}\right)}{0.866\dfrac{D}{H}} \cdot W_p & D/H \geq 1.333 \\ \left(1.0 - 0.218\dfrac{D}{H}\right) \cdot W_p & D/H < 1.333 \end{cases} \quad W_c = 0.230\frac{D}{H} \cdot \tanh\left(\frac{3.67H}{D}\right) \cdot W_p$$

The calculated value of V should not exceed the sliding resistance V_s (N) calculated by:

$$V_s = \mu(W_s + W_r + W_f + W_p)(1.0 - 0.4A_v)$$

4. **Determine the ringwall overturning moment M_{rw} (N-m) acting at the base of tank shell perimeter and the slab overturning moment M_s (N-m) used for slab and pile cap design.**

$$M_{rw} = \sqrt{\left[A_i(W_i X_i + W_s X_s + W_r X_r)\right]^2 + \left[A_c(W_c X_c)\right]^2}$$
$$M_s = \sqrt{\left[A_i(W_i X_{is} + W_s X_s + W_r X_r)\right]^2 + \left[A_c(W_c X_{cs})\right]^2}$$

where $X_{\bullet}$ and $X_{\bullet\bullet}$ refer to the height from the bottom of the tank shell to the center of action of various lateral seismic forces from liquid, tank shell and roof.

$$X_i = \begin{cases} 0.375H & D/H \geq 1.333 \\ \left(0.5 - 0.094\dfrac{D}{H}\right)H & D/H < 1.333 \end{cases} \quad X_c = \left[1.0 - \frac{\cosh\left(\dfrac{3.67H}{D}\right) - 1}{\dfrac{3.67H}{D}\cdot\sinh\left(\dfrac{3.67H}{D}\right)}\right]H$$

$$X_{is} = \begin{cases} 0.375\left[1.0 + 1.333\left(\dfrac{0.866\dfrac{D}{H}}{\tanh\left(0.866\dfrac{D}{H}\right)} - 1.0\right)\right]H & D/H \geq 1.333 \\ \left(0.5 + 0.060\dfrac{D}{H}\right)H & D/H < 1.333 \end{cases} \quad X_{cs} = \left[1.0 - \frac{\cosh\left(\dfrac{3.67H}{D}\right) - 1.937}{\dfrac{3.67H}{D}\cdot\sinh\left(\dfrac{3.67H}{D}\right)}\right]H$$

5. Determine σ_T, the total combined hoop stress in the shell (MPa).

$$\sigma_T(\pm) = \frac{N_h \pm \sqrt{N_i^{\,2} + N_c^{\,2} + (A_v N_h)^2}}{t}$$

where the product hydrostatic membrane force N_h (N/mm), and the impulsive and convective hoop membrane forces N_i (N/mm) and N_c (N/mm) in tank shell, respectively, are calculated by:

$$N_h = \frac{9.81\cdot GDY}{2}$$

$$N_i = \begin{cases} 8.48A_i GDH\left[\dfrac{Y}{H} - 0.5\cdot\left(\dfrac{Y}{H}\right)^2\right]\cdot\tanh\left(0.866\dfrac{D}{H}\right) & D/H \geq 1.333 \\ 5.22A_i GD^2\left[\dfrac{Y}{0.75D} - 0.5\cdot\left(\dfrac{Y}{0.75D}\right)^2\right] & D/H < 1.333 \text{ and } Y < 0.75D \\ 2.6A_i GD^2 & D/H < 1.333 \text{ and } Y \geq 0.75D \end{cases}$$

$$N_c = \frac{1.85A_c GD^2\cdot\cosh\left[\dfrac{3.68(H-Y)}{D}\right]}{\cosh\left(\dfrac{3.68H}{D}\right)}$$

6. Examine P_{AB}, the anchor load (N).

$$P_{AB} = \left(\frac{1.273M_{rw}}{D^2} - w_t(1 - 0.4A_v)\right)\cdot\left(\frac{\pi D}{n_A}\right)$$

The calculated value of P_{AB} should not exceed 80% of the yield strength of anchor bolts.

7. Examine σ_c, the maximum longitudinal shell compression stress (MPa).

$$\sigma_c = \left(w_t(1 + 0.4A_v) + \frac{1.273M_{rw}}{D^2}\right)\cdot\frac{1}{1000t_s}$$

The calculated value of σ_c should not exceed the allowable longitudinal shell-membrane compression stress F_C (MPa) calculated by:

$$F_C = \begin{cases} 83 \cdot t_s / D & GHD^2/t^2 \geq 44 \\ 83 \cdot t_s /(2.5D) + 7.5\sqrt{GH} < F_{ty} & GHD^2/t^2 < 44 \end{cases}$$

8. Examine that the overturning stability ratio is 2.0 or greater.

$$\frac{0.5D \cdot (W_p + W_f + W_T + W_{fd} + W_g)}{M_s} \geq 2.0$$

9. Determine δ_s, the height (mm) of sloshing wave above the product design height. Examine the sufficiency of tank freeboard to accommodate the calculated value of δ_s.

$$\delta_s = 0.5DA_f$$

where

$$A_f = \begin{cases} KS_{D1}I \cdot \left(\frac{1}{T_c}\right) & T_c \leq 4 \\ KS_{D1}I \cdot \left(\frac{4}{T_c^{\,2}}\right) & T_c > 4 \end{cases} \qquad A_f = \begin{cases} KS_{D1} \cdot \left(\frac{1}{T_c}\right) & T_c \leq T_L \\ KS_{D1} \cdot \left(\frac{T_L}{T_c^{\,2}}\right) & T_c > T_L \end{cases}$$

Nomenclatures	
A_v : vertical earthquake acceleration coefficient (g), taken as $0.14S_{DS}$ or greater for the ASCE 7 method	T_L : regional-dependent transition period for longer period ground motion (s)
D : nominal tank diameter (m)	t : thickness of shell ring under consideration (mm)
E : elastic modulus of tank material (MPa)	t_s : thickness of bottom shell (mm)
F_{ty} : yield strength of shell (MPa)	t_u : equivalent uniform thickness of tank shell (mm)
G : product specific gravity	W_f : weight of the tank bottom (N)
g : acceleration due to gravity (m/sec^2)	W_{fd} : total weight of tank foundation (N)
H : maximum design product level (m)	W_g : weight of soil over tank foundation footing (N)
I : importance factor coefficient; I = 1.0, 1.25 and 1.5 for SUG I, II and III, respectively	W_p : total weight of the tank contents (N)
K : coefficient for adjusting spectral acceleration (from 5 to 0.5% damping)	W_r : total weight of fixed tank roof (N)
n_A : number of anchors around the tank circumference	W_s : total weight of tank shell and appurtenances (N)
$S_{aD}(T)$: design earthquake spectral response acceleration coefficient for structural period T	W_T : total weight of tank shell, roof, framing, knuckles, product, bottom, attachments and appurtenances (N)
S_{D1} : design (5% damped) spectral response acceleration parameter at one second	w_t : tank and roof weight acting at base of shell (N/m)
S_{DS} : design (5% damped) spectral response acceleration parameter at short periods (0.2s)	Y : distance from liquid surface to any point (positive down (m)
	μ : friction coefficient for tank sliding (max. 0.4)
	ρ : density of fluid (kg/m^3)

SEISMIC ASSESSMENT OF STEEL CHEMICAL STORAGE TANKS

●Seismic Assessment Database of Tanks

The seismic assessment database of No. 2 Tank in Zhitan and No. 6 Tank in Changxing purification plant are given below as **Table 1**:

Table 1 –Seismic Assessment Database of Tanks

N0. of Tank	Zhitan Purification Plant No. 2 Storage Tank	Changxing Purification Plant No. 6 Storage Tank
Address.	No. 2, Zhitan Road, Xindian Dist. New Taipei City	No. 131, Changxing Street, Daan Dist. Taipei City
Coordinates	N 24.941647 E 11.529174	N 25.014429 E 121.549655
Type of Chemical	NaOH solution, concentration 45%, Sp.G: 1.48	Poly Aluminum Chloride solution, Sp.G 1.15
Shape and dimensions of tank body	■Cylinder □Rectangular OD： 7.6 m Height ： 7.665 m Effluent height： 6.735 m(from bottom up) Shell thickness： 6 mm Bottom plate thicknes： 6 mm Capacity ： 300 MT	■Cylinder □Rectangular OD： 6.8 m Height： 9.16 m Effluent height： 8.66 m Effluent height: 8.66 M(from bottom up) Shell thickness： 4.5-6 mm Bottom plate thicknes： 6 mm Capacity ： 300 MT
Building material of tank	■Steel ■W/inner lining： yes (FRP)	■Steel ■W/ Inner Lining： yes (FRP)
Placing Manner	■Elevated Height of bottom plate：2.80 m RC Base： yes Foundation pile: nil Anchored with bolts： yes Numbers of Anchoring Bolt: 18 Spec. of bolt: M20	■Ground RC Base： yes Foundation pile: yes Anchored with bolts： yes Numbers of Anchoring Bolt: ： 16 Spec. of bolt: M25
Location placed	■Outdoor ■W/O effluent pond/ channel	■Outdoor ■W/O effluent pond
Year completed	2013 ■No seismic resistance reinforcement	2007 ■No seismic resistance reinforcement

Seismic Assessment Database	$S_S^D = 0.6$ 、 $S_1^D = 0.35$ ； $N_a^{(D)}$=1.0、$N_v^{(D)}$=1.0； Type 2 Crust，$F_a^{(D)} = 1.1$ 、 $F_v^{(D)} = 1.4$ ； $S_{DS} = 0.66$ 、 $S_{D1} = 0.49$ ； $A_v = 0.14 S_{DS} = 0.0924$ ； $T_0^D = S_{D1} / S_{DS} = 0.74$ ； Steel elasticity modal $E = 207{,}000$ MPa ； $g = 9.81 \mathrm{m/s}^2$ ； $H / D = 0.887$ ，$C_i = 6.1$ ； $T_i = 0.0874\mathrm{s}$ 、 $T_c = 2.887\mathrm{s}$ (**procedure 1**)； $I = 1.5$ ； K=1.5 R_{wi}=4(mechanically-anchored) R_{wc}=2(mechanically-anchored) Ai=0.187、Ac=0.297(**procedure 2**); ρ_s=7850Kg/m^3 $W_s=8.46\times10^4$N ; $W_r=2.24\times10^4$N $W_f=2.1\times10^4$N ; $W_p=4.43\times10^6$N $W_i=3.34\times10^6$N ; $W_c=6.48\times10^5$N (**procedure 3**) ; $M_{rw}=2.62\times10^6$N-m;$M_s=3.01\times10^6$N-m (**procedure 4**) ;	$S_{DS} = 0.6$ 、 $S_{D1} = S_{DS} \cdot T_0^D = 0.78$ ； $A_v = 0.14 S_{DS} = 0.084$ ； $T_0^D = 1.30\mathrm{s}$ ； $S_{aD} = 0.6$ ； Steel elasticity modal $E = 207{,}000$ MPa ； $g = 9.81 \mathrm{m/s}^2$ ； $H / D = 1.27$ ，$C_i = 6.6$ ； $T_i = 0.117\mathrm{s}$ 、 $T_c = 2.727\mathrm{s}$ ； (**procedure 1**)； $I = 1.5$ ； K=1.5 R_{wi}=4(mechanically-anchored) R_{wc}=2(mechanically-anchored) Ai=0.225、Ac=0.675(**procedure 2**); ρ_s=7850Kg/m^3 $W_s=7.91\times10^4$N ; $W_r=1.35\times10^4$N $W_f=1.68\times10^4$N ; $W_p=3.59\times10^6$N $W_i=2.98\times10^6$N ; $W_c=6.48\times10^5$N (**procedure 3**) ; $M_{rw}=3.95\times10^6$N-m;$M_s=4.46\times10^6$N-m (**procedure 4**) ;
Photo		

●Results of Detail Seismic Resistance Assessment

Concluding the above database and analysis, the of No. 2 Tank in Zhitan and No. 6 Tank in Changxing purification plant seismic assessment results are shown in **Table 2** and **Table 3**.

Table 2 –Results of Detail Seismic Resistance Assessment- No. 2 Tank in Zhitan Purification Plant

Item	Results of Detail Seismic Resistance Assessment
The possibility of tank sliding	The total base shear for tank sliding $V=7.34\times10^5$N The sliding resistance $V_S=1.76\times10^6$N $V_S > V$ ……OK. (**procedure 3**)
The total combined hoop stress in the shell	$\sigma_T(+)$=70.84MPa(tension,at the bottom of the tank) $\sigma_T(-)$=-7.807MPa(compression,at the liquid surface) SUS304 stainless steel fy=206 Mpa > $\sigma_T(+)$ or $\sigma_T(-)$……OK. (**procedure 5**)
The anchor load	$w_t=4.48\times10^3$N/m $P_{AB}=7.09\times10^4$N 80% of the yield strength of anchor bolts=80%$\times6.47\times10^4$N=5.18×10^4N< P_{AB}……NG(**procedure 6**) Anchor bolts do not have sufficient anchorage
The maximum longitudinal shell compression stress	The maximum longitudinal shell compression stress σ_c=10.4 Mpa The allowable longitudinal shell-membrane compression stress F_C=49.87 Mpa $F_C > \sigma_c$ ……OK. (**procedure 7**)
The stability against overturning	The overturning stability ratio is 5.75 > 2.0……OK. (**procedure 8**).
The height of sloshing wave	The height of sloshing wave δ_S=0.97m The tank freeboard=7.665-6.735=0.93m≒ δ_S……OK. (**procedure 9**). The height of sloshing wave δ_S is slightly higher than the tank freeboard, but is determined as acceptable.

Table 3 –Results of Detail Seismic Resistance Assessment- No. 6 Tank in Changxing Purification Plant

Item	Results of Detail Seismic Resistance Assessment
The possibility of tank sliding	The total base shear for tank sliding $V=8.21\times10^5$N The sliding resistance $V_S=1.43\times10^6$N $V_S > V$ ……OK. (**procedure 3**)
The total combined hoop stress in the shell	$\sigma_T(+)$=62.33MPa(tension,at the bottom of the tank) $\sigma_T(-)$=-14.72MPa(compression,at the liquid surface) SUS304 stainless steel fy=206 Mpa > $\sigma_T(+)$ or $\sigma_T(-)$……OK. (**procedure 5**)

The anchor load	w_t=4.33×10^3N/m P_{AB}=1.4×10^5N 80% of the yield strength of anchor bolts=80%×1.01×10^5N=0.81×10^5N< P_{AB}……NG(**procedure 6**) Anchor bolts do not have sufficient anchorage
The maximum longitudinal shell compression stress	The maximum longitudinal shell compression stress σ_c=18.87 Mpa The allowable longitudinal shell-membrane compression stress F_C=52.96 Mpa F_C > σ_c ……OK. (**procedure 7**)
The stability against overturning	The overturning stability ratio is 3.64 > 2.0……OK. (**procedure 8**).
The height of sloshing wave	The height of sloshing wave δ_S=1.46m The tank freeboard=9.16-8.66=0.5m< δ_S……NG. (**procedure 9**). The height of sloshing wave δ_S is higher than the tank freeboard.

CONCLUSION AND SUGGESTION

Basis "API650 ,Appendix E(API, 2007) " and the basic data as well as site survey of the two steel chemical storage tanks in water treatment, the resistance against anchor load of Zhitan No. 2 Tank and Changxing No. 6 Tank is shown as insufficient. Under design seismic conditions, damage to anchoring position may be resulted. Taipei Water Department has established plan to reinforce anchoring bolts, either to increase or to replace so that the anchoring force will be meeting the need of design seismic resistance. Besides, the height of sloshing wave is higher than the freeboard of Changxing No. 6 Tank about 1 meter. This may lead damage to the top plate due to sloshing wave of fluid during earthquake. New requirement has been set that the liquid level operation height must be 1 meter or more lower than the sufficiency of tank freeboard.

The existing large capacity steel chemical storage tanks similar to Zhitan No. 2 Tank or Changxing No. 6 Tank ,may be existed with insufficient anchoring capacity and insufficient freeboard. This is probably a systematic issue and shall be inspected totally to avoid occurrence of any unnecessary damage.

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