MINIMUM COST SEISMIC DESIGN OF STEEL TANKS

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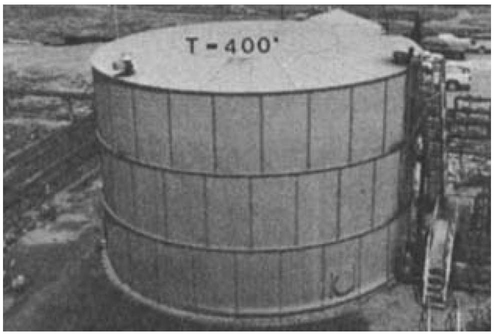
ABSTRACT

In this work the minimum cost seismic design of thin wall ground supported steel tanks is presented. Ground supported steel tanks are traditionally applied to store water and inflammable liquids due to their simple design, very good behaviour under the hydrostatic loads, low cost and easy construction. Despite these advantages, thin-wall steel tanks are sensitive for seismic loading. The aim of this work is the simple, fast and direct optimum seismic design of these special structures, avoiding complicated computational methods such as the finite or the boundary element method. The proposed method provides with the most economical dimensions for the tank and its foundation, for a predefined liquid volume. The proposed method can be treated as a baseline for determining minimum cost seismic design of thin-wall steel tanks that satisfy the structural and stability requirements.

1. INTRODUCTION

Ground supported steel tanks are traditionally applied to store water and inflammable liquids due to their simple design, to their very good behaviour under hydrostatic loads, to low cost and easy construction. However, they sustained severe damage during major seismic events such as Alaska (1964), Turkey (1999) and Iran (2003) earthquakes. It has been found that steel tanks are vulnerable to strong ground motions and their major failure modes have to do with a) the elephant foot buckling of the tank shell due to the uplift of the tank and bending type action of the shell (*Fig. 1a*); b) leakage of contains from the tank due to sloshing of the liquid and/or rupture of the wall nearby the connection of tank to pipes mainly due to the non-ductile action of welded junctions [1-3] (see *Fig. 1b*).

(a) 

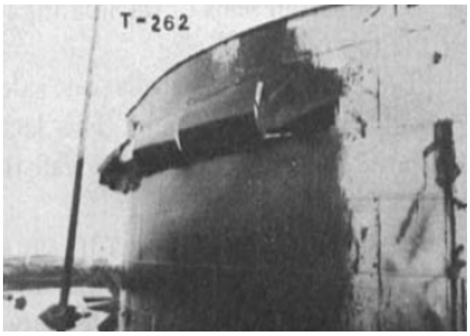
(b) 

Fig. 1 Ordinary failure modes of steel tanks due to earthquakes (taken from [1])

In the past, a lot of researchers studied the seismic response of the steel tanks. One can mention the pioneering works of Housner [4,5], where a simple and effective model with two degrees of freedom was developed to simulate the tank and liquid response using the concentrated mass approach. This model was based on the separation of the liquid in two parts, where the first one follows the movement of the tank while the other moves separately causing sloshing. Similar to this model, Epstein [6] recommended equations for the evaluation of the concentrated mass model and the ability to simulate the tank-liquid system. Malhotra et al [7] developed a simple methodology for the seismic analysis of the steel tanks, avoiding complicated methods such as the finite element method.

Finally, the results from three significant works on the evaluation of seismic behaviour of steel tanks [8-10] should be also mentioned. More specifically, in the two works of Haroun and Housner [8,9], tables for the estimation of the seismic behaviour of the ground supported steel tanks were provided and an improved model with three degrees of freedom to simulate the tank and the liquid response was suggested. This model appears to be an extension of Housner approach [4,5] and has been universally adopted by many structural codes. Furthermore, a comprehensive method that examines the stability of steel tanks under earthquakes was proposed [10] and its results have been adopted by Eurocode 8 [11]. The results from the works of Haroun-Housner [8,9] and Hamdan [10] are employed herein to perform the minimum cost seismic design of thin-wall steel liquid storage tanks.

2. SEISMIC DESIGN OF STEEL TANKS

3.1 Dynamic characteristics of thin-wall steel tanks

The response of thin wall steel tanks under seismic excitation is strongly influenced by the interaction between the flexible steel shell and the liquid within. It should be noted that the seismic response of thin-wall steel flexible tanks presents characteristics significantly different from those of corresponding rigid storage tanks [1-3]. The concentrated masses approach is adopted for the seismic analysis of tank-liquid system [4-7,8,9]. According to this approach, the tank and the liquid can be simulated with a system of concentrated masses, which are placed in a specific height. More specifically, three concentrated masses are used for this simulation approach (*Fig. 2*):

- System-S for the liquid sloshing motion with mass M_S, height H_S, fundamental frequency f_s and viscous damping ratio equal to 0.5%.
- System-F for the tank-liquid system with mass M_F, height H_F, fundamental frequency f_f and viscous damping ratio equal to 2.0%.
- System-G for the ground motion with mass M_G and height H_G.

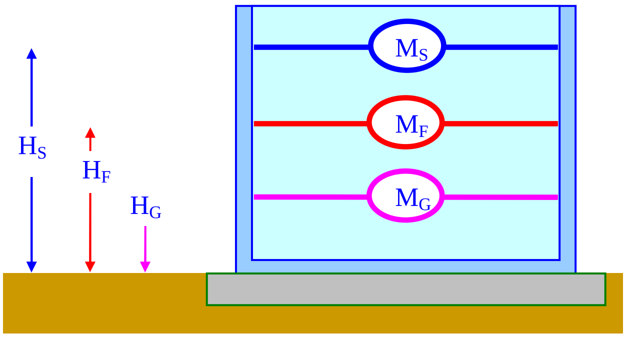


Fig. 2 Seismic analysis concentrated mass model

The total fluid mass, M_L, is given by

$$M_L = V_{fluid}\rho_{fluid} = \pi R^2 H\rho_{fluid} \tag{1}$$

The rest of the parameters of the examined model appear in the following.

System-S

Frequency:

$$f_S = 0.216\sqrt{\frac{g}{R}\tanh\left(\frac{1.84H}{R}\right)} \tag{2}$$

Mass:

$$M_S = 1.429\rho_L R^3 \tanh\left(\frac{1.84H}{R}\right) = 0.455 M_L\left(\frac{R}{H}\right)\tanh\left(\frac{1.84H}{R}\right) \tag{3}$$

Height:

$$H_S = H\left[1-\left(\frac{R}{1.84H}\right)\tanh\left(\frac{0.92H}{R}\right)\right] \tag{4}$$

System-F

Frequency:

$$f_f = c_{f1}\sqrt{\frac{E\cdot s}{\left(1-\nu^2\right)M_L}} \tag{5}$$

where the coefficient c_{f1} is given by

$$c_{f1} = 0.7254\sqrt{\frac{R}{H}} - 0.2275\frac{R}{H} - 0.2023 \tag{6}$$

Mass:

$$M_F = M_L\left[\left(\frac{1000\left(s/R\right)-1}{3}\right)\left(A_2 - A_1\right) + A_1\right] \tag{7}$$

where coefficients $A1$ and $A2$ result from *Fig. 3*.

Height:

$$H_F = H\left[\left(\frac{1000\left(s/R\right)-1}{3}\right)(B_2 - B_1) + B_1\right] \tag{8}$$

where coefficients $B1$ and $B2$ result from *Fig. 3*.

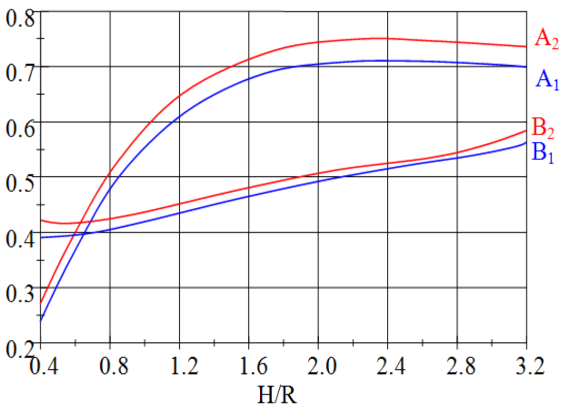


Fig. 3 Parameters A_1, A_2, B_1 and B_2

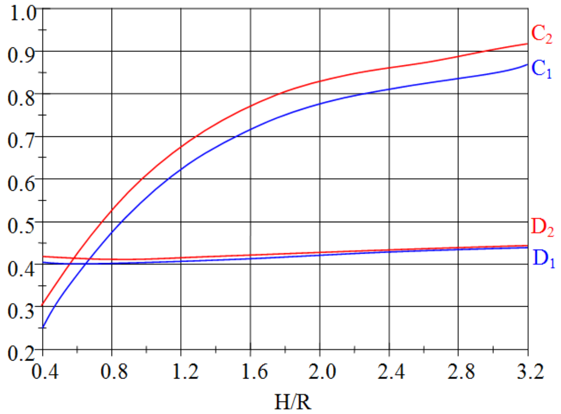


Fig. 4 Parameters C_1, C_2, D_1 and D_2

System-G

Mass:

$$M_G = M_L\left[\left(\frac{1000\left(s/R\right)-1}{3}\right)(C_2 - C_1) + C_1\right] \tag{9}$$

where coefficients $C1$ and $C2$ result from *Fig. 4*.

Height:

$$H_G = H\left[\left(\frac{1000\left(s/R\right)-1}{3}\right)(D_2 - D_1) + D_1\right] \tag{10}$$

where coefficients $D1$ and $D2$ result from *Fig. 4*.

3.2 Seismic excitation and response

The seismic response of the tank-liquid system is determined on the basis of the following steps:

Step 1

Setting the maximum expected (design) ground acceleration, a_g, the spectral accelerations S_{aS} and S_{aF} can be determined from the following equations of Eurocode 8 [11]:

$$\begin{aligned}
&0 \le T \le T_B: && S_e(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 2.5 - 1)\right] \\
&T_B \le T \le T_C: && S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \\
&T_C \le T \le T_D: && S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left[\frac{T_C}{T}\right] \\
&T_D \le T \le 4\text{sec}: && S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left[\frac{T_C \cdot T_D}{T^2}\right]
\end{aligned} \tag{11}$$

where $S_e(T)$ is the spectral acceleration of the horizontal components (S_{aS} or S_{aF}), T the period of an one degree freedom linear system (T_S or T_F), T_B and T_C the limits of the constant spectral acceleration branch, T_D is the value defining the beginning of the constant displacement response range of the EC8 spectrum [11], S is the soil factor and η the damping correction factor with reference value $\eta = 1$ for 5% viscous damping.

Step 2

The maximum fluid sloshing height ζ_{max} is computed from

$$\zeta_{max} = 0.837R\frac{S_{aS}}{g} \tag{12}$$

Furthermore, the maximum horizontal displacement of the tank-liquid system, w_{max}, is given by

$$w_{max} = B_F S_{dF} \tag{13}$$

where S_{dF} is the spectral displacement for the F-system and B_F results from

$$B_F = 2.0400 - 2.6450\left(\frac{H}{R}\right) + 2.8494\left(\frac{H}{R}\right)^2 - 1.3204\left(\frac{H}{R}\right)^3 + 0.2851\left(\frac{H}{R}\right)^4 \tag{14}$$

Step 3

The maximum response (base shear Q_{max} and overturning moment M_{max}) is determined using the SRSS approach

$$Q_{max} = \sqrt{(M_S S_{aS})^2 + (M_F S_{aF})^2 + [(M_G - M_F)A_{G\,max}]^2} \tag{15}$$

and

$$M_{max} = \sqrt{(M_S H_S S_{aS})^2 + (M_F H_F S_{aF})^2 + [(M_G H_G - M_F H_F)A_{G\,max}]^2} \tag{16}$$

Step 4

The maximum axial and hoop stresses are computed, taking also into account the static loads.

Step 5

In order to avoid the undesirable uplift of tank, steel anchors should be installed. In this step, the number of anchors and their maximum seismic forces are evaluated adopting the Wozniak [12] approach.

Step 6

In this step, the foundation dimensions are determined and the maximum expected soil stress is computed.

3.3 Design Criteria

In order to achieve the optimum seismic design of thin-wall steel tanks, the structural integrity against to elastic and elasto-plastic should be satisfied. Thus, the axial stress required to cause buckling in a cylindrical shell structure is assumed to be a function of the internal pressure, the amplitude of imperfections, shell thickness and the circumferential variation of the axial stress. In this work the Hamdan [10] approach is adopted.

3. NUMERICAL EXAMPLE

The optimum seismic design of a steel tank for petroleum storage is examined in the following. The structural and cost data of this example are shown in the *Table 1*.

Parameter	Value
Required storage volume	3000m^3
PGA	a_g=0,3g=2,943 m/sec^2
Soil type	B (acc. to EC8[11])
Allowable stress – soil	σ_{soil}=300kPa
Importance factor	γ_i=1,4 (acc. to EC8[11])
Foundation height	0,6 m
Yield stress – steel	f_y=200MPa
Mat. density – steel / concrete / petroleum	78,5 / 25 / 8 kN/m^3
Quality of the construction coeff.	1,5
Anchor cost (incl. installation)	100€/piece
Concrete cost	220€/m^3
Steel cost (incl. welding, painting, etc)	2.2€/kg
Land cost	70€/m^2

Table 1 : Example data

The optimum seismic design procedure according to the proposed methodology leads to the following results, which appear in *Table 2*.

Parameter	Value
Optimum tank ext. radius	R=12,4m
Optimum shell thickness	s=31,3mm (s/R≈1/400)
Optimum tank height (incl. sloshing height)	h=7,21m
Optimum foundation radius	R_f=12,6m
Maximum sloshing height	ζ_{max}= 1,47m
Maximum horizontal displacement	w_{max} = 0,0031m
Base shear	Q_{max} = 15060kN
Overturning moment	M_{max} = 38115kNm
Maximum hoop stress (ULS)	$\sigma_{\theta\,(ULS)}$ =26,56MPa
Maximum buckling stress (ULS)	$\sigma_{b\,(ULS)}$ =0.76MPa
Maximum hoop stress (ACC)	$\sigma_{\theta\,(ACC)}$ =40,91MPa
Maximum buckling stress (ACC)	$\sigma_{b\,(ACC)}$ =3,09MPa
Maximum soil stress (ULS)	$\sigma_{s\,(ULS)}$ =88,95kPa
Maximum soil stress (ACC)	$\sigma_{s\,(ACC)}$ =165,44kPa
Concrete volume (foundation)	V_f =299,3m^3
Steel weight	W_t =140838kg
Number of anchors	N_a =91
Foundation cost	C_f =65836€
Tank cost	C_t =309652€
Anchors cost	C_a =9100€
Land cost	C_l =39413€
Total cost	C_T =419502€

Table 2 : Results

4. CONCLUSIONS

An optimum seismic design procedure has been proposed to calculate the minimum cost design of thin-wall steel tanks with a simple and fast way. For the total cost optimization, the production, material and land costs are taken into account. The proposed method can be treated as a baseline for determining minimum cost seismic design of thin-wall steel tanks that satisfy the structural and stability requirements.

REFERENCES

[1] MANOS GC and GLOUGH RW, "Tank damage during the May 1983 Coalinga earthquake", *Earthquake Engineering and Structural Dynamics*, Vol. 13, 1985, pp. 449-466.

[2] VELETSOS A.S. and SHIVAKUMAR P., "Tanks containing liquids or solids", in *Computer Analysis and Design of Earthquake Resistant Structures: A Handbook*, Beskos DE and Anagnostopoulos SA (eds), Computational Mechanics Publications, Southampton, 1996.

[3] HATZIGEORGIOU G.D., *Introduction to Earthquake Engineering*, e-book (in Greek), Xanthi, Greece, 2008.

[4] HOUSNER G.W., "Dynamic pressures on accelerated fluid containers", *Bulletin of Seismological Society of America*, Vol. 1, 1957, pp. 15-37.

[5] HOUSNER G.W., "Dynamic behaviour of water tanks", *Bulletin of Seismological Society of America*, Vol. 53, 1963, pp. 381-387.

[6] EPSTEIN H.I., "Seismic design of liquid storage tanks", *Journal of Structural Division, ASCE*, Vol. 102, 1976, pp.1659-1673.

[7] MALHOTRA P.K., WENK T. and WIELAND M., "Simple Procedure for Seismic Analysis of Liquid-Storage Tanks", *Structural Engineering International*, Vol. 3, 2000, pp. 197-201.

[8] HAROUN M.A. and HOUSNER G.W., "Seismic design of liquid storage tanks", *Journal of Technical Councils of ASCE*, Vol. 107, No. TC1, 1981, pp. 191-207.

[9] HAROUN M.A., "Vibration studies and test of liquid storage tanks", *Earthquake Engineering and Structural Dynamics*, Vol. 11, 1983, pp. 179-206.

[10] HAMDAN F.H., "Seismic behaviour of cylindrical steel liquid storage tanks", *Journal of Constructional Steel Research*, Vol. 53, No 3, 2000, pp. 307-333.

[11] EUROCODE 8, *Design provisions for earthquake resistance of structures, Part 1-General rules and Part 4 – Silos, tanks and pipelines*, European Committee for Standardization, Brussels, 2005.

[12] WOZNIAK S.R., "Steel tanks", in *Structural Engineering Handbook*, Gaylord EH, Gaylord CN and Stallmeyer JE (eds), Mc Graw-Hill, 4th ed, 1996.

ΒΕΛΤΙΣΤΟΣ ΣΕΙΣΜΙΚΟΣ ΣΧΕΔΙΑΣΜΟΣ ΜΕΤΑΛΛΙΚΩΝ ΔΕΞΑΜΕΝΩΝ

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1. ΠΕΡΙΛΗΨΗ

Στην εργασία αυτή εξετάζεται ο βέλτιστος σχεδιασμός των μεταλλικών δεξαμενών αποθήκευσης υγρών κάτω από σεισμική καταπόνηση. Οι μεταλλικές δεξαμενές αποτελούν έναν ιδιαίτερο τύπο κατασκευών και η συμπεριφορά τους κατά τη διάρκεια του σεισμού είναι αρκετά σύνθετη. Η διερεύνηση επικεντρώνεται στην περίπτωση των λεπτότοιχων κυλινδρικών δεξαμενών από χάλυβα με άμεση στήριξη στο έδαφος. Πρέπει να σημειωθεί ότι παρά το μεγάλο εύρος εφαρμογών τους, οι λεπτότοιχες μεταλλικές δεξαμενές είναι σημαντικά ευαίσθητες έναντι της σεισμικής καταπόνησης. Στο παρελθόν, πλήθος ερευνητών έχουν εργαστεί για τον προσδιορισμό της σεισμικής απόκρισης των δεξαμενών. Στόχος της εργασίας είναι ο απλός, γρήγορος και πρακτικός βέλτιστος σεισμικός σχεδιασμός των δεξαμενών, αποφεύγοντας πολύπλοκες μεθόδους υπολογισμού όπως πεπερασμένα ή συνοριακά στοιχεία τα οποία οδηγούν σε σημαντικά πολυπλοκότερη εξέταση του φαινομένου της αλληλεπίδρασης υγρού-κατασκευής κάνοντας δυσχερή σε κάθε περίπτωση το βέλτιστο σχεδιασμό.