THE RESPONSE OF CYLINDRICAL LIQUID STORAGE TANKS TO EARTHQUAKES

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SUMMARY

It is not possible to evaluate the performance of tanks during earthquakes on the basis of statistical analysis alone because of incomplete ground motion data. Therefore, mathematical models of tank response need to be developed. The parameters defining the extent of the uplift of the tank base and the associated compression stresses in the tank walls are modified from those specified in the 1979 American Petroleum Institute (API) design code for unanchored tanks to correspond more closely with measurements from recent laboratory tests. The correlation between the seismic resistance predicted from the modified model and the observed incidence of damage to tanks is good.

INTRODUCTION

The discrepancy between the results of experimental studies and the ability of analytical techniques to predict the response of unanchored cylindrical liquid storage tanks to strong ground motion has been a subject of recent intensive research (Ref.'s 1, 2 and 3). Standard 650 of the API design Petroleum Institute (Ref. 4) and Reference 5 describe a relatively simple structural response model of unanchored tanks subjected to ground motion. This model was considered to represent more closely than previous design models the distribution of shell stresses around the base of uplifted tanks. However, since the development of this structural model, additional data on tank response have been collected from the M 5.5 Livermore, California, earthquake on January 24, 1980, and the M 7.4 Miyagi-Ken-oki, Japan, earthquake on June 12, 1978 (Ref. 6) from tanks located at the Tohoku Oil Refinery, located approximately 65 miles from the epicenter.

TANK DAMAGE DATA

An extensive set of damage data was collected to define the seismic response of 132 stainless steel wine tanks, located at Wente Bros. Winery, approximately 8 miles southeast of the epicenter of the Livermore earthquake (Ref. 7). The tanks were full at the time of the earthquake and have been categorized into 25 groups having the same geometric configuration.

The damage factor presented for each group of tanks in Table 1 was calculated as the average amplitude of buckle wave (in.) times

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the percentage of circumferential extent of damage. The damage index is defined (Ref. 7) to correspond to the values 1, 2, 3 and 4, representing minor, medium, major and severe damage, respectively.

Table 2 presents a summary of damage to oil and municipal water storage tanks due to three earthquakes from which detailed data of tank response are available (Ref. 7). In a number of cases where shell thickness of damaged tanks was not reported, the thickness is assumed to be in accordance with API Standard 650.

3. EVALUATION OF THE API APPENDIX E STRUCTURAL MODEL

The model used by API Standard 650 assumes that the primary load effective in producing response is overturning moment due to impulsive and convective components of the mass of the tank contents. The design overturning moment, Mo, may be approximated by the formula (Ref. 7): $Mo = C \times W \times 0.4h$

Tank Group	Dimensions				Aspect Ratio H/D	Anchor Bolts		Damage		
	Diameter, D (ft)	Height, H (ft)	Wall Thickness (in.)	Base Thickness (in.)		Number	Broken	Buckle Amplitude (in.)	Damage Factor	Damage Index
a	7.0	20.0	0.105	0.078	2.86	0	--	0.2	0.05	1
b	10.3	20.0	0.078	0.105	1.94	0	--	1.5	0.5	2
c	12.2	20.0	0.078	0.078	1.64	0	--	2.1	0.95	3
d	13.0	20.0	0.078	0.105	1.54	8	6	1.7	0.6	2
e	16.0	20.0	0.078	0.078	1.25	0	--	3.0	1.3	4
f	21.7	19.0	0.078	0.078	0.88	0	--	2.4	1.6	4
g	5.7	17.0	0.078	0.105	2.98	0	--	0.0	0.0	0
h	7.0	17.5	0.078	0.105	2.50	2	2	0.75	0.1	1
i	8.7	18.0	0.078	0.105	2.07	2	2	1.0	0.2	1
j	9.5	17.5	0.078	0.105	1.84	2	2	1.5	0.35	1+
k	10.25	17.5	0.078	0.105	1.71	2	2	1.6	0.6	2
l	12.2	18.0	0.078	0.105	1.48	2	2	2.0	0.9	3
m	13.0	17.0	0.078	0.105	1.31	2	2	2.2	1.0	3
n	5.7	16.0	0.078	0.105	2.81	2	2	0.0	0.0	0
o	5.7	16.0	0.06	0.078	2.81	0	--	0.2	0.05	1
p	9.0	16.0	0.078	0.105	1.78	0	--	1.0	0.3	1
q	9.0	16.0	0.06	0.078	1.78	0	--	0.3	0.1	1
r	12.0	16.0	0.078	0.105	1.33	0	--	1.5	0.75	2+
s	13.0	16.0	0.105	0.105	1.23	2	2	0.0	0.0	0
t	13.0	16.0	0.078	0.105	1.23	2	2	1.5	0.75	2+
u	13.0	16.0	0.06	0.078	1.23	2	2	1.5	0.75	2+
v	5.7	13.5	0.078	0.078	2.34	2	1	0.0	0.0	0
w	7.0	13.0	0.078	0.078	1.86	0	--	0.0	0.0	0
x	9.5	13.0	0.06	0.06	1.37	0	--	0.6	0.15	1
y	9.5	10.0	0.06	0.06	1.05	2	1	0.0	0.0	0

Inventory number of tank groups: a = 55, 56, 58-64; b = 9-16; c = 263, 264, 267, 276, 309-311; d = 801-804, 811-814, 17-20, 22, 37-41; e = 255, 256, 258, 269, 270, 274, 304, 312; f = 306, 314, 316, 318; g = 602; h = 601, 606; i = 640, 641; j = 621, 624; k = 625, 629, 630, 633, 634, 637, 617; l = 624, 627, 631, 635, 636, 638; m = 616, 619, 620, 623; n = 84, 85, 604; o = 265, 277; p = 521, 527, 528, 609, 613; q = 35, 36; r = 514, 516, 517, 608, 611; s = 65; t = 513, 520, 607, 612, 615; u = 42-50, 262, 279; v = 7, 8, 313, 603; w = 315; x = 26-33; y = 1-6.

Table 1 — Damage to stainless steel tanks at Wente Bros winery from the January 24 Livermore earthquake.

Tank Designation	Tank Dimensions				Contents		Aspect Ratio h/D	Damage Incidence†
	Diameter, D (ft)	Height, H (ft)	Wall Thickness* (in.)	Base Thickness* (in.)	Depth, h (ft)	Specific Gravity		
Alaska								
A13	12	33	0.19	0.25	27	0.8	2.25	--
AX1	12	33	0.19	0.25	29	0.8	2.4	--
A3	12	30	0.19	0.25	30	0.8	2.5	--
A7	20	28	0.19	0.25	28	0.8	1.4	--
AA6	20	40	0.19	0.25	40	0.8	2.0	B
AA5	28	40	0.19	0.25	40	0.8	1.4	C
A21	30	40	0.19	0.25	40	0.8	1.3	B
R200	30	48	0.21	0.25	48	0.8	1.6	C
AC1	40	42.5	0.23	0.25	42.5	0.8	1.1	B
AA7	42.5	40	0.23	0.25	40	0.8	0.94	B
S1	45	32	0.21	0.25	32	0.8	0.71	B
S2	45	34.5	0.21	0.25	34.5	0.8	0.77	B
R140	49	48	0.25	0.25	42	0.8	0.86	B
AC2	55	23	0.25	0.25	23	0.8	0.42	--
R120	70	48	0.41	0.25	39	0.8	0.69	--
XXX	70	48	0.45	0.25	46	0.8	0.66	B
AC3	90	48	0.62	0.25	36	0.8	0.40	--
R162, R163	90	48	0.62	0.25	48	0.8	0.53	--
AC4	100	32	0.46	0.30	32	0.8	0.32	--
R100	112	54	0.60	0.30	31.5	0.8	0.28	--
AC5	120	32	0.55	0.30	32	0.8	0.27	--
R110	144	56	1.2	0.35	39	0.8	0.27	--
AC6	160	56	1.29	0.35	56	0.8	0.35	--
San Fernando								
SF1	52	32	0.25	0.25	30	1.0	0.58	B
SF2	65	40	0.37	0.25	35	1.0	0.54	C
SF3	92	42	0.62	0.30	40	1.0	0.43	--
SF4	100	32	0.46	0.30	30	1.0	0.30	--
SF5	100	36.5	0.69	0.32	30	1.0	0.30	--
Miyagi-Ken-oki								
T132	124	72	0.63	0.25-0.31	53	0.8-0.9	0.43	--
T224	124	72	0.63	0.25††	53	0.9	0.43	C
T221	124	72	0.63	0.25††	60.5	0.8	0.49	C
T131	143	72	0.75	0.28-0.35	69.3	0.8	0.48	C
T217	143	72	0.75	0.28††	62	0.93	0.43	C
T218	143	72	0.75	0.28††	57	0.93	0.40	C
T215	143	72	0.75	0.28-0.35	57	0.8-0.9	0.40	--
T216	143	72	0.75	0.28-0.35	62	0.8-0.9	0.43	--

*Assumed

†B = shell buckled at bottom
C = tank ruptured

††20% reduction due to corrosion assumed

Table 2 — Incidence of damage to oil and water tanks from three earthquakes.

where: C = the effective lateral seismic resistance corresponding to the 2% damped ground motion spectral acceleration at the rocking period of the tank at the design load, W = the weight of the tank shell and its contents, h = the depth of the liquid.

Resistance to overturning for unanchored tanks is assumed to be provided by the weight of the portion of the tank contents that sits on the crescent- shaped section of the tank base which lifts off the foundation. The weight of liquid acting on this uplifted region is carried in the wall around the circumference to its arc of contact with the foundation, where it is resisted with compressive stress.

The maximum allowable longitudinal compression stress (Fa) and radial extent of the uplifted crescent-shaped section of the tank (L) define the resisting moment M of the tank according to the API model, the characteristics of which are summarized in Figure E-5 of API Standard 650. (The assumed relationship between uplift length L and contact arc B is defined in reference 5); M = f(Fa,L).

The correlation between the seismic resistance of the tanks predicted from this API model and the observed incidence of damage has been shown to be poor (Ref. 7). Therefore, the results of recent laboratory test measurements of tank response were studied to explore methods of improving the performance of the API model.

4. COMPARISON OF THE API MODEL WITH RECENT LABORATORY TEST MEASUREMENTS

The measured response of three tanks subjected to a range of simulated earthquake excitations on the shaking table at the University of California, Berkeley, has been published recently (Ref.'s 1, 2, 3, and 8). Tanks 1 and 2 were small-scale models resembling tall and broad oil storage tanks, respectively (Ref.'s 3 and 1). Tank 3 (Ref. 8) was a replica of a typical tall tank damaged at the Wente Bros. Winery during the Livermore earthquake. Critical tank response parameters, measured from a sample of the applied excitations, are listed in Table 3.

The agreement between the lateral seismic resistance calculated from the API model (based on the measured extent of uplift) and the applied lateral force coefficient is good. However, the experimental data suggest that the maximum uplift allowed along the diameter of the base plate of these tanks by API Standard 650, equal to 6.8% of the tank radius, is unrealistically low compared with the maximum allowable longitudinal compressive stress:

First, the length of uplift L measured along a radius of the bottom plate of tank 1 at the applied lateral force coefficient of 0.105g (less than half the API code design value) was 15% of the tank radius, which is more than twice the maximum allowed by the code. Also, the length of uplift L of the bottom plate of tank 3, when subjected to an applied lateral force coefficient sufficient to result in tank shell buckling (0.45g-0.55g), was more than 20% of the tank radius (Ref. 8). This is four times larger than the code limit for uplift at a working stress level of loading, specified as the minimum of 6.8% of the tank radius or;

$$L = 0.22t\sqrt{Fy/G\ h} \qquad \text{(Ref. 5)}$$

where:

t, Fy = thickness and yield strength of base plate respectively

G, h = specific gravity and depth of contents (ft.) respectively

Second, the maximum longitudinal stress measured at the buckling response of tank 3 was measured to be 14,800 psi (Ref. 8). This is two and one-half times the code-allowable maximum longitudinal compressive stress, whereas the uplift was at least four times that allowed by the code. A similar inconsistency is apparent from the results of tank 1. This inconsistency could explain the lack of correlation between the lateral seismic resistance predicted from the API method and the observed incidence of damage to tanks reported in Ref. 7. Therefore, the effect of modifying the API model to include a more realistic assumption of the maximum longitudinal compression stress in the tank wall in relationship to the associated uplift of the tank base is explored.

5. MODIFICATION OF THE API MODEL

The longitudinal compressive buckling stress Fb is estimated to be 2.0Fa minus 0.18 times the hydrostatic hoop tension stress, where Fa is the maximum allowable longitudinal compression stress defined in Appendix E of API Standard 650. The coefficient 2.0 was selected as a load factor consistent with the limited experimental results available, including the buckling stress of tank 3 (Ref. 8). The justification for the subtraction for a factor of the hydrostatic hoop tension stress is derived from limited experimental data measuring longitudinal stresses from hydrostatic and vertical acceleration loading of tanks and is discussed in Ref. 7.

The associated maximum uplift of the tank base at threshold damage levels of tank excitation is estimated, on the basis of limited experimental data, to be three times the value computed from a simple small deflection theory model as appropriate for an allowable, working stress level of excitation (Ref. 5), i.,e., the maximum uplift Lb is defined as:

$$Lb = 0.65t\sqrt{Fy/Gh}$$

and the resisting moment M= f(Fb,Lb)

6. CORRELATION OF THE MODIFIED API MODEL WITH TANK DAMAGE INCIDENCE

Figures 1 and 2 show the lateral seismic resistance predicted from the modified API model versus tank diameter for the wine tanks and the oil tanks respectively, along with the observed incidence of damage. The correlation between the predicted seismic resistance and the observed incidence of damage is good, and significantly improved from that obtained from the previous model reported in reference 7.

7. CONCLUSIONS

On the basis of the good correlation between the seismic resistance predicted from the modified API model and the observed incidence of damage to tanks it is concluded that unanchored tanks with an aspect ratio of h/D between 0.6 and 1.4 are more prone to damage than are broader or more slender tanks with the same depth of contents.

The data shown in figure 2 indicates that the large diameter tanks located at the Tohoku Oil Refinery have a lateral seismic resistance at damage threshold of approximately 0.3g which is consistent with ground motion records reported in Reference 7.

a. Dimensions

Tank Designation	Diameter, D (ft)	Height, H (ft)	Wall Thickness (in.)	Base Thickness (in.)	Height of Contents, h (ft)
1 (Niwa, 1978 and 1979)	7.75	15.0	0.09	0.09	13.0
2 (Clough, 1978)	12.0	6.0	0.08	0.08	5.0
3 (Niwa and Clough, 1981)	9.55	20.0	0.078	0.078	20.0

b. Laboratory Test Measurements

Tank Designation	Applied Excitation	Peak Horizontal Ground Acceleration (%g)	Maximum Axial Compression Stress (psi)	Contact Arc, β	Length of Baseplate Uplift, L (in.)	Period of Maximum Rocking Response (sec)	Applied Lateral Force Coefficient (%g)	Computed Lateral Seismic Resistance (%g)
1 (Niwa, 1978 and 1979)	6° static tilt		2,279	56°	7.1		0.105	0.116
	Time History, 1940 El Centro Earthquake	0.125	2,359	—	—	0.5-0.8	0.125-0.25*	—
2 (Clough, 1978)	Time History, 1940 El Centro Earthquake	0.5	2,380	—	—	0.15-0.35	1.0-1.7*	—
3 (Niwa, and Clough, 1981)	Time History, January 24 Livermore Earthquake	0.64 (0.37 vertical)	14,800	90°	>12	1.0	C.45-0.55*	0.47

*Lateral force coefficient assumed to be 2% critically damped spectral acceleration over the range of the period of maximum rocking response.

Table 3 — Comparison of API model with laboratory test measurements.

It is evident that the modified parameters defining the maximum longitudinal compressive strength in tank walls and the associated extent of uplift of the tank base are more accurate than the current design code specifications. However, furthur experimental work is required to establish these parameters.

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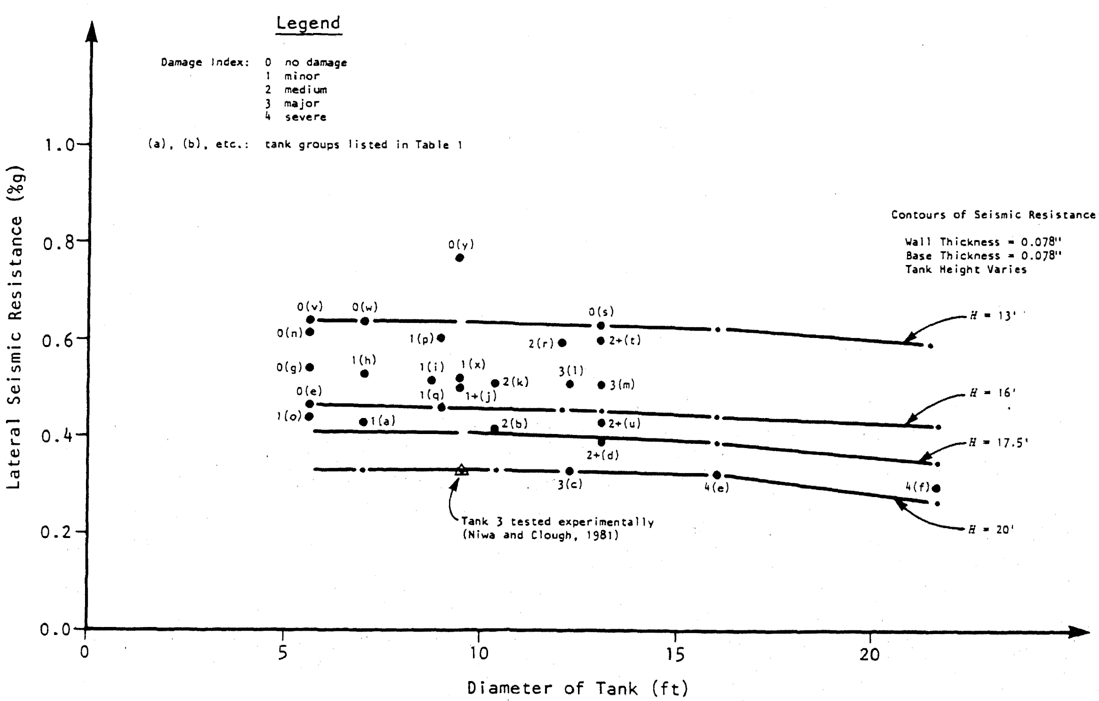

Fig. 1 — Damage index for tank shells at Wente Bros winery versus seismic resistance, modified API model.

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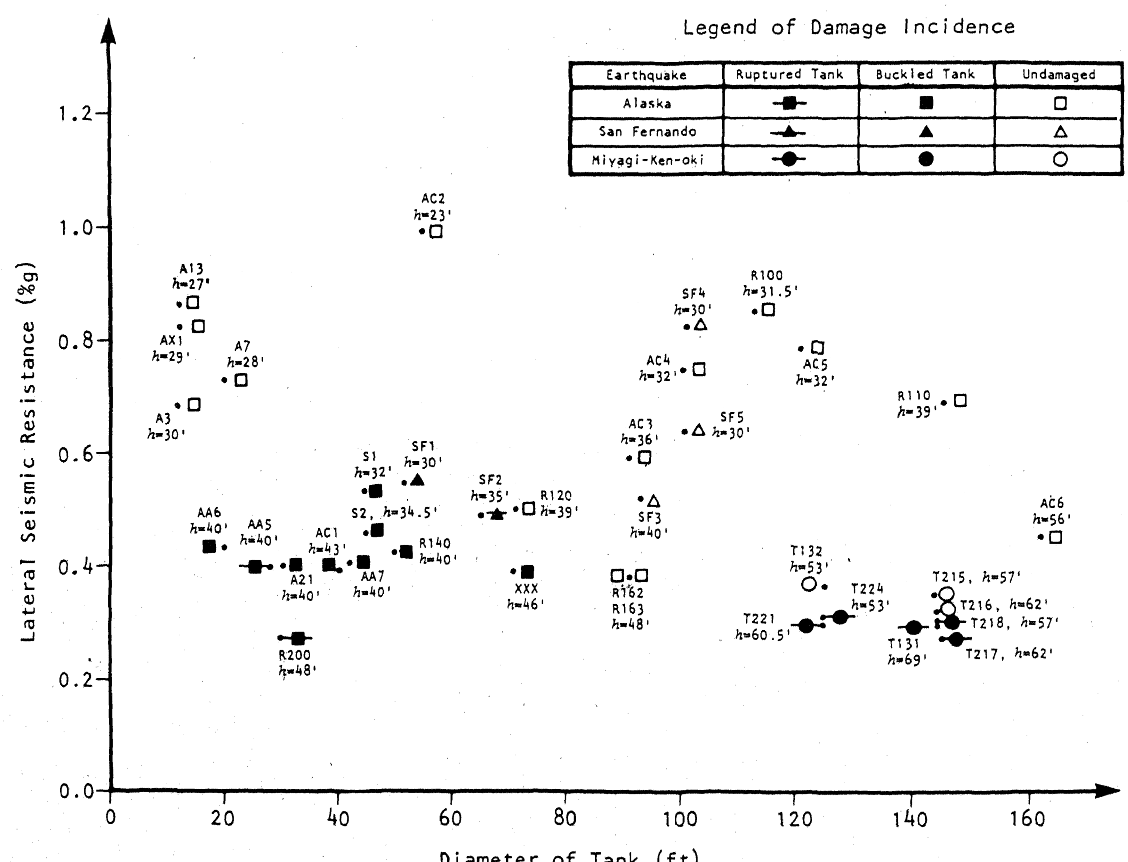

Fig. 2 — Incidence of damage to shells of oil and water tanks versus seismic resistance, modified API model.