Suggestion of Maximum Storage Capacity of Flat-Bottom Tank under Sloshing

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1. Introduction

Flat-bottom tanks are widely used in Nuclear Power Plants (NPPs). Especially it is used for Condensate Storage Tanks (CST), Aux. Feed Water Storage Tanks (AFWST) and Refueling Water Storage Tanks (RWST) which are designed by Seismic Category I in the existing NPPs and their failure results in one of the most significant contributors in Seismic Probabilistic Safety Assessment (Seismic PSA) or Seismic Margin Assessment (SMA).

Nowadays, strengthened seismic performance is required for flat-bottom tank. Specially, sloshing height could be an importance topic when we analyze the seismic capacity of Tank with enhanced seismic requirement. Excessive sloshing could crash to tank roof and junction of tank roof and wall (refer to Figure 1). Due to this crashing, sloshing could have structural harmful effect on tank roof and junction of tank roof and wall. To overcome this, engineers in the field of nuclear power plant (NPP) have thought that maximum sloshing height shall be under the free board height (H_{free}) conventionally. It could be a somewhat conservative approach when we compare it with the approaching a widely practicing in general industry.

However, this conservative approach could be permitted because NPP is a one of the most important facility and to be most carefully treated in one country. If the sloshing is expected to occur over the free board, stress checks on junction of tank roof and tank wall shall be needed as an alternatives. However, there are lack of detail methodologies for an alternative stress check in general references like EPRI NP-6041-SL, Generic Implementation Procedure and API-650. So, this kind of stress check used to be performed depending on the high skilled engineer's experience.

$$H_{free} = H_t - H_w$$

Where, H_{free} : Free board height
H_t : Tank height
H_w : Fluid height

This study mainly focuses on generalizing and suggesting the allowable storage capacity of tank without alternative stress check for the easy of intermediate engineers. In this study, sloshing heights are calculated with some design variables and compared each other. Allowable storage capacity (Q_{a1}) to avoid exceeding sloshing heights is suggested from the comparison results. The other allowable storage capacity (Q_{a2}) is suggested to ensure minimum HCLPF (High Confidence of Low Probability of Failure) capacity 0.3g. Sloshing height is calculated according to the reference [1] because EPRI NP-6041-SL give more conservative HCLPF capacity than Generic Implementation Procedure and API-650. (refer to [2]).

2. Methods and Results

EPRI NP-6041-SL App. H describes a detailed methodology of sloshing height calculation. Reference spectrum are calculated based on NUREG/CR-0098 (Damping 0.5%, Rock, PGA) (refer to [1]). Tank radius (R), height (H_t) and PGA are the variables in study as shown in Table 1. Totally, 36 cases are calculated according to the variable change. The calculation procedure are shown as from (1) to (6) and an example (CASE 14 in Table 4) is also shown as followings;

Table 1. Variables

Variable	Tank Size		PGA (g)
	R (ft)	H_t (ft)	
Values	20, 25, 30	30, 45, 60	0.2, 0.25, 0.3, 0.35

(1) Input tank size

- Tank radius : R (ft)
- Tank height : H_t (ft)
- Fluid storage amount: W (%)
- Example : R = 20ft, H_t = 45ft, W = 96%

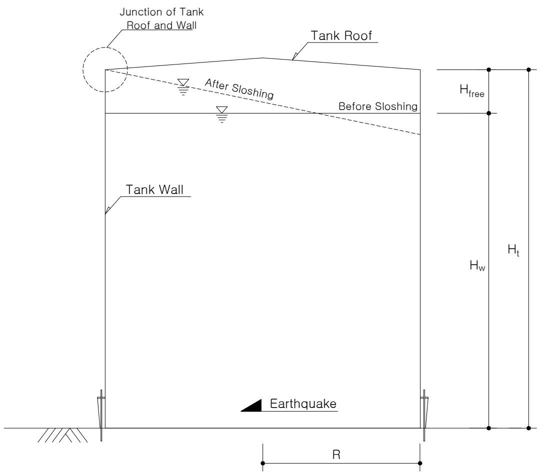

Figure 1. Example Tank

(2) Sloshing mode frequency (Fc)

$$Fc = \sqrt{\frac{1.50 ft/sec^2}{R} \tanh[1.835(H/R)]}$$

- Example : 0.274 Hz (R=20ft, H_t = 45ft)

(3) Sloshing mode spectral acceleration (Sac)

- Finding from reference spectrum
- Example : refer to Table 1 and Table 4 (CASE 13 ~ 16)

Table 2. Sloshing mode spectral acceleration (R : 20ft, H_t : 45ft)

PGA (g)	0.2	0.25	0.3	0.35
Sloshing Mode Frequency (Hz)	0.274			
Sac (g)	0.094	0.117	0.141	0.164

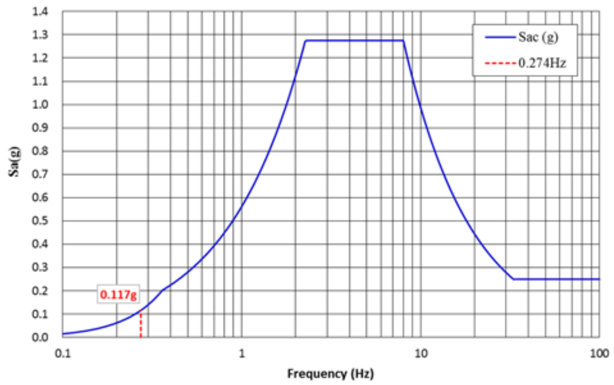

Figure 2. Example of reference spectrums (PGA=0.25g)

(4) Sloshing height

$$H_{sloshing} = 0.837R(\frac{Sac}{g})$$

- Example : 1.96ft (R=20ft, PGA = 0.25g)

(5) Free board height after sloshing
(refer to CASE 14 in Table 4)

$$H_{free\_after} = H_{free} - H_{sloshing}$$

- Example 1 : -0.16ft (NG)
- H_{free} = 1.80ft (R=20ft, H=45ft, W=96%)
- $H_{sloshing}$ = 1.96ft

- Example 2 : 1.19ft (OK)
- H_{free} = 3.15ft (R=20ft, H=45ft, W=93%)
- $H_{sloshing}$ = 1.96ft

(6) HCLPF (refer to CASE 14 in Table 4)

$$HCLPF = \frac{H_{free}}{H_{sloshing}} \times PGA$$

- For Example 1 in (5) : 0.23g

$$0.23g = \frac{1.8ft}{1.96ft} \times 0.25g$$

- Example 2 in (5) : 0.40g

$$0.40g = \frac{3.15ft}{1.96ft} \times 0.25g$$

The calculation is repeated according to the variable change and the results are summarized as shown Table 3, 4 and 5. Table 3 shows sloshing and HCLPF with 30ft tank height. Table 4 is for 45ft height tank and Table 5 is for 60ft height tank. In Tables, sloshing mode frequency of tank, spectrum acceleration, sloshing height, and HCLPF are shown.

Table 3. Sloshing and HCLPF calculation result (H : 30ft)

Radius (R)	Height (H)	Sloshing Mode Frequency of Tank (Hz)	Sloshing mode spectrum acceleration (g), Sac		Sloshing Height $H_{sloshing}$ (ft)	Free Board Height after Sloshing H_{free_after} (H_{free}-$H_{sloshing}$)			HCLPF			Remark
R(ft)	H(ft)	Refer : NP-6041	PGA (g)	Sac (g)	Refer : NP-6041	97.0%	94.0%	90.0%	97.0%	94.0%	90.0%	
20	30	0.273	0.20	0.093	1.56	-0.66	0.24	1.44	0.12	0.23	0.39	CASE 1
			0.25	0.116	1.94	-1.04	-0.14	1.06	0.12	0.23	0.39	CASE 2
			0.30	0.14	2.34	-1.44	-0.54	0.66	0.12	0.23	0.38	CASE 3
			0.35	0.163	2.73	-1.83	-0.93	0.27	0.12	0.23	0.38	CASE 4
25	30	0.242	0.20	0.073	1.53	-0.63	0.27	1.47	0.12	0.24	0.39	CASE 5
			0.25	0.092	1.93	-1.03	-0.13	1.07	0.12	0.23	0.39	CASE 6
			0.30	0.11	2.30	-1.40	-0.50	0.70	0.12	0.23	0.39	CASE 7
			0.35	0.128	2.68	-1.78	-0.88	0.32	0.12	0.24	0.39	CASE 8
30	30	0.218	0.20	0.059	1.48	-0.58	0.32	1.52	0.12	0.24	0.40	CASE 9
			0.25	0.074	1.86	-0.96	-0.06	1.14	0.12	0.24	0.40	CASE 10
			0.30	0.089	2.23	-1.33	-0.43	0.77	0.12	0.24	0.40	CASE 11
			0.35	0.104	2.61	-1.71	-0.81	0.39	0.12	0.24	0.40	CASE 12

Table 4. Sloshing and HCLPF calculation result (H : 45ft)

Radius (R)	Height (H)	Sloshing Mode Frequency of Tank (Hz)	Sloshing mode spectrum acceleration (g), Sac		Sloshing Height $H_{sloshing}$ (ft)	Free Board Height after Sloshing H_{free_after} (H_{free}-$H_{sloshing}$)			HCLPF			Remark
R(ft)	H(ft)	Refer : NP-6041	PGA (g)	Sac, 84% (g)	Refer : NP-6041	98.0%	96.0%	93.0%	98.0%	96.0%	93.0%	
20	45	0.274	0.20	0.094	1.57	-0.67	0.23	1.58	0.11	0.23	0.40	CASE 13
			0.25	0.117	1.96	-1.06	-0.16	1.19	0.11	0.23	0.40	CASE 14
			0.30	0.141	2.36	-1.46	-0.56	0.79	0.11	0.23	0.40	CASE 15
			0.35	0.164	2.75	-1.85	-0.95	0.40	0.11	0.23	0.40	CASE 16
25	45	0.245	0.20	0.075	1.57	-0.67	0.23	1.58	0.11	0.23	0.40	CASE 17
			0.25	0.094	1.97	-1.07	-0.17	1.18	0.11	0.23	0.40	CASE 18
			0.30	0.112	2.34	-1.44	-0.54	0.81	0.12	0.23	0.40	CASE 19
			0.35	0.131	2.74	-1.84	-0.94	0.41	0.11	0.23	0.40	CASE 20
30	45	0.223	0.20	0.062	1.56	-0.66	0.24	1.59	0.12	0.23	0.40	CASE 21
			0.25	0.078	1.96	-1.06	-0.16	1.19	0.11	0.23	0.40	CASE 22
			0.30	0.093	2.34	-1.44	-0.54	0.81	0.12	0.23	0.40	CASE 23
			0.35	0.109	2.74	-1.84	-0.94	0.41	0.12	0.23	0.40	CASE 24

Table 5. Sloshing and HCLPF calculation result (H : 60ft)

Radius (R)	Height (H)	Sloshing Mode Frequency of Tank (Hz)	Sloshing mode spectrum acceleration (g), Sac		Sloshing Height $H_{sloshing}$ (ft)	Free Board Height after Sloshing H_{free_after} (H_{free}-$H_{sloshing}$)			HCLPF			Remark
R(ft)	H(ft)	Refer : NP-6041	PGA (g)	Sac, 84% (g)	Refer : NP-6041	98.0%	96.0%	93.0%	98.0%	96.0%	93.0%	
20	60	0.274	0.20	0.094	1.57	-0.37	0.83	2.63	0.15	0.31	0.53	CASE 25
			0.25	0.117	1.96	-0.76	0.44	2.24	0.15	0.31	0.54	CASE 26
			0.30	0.141	2.36	-1.16	0.04	1.84	0.15	0.31	0.53	CASE 27
			0.35	0.164	2.75	-1.55	-0.35	1.45	0.15	0.31	0.54	CASE 28
25	60	0.245	0.20	0.075	1.57	-0.37	0.83	2.63	0.15	0.31	0.54	CASE 29
			0.25	0.094	1.97	-0.77	0.43	2.23	0.15	0.31	0.53	CASE 30
			0.30	0.112	2.34	-1.14	0.06	1.86	0.15	0.31	0.54	CASE 31
			0.35	0.131	2.74	-1.54	-0.34	1.46	0.15	0.31	0.54	CASE 32
30	60	0.223	0.20	0.062	1.56	-0.36	0.84	2.64	0.15	0.31	0.54	CASE 33
			0.25	0.078	1.96	-0.76	0.44	2.24	0.15	0.31	0.54	CASE 34
			0.30	0.093	2.34	-1.14	0.06	1.86	0.15	0.31	0.54	CASE 35
			0.35	0.109	2.74	-1.54	-0.34	1.46	0.15	0.31	0.54	CASE 36

For the convenient, spectrum acceleration and sloshing heights in Table 3 ~ 5 are re-summarized and shown at from Table 6 to 9. The results in Table 3~8 are analyzed and the allowable storage capacities (Q_{a1} and Q_{a2}) are estimated using the trial and error method. The estimation results are shown in Table 9.

Sloshing mode frequency of tank are similar each other regardless of tank size changes (radius and height) as shown in Table 6. Spectrum acceleration is decreased according to tank radius increasing at one tank height as shown in Table 7. Sloshing heights are calculated similar at same PGA regardless of tank size changes as shown in Table 8. Sloshing heights are also calculated similar at same PGA.

Table 6. Sloshing Mode Frequency of Tank (Hz)

H(ft) \ R(ft)	20	25	30
30	0.273	0.242	0.218
45	0.274	0.245	0.223
60	0.274	0.245	0.223

Table 7. Spectrum Acceleration (g) (PGA = 0.25g)

H(ft) \ R(ft)	20	25	30
30	0.116	0.092	0.074
45	0.117	0.094	0.078
60	0.117	0.094	0.078

Table 8. Sloshing Height (ft) (PGA = 0.25g)

H(ft) \ R(ft)	20	25	30
30	1.94	1.93	1.86
45	1.96	1.97	1.96
60	1.96	1.97	1.96

1) R : 20ft, H : 60ft

$$1.96\text{ft} = 0.837 \times 20(\text{ft}) \times \left(\frac{0.117\text{g}}{\text{g}}\right)$$

2) R : 30ft, H : 60ft

$$1.96\text{ft} = 0.837 \times 30(\text{ft}) \times \left(\frac{0.078\text{g}}{\text{g}}\right)$$

Table 9. Allowable Storage Capacities (Q_{a1} and Q_{a2})

Height (ft)		30	45	60
Maximum Storage Capacity (%)	Q_{a1}	93.0	95.2	96.4
	Q_{a2}	92.4	94.8	96.1
	Average	92.7	95	96.2

3. Conclusions

In this study, sloshing heights and HCLPF are calculated and analyzed under various conditions (Tank size, PGA, Fluid amount) to avoid sloshing effect. From the calculation and analysis results, we can get the following results.

(1) Sloshing mode spectral acceleration (Sac) is decreased according to the tank radius (R) is getting larger and has nothing to do with tank height otherwise.

(2) Sloshing heights are calculated similar regardless of tank size changes at same PGA.

(3) 92.7% is suggested as a maximum storage capacity for the 30ft height tank. Similarly, 95.0% is for the 45ft height tank and 96.2% for the 60ft height tank.

REFERENCES

[1] Electric Power Research Institute, NP-6041-SL, Rev.01, A Methodology for Assessment of Nuclear Power Plant Seismic Margin (Revision 1), Palo Alto, CA, August 1991.

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