Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division VI

Comparative Seismic Evaluation of Circular Liquid Storage Tank According to Practical Design Guidelines and Standards

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ABSTRACT

During an earthquake, the damage to water storage tank in a nuclear power plant may result in an inability to supply cooling water which in turn can lead to a severe accident. Therefore, it is important to understand its seismic behaviour and develop design guidelines that are safe and consistent. Various design standards provide guidelines for seismic analysis and assessment of liquid storage tanks. This study focuses on comparing the seismic safety evaluation methods for vertical cylindrical tanks, as prescribed in different design standards and evaluate the consistency among different methods. It is noted that the different design standards leads to highly varying outcome on the seismic assessment of such tanks and the various guidelines have a high degree of inconsistency. This manuscript provides the details on this comparative study and identifies key differences. More specifically, methods prescribed in GIP and NP-6041, which are focused on nuclear facilities, are compared with that in API650 which focuses on general industrial facilities. The guidelines in these three standards are compared considering the effect of maximum height of liquid as well as the tank diameters for such tanks.

1. INTRODUCTION

The 2008 Sichuan earthquake cut off the power supply to a nearby nuclear facility, which resulted in the rupture of a coolant tank. In 2011, an earthquake off the Pacific coast of Tohoku led to radioactive leakage from a waste water tank at the Fukushima Daiichi nuclear power plant (NPP). If the tanks of NPP are damaged or destroyed due to earthquakes, it may result in a lack of ability to supply cooling water which in turn could lead to an accident resulting in the leakage of radioactivity.

Following the release of USI A-46 by NRC in 1980, NPPs have been subject to regular, continuous seismic safety evaluations. SQUG's GIP and EPRI's NP-6041 have been implemented to evaluate the seismic safety of NPPs. GIP is a method to perform seismic safety evaluation of NPP equipment based on experience and experiment, and NP-6041 is a method to estimate the seismic margin of NPPs. GIP and NP-6041 include seismic performance evaluation procedure by applying the ground response spectrum of ASCE 4. In the case of GIP, seismic performance is evaluated based on empirical factors. NP-6041 does the same by applying equations that consider various factors such as the gravity load and the number and location of anchor bolts.

Seismic design methods used for general liquid storage tanks include API650, Eurocode8, NZSEE, and JEAC3605. Developed by the American Petroleum Institute (API), the most widely used design standard, API650, establishes requirements for welded, flat-bottom liquid storage tanks. The API650 recommendations use allowable stress design method and evaluates the seismic performance of the liquid storage tank after calculating the eigenvalue of the tank and determining the spectral acceleration for the site conditions. In the "Guidance for California Accidental Release Prevention (CalARP) Program Seismic Assessments," the CalARP guidance recommends API650 as a seismic performance evaluation method for

liquid storage tanks supported on the ground. This guidance categorizes the type of tank damage based on the observations from past earthquakes and provides recommendations for seismic evaluation of tanks. This guidance also recommends that API650 be applied to perform the linear static analysis of tanks. When performing a linear static analysis of a tank according to API650, a reduction factor (Q) is considered to account for ductility. The reduction factor of a steel circular tank is 3 or 4 depending on the anchorages.

For the same liquid storage tanks, varying results can be obtained by utilizing different guidelines and standards. This disparity in the results can be confusing to the design engineers, during the selection of the evaluation methods. Therefore, various seismic safety evaluation methods for liquid storage tanks should be examined and compared to assure the conservatism of design. Many analytical verifications have been conducted on seismic performance evaluation using API650 that is considered as a representative method for large steel tanks for storing liquids (Alejandro et. al., (2003), Kazem & Mehrpouya, (2012), Naghdali et. al., (2013), Chikhi & Djermane, (2017)). This study reviews and compares the evaluation equations from GIP, NP-6041, and API650 for vertical cylindrical tanks. Also, numerical evaluations of a sample tank are performed considering the ratio of the height (H) of the liquid to the tank diameter(D) as parameters.

2. Seismic Evaluation Methods by Three Guidelines

2.1 Evaluation Procedure

Fig. 1 summarizes the seismic evaluation procedure of the liquid storage tank recommended by guidelines from GIP, NP-6041, and API650. The flow of the seismic evaluation is almost identical for each of the various guidelines as the steps in each consists of an eigenvalue analysis, calculation of demand, stress review, stability check, evaluation of overturning moment, base shear, and finally the sloshing height. Some guidelines require additional investigation of buckling and hoop stresses.

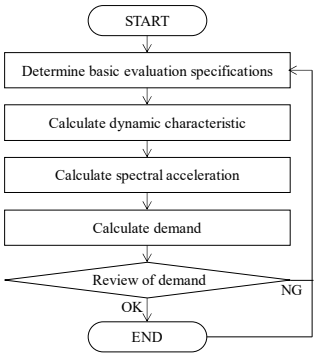


Figure 1. Seismic evaluation steps according to guidelines

2.2 Dynamic Modal Frequencies

When a seismic force is applied to a liquid storage tank, the vibration of liquid is represented by using two modes. The first mode occurs due to the movement of the liquid with the tank. This is an impulsive mode that moves horizontally due to the inertia of the liquid mass. The second mode is a convective mode that occurs due to liquid particles near a vertically oscillating liquid surface. In general, the impulsive mode is a short period vibration, and the convective mode is a long period vibration. The impulsive mode and the convective mode are simplified to a spring-mass model as shown in Fig. 2 to calculate the modal frequencies and the hydrodynamic pressure, where m is the mass, H is the height of the action point, I in the subscript denotes impulsive mode, and C indicates convective mode.

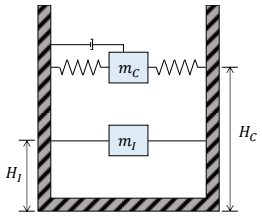


Figure 2. Spring-mass model

Table 1 compares the calculation equations as defined in three guidelines. First, the frequency of the impulsive mode is affected by the factor for H/D, the elastic modulus of the tank material, and the density of the storage liquid. Also, each method is multiplied by a specific value. Convective mode was the

same for each method.

Table 1. Frequency Comparison

Standard	Calculation Equation	
	Impulsive Mode (f_I)	Convective Mode (f_C)
GIP	Fig. 4	$\frac{1}{2\pi}\sqrt{\frac{1.84g}{R}\tanh\left(1.84(H/R)\right)} = \sqrt{\frac{0.914m/sec^2}{D}\tanh\left(3.68(H/D)\right)}$
NP-6041	$\frac{C_{LI}}{2\pi H}\sqrt{\frac{E_S}{\rho_S}}$	$\sqrt{\frac{1.5ft/sec^2}{R}\tanh\left(1.835(H/R)\right)} = \sqrt{\frac{0.914m/sec^2}{D}\tanh\left(3.67(H/D)\right)}$
API650	$\frac{\sqrt{2000}}{C_i H}\sqrt{\frac{t}{D}}\sqrt{\frac{E_S}{\rho_L}}$	$\frac{\sqrt{\tanh\left(3.67(H/D)\right)}}{0.578\times 1.8\sqrt{D}} = \sqrt{\frac{0.924m/sec^2}{D}\tanh\left(3.67(H/D)\right)}$

C_{LI}: Horizontal impulsive mode factor C_i: Impulsive mode factor

2.3 Response Spectrum

Spectral acceleration indicates the seismic load on the structure in seismic evaluation and is input in the form of acceleration (g). For GIP and NP-6041 as shown in Table 2, the horizontal design response spectrum is created using Regulatory Guide 1.60 (RG 1.60), and the values at the frequencies for the design response spectrum are used. In the case of API650, the horizontal design response spectrum is applied using ASCE 7, and the value at this frequency is multiplied by a correction factor. For the impulsive mode, the response spectrum of 4% damping ratio for GIP and 5% damping ratio for NP-6041 and API 650 are used. Convective mode uses a response spectrum of 0.5% damping ratio for all three criteria. In this case, the amplification factor of the response spectrum according to the damping ratio is determined according to NUREG / CR-0098 for GIP and NP-6041; the value is 1.5 for the response spectrum for the 0.5% damping ratio for API650.

Table 2. Comparison of spectral acceleration of impulsive mode and convective mode

Standard	Calculation Equation	
	Impulsive Mode (A_I)	Convective Mode (A_C)
GIP	The value at f_I in RS of 4% damping	The value at f_C in RS of 0.5% damping
NP-6041	The value at f_I in RS of 5% damping	The value at f_C in RS of 0.5% damping
API650	The value at f_I in RS of 5% damping $\times \frac{I}{R_{wi}}$	The value at f_C in RS of 0.5% damping $\times \frac{I}{R_{wc}}$

R_{wi}: Force reduction factor for the impulsive mode using ASD
R_{wc}: Force reduction factor for the convective mode using ASD
I: Importance factor

Table 3. Response spectral amplification factor with damping ratio

Source	NUREG/CR-0098			API650
Damping Ratio (%)	5	4	0.5	0.5
Response Spectral Amplification Factor	1.0	1.07	1.74	1.5

2.4 Seismic Response Calculation

1) Sloshing height

To prevent damage to the roof of the liquid storage tank, the height of the shell of the tank is designed to be higher than the height of the storage liquid. The area from the top of the storage liquid to the tank shell

top is called the freeboard; this freeboard should be higher than the sloshing height. The equation for the sloshing height is expressed as the product of the diameter of the tank and the spectral acceleration of the convective mode. In Table 4, the calculation equations were very similar except for R_{wc} in API 650.

Table 4. Comparison of calculation equation for sloshing height

Standard	Calculation Equation (h_S)
GIP	$0.837RA_C = 0.4185DA_C = 0.4185D\frac{S_{D1}}{T_C}$
NP-6041	$0.837RA_C = 0.4185DA_C = 0.4185D\frac{S_{D1}}{T_C}$
API650	$0.42DA_F = 0.42D\frac{K\,S_{D1}\,I}{T_C}$

2) Base Shear

The base shear is considered to be safe if the frictional load acting on the tank bottom is greater than the shear force exerted by the seismic load. The frictional load acting on the tank bottom plate is called the capacity; shear force due to earthquake is demand. Capacity/demand is indicated as C/D, and when C/D> 1, the seismic performance satisfies the evaluation criteria. Table 5 compares the capacity and demand for base shear. To compare demand, NP-6041 and API650 equations are combined with SRSS method for base shear in impulsive and convective modes. In the case of GIP, this value is calculated by multiplying the base shear factor by H/R, t/R, total weight of storage liquid, and spectral acceleration of impulsive mode.

In case of the capacity, it is calculated by multiplying the weight while considering the effect in the vertical direction of the friction factor. As shown in Table 5, the friction factor was largest in NP-6041; the value from API650 is the smallest, at about half the value from NP-6041. In Table 5, the allowable force for the base shear is added to the anchor bolt's resistance and hydrostatic pressure resistance for NP-6041. As a result, NP-6041 is the most conservative among the seismic evaluation methods for NPPs.

Table 5. Comparison of calculation equation for base shear

Standard	Calculation Equation		Friction Factor (μ)
	Demand (V_D)	Capacity (V_C)	
GIP	$Q'W_WA_I$	$\mu(1-0.21A_I)W_W$	0.55
NP-6041	$\sqrt{\left(A_I(W_H+W_S+W_I)\right)^2+(A_CW_C)^2}$	$\mu\left[\left((W_H+W_S)(1-0.4A_V)+(P_{ST}-0.4P_V)\pi R^2\right)+\sum T_a\right]$	0.7 or more
API650	$\sqrt{\left(A_I(W_H+W_S+W_I)\right)^2+(A_CW_C)^2}$	$\mu(W_H+W_S+W_B+W_W)(1-0.4A_V)$	0.4 or less

W_W: Weight of storage liquid
W_I: Effective weight by impulsive mode of storage liquid
W_C: Effective weight by convective mode of storage liquid
W_H: Weight of tank roof
W_S: Weight of tank shell
W_B: Weight of tank bottom
μ: Friction factor between tank bottom plate and base
Q': Bottom Shear Force Factor
P_{ST}: Hydrostatic pressure
P_V: Vertical hydrostatic pressure
A_V: Vertical spectral acceleration

3) Review of overturning moment

The demand and capacity of the overturning moment are compared in Table 6. The demand for overturning moment is similar to that of the base shear, and the effective weight is multiplied by the height of the action point. Therefore, it is expected to present a graph similar to the graph of demand of base shear.

Table 6. Comparison of calculation equation for overturning moment

Standard	Calculation Equation	
	Demand (M_D)	Capacity (M_C)
GIP	$M'W_W HA_I$	$M'_c(2T_a)R^2t(h_b/h_c)$
NP-6041	$\sqrt{\left(A_I(W_H H_H + W_S H_S + W_I H_I)\right)^2 + (A_C W_C H_C)^2}$	$C'_m \frac{\sin\beta\cos\beta+\pi-\cos\beta}{1+\cos\beta}R^2 + \sum_{i=1}^{n}\left(T_{a_i}R\cos\alpha_i\right) + T_{eo}R^2(2\sin\beta) + \Delta T_e \frac{\beta-\sin\beta\cos\beta}{1-\cos\beta}R^2$
API650	$\sqrt{\left(A_I(W_H H_H + W_S H_S + W_I H_I)\right)^2 + (A_C W_C H_C)^2}$	$0.785D^2\left(\frac{W_H+W_S}{\pi D}(1-0.4A_V) + T_a\frac{N_a}{\pi D}\right)$

H_I: Action point of impulsive mode
H_C: Action point of convective mode
H_H: Action point of tank roof $= H$
H_S: Action point of tank shell $= H/2$
M': Factor of overturning moment
M'_c: Factor of overturning moment capacity
α: Anchor bolt location (radian)
β: Up-lift location (radian)
C'_m: Maximum tank shell compression
T_e: Hold-down tension

For capacity, GIP and NP-6041 are calculated as the resistance of the anchor bolts; API650 is the sum of the weight of the tank wall and roof and the resistance of the anchor bolts. The resistance of the overturning moment was found to have a great influence on the resistance of the anchor bolts. The resistance of the anchor bolts is calculated by applying the pure resistance of the anchor bolts to the number of anchor bolts for API650. In the case of GIP, considering the embedded length and the thickness of the bottom of the tank, and considering the influence of the position of the anchor bolts in the case of NP-6041, it is found that the calculation is more precise than that of API650.

3. Numerical Evaluation of Example Tank

3.1 Structural Model of Tank

A circular steel tank as shown in Fig. 3, was selected for the comparative seismic evaluation study, as outlined by the previously described three guidelines. This study considers various shape of the tank. The parameters for H/D were set as follows.

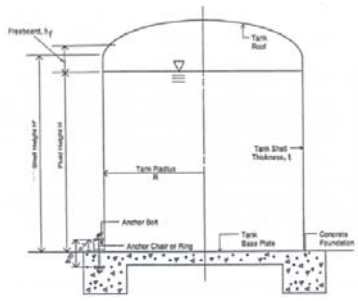


Figure 3. Lquid storage tank for analysis

Table 7. Parameter of tank

- Tank material: SS400
- Young`s modulus of tank: $E_S = 205000\ MPa$
- Unit weight of tank: $\rho_S = 7.850\ tonf/m^3$
- Tank Diameter: $D = 30\ ft = 9.144\ m$
- Tank Radius: $R = 15\ ft = 4.572\ m$
- Liquid Height: $H = 0.25D \sim 2.0D$
- Thickness of tank shell: $t = 0.36\ in = 9.144\ mm$
- Unit weight of Liquid: $\rho_L = 1.0\ tonf/m^3$
- Diameter of anchor bolts: $d_a = 2\ in = 51\ mm$
- Number of anchor bolts: $N_a = 8\ EA$
- Tensile force of anchor bolts: $T_a = 107\ kip = 475.94\ kN$

3.2 Eigen analysis

Fig. 4 shows the change in the frequency according to the parametric study. In the case of the impulsive mode, the difference in frequency under each seismic evaluation method was shown to decrease as H/D

increased. The largest difference was H/D = 0.25, omit a difference of about 21% between GIP and API650. However, when H/D ≥ 0.5, it is very similar and less than 3%. NP-6041 showed similar results, with an error within 10%. As a result, it can be seen that the frequency of the impulsive mode may vary according to the seismic evaluation method as the H/D becomes smaller (i.e., the broad tank).

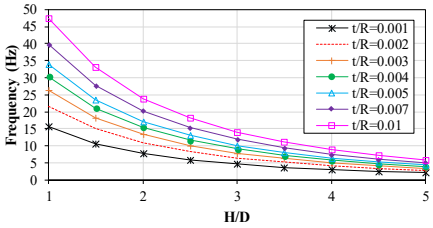
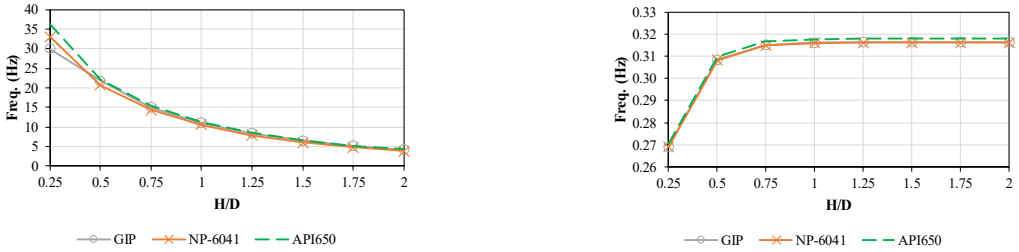


Figure 4. Impulsive mode frequency calculated by GIP



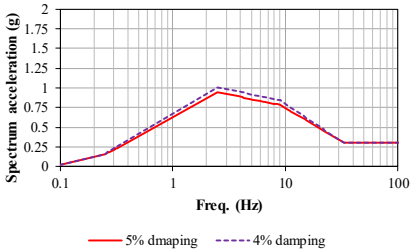
(a) Impulsive Mode (b) Convective Mode

Figure 5. Comparison of frequencies calculated by three guidelines

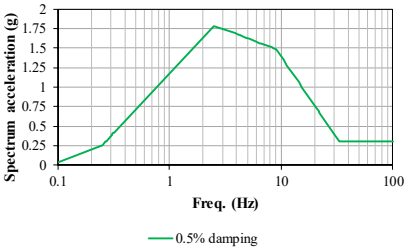
3.3 Spectral Acceleration

In this paper, for the comparison of evaluation equations, the design response spectrum of US NRC R.G 1.60 was modified to PGA 0.3g. The design response spectrum is shown in Fig. 6; Table 3 shows the amplification factor of the response spectrum according to the damping ratio.

Fig. 7 shows the spectral acceleration for the frequencies of impulsive mode and convective mode for RG 1.60. For impulsive mode, the GIP and the NP-6041 were similar, whereas the frequency calculated by API650 was four time smaller than that obtained from NP-6041. In the API650, when the spectral acceleration of the impulsive mode is calculated, a difference is generated because the calculation is performed once again using the correction factor, without using the spectral acceleration value for the frequency. In the convective mode, GIP and NP-6041 were identical, but API650 generated results which were about 25% different from NP-6041. This difference was found to occur in API650 because the spectral acceleration was further reduced using a correction factor similar to the spectral acceleration estimate of the impulsive mode. It is found that the seismic evaluation method of NPPs conservatively estimates the seismic force acting on the liquid storage tank.

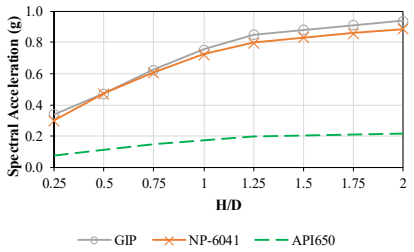


(a) Impulsive Mode

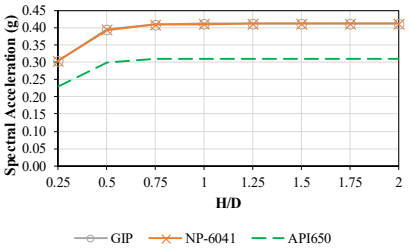


(b) Convective Mode

Figure 6. Comparison of design response spectra for impulsive mode and convective mode



(a) Impulsive Mode



(b) Convective Mode

Figure 7. Comparison of parametric study for spectral acceleration of impulsive and convective mode

3.4 Review of seismic performance

In this section, review of seismic performance of liquid storage tanks by seismic evaluation method was compared. In this paper, seismic performance evaluation items of liquid storage tanks are base shear, overturning moment and sloshing heights.

1) Review of sloshing height

In Table 4, the calculation equations were very similar except for R_{wc} in API 650. However, as shown in Fig. 8, GIP and NP-6041 were identical, and NP-6041 was about 17% larger than API650. Tank of NPPs are expected to be somewhat more conservative than API650 because these tanks are intended to store radioactive material that should not leak.

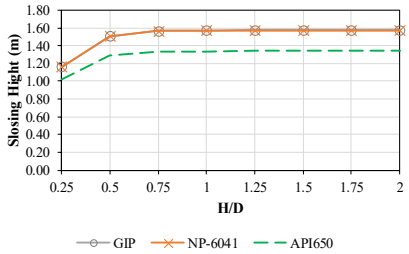
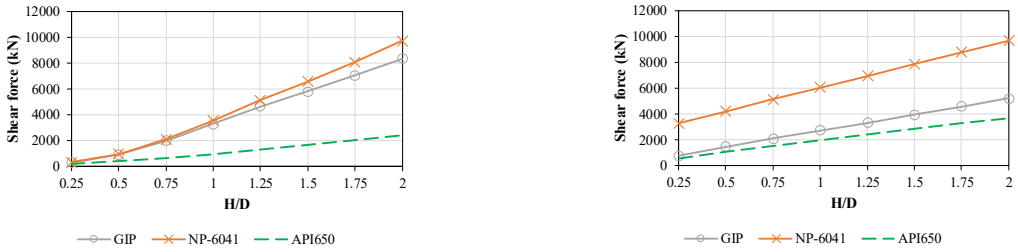


Figure 8. Comparison of parametric study for sloshing height

2) Review of base shear

Fig. 9 shows the demand and capacity parametric study results for the base shear. As the demand increases, the gap between the API650 and other seismic evaluation methods widens. NP-6041 and GIP were about 20% different from each other, and NP-6041, the largest of them, was about 5 times larger than API650.

The capacity of NP-6041 was 1.5 times larger than that of API650, and the difference between GIP and API 650 was about 20%. Demand is assumed to be caused by the difference in spectral acceleration, and the estimation of spectral acceleration has a great influence on demand calculation. The capacity of NP-6041, including the anchor bolt effect, was larger than that of GIP and API650, and the anchor bolts were found to have a significant effect on the capacity of base shear. The capacity of the base shear is 20% larger than the API650 because the difference in the friction factor between the bottom plate and the foundation of the tank, which is judged as the capacity of the GIP, increases when using a friction factor higher than API650.



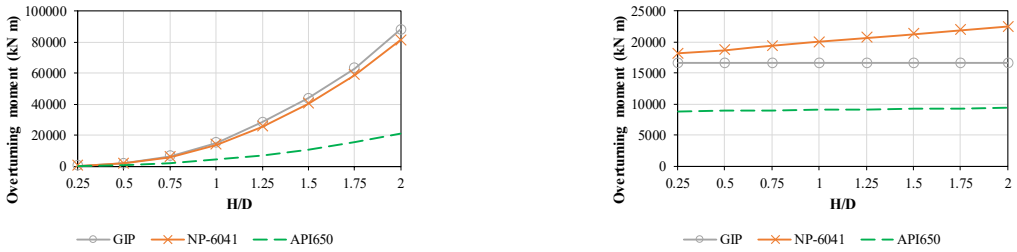
(a) Demand (b) Capacity

Figure 9. Comparison of parametric study for base shear

3) Review of overturning moment

Fig. 10 shows the results from the parametric study of the overturning moment. Similar to our comparisons in base shear, it is seen that the demand increased as H/D increased. GIP and NP-6041 resulted in 4.5 times larger values than API650. Therefore, the demand of the liquid storage tank of NPP is considered to include a safety factor for spectral acceleration, and it can be seen that a conservative methodology is achieved by increasing the seismic force acting on the tank.

The capacity values obtained from GIP and NP-6041 were observed to be about twice as large as those obtained from API650. The capacity for the overturning moment was constant regardless of H/D for GIP. For NP-6041 and API650, values of 20% and 7% were obtained, respectively, at H/D = 0.25 ~ 2. As H/D increases, the diameter and the number of anchor bolts installed in the tank are set to identical values. As a result of evaluating the variation in capacity with H/D, GIP showed a dependence of overturning moment only on the number of anchor bolts. The same was true for API650. However in the case of NP-6041, the overturning moment capacity is affected by the anchor bolts as well as their contribution to the uplifting of the tank.



(a) Demand (b) Capacity

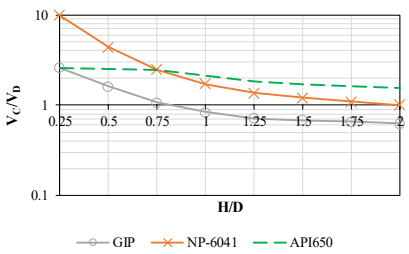
Figure 10. Comparison of parametric study results for the overturning moment

4) Seismic performance review results

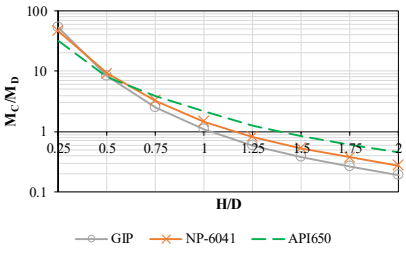
Fig. 11 shows the seismic performance evaluation results according to the parametric study. The seismic performance of the base shear was investigated. As the H/D increased, the capacity/demand(C/D)

of the base shear converged to a specific value. Amongst all the methodologies, GIP was the smallest at 0.6, and API650 converged to 2, about 3.5 times of GIP. The seismic performance was not satisfied at H/D> 0.75 for GIP and at H/D = 2 for NP-6041. Additional anchor bolts or larger diameter anchor bolts were required. For API650, the seismic performance against base shear was satisfied at H/D = 0.25 ~ 2. Through this study, it is observed that the seismic evaluation method of the NPP, especially the seismic performance of bottom shear force against GIP, is more conservative than other evaluation criteria.

As a result of investigating the seismic performance against the overturning moment, the C/D of the conduction moment gradually decreased as the H/D increased with the base shear. Particularly, GIP and NP-6041 did not meet the seismic performance requirements at H/D > 1 and for a higher tank. As the H/D increases, it was observed that the stability against overturning moment is low. It is observed that GIP is about 3 times more conservative than API650, and NP-6041 is about twice as conservative as API650.



(a) Base shear



(b) Overturning moment

Figure 11. Comparison of Seismic Performance Review Results

4. CONCLUSION

In this paper, evaluation equations of liquid storage tanks are compared and parametric studies of H/D were analyzed. In this paper, seismic evaluation methods (US GIP and NP-6041) for liquid storage tanks of NPPs are compared against each other and these evaluations are further compared against API650.

Based on API650, the results of the comparison of seismic performance evaluation method of NPP were as follows.

- The frequency of the eigen values from GIP, NP-6041, and API650 were the same, but the spectral acceleration from API650 was about 4 times smaller in impulsive mode and about 6 times smaller in convective mode, when compared to the other two evaluation methods. It is found that the seismic evaluation method of NPPs is conservative for increasing seismic force applied to liquid storage tanks.

- Examination of the sloshing height revealed that the values obtained from GIP and NP-6041 were about 17% larger than that of API650 despite the very similar calculations techniques for sloshing height. The reason for the difference in sloshing height values, according to the seismic evaluation method, is the difference in spectral acceleration for the convective mode. In addition, the sloshing height also has a great influence on the applied response spectrum.

- The seismic performance of the base shear and of the overturning moment was found to be insufficient as the capacity/demand for the tank increases with increasing H/D ratio. The base shear and overturning moment values obtained from API650 were about 40 ~ 60% larger than those obtained from the other evaluation methods. For the base shear, the seismic performance is not satisfied at H/D> 0.75 for GIP and at H/D = 2 for NP-6041. All seismic evaluation methods for overturning moment did not satisfy seismic performance at H/D> 1. It is found that the liquid storage

tank is vulnerable to earthquake overturning moment rather than the base shear. Particularly, a tall tank with a high H/D ratio needs to be reinforced against overturning moment.

As a result of comparing the results of the seismic evaluation method and the parametric study, it was found that the seismic performance evaluation results were greatly affected by the spectral acceleration. In the case of API650, it can be seen that the spectral acceleration is corrected to a more realistic value by multiplying by a specific factor without directly using the value of the design response spectrum.

Also, since the safety factor of the liquid storage tank decreases as the H/D increases, it is necessary to provide a mechanical fixing device such as an anchor bolt when constructing a liquid storage tank with a large H/D ratio.

ACKNOWLEDGEMENTS

This work was supported by the Energy R&D program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant financial resource from the Ministry of Trad, Industry & Energy, Republic of Korea (No. 20171510101960)

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