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Seismic Analysis of Reactor Coolant System Considering the Effect of Sloshing in Pressurizer

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1. Introduction

Various researches have been carried out for the movement of the liquid storage tanks during a seismic event. Housner [1] proposed a simple mechanical analogue for evaluating the fluid dynamic effect of earthquake on the rigid liquid storage tank. The plausibility of Housner-method is supported by experimental study [2]. Subsequently, Haroun [3] and Vetelsos [4] have extended Housner-method to deformable liquid storage tanks. Previous studies concluded that the dynamic behavior of liquid storage tank is affected by fluid in the tank.

However, the coolant of the vessel has been treated as mass in many cases of reactor coolant system (RCS) seismic analysis. In this study, the effect of sloshing in pressurizer (PZR) on the RCS seismic analysis is investigated.

2. Methods and Results

2.1 PZR modal analysis with solid model

A finite element model of PZR with coolant is made with three dimensional solid elements using ANSYS [5]. The PZR is modelled with solid element and the contained coolant is modelled with fluid element. The fixed boundary condition to the bottom of PZR is applied. To consider fluid-structure-interaction at the PZR and coolant interface, no-separation-contact condi--tion is applied to the interface of the fluid elements and solid elements.

A modal analysis is performed and the sloshing of coolant occurs in the low frequency region as shown in Fig. 1.

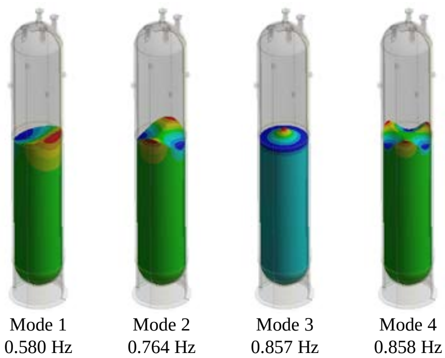

Fig. 1. Sloshing modes of coolant inside the PZR

The fundamental frequency of sloshing, 0.580 Hz, will be compared with the sloshing frequency of the converted equivalent beam model.

2.2 Equivalent beam model

The three dimensional solid model of PZR and contained coolant is converted to equivalent beam model by implementation of the Housner-method [6] and the equivalent dynamic system of a cylindrical tank is shown in Fig. 2.

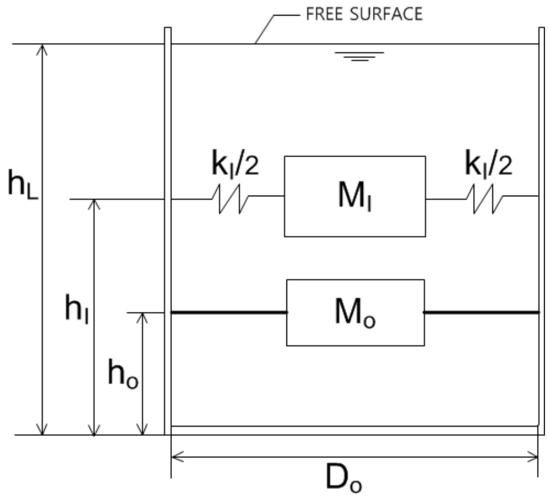

Fig. 2. Equivalent dynamic system of a cylindrical tank

The related simple mechanical analogue is shown as follows;

$$M_I = M_T\left(\frac{D_o}{4.4h_L}\right)\tanh\left(3.68\frac{h_L}{D_o}\right) \tag{1}$$

$$M_o = M_T - M_I \tag{2}$$

$$k_I = M_T\left(\frac{g}{1.19h_L}\right)\left[\tanh\left(3.68\frac{h_L}{D_o}\right)\right]^2 \tag{3}$$

$$h_I = h_L - \frac{D_o}{3.68}\tanh\left(3.68\frac{h_L}{D_o}\right) \tag{4}$$

$$h_o = h_L - \frac{M_T}{M_o}\left[\frac{h_L}{2} - \frac{D_o^2}{8h_L}\right] - \frac{D_o M_I}{3.68M_o}\tanh\left(3.68\frac{h_L}{D_o}\right) \tag{5}$$

$$f_s = \frac{1}{2\pi}\sqrt{\frac{k_I}{M_I}} \qquad (6)$$

where
M_I: mass of the convective fluid,
M_o: mass of the impulsive fluid,
M_T: total mass of the fluid,
h_I: height of the convective fluid mass,
h_o: height of the impulsive fluid mass,
h_L: height of the total fluid,
D_o: diameter of tank,
f_s: fundamental frequency of the sloshing mode, and
k_I: equivalent spring constant of the fundamental sloshing mode.

The above equations are calculated using the PZR dimensions and coolant mass and the results are presented in Table 1. The first column of the table is the parameters at the maximum coolant volume in the insurge condition, and the second column shows the parameters at the minimum coolant volume in the outsurge condition.

Table 1: Parameters of PZR beam model

	Max. coolant in PZR	Min. coolant in PZR
M_T (lb)	51231	21278
M_I (lb)	3258	3062
M_o (lb)	47973	18216
k_I (lb/in)	48358	45453
h_I (in)	195	155
h_o (in)	347	105
f_s (Hz)	0.613	0.613

The variations of convective fluid mass (M_I) and equivalent spring constant (k_I) for two cases are relatively small. As a result, the fundamental sloshing frequencies are the same at the two cases. The difference of sloshing frequency between three dimensional solid model and beam model is about 5%. However, the converted beam model is acceptable considering different shape of the PZR bottom head and the cylinder tank used in the Housner-method.

2.3 RCS seismic analysis and results

The equivalent beam model of PZR is added to RCS –building coupled model and the RCS and PZR seismic analysis for Safe Shutdown Earthquake (SSE) is performed. The analysis model is shown in Fig. 3. Three translational and three rotational acceleration time histories are applied to the basemat and the linear time history analyses are performed using the mode superposition method. The RCS seismic analyses are performed twice for maximum coolant case and minimum coolant case. As expected, the sloshing effect of the PZR affects only the PZR response. Therefore the acceleration response spectra and maximum support loads of PZR are obtained from the analysis.

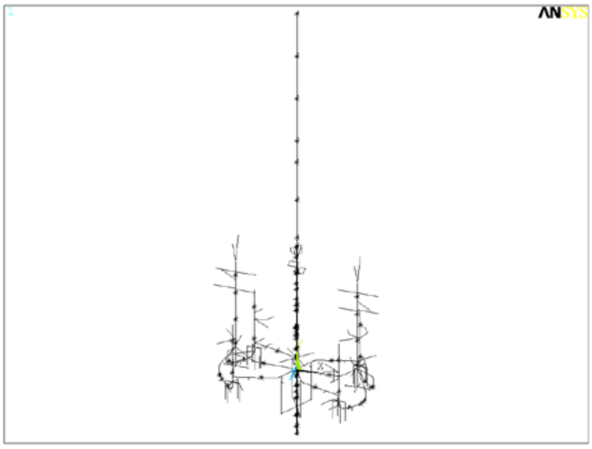

Fig. 3. RCS seismic analysis model

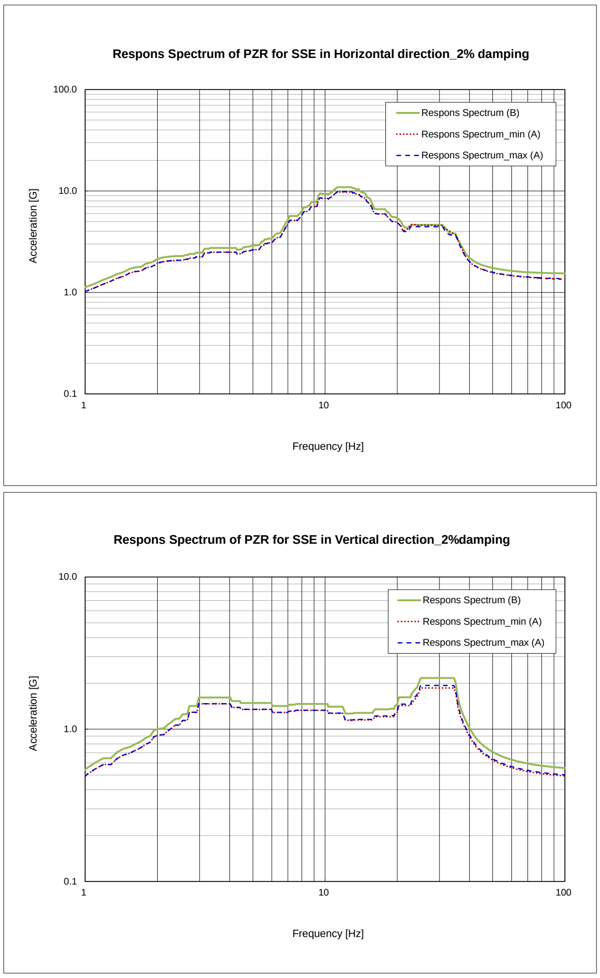

Fig. 4. Comparison of response spectra of conventional design with that of seismic analysis considering effect of PZR sloshing

Fig. 4 presents the spectra (A) of RCS seismic analysis considering the effect of PZR sloshing and the spectra (B) of the conventional RCS seismic analysis. The coolant mass of the conventional analysis is the same as the maximum coolant case. Though the horizontal spectrum of the minimum coolant case is slightly higher than that of the maximum coolant case, the spectra of both cases are enveloped by the conventional design spectra.

The PZR support load ratios are presented in Table 2. All numbers in this table have been normalized to conventional analysis results and subscripts of force and moment mean that v= vertical, h= horizontal, t=torsion, b=bending, and k= key. All loads of both cases are smaller than the conventional analysis result except horizontal force of PZR support in maximum coolant case. However, the increases are not significant.

Table 2: PZR support load ratios

Force & Moment \ Analysis Case		Max. coolant in PZR	Min. coolant in PZR	Conventional analysis (w/o sloshing)
FLANGE	F_v	0.95	0.85	1.00
	F_h	1.01	0.88	1.00
	M_t	1.00	1.00	1.00
	M_b	0.91	0.81	1.00
KEY	F_k	0.92	0.88	1.00

3. Conclusions

To evaluate the sloshing effect of the coolant contained in the PZR, several seismic analyses are performed. The analyses results show the sloshing effect is negligible on the response spectra, and the forces and moment at the PZR supports. From the analysis results, it is concluded that the sloshing does not affect the dynamic responses of PZR, and the conventional structural analysis methodology is appropriate.

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