Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division IX (include assigned division number from I to X)

PRACTICAL SEISMIC FSSI ANALYSIS OF MULTYPLY-SUPPORTED SECONDARY TANKS SYSTEM

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ABSTRACT

The recent explosion of nuclear power plant (NPP) in Japan was mainly due to performance malfunction in cooling system caused by an earthquake. Thus, seismic analysis has been of great importance for auxiliary feed water (AFW) tank, which is one of the cooling systems in NPP. The existing simple analysis of the water tank is based on the entire aux stick finite element model with AFW tank, which leads to a very conservative result. In this research, two types of fluid tank analysis methods, static analysis including the effect of dynamic pressure and frequency domain analysis accounting for both dynamic mass and spring, have been proposed using the substructure method for an AFW tank.

The proposed analysis method accounted for multi-physical interactions (Fluid-Structure-Soil interaction, FSSI), soil-structure, fluid-structure, and structure-structure interactions and needed only finite element model of the AFW tank for effective substructure method. The fluid forces subjected to the tank wall were displaced to the fluid pressures or the hydrodynamic model in the existing Code & Standard. The control motion was the floor responses at the Auxiliary Building (AB) 100ft, and it was computed by SASSI analysis. The effective stiffness was taken as the constants identifying the structure-structure interaction of the AB-Fluid tank. Compared to existing conventional analysis packages, the results of the proposed analysis methods showed an effective solution for seismic analysis of fluid storage tanks in nuclear power plant.

INTRODUCTION

Cooling system of Nuclear Power Plant (NPP) related to Fukushima NPP explosion caused by an earthquake belongs to seismic category I. Since then, The seismic design and analysis of AFW tanks associated with refrigerating NPP has been of great attention to researchers. In the existing analysis methods of the AFW tanks, finite element model has the entire aux stick model with AFW tank, and ground is displaced to fixed conditions. Fluid forces subjected to the tank wall were displaced to the fluid added mass, and then the response spectrum analysis was performed. Since input motion, boundary condition, and fluid effect are different from those of the real structure, existing analysis method cannot reflect the actual behavior of NPP structures. Furthermore, the analysis method requires an entire FE model resulting in a very conservative value.

The development of an effective seismic analysis method that could account for all the multi-physical interactions, that is, soil-structure, fluid-structure, and structure-structure interactions, is highly required. In this research, two types of fluid tanks analysis methods, static analysis considering the dynamic pressure and frequency domain analysis method considering dynamic mass and spring have been proposed based on the substructure method for an AFW tank. In order to evaluate the applicability of the proposed analysis methods, the result of the proposed methods were compared with those of the existing analysis method.

THEORETICAL BACKGROUND

Dynamic Pressure for Fluid Tanks

When a rectangular tank is subjected to the simultaneous action of three components of seismic motion, the tank wall may experience hydrodynamic pressures and inertia force in addition to the hydrostatic pressure. The hydrodynamic pressures on tank walls and base slab corresponding to the impulsive, convective and vertical response modes are defined according to the codes, TID-7024 and ACI 350.3. The mechanical FSI model can be illustrated as below. The hydrodynamic and hydrostatic pressures are calculated on the walls for each direction. In this research, a rectangular tank of cross-sectional dimensions of $2L_1$ and $2L_2$, height H and liquid level z is considered, as shown in Figure 1.

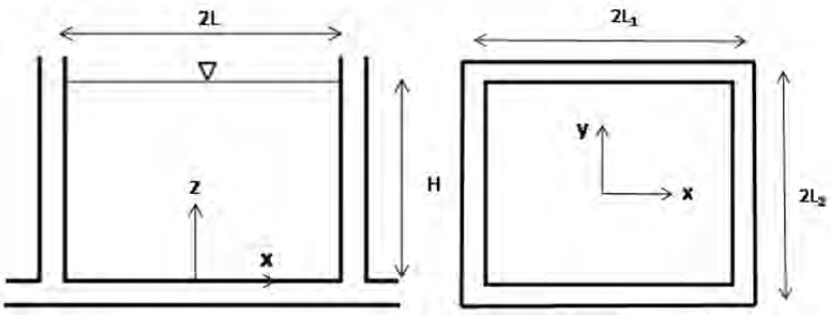


Figure 1. Description of tank dimensions and mechanical model

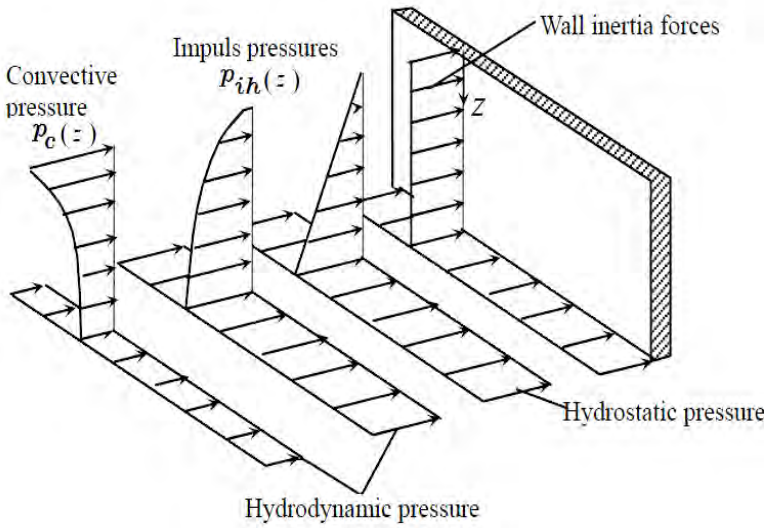


Figure 2. Impulsive and convective pressure for fluid tanks

The TID-7024 and ACI 350.3 provide the impulsive pressure of the rectangular tank as following.

$$P_i(z) = 0.132 S_a(T_i)\gamma_f (L/H)^2 \tanh(1.732L/H)[4H - 6h_i - (6H - 12h_i)(z/H)] \quad (1)$$

$$T_i = 2\pi\sqrt{(W_i + W_w)/(gk)} \quad (2)$$

$$W_i = W_t \frac{\tanh\left(\sqrt{3}\frac{L}{H}\right)}{\sqrt{3}\frac{L}{H}} \tag{3}$$

$$h_i = L(0.5 - 0.1875(L/H)) \quad (if \;\; L/H \geq 1.333) \tag{4}$$

where P_i is the impulsive pressure at level z; S_a is the value of the floor response spectral acceleration with SSI effect corresponding to the fundamental impulsive period T_i; h_i is the height of impulsive lateral force; γ_f is the unit weight of fluid; W_i is the effective impulsive weight, W_w is the weight of the wall and W_t is total weight of the fluid; k is the flexible stiffness of the wall; and g is the gravity acceleration(=32.17 ft/sec^2)

The TID-7024 and ACI 350.3 also provide the convective pressure of the tank as following.

$$P_c(z) = 0.132 S_a(T_c)\gamma_f (L/H)^2 \tanh(1.732L/H)[4H - 6h_c - (6H - 12h_c)(z/H)] \tag{5}$$

$$T_c = \frac{2\pi}{w_c} = \frac{2\pi}{\sqrt{\frac{1.58g}{L}\tanh\left(1.58\frac{H}{L}\right)}} \tag{6}$$

$$W_c = 0.264 W_t \left(\frac{L}{H}\right)\tanh\left(3.16\frac{L}{H}\right) \tag{7}$$

$$h_c = H\left(1 - \frac{\cosh\left[1.58\left(\frac{H}{L}\right)\right] - 1}{1.58\left(\frac{H}{L}\right)\sinh\left(1.58\frac{H}{L}\right)}\right) \tag{8}$$

where P_c is the convective pressure at level z; T_c is the fundamental convective period; and h_c is the height of convective lateral force.

Frequency Domain Analysis Method

Frequency domain analysis can be carried out by transforming the equation of motion on time domain to frequency domain and then calculating the solution, for the equation of motion. In general, the equation of motion can be formally transformed into the frequency domain using the Fourier or Laplace transform. In addition, this method can calculate the solution more effectively than the time domain method.

Fourier transform is more common than Laplace transform in the frequency domain analysis field. Specifically, the integral transformation of the discrete data can be processed easily by using fast Fourier transform technique. The inverse Fourier transform for the dynamic response is shown below.

$$U(\omega) = \Im\{u(t)\} = \int_{-\infty}^{\infty} u(t)e^{-i\omega t}dt \rightleftarrows u(t) = \Im^{-1}\{U(\omega)\} = \frac{1}{2\pi}\int_{-\infty}^{\infty} U(\omega)e^{i\omega t}d\omega \tag{9}$$

In the above formula, the frequency response function $U(\omega)$ can be found by multiplying the simple both transfer function $H(\omega)$ and input load $F(\omega)$. In particular, transfer function in single degree of freedom system represents the inverse of dynamic stiffness $S(\omega)$.

$$U(\omega) = H(\omega)F(\omega) \leftarrow H(\omega) = S^{-1}(\omega) = \frac{1}{-\omega^2 m + i\omega c + k} \tag{10}$$

Frequency domain analysis follows the hysteretic behavior damping. This damping does not change the damping characteristics depending on the frequency. The hysteretic behavior damping considers the modulus of elasticity by changing the complex elasticity modulus such as $E^* = E(1 + i2\beta)$.

In the formula, $i = \sqrt{-1}$ and E is the modulus of elasticity. β is hysteretic behavior damping ratio. Frequency domain analysis method is less commonly used than the time domain analysis method for seismic analysis. However, if the frequency dependent characteristics such as soil-structure interaction are apparent, frequency domain analysis method is more efficient than time domain analysis method.

Earthquake Analysis for Fluid Tanks in Nuclear Power Plant

Simple Analysis Method

Simple analysis method for AFW tanks in NPP is the response spectrum analysis method for the Auxiliary building. The Finite element model and sequence of existing analysis method is shown in Figure 3, 4.

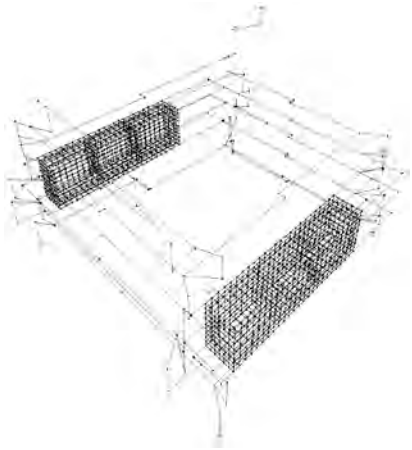


Figure 3. The finite element model for simple analysis

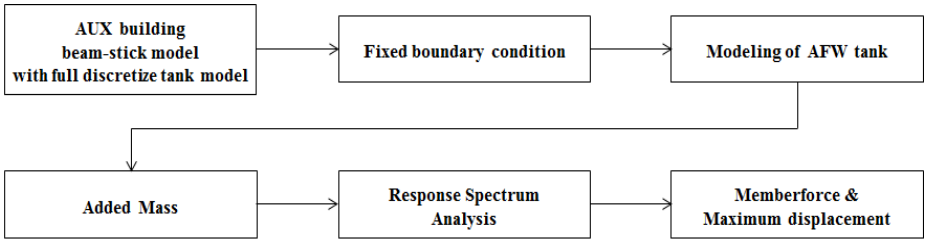


Figure 4. Flow for the simple analysis scheme

In the analysis methods for AFW tanks, finite element model has the entire stick model with AFW tank on the fixed base. This method defines that all fluid mass would be considered as the added mass on the tank wall, and then uses the response spectrum analysis. For these reasons, the existing analysis method cannot reflect the actual behavior of NPP structures. The input motion, boundary condition, and fluid effect of the model structure method are different from those of the real structure. Furthermore, this method is conservative for the modeling and analysis of a NPP structure. Therefore, the development of an effective seismic analysis method that could take into account the multi-physical interactions is demanded.

Proposed Seismic Analysis Method using Static Analysis

If the ratio of the entire structure with target structures is less than 1/100, then target structure can be analyzed as an interpreted condition from the entire structure. Two types of fluid tanks analysis methods (static analysis considering the dynamic pressure and frequency domain analysis method considering dynamic mass and spring) have been proposed based on the above substructure method for an AFW tank. For this reason, the proposed methods can construct a FE model more simply than the existing analysis method. The sequence of proposed Method 1 is shown in Figure 5.

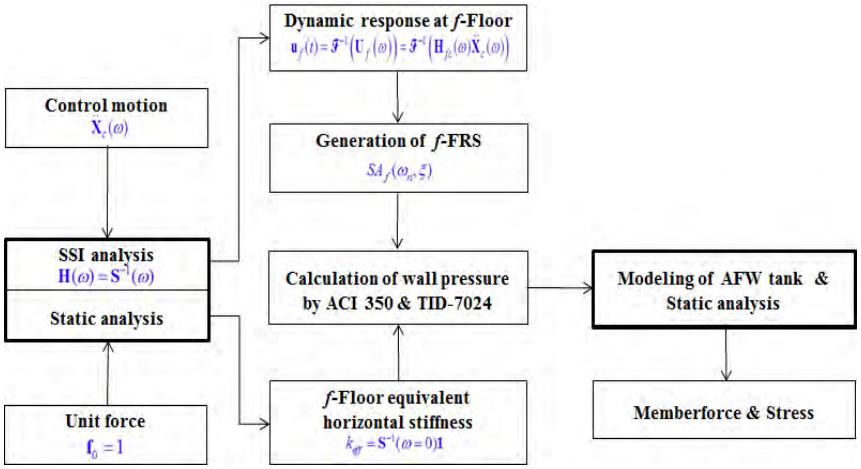


Figure 5. Flow for the proposed method 1 scheme

In the proposed analysis methods, the applied fluid forces subjected to the tank wall were displaced to the fluid pressures in the ACI 350.3 & TID-7024. The control motion was the floor responses at aux building 100ft, and it was computed by SASSI(A System for Analysis of Soil-Structure Interaction) analysis. The equivalent stiffness was considered as the constants identifying the AB-Fluid tank (structure-structure) interaction. Finally, static analysis is carried out. For this reason, the proposed analysis method is more advanced than the existing analysis method to account for the multi-physical interactions of soil-structure, fluid-structure, and structure-structure.

Table 1 : Spectral Acceleration

Period[sec]		S_a [g]
T_i	0.009	0.367
T_c	4.349	0.485

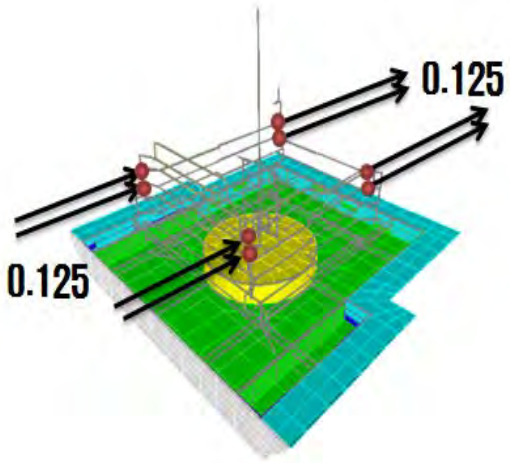


Figure 6. The finite element model considered unit forces

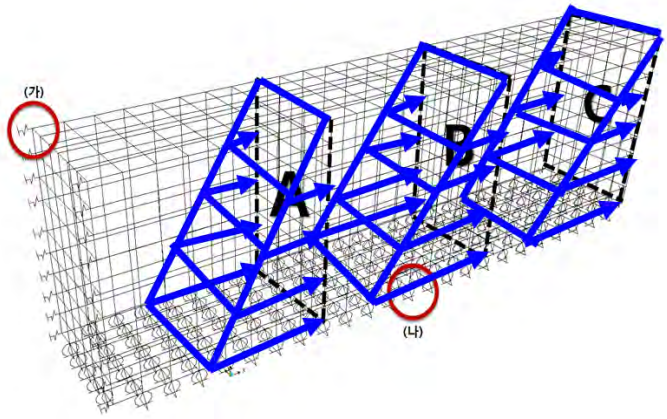


Figure 7. The finite element model for the AFW tank considered dynamic pressures

Table 2 : Unit pressure subjected to the tank wall

Height[ft]	Impulsive [kips/ft^2]	Convective [kips/ft^2]	Total Pressure [kips/ft^2]
2.00	0.654	0.004	0.658
6.00	0.593	0.009	0.602
10.00	0.532	0.014	0.546
14.00	0.471	0.019	0.490
18.00	0.409	0.024	0.434
22.75	0.337	0.030	0.367
27.50	0.264	0.036	0.301
31.50	0.203	0.042	0.245
35.50	0.142	0.047	0.189

Proposed Seismic Analysis Method using Frequency Domain Analysis

Frequency domain analysis is not widely used in the commercial FE analysis programs. Thus, this study shows, that a frequency domain analysis method has a good application for the hydro-dynamic analysis. The sequence of the proposed method 2 is shown in Figure 8.

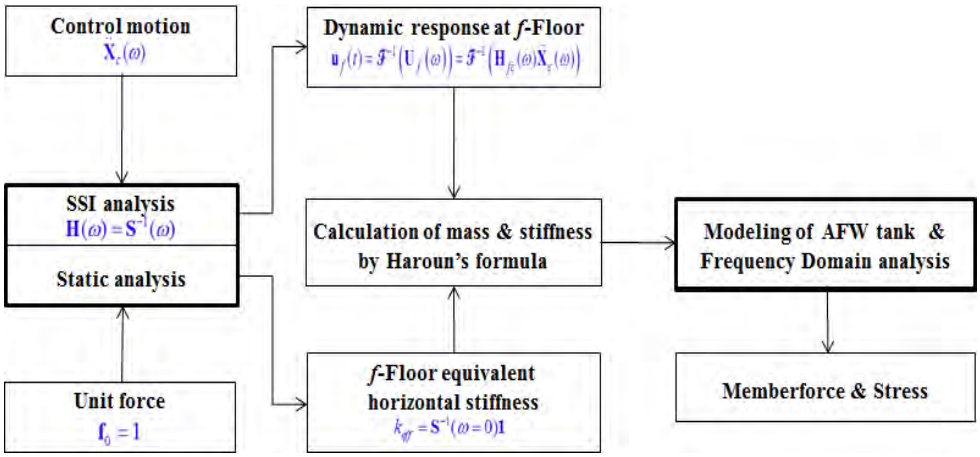


Figure 8. Flow for proposed method 2 scheme

The background of the proposed method 2 is the same with the background of proposed method 1. However, in the proposed method 2, fluid is replaced with equivalent mass and spring damper system by using Haroun's method. The method 2 can find the final results of time history. Table 3 shows the constants of dynamic mass, spring stiffness, and equivalent height of the applied fluid.

Table 3 : Hydro-dynamic properties

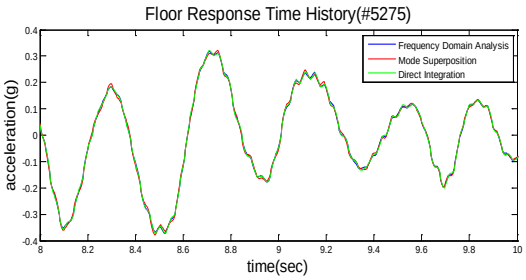
Dynamic mass [kip]		Dynamic spring stiffness[kip/ft]		Equivalent height[ft]	
m_i	60.77	k_i	1.58e7	h_i	14.25
m_c	27.93	k_c	29.15	h_c	24.68

CONCLUSION

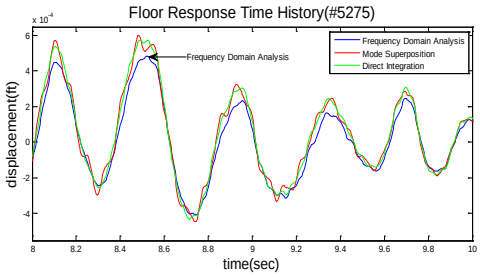
In order to evaluate the usability of the proposed analysis methods, the results of the proposed methods were compared with those of the existing analysis method. Table 4 shows the displacements at a top node obtained from the existing and proposed methods. The existing analysis method was found to be more conservative. In addition, compared with the mode superposition and the direct integration methods, accelerations obtained from the frequency domain analysis were in very good agreement with those of the methods shown in Figure 9(a). However, there was a small difference in displacements as shown in Figure 9(b). This causes the difference between the frequency and time domain analysis methods in addition to the difference between the applied damping theory (direct integration method - Rayleigh damping, mode superposition method - modal damping, and frequency domain analysis method - Hysteresis damping). The future study would further verify the difference between the proposed and the existing methods.

Table 4 : Maximum displacement at a top node

Direction	Simple Analysis method	Proposed method 1	Proposed method 2
U_1[ft]	0.0010	0.0004	0.0005



Time history of acceleration($8 \le t \le 10$)



Time history of displacement($8 \le t \le 10$)

Figure 9. Time history response at a top node

ACKNOWLEDGEMENT

This work was partly supported by the IT R&D program of MOTIE/KEIT(No. 10040909, Development of an Integrated Design Solution based on Codes and Field Data for the advancement of the Plant Industry) and the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy(No. 20104010100520)

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