



Seismic assessment of KNGR in-containment refueling water storage tank

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ABSTRACT

Considering fluid-structure interaction(FSI), the seismic effects on the internal structures of the containment building due to the presence of an in-containment refueling water storage tank(IRWST) is evaluated. Three different approaches for the FSI analysis are adopted and their results are compared. The study results show that the seismic design effects on the internal structures with IRWST are not significant and the mass-spring method provides reasonable results from a design aspect with some conservatism.

1. INTRODUCTION

One of the advanced design features of the Korean Next Generation Reactor (KNGR) is the use of an IRWST. This tank is a major contributor to reduced core damage frequency and improved severe accident performance for the KNGR. The IRWST concept has been considered in the conceptual design stage of a spherical containment used in an advanced light water reactor project in the USA, but there has been no previous detailed design or actual construction performed. Specifically, the IRWST for the KNGR cylindrical containment is a new design concept for the containment of a pressurized water reactor.

This study evaluates the containment structural design impact resulting from the arrangement of the IRWST during design basis earthquake loads focusing on FSI effects. The first phase of this study is to evaluate seismic effects on the internal structures due to the presence of the IRWST. For this study, two analytical models of the containment; with and without an IRWST; were constructed. Seismic analyses were performed for both models and the IRWST influence was evaluated by comparing structural responses.

The structural impact of the IRWST will likely be controlled by the accuracy of the FSI modeling due to the fact that the IRWST is filled with a large amount of water to perform its intended function. Therefore, the second phase of this study concentrates on modeling techniques of the FSI system. For this purpose, three different analytical models corresponding to three different approaches were constructed and their results were compared with each other. The modeling techniques adopted are the sprung-unsprung method presented in Report TID-7024 [1], the distributed mass-spring method in ASCE Standard 4-86 [2], and a finite element method using acoustic fluid elements [3].

2. SEISMIC ANALYSIS OF FSI SYSTEM

2.1 Equation of Motion

The dynamic response of a multi-degree-of-freedom system subjected to ground motion can be obtained by application of either the time-history method or the complex frequency method, and the equation of motion of the dynamic system is represented by :

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -\{\ddot{u}_g\}[M] \quad (1)$$

where, $[M]$, $[C]$, and $[K]$ are mass, damping, and stiffness matrices, respectively. $\{\ddot{x}\}$, $\{\dot{x}\}$, and $\{x\}$ are the relative acceleration, velocity, and displacement vectors, respectively, and $\{\ddot{u}_g\}$ is the load vector as a ground acceleration.

The presence of a fluid may significantly influence the behavior of a structure and vice versa the deformations of the structure can change the loads transmitted to the fluid. These phenomena are referred to as FSI problems. To formulate the equation of motion of a FSI system, the fluid system is first transformed into the pressure domain using the acoustic wave equation [3].

$$\frac{\partial^2 p}{\partial t^2} = c_f^2 \nabla^2 p + c_f^2 \frac{\partial q}{\partial t} - c_f^2 \rho_f \nabla \bar{b} \quad (2)$$

where

$$\nabla = \vec{i} \frac{\partial}{\partial x} + \vec{j} \frac{\partial}{\partial y} + \vec{k} \frac{\partial}{\partial z} \quad (3)$$

and p is the pressure, c_f is the speed of sound, ρ_f is the static fluid density as a time-independent variable, \bar{b} is a body force acting on the fluid, and q is the added fluid mass which can be determined from the continuity equation.

The equation of motion of a coupled FSI system can be expressed by expansion of equation (1) as equation (4).

$$\begin{bmatrix} [M_s] & [0] \\ [-A^T] & [M_f] \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \dot{p} \end{Bmatrix} + \begin{bmatrix} [C_s] & [0] \\ [0] & [C_f] \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \dot{p} \end{Bmatrix} + \begin{bmatrix} [K_s] & [A] \\ 0 & [K_f] \end{bmatrix} \begin{Bmatrix} x \\ p \end{Bmatrix} = \begin{Bmatrix} F_s \\ F_f \end{Bmatrix} \quad (4)$$

where, the sub-characters, s and f refer to the structure and the fluid, respectively. $[A]$ is the coupling matrix that represents the interface of the fluid and the structure, and $\{F\}$ represents the load vector.

2.2 Practical Approaches for FSI Analysis

The hydrodynamic forces associated with the seismic response of a fluid filled tank are of two distinct types; convective forces and impulsive forces. The convective forces are associated with the fluid sloshing motion, while the impulsive forces are the inertial forces imparted to the tank wet boundary as a result of the contained fluid acceleration. The impulsive forces are also referred to in literature as the added mass effect. Determination of the convective and impulsive hydrodynamic forces require the use of a finite element model that incorporates fluid finite elements along

with structural elements, with the proper modeling at their interface boundary.

These forces can be calculated using acoustic fluid elements and the seismic response of the structure can be obtained by coupled FSI analysis using the finite element method. The following approximate simple and straight forward approaches can also be applicable to FSI analysis.

(1) Sprung-unsprung Method

This method presented in TID-7024 [1] is based on simplifications which involves some approximation and may apply to flat-bottomed, vertically oriented tanks of uniform rectangular or circular section assuming the tank moves as a rigid body.

In this method, the hydrodynamic pressures are considered by adding a rigid mass as an impulsive mass and the single sloshing mode that is expressed by a sloshing mass and spring constant. The formulas for determination of the fluid masses and spring constants for a circular tank and a rectangular tank are given by Table 1.

(2) Distributed mass-spring method

This method is presented in ASCE 4-86 [2] and is applicable when the basin walls respond as a flexible body or when local stresses are of interest. The impulsive mass shall be uniformly distributed over a height equal to twice the distance from the bottom of the basin to the center of mass (as determined for the case of a single impulsive mass). Similarly, the horizontal springs for the sloshing effect shall be distributed over a height equal to twice the distance from the top of the water surface to the center of mass in which the sloshing mass shall be attached through a rigid link to the distributed springs.

3. STRUCTURAL MODEL OF KNGR CONTAINMENT BUILDING

The Containment Building of KNGR is a double containment and consists of a Outer Containment, a steel-lined Inner Containment, and Internal Structures. It is on a common, thick reinforced concrete foundation mat which forms a monolithic structure with the Auxiliary Building. The Inner Containment houses the pressurized water reactor, steam generators, reactor coolant loops, IRWST, and portions of the auxiliary systems. Figure 1 shows a section of the KNGR general arrangement that was developed at the conceptual design stage.

The Outer Containment is composed of a reinforced concrete right circular cylinder with a shallow domed roof. Its cylindrical wall has a height of 244.5 feet and an inner radius of 86.0 feet, with a wall thickness of 4.0 feet up to the Auxiliary Building roof line where it decreases to 2.5 feet. The shallow dome is 2.0 feet thick. The Inner Containment is a post-tensioned concrete cylinder with a hemispherical dome. The internal radius of the Inner Containment is 75.0 feet, with a wall thickness of 4.0 feet and a dome thickness of 3.5 feet. The height of the cylindrical wall is 176.5 feet. An annular space of 7.0 feet between the Inner and Outer Containments is provided for filtration of any accidental leakage from the inner containment.

The Internal Structures are a group of reinforced concrete structures and include the Reactor Cavity, Refueling Cavities, IRWST, and Primary and Secondary Shield Walls. The IRWST which is a new feature and increases the safety of a nuclear power plant for the advanced light water reactor is an annular refueling water storage tank located

inside and at the bottom of the Inner Containment. The IRWST rests on the basemat with a separation gap of 2 inches from the Inner Containment. The inner and outer radii of the IRWST are 53.0 feet and 71 feet-10 inches, respectively. The thicknesses of outer wall and slabs are all 3.0 feet. The normal water depth is 12.0 feet, and the total height of the tank including the slab depth is 22.0 feet.

4. COMPARATIVE ANALYSIS

Two types of comparative analyses have been performed. The purpose of the first analysis is to evaluate seismic effects on the internal structures due to the presence of the IRWST. The second is to evaluate the differences in structural response resulting from the various modeling techniques of the FSI system.

4.1 *Analytical Model*

The containment building is idealized as two lumped mass-stick models constructed on a fixed base; with and without the IRWST; while the fluid-structure interaction is modeled as a distributed mass-spring with flexible wall. The fluid masses and sloshing stiffnesses for the IRWST model included in the stick model were determined by the formulas for the circular type tank with the equivalent radius to the annular tank. The two stick models plotted on the concrete outline of the containment building are shown in Figure 2.

The analytical models to evaluate the differences resulting from the modeling techniques of the fluid are shown in Figure 3. Two of them are 2-dimensional lumped-mass stick models and one is a 3-dimensional solid element model. The 2-dimensional stick models have the fluid masses and springs whose values were calculated by the formulas for a rectangular tank with unit width using TID-7024 and ASCE 4-86 methods, respectively, and were validated through numerous test runs. The 3-dimensional model was idealized with 2016 HEXA elements and 54 axisymmetric hydroelastic elements of MSC/NASTRAN [4].

4.2 *Input Motion*

An artificial earthquake acceleration time-history was generated and used as horizontal seismic motion compatible with Reg. Guide 1.60 [5], scaled to 0.3 g as shown in Figure 4. The duration and time interval are 24.0 seconds and 0.005 seconds, respectively.

4.3 *Results and Evaluation*

The seismic analyses for both the models with and without the IRWST were performed to evaluate the seismic effects on the internal structures due to the presence of the IRWST. The fluid masses and stiffnesses were calculated by ASCE 4-86 method and attached to the containment building model with the IRWST. The analyses were performed by the time-history analysis method of modal superposition using the computer program SAP90 [6], in which the same modal damping for all modes was considered. The floor response spectra for 2% damping at the top of the secondary shield wall were generated and compared in Figure 5. The maximum seismic forces at the secondary shield wall were also generated and compared in

Table 2. The comparative results show that the presence of the IRWST increases the seismic response of the internal structures by 14% to 20%. Amount of increment of seismic forces are not significant from the structural design viewpoint.

The fluid modeling techniques were evaluated by comparison of the response spectra for 2% damping at the mid-height of the IRWST wall from the seismic analyses of the three different analytical models. The analyses were performed using the direct frequency response analysis method [7]. Different structural dampings were used for the sloshing and structural behaviors in the two 2-dimensional stick models which were 0.5% and 4%, respectively. The fluid elements used in the 3-dimensional model are considered compressible and the damping effect resulting from sloshing was neglected. The comparative results are shown in Figure 6. As shown in the figure, the results from the mass-spring methods of TID-7024 or ASCE 4-86 give conservative results compared with the finite element method using the acoustic fluid element.

5. CONCLUSION

The following concluding remarks can be made based on the results of the comparative evaluations Containment Building and IRWST for KNGR.

- The seismic design effects on the internal structures with the IRWST are not significant when compared with the results from the model without the IRWST. The presence of the IRWST slightly increases the seismic response of the internal structures, but is considered acceptable from engineering design point of view.
- In a comparative study on fluid modeling techniques, the methods presented in both TID-7024 and ASCE Standard 4-86 provide similar and acceptable results with reasonable conservatism and they are also applicable to the annular tank.

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Table 1 Formulas for the Water Mass and Spring Constant [1]

	Rectangular Tank	Circular Tank
Impulsive Water Mass	$\frac{M_o}{M} = \frac{\tanh\left(\sqrt{3} \frac{l}{h}\right)}{\sqrt{3} \frac{l}{h}}$	$\frac{M_o}{M} = \frac{\tanh\left(\sqrt{3} \frac{R}{h}\right)}{\sqrt{3} \frac{R}{h}}$
Location of Impulsive Mass	$h_0 = \frac{3}{8} h$	$h_0 = \frac{3}{8} h$
Sloshing Water Mass	$\frac{M_1}{M} = 0.527 \frac{l}{h} \tanh\left(1.58 \frac{h}{l}\right)$	$\frac{M_1}{M} = 0.318 \frac{R}{h} \tanh\left(1.84 \frac{h}{R}\right)$
Stiffness for Sloshing Mode	$K = \omega^2 \cdot M_1$ $\omega^2 = \frac{1.58}{l} \cdot g \cdot \tanh\left(1.58 \frac{h}{l}\right)$	$K = \omega^2 M_1$ $\omega^2 = \frac{1.84}{R} \cdot g \cdot \tanh\left(1.84 \frac{h}{R}\right)$
Location of Sloshing Mass	$\frac{h_1}{h} = 1 - \left\{ \frac{\cosh\left(1.58 \frac{h}{l}\right) - 1}{1.58 \frac{h}{l} \sinh\left(1.58 \frac{h}{l}\right)} \right\}$	$\frac{h_1}{h} = 1 - \left\{ \frac{\cosh\left(1.84 \frac{h}{R}\right) - 1}{1.84 \frac{h}{R} \sinh\left(1.84 \frac{h}{R}\right)} \right\}$
where, M=total water mass, h=water height, l=half width of the tank, R=radius of the tank, and g = gravitational acceleration		

Table 2. Maximum Seismic Forces of the containment building Models (with and without IRWST) at the Secondary Shield Wall

Response Type	Location	Model		Response Ratio (%)
		without IRWST	with IRWST	
Shear Force (kips)	at the bottom	122.84	141.82	115.5
	at the mid-height	103.79	122.14	117.7
	at the top	18.48	22.17	120.0
Moment (kips-ft)	at the bottom	0.84×10^4	1.01×10^4	120.2
	at the mid-height	3.06×10^3	3.66×10^3	119.6
	at the top	0.99×10^2	1.13×10^2	114.1

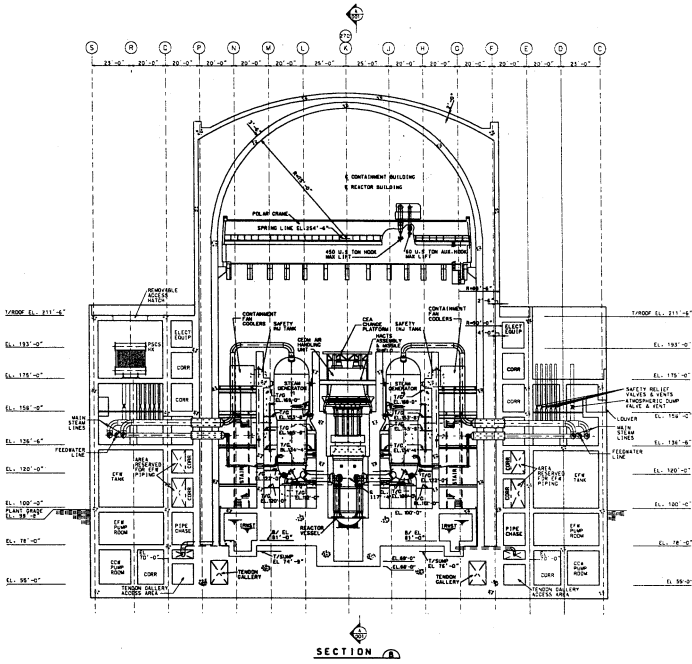


Figure 1. General Arrangement of KNGR

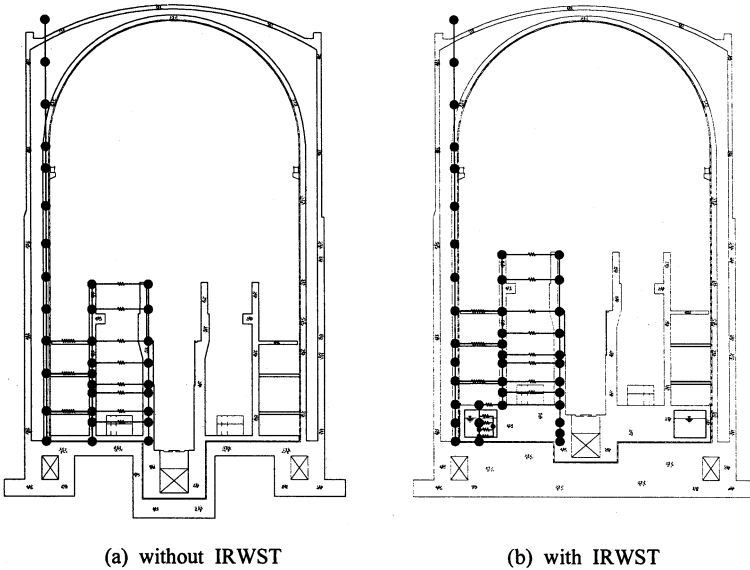


Figure 2. Analytical Models of the Containment Building

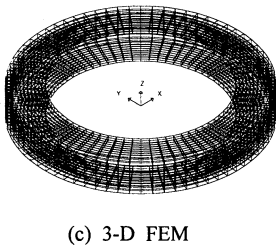
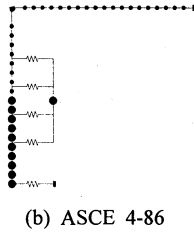
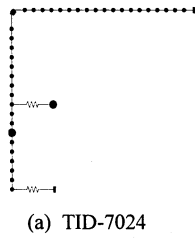


Figure 3. Analytical Models of IRWST

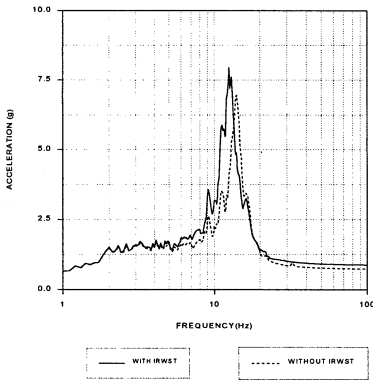
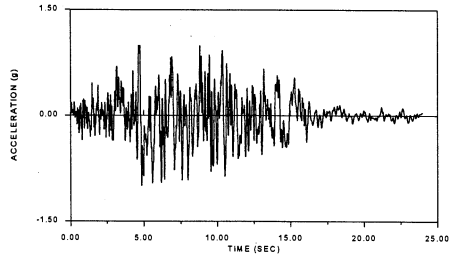
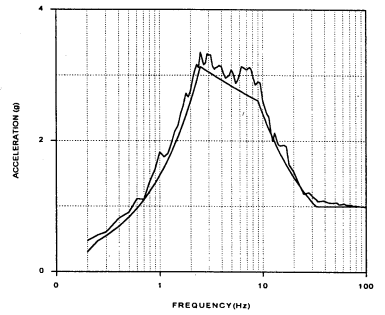


Figure 5. Floor Response Spectra of the Containment Building Model at the Top of Secondary Shield Wall (2% Damping)



(a) Time History Acceleration



(b) Response Spectrum (5% Damp.)

Figure 4. Horizontal Input Motion Scaled to 1.0 g

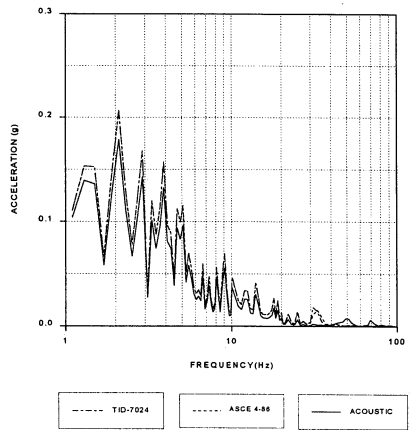


Figure 6. Fourier Spectrum of Acceleration Responses at the Mid-Height of Wall