DEVELOPMENT OF STRUCTURAL MODELS OF A CONDENSATE STORAGE TANK IN NUCLEAR POWER PLANTS

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Condensate storage tanks (CSTs) are one of the essential structural components in NPPs. Their dynamic behavior is highly nonlinear under seismic shakings and their failure modes are complex. In order to capture the dynamic behavior of a CST and its failure modes, a detailed 3D CST model and three sets of 2D models are generated, and their accuracy and efficiency are compared regarding dynamic characteristics and seismic performance using modal and time history analyses. Results of these analyses enable proper evaluation of the errors associated with the lower fidelity simulations. It is also found out that correction factors can be developed based on the 3D model to apply to the 2D models to support the computationally efficient uncertainty analysis of CST failure probability for use in seismic PRA.

I. INTRODUCTION

Seismic probabilistic risk assessment (SPRA) requires dynamic analysis of structures, systems and components (SSCs) in a nuclear power plant (NPP). In order to evaluate the variations and uncertainties in calculated seismic performance of components under different ground motions, it is necessary to develop relatively simple structural representative models that can be analyzed a large number of times but with sufficient accuracy. Among various buildings and components that constitute a NPP, this study focuses on condensate storage tanks (CSTs) or other large tanks containing water whose failure could result in the common cause failure (CCF) of other safety related components. The CST is one of the essential components of a NPP (Section II.A), but its seismic performance is very complex and complicated because of the coupled fluid-structure dynamic effects including sloshing. Therefore, it is not easy to estimate its failure probability, particularly due to the presence of significant uncertainties associated with modeling and simulation of its behavior under seismic shakings.

In this study, the dynamic characteristics and seismic performance of the CST are simulated using approaches with different levels of fidelity and nodalization to determine the degree of realism in the results, as well as the computational efficiency in obtaining them. For the highly nonlinear dynamic analyses, detailed 3D finite element models of CST are generated in ANSYS [1] (Section II.B) to more accurately account for the effects of fluid-structure interaction. Three different simplified 2D models (Section II.C) are used considering impulsive and convective fluid pressure. In the 2D models, the stored fluid (water) in the tank is modeled using horizontal springs between the mass of liquid and tank walls. In order to evaluate the dynamic characteristics and failure modes of CST, various sets of engineering demands such as displacement and stresses are examined and the results produced by the developed models are compared.

Using the simplified 2D and detailed 3D models, a set of time history analyses are conducted (Section III) to evaluate the seismic performance of CSTs. Time history analysis results from different CST models are analyzed and compared. For the evaluation of the seismic failure probability of the CST, a set of failure modes is considered including yielding of restrainers and buckling of tank walls. The locations and values of maximum stresses of tank walls are determined and compared. Developed models are compared in terms of accuracy, time required for analysis, and simplicity. The dynamic characteristics of 2D and 3D models are summarized, the variations of simulation results are analyzed, and the limitations of each model are explained.

Through these comprehensive comparisons, differences in the characteristics of the CST models are identified. Results of this study help to develop more accurate but simpler models of CSTs so that the suggested models can provide the computational efficiency required in SPRA.

II. MODEL DESCRIPTION

II.A. Condensate Storage Tank (CST) in NPPs

The condensate storage tank (CST) is one of the most important structures for the SPRA of NPPs. Not only are the CSTs the source of water for the auxiliary feedwater system, but they also contain very large volumes of water that could result in internal flooding and the loss of other safety related equipment. Although the mechanical characteristics of CST vary depending on capacities and locations, most of them have a large diameter and relatively low height. A typical damage mode that is of concern is referred to as elephant-foot buckling or shear buckling, where the tank wall buckles under high axial stresses. The design details of the CST used in this study are based on Nie et al. (2012). The design of this CST, dimensions and mechanical characteristics are provided in Fig. 1 and Table I. Based on these features, three sets of simplified 2D models and a detailed 3D model are generated, and their dynamic characteristics and seismic performance are analyzed.
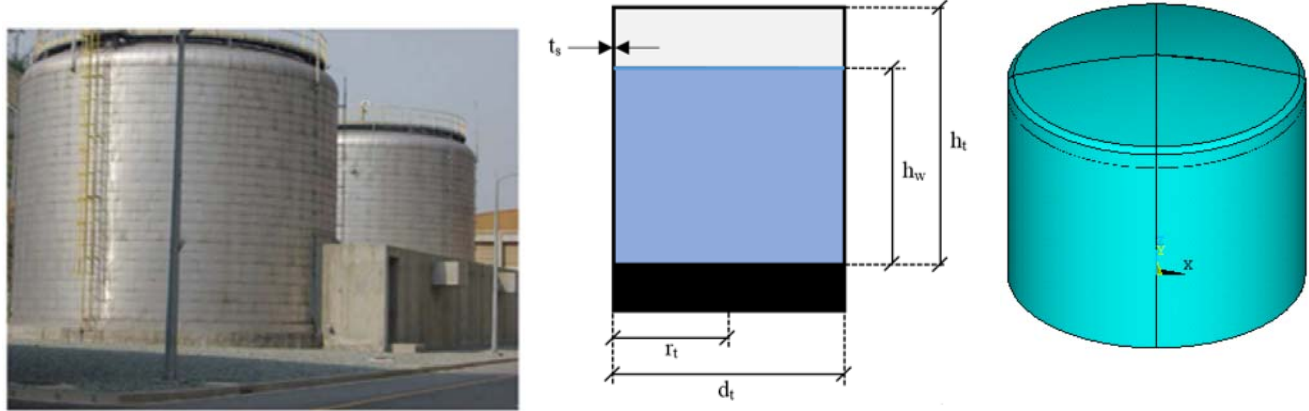

Fig. 1. CST example: (a) picture of Nie et al. (2012) example and (b) visual representation

TABLE I. Key dimensions and properties of CST model (Nie et al. 2012)

Parameter and unit	Parameter variable	Parameter value
Inner diameter of tank (m)	d_t	15.2
Tank height (m)	h_t	11.4
Water height (m)	h_w	10.7
Shell thickness (mm)	t_s	12.7
Bottom plate thickness (mm)	t_p	6.35
Density of tank steel (kg/m^3)	ρ_s	7,834
Density of water (kg/m^3)	ρ_w	1,000
Young's modulus of tank wall (GPa)	E_s	200
Poisson's ratio of tank wall	v	0.30

II.B. 3D Finite Element Models of CST

II.B.1. Tank Body and Fluid Modeled Using 3D Finite Elements

A 3D finite element (FE) model of the CST is developed using FLUID220 and SHELL181 elements in ANSYS [1]. SHELL181 is used to model the tank body. This element type is suitable for thin to moderately thick shell structures. The selected 3D shell element combines both membrane and bending actions with six degrees of freedom at each of the eight nodes, i.e., translations in the *x, y,* and *z* directions, and rotations about the *x-, y-,* and *z*-axes, respectively. The fluid inside is modeled by FLUID80 element with eight nodes each having three degrees of freedom. Given incompressible fluid properties, FLUID80 is particularly well-suited for tracing hydrostatic pressures, fluid-solid interaction and acceleration effects, such as sloshing. The meshing and the generation of 3D tank model are based on adequately small dimensions to simulate the CST response relatively quickly and accurately (Fig. 2).
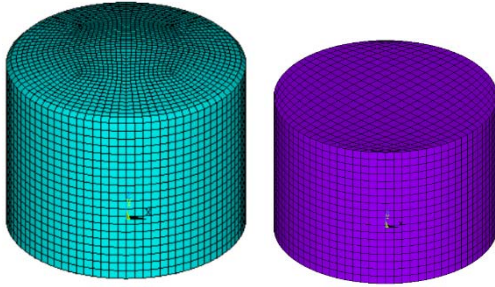
Fig. 2. Meshed 3D models: (a) Tank body and
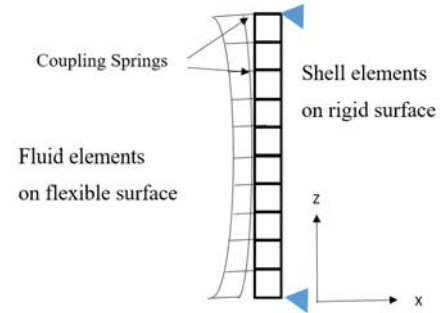(b) water inside

Fig. 3. Fluid-structure interaction model
on the contact surfaces

II.B.2. Contact Elements

   In order to capture the nonlinear interaction between the tank body and fluid, contact elements are added to the FE model between the tank wall and fluid. Contact elements are attached to the neighboring surfaces to enable transfer of forces in terms of pressure and friction as shown in Fig. 3. In this study, there are a set of coincident nodes that are coupled only in the direction normal to the interface as shown in Fig. 3. Special associations among nodal degrees of freedom can be modeled through coupling springs connecting the neighboring nodes that belong to different types of elements. Coupling springs are applied at the contact surface of the inside tank walls and the bottom and ceiling of the tank as illustrated in Fig. 4.

   In order to generate such coupling effects at the location where the nodal degrees of freedom are combined, there must be two coincident lines at the same level or point that belong to fluid and shell elements, respectively. In this case, tank shell only restrains the normal component of fluid movements along the contact surface by coupling a prime degree of freedom in the horizontal direction. The fluid elements inside can flow up and down freely to simulate the dynamic sliding or sloshing effects due to ground motions. The coupling strategy is achieved with the CPINTF command in ANSYS.
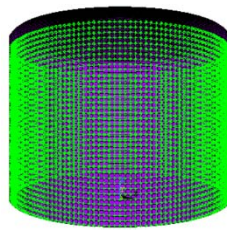
(a) An example of coupling springs
on the fluid-shell interaction surface
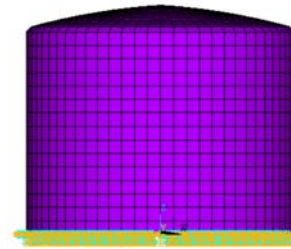
(b) Boundary condition of 3D CST

Fig.4 Contact Element and Boundary Condition of 3D CST

II.B.3. Boundary Conditions

   As one of the critical steps related to the FE modeling of typical structures, the boundary conditions need to be properly modeled through application of force or deformation constraints at specific points or areas. Incorrect boundary conditions may cause substantial errors by generating unrealistic deformation of the tank body. Since this study focuses more on the nonlinear behavior of fluid-structure interaction, the boundary condition of tank body is assumed to be fully restrained or fixed to a rigid foundation. Boundary conditions at the tank bottom shown in Fig. 5 allow the soil and structure connection to translate resistance and friction forces horizontally. Along the circumferential length of tank bottom, translational (displacement) degrees of freedom in the three directions are constrained assuming anchor bolts provide full rigidity. Also, due to the weight of fluid inside the tank, the inner pressure of fluid causes distributed tensile stresses in the tank walls in the circumferential direction. Axial load in tank walls due to gravity maintains equilibrium with the distributed fluid pressure at different tank heights.

II.C. 2D Simplified Models of CST

   Three different simplified 2D models are considered in this study. The first method by Housner (1963) was also adopted by the American Concrete Institute (ACI) and codified in the ACI 350.3 (2001) to be used for design of CSTs. Both models

were examined in this research and the dynamic analysis results were very similar. Therefore, only the Housner model is discussed herein.

II.C.1. Approach 1: Housner Model (1963)

The first 2D approach considered here was developed originally by Housner (1963) and derived under the assumption of rigid behavior of tank walls. In this model, the water inside the CST is modeled as one impulsive mass, which represents the water that moves in synchronization with the tank walls, and one convective mass, which represents the sloshing effect of the water. Fig. 5 illustrates the Housner model along with the corresponding FE model generated in SAP2000.

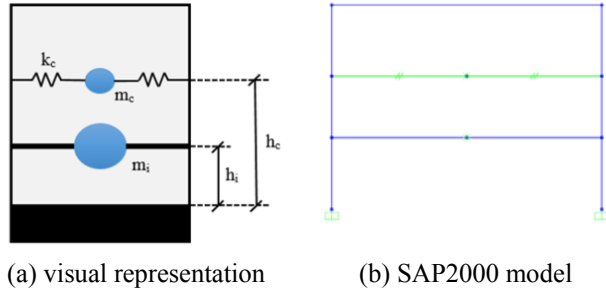| (a) visual representation | (b) SAP2000 model | (a) visual representation | (b) SAP2000 model |

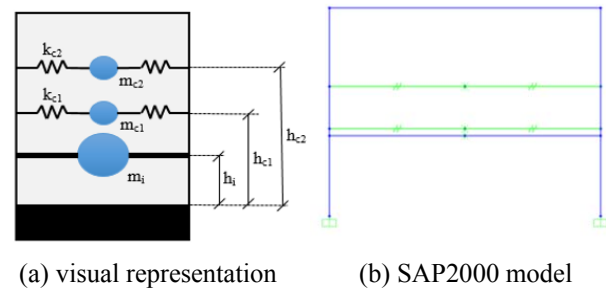Fig. 5. Housner (1963) 2D CST models   Fig. 6. Haroun and Housner (1981) 2D CST models

To obtain the parameters required to develop and analyze the CST model in SAP2000, required values of parameters are given in Table II.

TABLE II. 2D CST parameters for the Housner model

Parameter and unit	Parameter variable	Parameter value
Equivalent mass of impulsive component (kg)	m_i	1,343,000
Height to center of gravity of impulsive mass (m)	h_i	3.99
Equivalent mass of convective component (kg)	m_c	457,300
Height to center of gravity of convective mass (m)	h_c	7.41
Total stiffness of convective mass spring (kg/m)	k_c	3,457,000
Stiffness of each convective mass spring (kg/m)	$k_c/2$	1,728,500

II.C.2. Approach 2: Haroun and Housner Model (1981)

Another 2D approach that is considered here was developed by Haroun and Housner (1981). This model was built upon the previous research by Housner (1963). After experimental results suggested that liquid storage tank walls do not behave rigidly under seismic shakings, a second convective mass was added to model the flexible nature of the tank walls. This second convective mass represents the small mass of sloshing water that does not move in synchronization with either of the other two masses of water or the seismic ground motion. The modeling parameters are presented in Table III. The configuration and the FE representation of the CST in SAP2000 are shown in Fig. 6.

TABLE III. 2D CST parameters for the Haroun and Housner model

Parameter and unit	Parameter variable	Parameter value
Equivalent mass of impulsive component (kg)	m_i	1,323,000
Height to center of gravity of impulsive mass (m)	h_i	4.42
Equivalent mass of first convective component (kg)	m_{c1}	1,265,000
Height to center of gravity of first convective mass (m)	h_{c1}	4.80
Total stiffness of first convective mass spring (kg/m)	k_{c1}	1.30×10^{10}

Stiffness of each first convective mass spring (kg/m)	$k_{c1}/2$	6.5 x 10^9
Equivalent mass of second convective component (kg)	m_{c2}	625,000
Height to center of gravity of second convective mass (m)	h_{c2}	7.10
Total stiffness of second convective mass spring (kg/m)	k_{c2}	4,603,000
Stiffness of each second convective mass spring (kg/m)	$k_{c2}/2$	2,301,500

II.C.3. Approach 3: Bauer Model (1964)

The third 2D approach was developed by Bauer (1964). This model was intended to analyze fluid movement in vehicles and tanks in space when subjected to lateral forces. However, the same mechanistic principles are shared among seismic shaking and lateral forces in space and subsequently this approach was adopted here for analysis. While the Bauer model allows for several convective masses to be considered, depending on the type of structure being modeled, a model with two convective masses and one impulsive mass, similar to Haroun and Housner (1981), is created. The parameters used for this model are given in Table IV.

TABLE IV. 2D CST parameters for the 1964 Bauer model

Parameter and unit	Parameter variable	Parameter value
Equivalent mass of impulsive component (kg)	m_i	1,884,500
Height to center of gravity of impulsive mass (m)	h_i	5.28
Equivalent mass of first convective component (kg)	m_{c1}	53,000
Height to center of gravity of first convective mass (m)	h_{c1}	6.73
Total stiffness of first convective mass spring (kg/m)	k_{c1}	858,300
Stiffness of each first convective mass spring (kg/m)	$k_{c1}/2$	429,150
Equivalent mass of second convective component (kg)	m_{c2}	8215
Height to center of gravity of second convective mass (m)	h_{c2}	8.50
Total stiffness of second convective mass spring (kg/m)	k_{c2}	243,500
Stiffness of each second convective mass spring (kg/m)	$k_{c2}/2$	121,750

III. DYNAMIC ANAYSIS

III.A. Modal Analysis Result of 3D Model and 2D Models

Modal analysis is conducted to determine dynamic characteristics of the 3D CST model including its fundamental frequencies and mode shapes. The fundamental mode shapes and frequencies are summarized in Fig. 7. A total of four mode shapes and their frequencies are listed. Three views of each mode are illustrated including 3D and top views of tank body and the fluid inside the tank. As shown in fluid shapes, the sloshing effects are captured. The first two mode shapes and frequencies are identical in the two horizontal directions. Since the CST is a cylindrical shape, the mass and stiffness distributions in orthogonal horizontal directions remain the same. It is observed from the results of the modal analysis that the mass participation factors for these first several modes are relatively small. Consequently, it is expected that their effects on the dynamic behavior of the system are less significant compared to other modes with larger mass contribution factors.

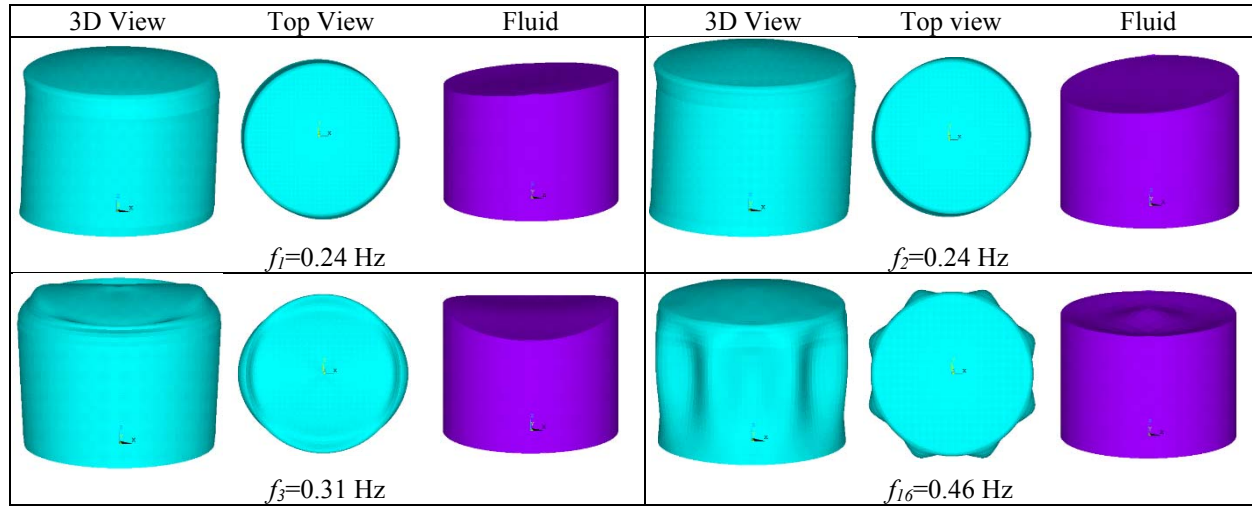| 3D View	Top View	Fluid	3D View	Top view	Fluid
	f_1=0.24 Hz			f_2=0.24 Hz	
	f_3=0.31 Hz			f_{16}=0.46 Hz	

Fig. 7. Fundamental frequencies and mode shapes for 3D CST

The modal analysis results of the 3D model are compared to those of the 2D models in Fig. 8. As expected, the first two mode shapes and frequencies of the 3D model are close to the first mode and frequency of the 2D models. However, the detailed 3D model has a larger number of mode shapes and frequencies compared to the 2D models. The first five modes of the 2D models significantly affect the dynamic behavior of the CST since the sum of the mass participation factor of these five modes is close to 100%. Among the three 2D models, however, the higher mode frequencies and mass participation factors are very different. The 2D model from Haroun & Housner is relatively flexible since it includes the flexibility of the tank body itself.
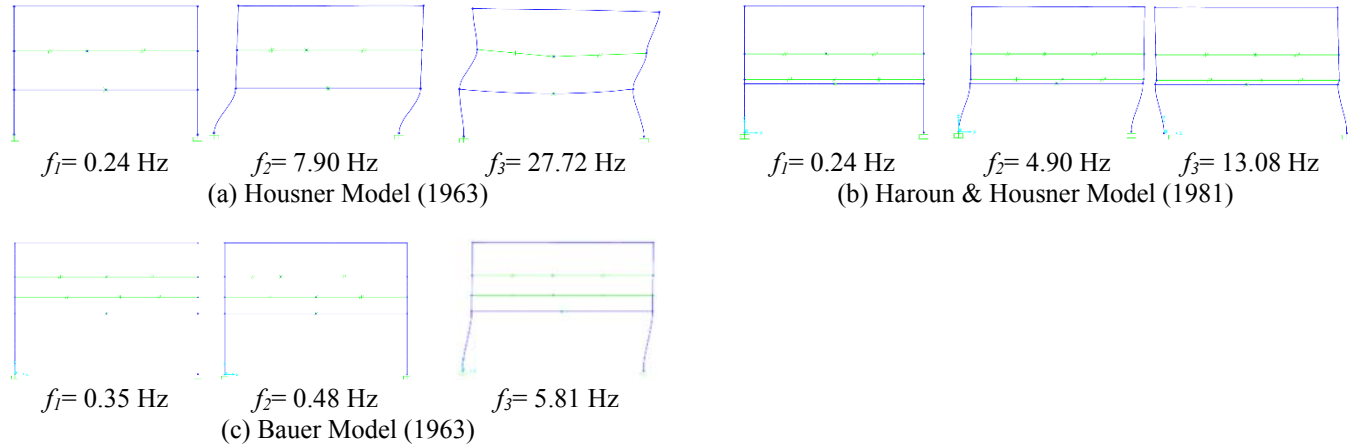
f_1= 0.24 Hz f_2= 7.90 Hz f_3= 27.72 Hz f_1= 0.24 Hz f_2= 4.90 Hz f_3= 13.08 Hz
(a) Housner Model (1963)   (b) Haroun & Housner Model (1981)

f_1= 0.35 Hz f_2= 0.48 Hz f_3= 5.81 Hz
(c) Bauer Model (1963)
Fig.8. First three mode shapes and frequencies for 2D tank models

III.B. Time History Analysis of 3D Model

This section presents the time history analysis (THA) results of the 3D model and the three 2D models. THA was conducted using the recorded acceleration record of the El Centro earthquake. The ground motion was recorded at USGS STATION 117 during the 1940 Imperial Valley earthquake. The recorded positive and negative peak accelerations are 0.271 g and -0.313 g, respectively.

Fig. 9 shows the displacement response history calculated at the top of the 3D CST model and three 2D models. The largest response is calculated from the Haroun & Housner model, which is the most flexible model. The smallest response is calculated from the 3D model. In the 3D model, the radial water pressure to the interior of the tank wall causes an initial tensile stress in the circumferential direction of the tank as well as some small deformations. The small lateral deformation is observed at the beginning of the time history analysis.
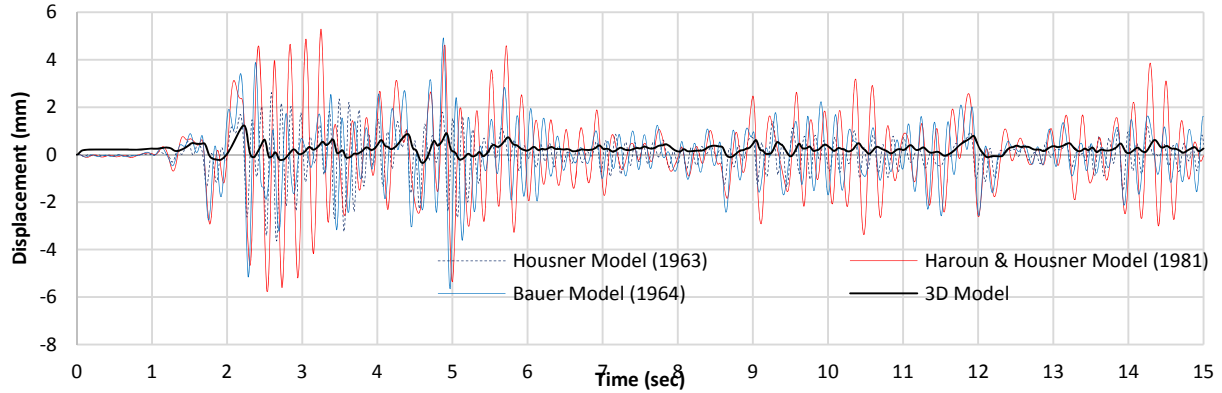
Fig. 9. Displacement response at the roof level of the 3D CST model

Figure 10 presents the stress response of tank wall derived from the time history analysis. It is a contour of the 1st principal stress at the initial condition and at the specific time when the peak ground acceleration occurs (at 2.2 sec). Figure 10(a) shows the gravity effect due to the water pressure and self-weight of the tank body. Figure 10(b) illustrates the moment when the tank body experiences the maximum stresses due to the seismic shaking. These stress responses provide the maximum stresses of tank wall as well as the critical locations for local buckling. Once the maximum stresses exceed the yield stress, elephant-foot buckling or shear buckling can happen. It is the most common form of mechanical failure in CSTs.
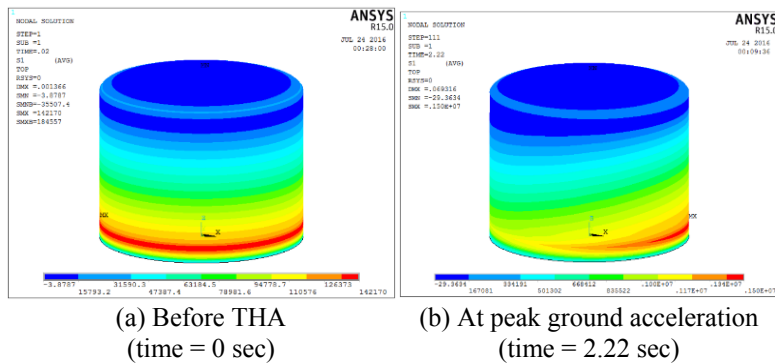

(a) Before THA
(time = 0 sec)

(b) At peak ground acceleration
(time = 2.22 sec)

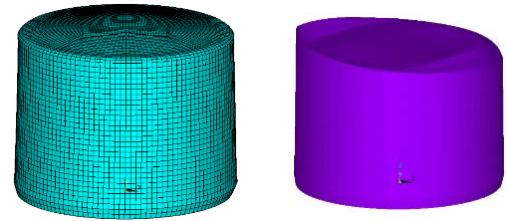Fig. 10. 1st Principal stress distribution contours by Time Hisotry Analysis (THA)

Fig. 11. Deformation shapes of tank body and fluid at the specific time (time =2.22s)

IV. CONCLUSIONS

In this study, the highly nonlinear dynamic behavior of a CST was investigated. A detailed 3D model and three different 2D models were subjected to seismic shaking. For the efficiency and accuracy of simulations, modal analysis and time history analysis were conducted, and the analysis results were compared. It was observed that four different CST models have slightly different dynamic characteristics and seismic responses. For example, the displacement response of the 3D model is relatively smaller than the 2D models due to membrane effects, which requires further investigations with various types of ground motion histories. The 2D models could capture limited numbers of global modes, while the 3D model captures not only various global modes but also local modes. Therefore, the 3D detailed model provides more information regarding maximum stresses of tank walls and their locations depending on ground motion histories. Therefore, the spatial distribution of critical locations where the maximum stress can occur and the values of distributed stresses on tank body enable an assessment of the seismic failure probability of the CST at a specific magnitude of earthquake or possibly to develop a correction factor that could be applied to a 2D model. The 2D models are much faster to analyze and to perform uncertainty analyses. Furthermore, if the failure mode being examined is associated with anchorage or the fastener to the floor, the simpler models should be adequate. Comparisons and differences in the characteristics of different CST models help to better understand seismic performance of CSTs and to conduct computationally efficient uncertainty analyses in support of SPRA.

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