Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division III

SEISMIC FRAGILITY ANALYSIS OF STORAGE TANK CONSIDERING FLUID-SOLID COUPLING AND SOIL-PILE INTERACTION EFFECTS

Chang-Ching Chang[1], Chia-Han Chen[2], Chiun-Lin Wu[3], Hsuan-Teh Hu[4]

[1] Associate Research Fellow, National Center for Research on Earthquake Engineering, National Applied Research Laboratories, Taipei, Taiwan (ccchang@narlabs.org.tw)
[2] Associate Research Fellow, National Center for Research on Earthquake Engineering, National Applied Research Laboratories, Taipei, Taiwan
[3] Research Fellow&Deputy Director General, National Center for Research on Earthquake Engineering, National Applied Research Laboratories, Taipei, Taiwan
[4] Professor, Department of Civil Engineering, National Cheng Kung University

ABSTRACT

Liquid storage tanks are essential structures in electric plants. Typical damage of ground-supported tanks during past earthquakes was in the form of cracking at the corner of the bottom plate and compression buckling of tank wall due to uplift, sliding of the base, anchorage failure, sloshing damage around the roof, failure of piping sys-terms and plastic deformation of the base plate. This study compares a sophisticated finite element (FE) model and a simplified lumped mass model for seismic fragility analysis. A sophisticated FE model can reflect the hydrodynamic effect of an oscillating liquid, and detailed structural responses of the entire wall shells with seismic soil-structure interaction can be estimated. A seismic fragility analysis is performed for liquid storage tanks using the real earthquake ground motion records, constructed FE model, and limit states. Failure modes, including sloshing of contents, tensile cracking, and compression failure of the tank wall due to bending, are accounted for. In addition, a simplified lumped mass model is investigated for comparison purposes to derive a seismic fragility curve. This study will develop a methodology for seismic fragility analysis of liquid storage tanks considering fluid-solid coupling and soil-pile Interaction effects.

INTRODUCTION

Seismic probabilistic risk assessment (SPRA) determines the annual frequency of unacceptable performance of a nuclear power plant (NPP), such as core melt and release of radiation. In recent years, SPRA studies have been performed on a large number of nuclear power plants in USA. Seismic fragility analysis for structural and nonstructural components in NPPs are needed in the SPRA procedure. The methodology for evaluating seismic fragilities of structures and equipment is documented in the PRA Procedures Guide (USNRC, 1983) and is more specifically described for application to NPPs in Kennedy and Revindra (1984) and Reed and Kennedy (1994). In-depth guidelines for performing a fragility analysis are available in EPRI (2002). This document updates the fragility analysis methodology provided in EPRI TR-103959 (Reed and Kennedy, 1994), and EPRI 3002012994 (2018) .

To investigate the fluid-structure coupling effects resulting from the oscillation of fluids inside tanks under seismic actions, as well as the pile-soil interaction effects, this study utilizes the National Center for Research on Earthquake Engineering (NCREE)'s large-scale biaxial shear box to establish a fluid model of the tank. Large-scale shake table tests are conducted to consider the fluid-structure coupling and soil-structure interaction effects on the tank's response to seismic loading. Subsequently, a numerical model in SAP2000 is developed based on the experimental model.

To establish the relationship between seismic intensity and the degree of tank damage after seismic events, this paper constructs seismic fragility curves to predict the damage condition of tank structures under seismic motion. These curves calculate the probability of structural failure when subjected to loading exceeding their ultimate limit state.

MATERIALS AND METHODS

The foundation pile and part of the base are made of aluminum material, while the bucket section is constructed from acrylic material .This study utilizes soil springs to simulate the pile-soil interaction effects and employs a simplified liquid model to simulate fluid-structure coupling effects. Based on this, an SAP2000 model is constructed for seismic fragility curve analysis as shown Figure 1.

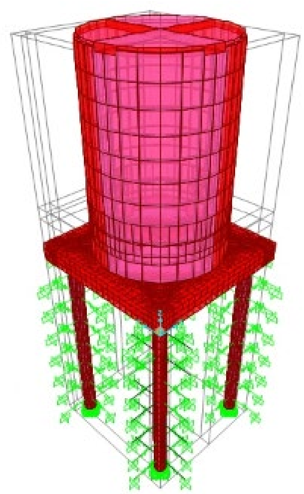

Figure 1. Tank Model (SAP2000)

RESULTS AND DISCUSSIONS

The natural frequency of the model calculated using SAP2000 is 33.83 Hz, with an error of 0.29% compared to the results from the white noise test. The seismic time histories used in this study are mostly close to the fluid's significant frequency of 2Hz, which is far from the significant frequency of the sand soil. Therefore, the acceleration response inside the sand soil is very close to the acceleration response of the outer frame of the shear force box. According to the comparison of the maximum horizontal accelerations at the bucket top, base top, and pile base in the SAP2000 model for a 100mm fluid at 2Hz dynamic analysis, it can be seen that the SAP2000 model's maximum acceleration occurs at a seismic duration of 2.024 seconds, which is the same as the maximum acceleration time observed in the experimental results. By examining the 95% confidence level seismic fragility curve for convective mode in the horizontal direction (Sa), it is found that for the high confidence of low probability of failure (HCLPF) capacity values vary depending on the limit state and are 5.72 m/s^2 and 10.43 m/s^2, respectively, the fragility curve is shown as in Figure 2 and 3.

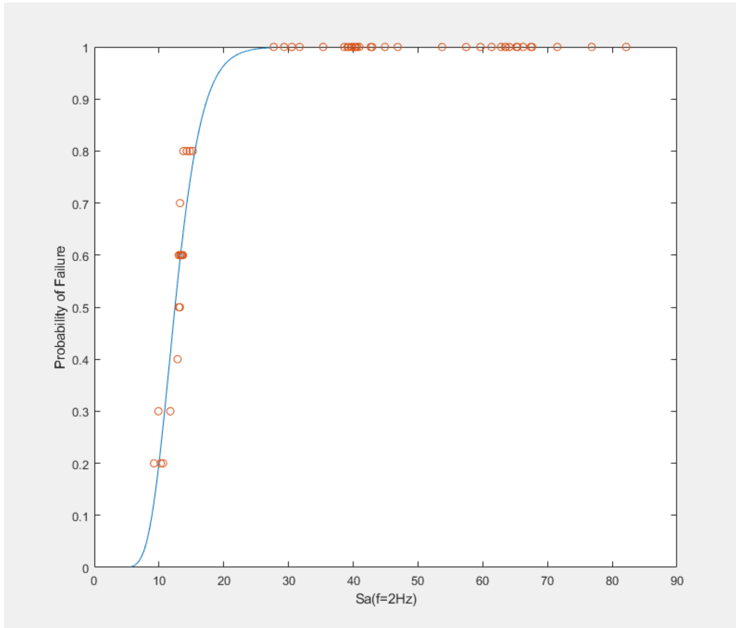

Figure 2. fragility curve (limit state: 125mm)

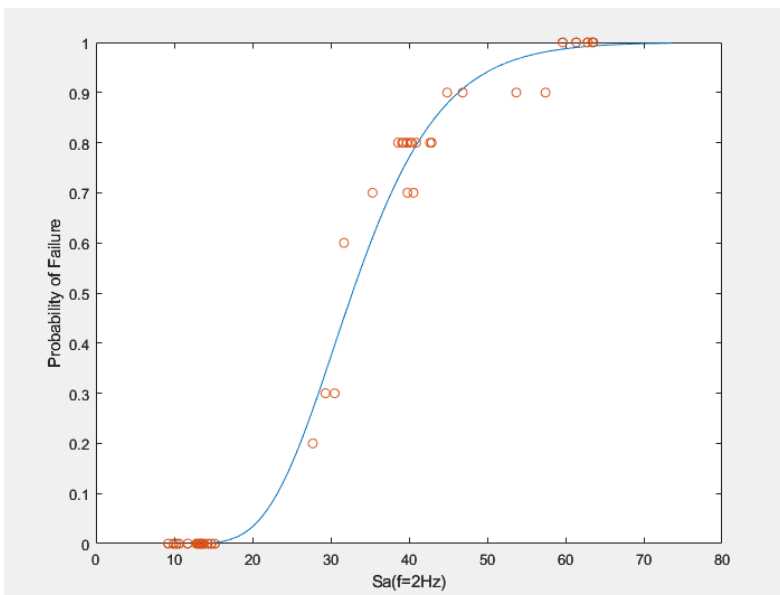

Figure 3. fragility curve (limit state: 300mm)

CONCLUSION

Modal analysis in SAP2000 can determine the natural frequencies and effective mass participation of the structure based on the system characteristic equation. The significant frequencies of the tank structure's main control modes obtained from effective mass participation closely match the significant frequencies obtained from the white noise test analysis, with an error of 0.29%. This confirms the accuracy of SAP2000's modal analysis solver.

The seismic time histories used in this study are mostly close to the fluid's significant frequency of 2Hz, which is far from the significant frequency of the sand soil. Therefore, the acceleration response inside the sand soil is very close to the acceleration response of the outer frame of the shear force box.

According to the SAP2000 model's dynamic analysis of the bucket top, base top, and pile base horizontal maximum accelerations at 2Hz seismic duration, it is observed that the maximum acceleration values occur at the tank top, at a seismic duration of 2.024 seconds, which matches the experimental results. The maximum acceleration at the bucket top is 1.069 m/s^2. By comparing SAP2000 model's tank top acceleration, velocity, and displacement time history with experimental and ABAQUS simulation results, it is evident that SAP2000 simulation results closely match experimental results, further verifying the feasibility of using SAP2000 to establish a tank model without fluid and nonlinear soil springs.

By comparing the time history of the maximum horizontal acceleration at the tank top, base top, and pile base in the SAP2000 model for a 100mm fluid at 2Hz seismic analysis, it is found that the accelerations at these three points are very close. This is because the stiffness of the tank structure is relatively high, resulting in similar responses at these three points. The maximum acceleration values in the SAP2000 model occur at a seismic duration of 2.024 seconds, which is consistent with the experimental results. The maximum structural acceleration occurs at the bucket top, measuring 1.07 m/s^2. Comparing the tank top acceleration and displacement time history with experimental and ABAQUS simulation results, it is confirmed that SAP2000 simulation results closely match experimental results, validating the feasibility of using SAP2000 to create a simplified model for liquid storage tanks.

The research discusses the fragility curves for the liquid storage tank obtained in this study. To highlight the seismic response under the convective mode, the significant frequencies used in the seismic time histories closely match the convective mode's significant frequency of 2Hz. By observing the 95% confidence level seismic fragility curves for convective mode in the horizontal direction (Sa), the values for high reliability and low damage probabilities are 5.72 m/s^2 and 10.43 m/s^2, respectively. However, for the fragility curve corresponding to PGA, due to a limited number of data points in the 0-1 range of the failure probability, the calculated logarithmic standard deviation is too small, requiring more sampling points for a reasonable representation..

REFERENCES

Malhotra, P. K. (2006), "Earthquake Induced Sloshing in Tanks with Insufficient Freeboard," *Structural Engineering International*, 16:3, 222-225, DOI: 10.2749/101686606778026466

Malhotra, P. K., Wenk, T., Wieland, M. (2000), "Simple Procedure for Seismic Analysis of Liquid-Storage Tanks", *Structural Engineering International*, 10:3, 197-201, DOI: 10.2749/101686600780481509

Phan, H. N., Paolacci, F., Alessandri, S. (2016), "Fragility analysis methods for steel storage tanks in seismic prone areas", . ASME 2016 Pressure Vessels and Piping Conference, Paper No: PVP2016-63102, July 17–21, Vancouver, British Columbia, Canada..

Malhotra, P.K. (2021). Seismic Response of Liquid-Storage Tanks. In: Seismic Analysis of Structures and Equipment. Springer, Cham. https://doi.org/10.1007/978-3-030-57858-9_8

ASCE/SEI 4-16, (2016), "Seismic Analysis of Safety-Related Nuclear Structures", American Society of Civil Engineers.

EPRI, (1994), "Methodology for Developing Seismic Fragilities", Palo Alto, California, Electric Power Research Institute, EPRI TR-103959, 1994..

EPRI, (2018), "Seismic Fragility and Seismic Margin Guidance for Seismic Probabilistic Risk Assessments", Palo Alto, California, Electric Power Research Institute, EPRI TR-3002012994.