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Uncertainty quantification and seismic fragility of base-isolated liquid storage tanks using response surface models

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ABSTRACT

Seismic response of base-isolated liquid storage tank is represented using response surface model (RSM) to consider the uncertainty in the isolator parameters. The effectiveness of RSM to represent the probability distributions of the peak seismic response quantities of the base-isolated liquid storage tank is studied in the framework of Monte Carlo (MC) simulation. Broad and slender configurations of the tanks isolated by lead–rubber bearing (New Zealand – NZ system) characterized with non-linear force-deformation behavior is considered in the present study. The influence of the uncertain isolator parameters on the seismic response of the base-isolated liquid storage tanks is investigated. Subsequently, seismic fragility of the base-isolated liquid storage tanks is evaluated using the RSM based MC simulation. The RSM estimates the non-linear seismic response of the base-isolated liquid storage tanks with sufficient accuracy. It is observed that the uncertainties in the isolator parameters significantly influence the peak response quantities of the base-isolated liquid storage tanks. The effectiveness of the base isolation technique, in terms of the reduced probability of failure, is observed by comparing the fragility curves for the fixed-base and base-isolated liquid storage tanks. It is also observed that increase in the isolation time period decreases the probability of failure for the base-isolated liquid storage tanks. It is concluded that the peak ground acceleration (PGA) of the earthquake ground motion can be included in the RSM to reduce the computational efforts for seismic fragility analysis.

1. Introduction

Liquid storage tanks demand greater safety measures against natural disaster like earthquake. Failure of industrial tanks may trigger more severe consequences on human life through fire, chemical contamination, nuclear radiation etc. Moreover, water storage tanks are required to be maintained functional to serve the society even after devastating earthquake. Hence, protection of liquid storage tanks against earthquake is essential. Dynamic analysis and design of liquid storage tanks against seismic loading are presented in several international standards and design guidelines [1–5]. However, conventional design approaches may not be sufficient to safeguard such important lifeline structures against devastating earthquakes. Base isolation is an efficient technique to enhance the seismic protection level of structures by reducing the transmission of earthquake force from the ground to the structure [6–10]. Suitability of the base isolation technique to protect liquid storage tanks against seismic loading is reported in several studies using deterministic approach [11–15]. It has been demonstrated that the interplay among the system parameter uncertainty and loading uncertainty can markedly change the structural response [16], and thereby the safety of structures [17–19]. The presence of uncertainty is expected to cause a variation of the optimum value of the isolator parameters and may affect the efficiency of the system. Therefore, apart from the stochastic nature of the earthquake load, uncertainty with regard to the system parameters should also be considered. Mishra and Chakraborty [20] studied the effects of considering uncertainties in the isolator parameters on stochastic performance of the base-isolated buildings. They concluded that the influences of the uncertainties in the excitation are more; nevertheless, uncertainties in the isolation parameters cannot be ignored for accurate estimation of the stochastic response of the base-isolated structures. Roy and Chakraborty [21] studied robust design optimization (RDO) of base-isolated system considering random system parameters characterizing the structure, isolator and ground motion model, and they

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observed that neglecting the effect of uncertainty in the optimum design of base-isolated system may be a potential problem. Earlier, Saha et al. [22] investigated the stochastic response of base-isolated liquid storage tanks under random sinusoidal excitation considering uncertainties in the isolation parameters as well as amplitude and frequency of the sinusoidal excitation. They observed that the uncertainties in the amplitude and frequency of the sinusoidal excitation have significant effects on the stochastic response of the base-isolated liquid storage tanks. However, uncertainties in the isolator parameters also play crucial role on the stochastic peak response of the base-isolated liquid storage tanks. Moreover, in that study, they did not consider the parameters that define the non-linear behavior of the isolator. Therefore, it is felt important to investigate the effects of the uncertainties in the isolator parameters on the peak response of the base-isolated liquid storage tanks considering non-linear behavior of the isolation system.

Seismic performance of a structure, considering uncertainties in the system parameters and earthquake excitation, is conveniently represented by fragility curves. Seismic fragility analyses of various structures were presented in several earlier studies [23–27]. Seismic fragility curves for the liquid storage tanks were presented in HAZUS [28] considering five damage states. These fragility curves were developed based on the experts' opinions on the failure of the liquid storage tanks during past earthquakes. Therefore, this approach of fragility curve development is classified as the judgmental approach. However, dependency on the experience of the individual experts and large variation among the judgments are unavoidable shortcomings of this approach. O'rourke and So [29] and Salzano et al. [30] developed empirical seismic fragility curves for cylindrical liquid storage tanks based on the post-earthquake failure data. However, application of the empirical fragility relationships largely depends on the characteristics of the past earthquakes, variation in the structure, and accuracy of the data collection. Razzaghi and Eshgi [31] carried out assessment of the seismic fragility for the liquid storage tanks using dynamic response analysis, and concluded that the slenderness ratio of the tank significantly influences the fragility. Buratti and Tavano [32] developed the fragility curves for the fixed-base liquid storage tanks by conducting dynamic analysis using the added mass modeling approach. They observed secondary buckling of the tank wall before reaching the inelastic buckling limit, i.e. elephant foot buckling.

From the literature review, it is observed that there are several studies carried out on the fragility of the liquid storage tanks. However, fragility of the base-isolated liquid storage tanks is rarely reported. Saha et al. [33] carried out the seismic fragility analysis of the base-isolated liquid storage tanks considering non-stationary earthquake using Monte Carlo (MC) simulation. However, in their study the uncertainties in the isolator characteristic parameters were not considered. Moreover, computational involvement is considerably high in case of the direct MC simulation; wherein, non-linear dynamic analyses are performed by solving the equations of motion for several sets of input parameters. Therefore, for base-isolated liquid storage tanks, which essentially show non-linear behavior, the direct MC simulation may not be a suitable option for fragility analysis. In that case, a less computationally involved representation for the seismic response quantities of the base-isolated liquid storage tanks may prove to be a better choice. Nevertheless, the approximate representation must be accurate enough to estimate the seismic response of the base-isolated liquid storage tanks. Response surface based approximate models are used by several researchers to reduce the computational efforts for structural optimization, uncertainty quantification, reliability assessment, and seismic fragility analysis [34–37]. Iervolino et al. [38] used response surface model (RSM) in combination with first order reliability analysis to develop the fragility curves for ground supported liquid storage tanks considering uncertain liquid filling height. However, the uncertainties in the system parameters and excitation, which significantly influence the seismic response, were not considered in the model.

Herein, response surface method is used to approximate the seismic response quantities of the base-isolated liquid storage tanks duly considering the uncertainties in the isolator parameters. Seismic fragility of the base-isolated liquid storage tank is evaluated using the RSM based simulation. Lumped mass mechanical analog of the liquid storage tank is used to obtain the seismic response quantities at specific design points for development of the RSM. The isolation system is considered as lead–rubber bearing (New Zealand – NZ system) with non-linear force-deformation behavior. Effectiveness of the developed RSM to evaluate the peak response distribution is compared with the direct MC simulation by performing non-linear dynamic analyses for several sets of input parameters. Thereafter, the intensity measure (IM) of the earthquake is included in the RSM to further reduce the computational efforts.

The specific objectives of the present study are: (i) to represent the seismic response of the base-isolated liquid storage tanks by RSM, duly considering the uncertainties in the isolation parameters, namely its yield strength, yield displacement, and damping, (ii) to investigate influence of the uncertain isolator parameters on the seismic response of the base-isolated liquid storage tanks using the RSMs, (iii) to develop seismic fragility curves for the base-isolated liquid storage tanks using the RSM based simulation, and (iv) to assess the RSMs, with and without including the earthquake IM in the model, for evaluating seismic fragility of the base-isolated liquid storage tanks.

2. Modeling of base-isolated liquid storage tank

Several researchers recommended the use of lumped mass modeling of liquid storage tank for seismic analysis [11–13,39–41]. Especially, in routine design of liquid storage tanks, such models are conveniently used as compared to the computationally complex continuum models. Here, the lumped mass mechanical analog, proposed by Haroun and Housner [39], is used to model the cylindrical base-isolated liquid storage tank as shown in Fig. 1a. The sloshing or convective mass (m_c), the impulsive mass (m_i), and the rigid mass (m_r) are lumped at the heights H_c, H_i, and H_r, respectively, from the tank base. The height and radius of the liquid column are denoted by H and R, respectively. The stiffness corresponding to the sloshing mass (k_c) and impulsive mass (k_i) are given as,

$$k_c = 1.84\left(\frac{m_c g}{R}\right)\tanh(1.84S) \quad (1)$$

and

$$k_i = m_i\left(\frac{P}{H}\right)^2 \frac{E_s}{\rho_s} \quad (2)$$

where, $S = H/R$ is the slenderness ratio of the liquid column; E_s and ρ_s are the elastic modulus and mass density of the tank wall material, respectively; and g is the gravitational acceleration. The dimensionless parameter P depends on the tank wall thickness (t_s) and slenderness ratio [40]. The damping coefficients corresponding to the sloshing mass (c_c) and the impulsive mass (c_i) are computed as,

$$c_c = 2m_c\omega_c\xi_c \quad (3)$$