EFFECT OF BASE ISOLATION ON SEISMIC FRAGILITY OF ABOVEGROUND LNG STORAGE TANKS

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ABSTRACT

Fragility curves of base-isolated and non-isolated LNG storage tanks are developed to investigate the effect of the base isolation design to seismic performance of LNG storage tanks. A non-isolated LNG storage tank is selected and two base isolation designs with respect to acceleration and displacement criteria are applied to this tank. Nonlinear time history analyses of the fixed and two base-isolated models are performed for a suite of 20 ground motions scaled to have a specified PGA. Thresholds based on the crack strain at the base of the concrete tank wall defined the limit states for fragility curves. Finally, empirical fragility curves are fitted by lognormal CDF. Comparison of fragility curves of fixed and base-isolated tanks revealed that the base isolation considerably reduces the risk of damage under a specified level of earthquake. The identified performance demand will be later used for constructing tailor-made base isolation devices.

Keywords: Base isolation, Seismic fragility, Failure probability, Limit state, LNG tank.

1. INTRODUCTION

Base isolation has been known to be one of the effective approaches for seismic hazard mitigation of infrastructural systems. As the tools for estimating the behavior of infrastructures under seismic loadings advances both experimentally and numerically, the accurate prediction of performance demand of the base isolation devices becomes possible. At the same time, using constantly improving technologies for constructing damping devised and adopting innovative materials, more fine-tuned base isolation devices can be provided for optimal performance of earthquake resistant infrastructures.

Most researches on the seismic base isolation of infrastructures are focused on the development of effective base-isolators and optimization design of base-isolators (e.g. Marti et al. 2010) while only a few studies on the effect of the base-isolation to the seismic performance of infrastructures are found. The objective of this study is to investigate the effect of the base-isolation design of infrastructure to its seismic performance in terms of fragility functions. As an example

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infrastructure, a liquefied natural gas (LNG) storage tank is selected because the base isolation is commonly used to protect LNG storage tanks from earthquakes. Seismic fragility curves of the non-isolated and base-isolated LNG storage tanks are developed and compared to each other. A suite of 20 different ground motions are adopted to consider uncertainty in the ground motion profile in order to develop fragility curves.

2. BASE ISOLATION DESIGN OF LNG TANKS

The purpose of the base-isolation design is to reduce the inertial force induced by ground accelerations by shifting the fundamental period of the non-isolated structure to a longer period. However, a structure with a longer fundamental period would experience a larger relative lateral displacement. Therefore, a base isolation design is usually controlled by a window of periods defined by an acceleration-induced and displacement-induced periods.

2.1. Description of LNG Tank

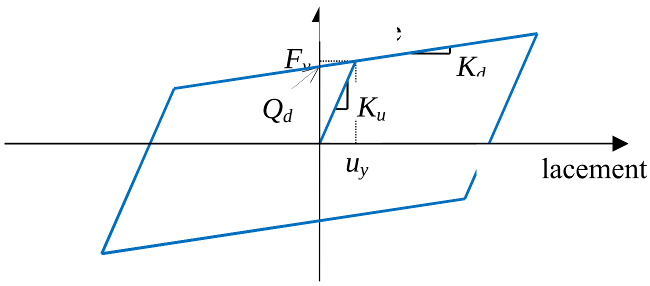
In this study, 140,000kL-capacity aboveground LNG storage tank is selected for example. A full containment tank consists of an inner steel tank and an outer concrete tank. The concrete outer tank protects the inner tank and the insulation from various outside hazards, and also prevents leakage of LNG when it is accidentally spilled or leaked from the inner tank. The inner tank is not considered in this study. The radius and wall height are 82.4m and 35.4m, respectively, and the height of the dome peak is 10.03m. This fixed (as opposed to base isolated) tank is seismically designed for the horizontal peak ground acceleration of 0.2g for a Safe Shutdown Earthquake (SSE).

2.2. Selection of Base-Isolators

The mechanical property of a base isolation system is commonly represented by a bi-linear force-displacement relation as shown in Figure 1. A base isolator is designed by properly defining the initial stiffness (K_u), the yield strength (F_y), and the hardening stiffness (K_d) to guarantee a desired performance of the superstructure. In this study, two different base isolation designs are considered; acceleration-based design and displacement-based design. The former is determined based on reduced acceleration demand and the latter is determined by the displacement limitation.

2.3. Finite Element Modeling of LNG Storage Tanks

To evaluate the dynamic behavior of the fixed and base-isolated LNG storage tanks, finite element models are developed within the capability of OpenSees, a software framework for earthquake engineering simulations. LNG storage tanks are often modeled by so-called ‘tuning-fork model’ (Haroun and Housner 1981) where the flexural and shear stiffness of the tank are modeled by frame elements and the mass is lumped at nodes. In the present study, only the concrete outer wall is modeled where the tank wall and the dome roof are modeled using elastic frame elements and the base-isolator is modeled using *elastomericBearing* element, explicitly designed to model a base-isolator in OpenSees.



olator.

The fundamental period of the fixed model is computed as 0.37sec. The target periods of the acceleration-based and displacement-based designs are determined as 3.5sec. and 5.5sec., respectively, based on the corresponding acceleration and displacement response spectra. The corresponding models are referred to as 3.5T and 5.5T, respectively. The initial stiffness (K_u) of base-isolated models is determined as 3.80×10^3kN/m and 1.54×10^3kN/m for 3.5T and 5.5T models, respectively. The base isolators for 3.5T and 5.5T models are assumed as elastic, leaving K_u the only controlling parameter for seismic design.

3. SEISMIC FRAGILITY OF LNG TANK

3.1. Selected Ground Motions

In this study, variability in the ground motion profile (or record-to-record variability) is considered as the source of uncertainty to develop seismic fragility curves of LNG storage tanks. A set of 20 ground motion records are arbitrarily selected from reference (Lee and Mosalam 2005). Figure 2 shows the response spectra of the 20 selected ground motion records. It is noted that the base isolation designs addressed in the previous section are based on these response spectra.

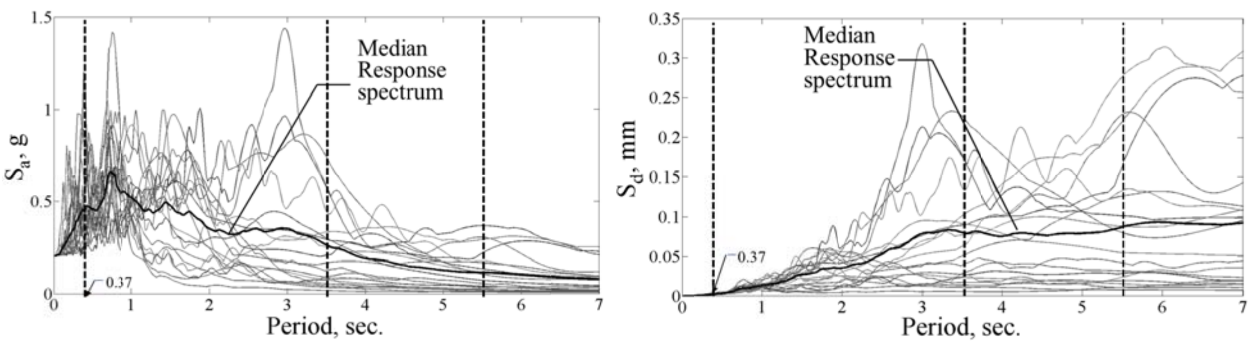


Figure 2: Acceleration (S_a) and displacement (S_d) response spectra of the 20 selected earthquakes.

3.2. Limit States

Seismic fragility is the conditional probability that a structural system exceeds a limit state when subjected to a specified level of earthquake intensity. The most critical part of the concrete outer tank is the base of the concrete wall because the maximum bending moment is expected to occur in this region when an earthquake occurs. In this study, the limit state based on the crack of the critical concrete section is considered. According to the literature (Hurlbut 1985), the tensile strain of 125με causes the crack initiation in concrete sections. Therefore, the maximum axial strain of 125με at the critical section of the concrete tank wall is defined as the threshold of Damage State 2 (DS2). Damage State 1 is considered as no damage. Subsequently, Damage States 3, 4, and 5 (DS3, DS4, and DS5, respectively) are defined also by the maximum axial strain at the critical section, of 250με, 375με, and 500με, respectively. It should be noted that limit states DS2 to DS5 denote minor, moderate, major, and complete damage.

3.3. Fragility curves

Fragility curves of the fixed, 3.5T, and 5.5T models with respect to four limit states, i.e., DS2 to DS5, are developed. Sample probability that the maximum axial strain exceeds the damage state for specified earthquake intensity is computed based on a set of 20 time-history analyses where the peak ground acceleration (PGA) is used as the measure of earthquake intensity. Sample probabilities are computed for a range of PGAs, i.e. from 0.01g to 5.0g with 0.01g interval.

Empirical fragility curves are developed based on the sample probabilities where these curves are fitted by lognormal cumulative distribution functions (CDFs). A lognormal CDF is expressed as

$$\mathrm{P} = \Phi\left(\frac{\ln PGA - \ln c}{\zeta}\right) \tag{1}$$

where c is the median and ζ is the standard deviation of the lognormal distribution. Parameters defining fragility curves are listed in Table 1 and fragility curves are shown in Figure 3.

It is observed that the crack will not likely initiate when the design level earthquake (0.2g) occurs for all three tanks. Furthermore, the two base-isolated tanks will not experience any crack in the tank when an earthquake with PGA of 1.5g or less occurs. For DS2 limit state, the median values of the lognormal distribution for the fixed, 3.5T, and 5.5T models are computed as 0.66g, 4.70g, and 10.0g, respectively, as shown in Table 1. It can be concluded that vulnerability of the LNG storage tank is greatly reduced by the base-isolation design. A large displacement demand of a higher PGA is taken care of by the base isolator while relative displacements of the LNG tanks are kept small.

Table 1: Parameters of fragility curves.

Parameter	Fixed model				3.5T model		5.5T model
	DS2	DS3	DS4	DS5	DS2	DS3	DS2
c	0.66	1.22	1.81	3.7	4.70	8.00	10.0
ζ	0.26	0.26	0.27	0.28	0.35	0.37	0.40

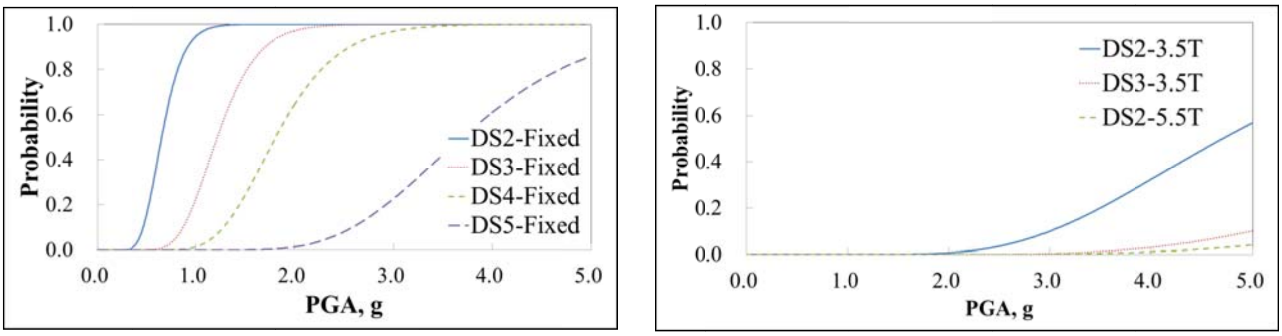


Figure 3: Fitted fragility curves of fixed (left) and 3.5T/5.5T (right) models.

4. CONCLUSION

Fragility curves of base-isolated and non-isolated LNG storage tanks are developed to investigate the effect of the base isolation design to seismic performance of LNG storage tanks. A non-isolated LNG storage tank is selected and two base isolation designs with respect to acceleration and displacement criteria are applied to this tank. Thresholds based on the crack strain at the base of the concrete tank wall defined the limit states for fragility curves. Finally, empirical fragility curves are fitted by lognormal CDF. Comparison of fragility curves of fixed and base-isolated tanks revealed that the base isolation considerably reduces the risk of damage under a specified level of earthquake.

The result and discussion of this study are bound by the assumption that the base isolator is in elastic state. In spite of this unusual and impractical assumption, it is adopted in this study to show the procedure. The eventual goal of the extension of this study is to develop a base isolator designed to control the performance of the structure with respect to its seismic fragility.

5. ACKNOWLEDGMENTS

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