Research Article

Seismic Fragility Assessment of Base-Isolated Steel Water Storage Tank

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Steel water storage tanks (WSTs) are among the important components of water treatment industry facilities that are expected to remain functional and applicable after strong earthquakes. In this study, the seismic vulnerability of base-isolated steel WST is investigated. A three-dimensional finite element stick model of the targeted tank is created using OpenSees. This model is capable of reproducing convective, impulsive, and rigid responses of fluid-tank systems. Time-history responses of convective displacement, bearing displacement, and base shear force for base-isolated tank subjected to a typical ground motion are compared. Furthermore, time-history analysis based on a suite of 80 ground motions is conducted. Seismic demand models for various responses are established and the most efficient intensity measure (IM) is determined based on the dispersion and coefficient of determination. Seismic fragility curves for different responses are derived for all three damage states using cloud analysis. The results from this study reveal that (i) the convective displacement is significantly greater than bearing displacement; (ii) peak ground displacement (PGD) is the most efficient and sufficient IM for the targeted tank; and (iii) the characteristic of isolation bearing significantly influences the seismic fragilities of convective displacement and bearing displacement and has a little impact on base shear force, which makes the selection of the proper characteristic parameters for isolation bearing very essential. The analysis technique and procedure mentioned above as well as derived insights are of significance to general liquid storage tank system configuration.

1. Introduction

Liquid storage tanks (LSTs), as lifeline structure, are extensively used to store a variety of liquids, for example, water, petroleum, chemicals, and liquefied natural gas [1, 2]. With the development of economics, the amount and capacity of LST are gradually increasing. At present, the capacity and radius of large-scale LST can reach $20 \times 10^4 \text{ m}^3$ and 50 m, respectively. Once the damage of such large-scale LST occurs due to natural disaster, this will cause a tremendous hazard for social and public safety. Earthquake is one of the most common and destructive natural disasters. Especially in recent years, a large number of LSTs are constructed in coastal region, southeast of China. In addition, these coastal regions are significantly influenced by Ring of Fire (i.e., Circum-Pacific Belt). As such, seismic performance of LSTs during earthquake has attracted increased attention in industrial and academic communities. Previous earthquake investigations have demonstrated that the buckling of LST wall and uplift of LST base are the most common types of damage due to strong ground motion. For example, Malhotra [3] presented an approximate method for the analysis of earthquake-induced uplifting in base plate of unanchored liquid storage tanks supported on flexible soil foundations. Malhotra et al. [1] reported that the larger axial compressive stress of tank wall can cause bulking of the tank wall. Alembagheri and Estekanchi [4] investigated the seismic response of unanchored steel LST using the endurance time dynamic analysis procedure. They found that the uplifting of the tank base obviously influenced the seismic response of the tank.

Various studies have been performed to explore the dynamic characteristic and failure mechanism of LST during earthquake. In fact, the liquid in the LST demonstrates three
distinct motions [2]: (1) convective (or sloshing) motion, that is, motion of top liquid; (2) impulsive motion, that is, motion of intermediate liquid along with tank wall; and (3) rigid motion, that is, rigid motion of lower liquid along with tank wall. Based on the above, Malhotra et al. [1] presented a simplified analysis procedure for ground-supported cylindrical tanks. Such procedure can consider impulsive and convective action of the liquid in the tank. Haroun [5] systematically studied the dynamic response of ground-supported cylindrical LST through theoretical and experimental investigation. Barton and Parker [6] investigated the seismic response of anchored and unanchored cylindrical LST using finite element method. Their results illustrated that the base restraint conditions should be carefully considered in the seismic design of LST. Tedesco et al. [7] developed an analytical procedure for ground-supported cylindrical LST to estimate its seismic response subjected to a horizontal ground motion. Veletsos and Tang [8] investigated the effect of soil-structure interaction on the response of cylindrical tanks subjected to a horizontal ground motion. Cho et al. [9] performed seismic response analysis of LST using refined numerical technique along with added mass method. Virella et al. [10] reported the fundamental impulsive modes of liquid-tank system during horizontal motions through general finite element program. Recently, Shakib and Alemzadeh [11] investigated the effect of earthquake site-source distance on the seismic response of reinforced concrete elevated water tanks with shaft type support. The results showed that the seismic response of fluid-tank system highly depended on site-source distance of the earthquake records. Li et al. [12] conducted the shaking table tests and finite element modeling on the 1/20 scale liquid-tank-foundation system to investigate the dynamic response of the cylindrical oil-storage tank under seismic excitation.

However, in order to mitigate the hydrodynamic-induced seismic response of fluid-tank system due to strong ground motion, the base isolation is a very common technology and is extensively employed in the industrial design. In the aspect of base-isolated tank subjected to earthquake excitation, Liang and Tang [13] reported the effect of lead-rubber bearing isolator on the seismic response of flexible LST. They showed that such isolator can greatly reduce the hydrodynamic pressure, shell, and liquid sloshing amplitudes. Malhotra [14] proposed a seismic base isolation method for ground-supported cylindrical LST through using a flexible membrane between tank wall and base plate and found that such isolation method can decrease significantly the hydrodynamic-induced base shear force, overturning moment, and axial compressive stress in the tank wall and does not obviously increase the vertical displacements of the free liquid surface due to convective motion. Shirimai and Jangid [15] studied the seismic response of elevated liquid storage steel tanks isolated by the linear elastomeric bearings under real earthquake ground motion. Furthermore, Jadhav and Jangid [16] investigated the seismic response of the liquid storage tanks isolated by the elastomeric bearings and sliding systems subjected to near-fault earthquake motions. In their paper, it was shown that the seismic response of the isolated tank is mainly governed by fault normal component of earthquake motions. At present, based on an equivalent mechanical model, Hashemi and Aghashiri [17] analyzed the seismic response of base-isolated flexible rectangular fluid containers under horizontal motion. The results demonstrated that the base isolation can efficiently reduce base shear force, wall deformation, and hydrodynamic pressure. Tsipianitis and Tsompanakis [18] focused on the influence of damping modeling approach on the dynamic response of base-isolated LST subjected to strong near-fault ground motion.

Seismic vulnerability assessment of engineering structure is carried out by fragility curve. The assessment based on fragility curve is used extensively in building engineering [19], bridge engineering [20], and harbor engineering [21]. Seismic vulnerability assessment of LSTs plays a critical role in uninterrupted operation of an industrial facility. Technically, seismic fragility can present capacity of tank component resistance to failure subjected to different seismic hazard levels. For instance, Phan et al. [22] assessed the seismic vulnerability of steel tank supported by reinforced concrete columns using probabilistic seismic assessment approach. A three-dimensional finite element stick model is established to perform the nonlinear time history analyses using OpenSees. Their results illustrated that a higher damage vulnerability of tank-supported column occurs due to excessive lateral displacement of tank base. Lately, for base-isolated tank, Tsipianitis and Tsompanakis [23] carried out the fragility analysis of tank isolated by sliding-bearing under near-fault earthquakes using a surrogate model. Kildashti et al. [24] explored the influence of base flexibility on the seismic performance of fully anchored LST using fragility curve. In summary, there are a large number of researches regarding seismic response of base-isolated tanks and seismic fragility of LSTs. Nevertheless, until recently, only very limited studies were reported about seismic fragility of base-isolated tanks.

Based on the above, in this study, the seismic fragility of base-isolated water storage tank is studied. A three-dimensional (3D) finite element stick model is created through OpenSees computer program. Seismic response of base-isolated tank is analyzed under a typical earthquake ground motion. A suite of 80 earthquake ground motion records are employed to assess the seismic performance of base-isolated tank. The seismic demand models of base-isolated tank are constructed from the obtained intensity measure-seismic demand data pairs. Combining with the obtained seismic demand models and appropriate bound limit for various damage states, seismic fragility curves are derived based on the cloud analysis. The influence of the characteristic of isolation bearing on the seismic fragility curve of the tank is systematically investigated. In short, the novelties of this study are twofold: (1) A simplified 3D FE stick model of fluid-tank system is created considering fluid-structure interaction; (2) the seismic fragility of such a system is investigated under various properties of isolation bearing.

2. Numerical Models of Storage Tank

A targeted cylindrical steel WST is commonly used in the water treatment project (SunRui Marine Environment
3. Seismic Response Analysis of Storage Tank

To investigate the seismic response of storage tank, various earthquake ground motions are employed as a base excitation, including El Centro station record of 1940 Imperial Valley Earthquake (El Centro record), Capitola station record of 1989 Loma Prieta earthquake (Capitola record), and Rinaldi Receiving station record of 1994 Northridge earthquake (Rinaldi Receiving record), shown in Figure 2. The peak ground acceleration of El Centro, Capitola, and Rinaldi Receiving records is 0.348 g, 0.511 g, and 0.445 g, respectively. As recommended by Shrimali and Jangid [2], the seismic demands/responses of interest are as follows: the convective displacement ($x_c$), the bearing displacement ($x_b$), and the base shear force ($F_b$). In fact, the base shear force is directly proportional to earthquake loading exerted in the tank and the convective and bearing displacements are very important from the design point of view. To validate the effectiveness of 3D FE stick model created by OpenSees, a similar stick model of broad tank is established based on [2] and seismic response of broad tank is computed. Figure 3 presents the comparison of the computed time history response for broad tank [2] subjected to El Centro record through the finite element method and modal superposition method. From Figure 3, the seismic response computed by the stick model is similar to that obtained by modal superposition method in the reference, especially for the convective displacement. This indicates that the proposed stick model can reproduce the seismic response of WST. Figure 4 demonstrates time-history response of stick model for water storage tank subjected to various ground motions. From Figure 4(a), different seismic demands present similar sinusoidal responses under base excitation. The amplitude of convective displacement is significantly greater than that of bearing displacement. The main reason is that the mass and height of the convective part are larger than those of the impulsive part. In addition, the stiffness of the impulsive part is significantly greater than the counterpart of the convective part. The similar comments are made for Capitola and Rinaldi Receiving records, demonstrated in Figures 4(b) and 4(c).

4. Seismic Fragility Assessment

4.1. Selection of Ground Motion. In order to perform the seismic fragility analysis of WST, the existing ground motion set is selected. This ground motion set comprised 80 ground motions extracted from the Pacific Earthquake Engineering Research Center’s (PEER) Strong Motion Database by Medina and Krawinkler [27]. These 80 ground motions are classified into four magnitude-distance bins according to various moment magnitudes ($5.8 < M_w < 7.0$) and epicentral distances ($13 \text{ km} < R < 60 \text{ km}$) and their peak ground displacement (PGD) distribution is illustrated in Figure 5.

4.2. Seismic Demand Models. Based on the above-mentioned seismic demands (i.e., responses of interest), the seismic demand models for the convective displacement, the bearing displacement, and the base shear force are established to map the relationship between intensity measure (IM) and seismic demand ($D$). Reference [28] recommended that the estimate for the median of the seismic demand be predicted by a power function expressed in the following equation:

$$S_D = a (IM)^b,$$

where $a$ and $b$ are the power-law model regression coefficients based on the collection of the peak demand and IM quantity from time-history analyses of the targeted tank.
Figure 1: Base-isolated steel water storage tank: (a) physical model; (b) stick model.

Table 1: Mechanical properties of steel storage tank.

| Component                      | Properties       | Unit    | Value  |
|--------------------------------|------------------|---------|--------|
| 16 mm thickness steel tank     | Young’s modulus  | MPa     | 200000 |
| 16 mm thickness steel tank     | Yield strength   | MPa     | 205    |
| 16 mm thickness steel tank     | Density          | kg/m³   | 7900   |
| Water                          | Density          | kg/m³   | 1000   |

Figure 2: Various earthquake ground motions: (a) El Centro station record of 1940 Imperial Valley earthquake; (b) Capitola station record of 1989 Loma Prieta earthquake; (c) Rinaldi Receiving station record of 1994 Northridge earthquake.
Table 2: Dynamic properties of steel water storage tank.

| Component       | Unit | Impulsive | Convective |
|-----------------|------|-----------|------------|
| Mass            | T    | 223.7     | 69.5       |
| Damping         | %    | 2         | 0.5        |
| Frequency       | rad/s| 132.4     | 2.2        |
| Stiffness       | kN/m | 3923816.5 | 347.3      |
| Height of mass  | m    | 3.22      | 5.41       |

\[
\beta_{\text{DIM}} = \sqrt{\frac{\sum_{i=1}^{n} [\ln(d_i) - \ln(S_D)]^2}{n - 2}},
\]

where \(\beta_{\text{DIM}}\) is the coefficient of determination for the linear regression model of seismic demand on various IMs.

4.3 Determination of Seismic Fragility Curve.

Typically, the fragility curve can be determined through many approaches, for example, observation of earthquake damage, static structural analyses, and analytical fragility function [22]. The analytical fragility function is extensively used and is derived from a proper seismic demand model [30, 31]. The cloud analysis approach is one of the most common procedures for deriving the fragility curve. In this approach, firstly, the seismic response analysis for the target tank is performed subjected to a suite of ground motions; secondly, the linear regression-based seismic demand model is built based on the numerical results; finally, the fragility curve is obtained. The seismic fragility curve is defined as the conditional probability that the target tank’s demand is greater than or equal to the IM value.
probability that a seismic demand required for a specific structure exceeds its bound limit state for a specific IM in the form of the following equation:

\[
P(D \geq C \mid IM) = \Phi \left( \ln(S_D) - \ln(S_{LS}) \right) \left/ \sqrt{\beta_{DIM}^2 + \beta_{LS}^2} \right.,
\]

where \( S_{LS} \) is the median estimate of the bound limit state of seismic demand; \( \beta_{LS} \) is the dispersion of the limit state; \( \Phi(\bullet) \) denotes the cumulative standard normal distribution function. As such, the fragility curve of seismic demands for the targeted tank will be obtained if the associated parameters \( S_D, S_{LS}, \beta_{DIM}, \) and \( \beta_{LS} \) are first determined. Herein, \( S_D \) is given based on the above obtained seismic demand models.
Figure 6: Linear fit demand model of convective displacement with different intensity measures.
depicted in Figures 6 and 7. $S_{LS}$ of different bound limit states is extremely important for fragility assessment. In fact, the determination of the value of $S_{LS}$ is rather difficult. A variety of approaches are used to determine $S_{LS}$ for LSTs, for example, earthquake investigation, experimental data, and analytical method. In particular, $S_{LS}$ of different bound limit states for various seismic demands is assumed according to the computed results of the targeted tank, summarized in Table 4. In fact, $S_{LS}$ of different bound limit states is determined by the following steps: (1) for every hazard level (i.e., damage state), the seismic response analysis is conducted using seven input earthquake motions, which have similar spectra accelerations; (2) the seismic response of tank is obtained under different hazard levels; (3) the average of maximum response for different hazard levels is used as $S_{LS}$ of different bound limit states. $\beta_{LS}$ is assumed to be 15%.

### 4.4. Fragility Analysis.

Based on equation (5), the fragility curves of different seismic demands for the targeted tank are obtained and are illustrated in Figure 8. The fragility curves associated with convective displacement for different damage states are compared in Figure 8(a), which provides a clear picture of damage exceedance probability for different damage responses with respect to the different PGD levels. For example, the fragilities of the convective displacement are 95.2%, 67.1%, and 48.7% for the light, moderate, and extensive damage states, respectively, while the PGD is specified as 1.0 m. Obviously, the fragility of the convective displacement for the extensive state is greater than that for slight and moderate states. The fragilities of the convective displacement for all three damage states reach 100% at the PGD of 6 m. Figure 8(b) presents the fragility curves of bearing displacement. The same characteristics are observed for bearing displacement. Figure 8(c) shows the fragility curves of base shear force. It is clear that the fragilities of base shear force for all three damage states are similar, when the PGD is under 0.1 m. The fragility of base shear force for the slight state is obviously greater than that for the moderate and extensive states, while the PGD is above 0.1 m. The fragilities of base shear force for moderate and extensive states reach 60.9% and 54.8% at the PGD of 6 m, respectively.

To explore the influence of isolation bearing characteristics on the seismic fragility curves, the parametric study is performed through changing the period and damping ratio of isolation bearing. Figure 9 displays the influence of isolation bearing period on fragility curves of different seismic demands through changing isolation period from 1.0

| Intensity measure | Convective displacement | Bearing displacement | Base shear force |
|-------------------|-------------------------|----------------------|-----------------|
|                   | $\beta$ | $R^2$   | $\beta$ | $R^2$ | $\beta$ | $R^2$ |
| PGA               | 1.03   | 0.03    | 0.86   | 0.07  | 0.86   | 0.07  |
| PGD               | 0.57   | 0.71    | 0.52   | 0.66  | 0.52   | 0.66  |
| PGV               | 0.61   | 0.66    | 0.46   | 0.74  | 0.46   | 0.74  |
| CAV               | 0.68   | 0.58    | 0.54   | 0.64  | 0.54   | 0.64  |
| $I_a$             | 0.86   | 0.33    | 0.67   | 0.43  | 0.67   | 0.43  |
| $Sa(T_2)$         | 1.05   | 0.01    | 0.89   | 0.02  | 0.89   | 0.02  |

Note: $\beta$ is standard deviation; $R^2$ is coefficient of determination; CAV is Cumulative Absolute Velocity; $I_a$ is Arias Intensity.
As seen from Figure 9(a), for convective displacement, the fragilities for all three damage states present an increasing trend with increasing of isolation period, which indicates that the fragility of convective displacement can be increased by increasing the isolation bearing period. In Figure 9(b), for bearing displacement, the fragilities for all three damage states significantly increase with increasing of isolation period. This demonstrates that the isolation period of bearing influences the fragility of bearing displacement. From Figure 9(c), the fragilities of

Table 4: Limit states for fragility assessment of tank.

| Response of interest          | Slight | Moderate | Extensive |
|------------------------------|--------|----------|-----------|
| Convective displacement, $x_c$ (m) | 0.05   | 0.1      | 0.15      |
| Bearing displacement, $x_b$ (m)   | 0.006  | 0.012    | 0.018     |
| Base shear force, $F_b$ (kN)    | 15     | 45       | 75        |

Figure 8: Seismic fragility curves: (a) convective displacement; (b) bearing displacement; (c) base shear force.
baseshearforceforallthreedamagestatesslightlyincreased withincreasingofisolationperiod.Basedontheabove,this showsthatthefragilitiesofdifferentseismicdemandsare influencedbytheisolationperiodofbearing.

Figure10presentsthedifficultonfragilitycurveofdifferentseismicdemandsthroughchangingdampingratiofrom0.02to0.1, referringtoShrimaliandJangid[2].InFigure10(a),thefragilitiesoftheconvective displacementforallthreedamagestatesincreasewithincreasingofdampingratio. A similarcharacteristicisalsofoundinthefragilitiesof thebasebearforce,showninFigure10(c).Thissignifies thatthesmallerdampingratioofisolationbearingcan effectivelydecreasethefragilitiesofconvective
displacement and base shear force. As illustrated in Figure 10(b), the increasing of damping ratio can decrease the fragilities of base shear force.

In summary, the isolation period and damping ratio of bearing appreciably influence the fragilities of convective displacement and bearing displacement and have a little influence on base shear force. The decreasing of isolation period can decrease the fragilities of various seismic demands for different damage states. The decreasing of damping ratio can reduce the fragilities of the convective displacement and base shear force and increase the fragility of the bearing displacement for all three damage states. For the above reason, to decrease the fragilities of convective displacement and base shear force, the damping ratio and period of isolation bearing are designed as small as possible. A proper damping ratio for bearing should be designed to obtain the appropriate fragilities for bearing displacement.

Figure 10: Influence of bearing damping ratio on fragility curve: (a) convective displacement; (b) bearing displacement; (c) base shear force.
5. Summary and Conclusions

Seismic fragility curve, which represents the probability of exceeding a specified damage limit state for a given IM, is a very powerful tool for seismic fragility assessment. The characteristic of isolation bearing has been found to have a significant impact on seismic response of liquid storage tanks. Seismic response of liquid-tank system with base isolation bearing is a complex fluid-structure process involving convective vibration, impulsive vibration, and rigid vibration. As such, this study performs the seismic fragility assessment of base-isolated steel water storage tank. A three-dimensional finite element stick model with the lumped mass is established using the open-source OpenSees computational platform. The modeling in details is provided. The seismic vulnerability of the tank has been assessed according to fragility curves. The seismic demands for the targeted tank are selected. The PGD, the most efficient IM for various seismic demands, is determined based on the dispersion and coefficient of determination. The seismic demand models and fragility curves in terms of PGD have been derived through the cloud analysis. The influence of isolation period and damping ratio of bearing on seismic fragility curves has been investigated. The related key findings are obtained as follows:

(1) The time-history responses of convective displacement, bearing displacement, and base shear force present the similar sinusoidal trend, and the amplitude of convective displacement is obviously larger than the counterpart of bearing displacement.

(2) The fragilities of various seismic demands present an increasing trend from slight damage state to extensive damage state. The fragilities of base shear force for slight damage state are substantially greater than those for moderate and extensive damage states.

(3) The isolation period and damping ratio of bearing have a significant influence on convective displacement and bearing displacement and have a little impact on base shear force, which tell designer that more close attention should be paid to the selection of parameters for bearing of base-isolated tank to decrease seismic fragilities of the tank during earthquake.

Data Availability

Some data or models used during the study are available from the corresponding author by request, including the ground motions and the finite element model.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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