Numerical Simulation Analysis of Seismic Fragility of Vertical Floating-roof Storage Tanks

Mengzhu Wang1,a, Zongguang Sun1*, Jiangang Sun2,b, Lifu Cui2,3,c

1College of Transportation Engineering, Dalian Maritime University, Dalian, Liaoning, 116026, China
2College of Civil Engineering, Dalian Minzu University, Dalian, Liaoning,116650, China
3College of Civil Engineering, Tongji University, Shanghai, 200092, China
aemail: calmquark@outlook.com, bemail: sjg728@163.com,
cemail: fangzaijianzai@163.com
*Corresponding author’s e-mail: sun@dlmu.edu.cn

Abstract. To study seismic response of tank, 10×104m³ vertical floating-roof tank model is established. The probability relationship between the intensity measure and engineering demand parameters is established based on extensive nonlinear dynamic time-history analysis. Four failure modes of tank were determined, and seismic fragility curve of under each failure mode was obtained. The results show that under frequent earthquake, the exceeding probability of circumferential tensile damage, and instability of tank wall in intact state were 40% and uplift of the bottom sheet was 75%. Under design-based earthquake and rare earthquake, circumferential tensile damage was in intact state, and the exceeding probability of instability were 66.9% in medium damage and 52.9% in severe damage. The exceeding probability of bottom uplift in severe damage is 90%. The method takes the randomness of ground motion into account, which can provide an effective idea for the evaluation of the seismic safety of tank structure.

1. Introduction
Vertical steel cylindrical oil storage tanks are widely used containers in oilfield and petrochemical and its related enterprises. The floating-roof tank is composed of a floating roof floating on the liquid surface, a vertical cylindrical tank wall, a bottom plate, and its accessories. With the development of petroleum and petrochemical industry and its economic input efficiency needs, storage tanks have a trend of large-scale and unanchored development[1-2]. The storage tank is large, unanchored, thin-wall and liquid inside, and structural response is more complex under seismic action. Several studies have been conducted on the seismic fragility of tanks by domestic and foreign scholars. Sun et al.[3] proposed a probabilistic model of random variables and a failure probability calculation method by establishing the dynamic equations of storage tanks under horizontal seismic excitation. Wei et al.[4] proposed a calculation method for estimating seismic fragility based on Probit-Bayes method by combining historical storage tank seismic damage information for damage classification. Mehran et al.[5] performed an empirical probabilistic seismic safety analysis by plotting seismic fragility curves based on tank height-to-diameter ratios and liquid filling level for storage tanks designed according to earlier seismic codes. Liquid sloshing must be considered when designing floating-roof tank, however, in the
existing tank design code[6], often ignoring the impact of sloshing on the floating-roof, liquid boundary conditions are assumed to be free surface. When unexpected seismic excitation occurs, even if the theory is more accurate, the liquid boundary condition is not satisfied due to the existence of floating roof, and floating roof will also have an impact on the stress distribution of tank structure. The Tokachi-oki earthquake in 2003 caused severe damage to seven floating-roof tanks in Japan and sinking of floating roof caused serious fires in the tank farm. At present, there are few seismic studies of tank considering floating-roof effects.

Towards the above issue, the finite element model (FEM) of a vertical floating-roof tank is established in this paper. The model refines key locations that are neglected in the past studies[3,5,7-8], such as wall thickness, floating roof, floating boat and sealing materials. The seismic fragility of floating-roof tanks is analyzed in the framework of performance-based earthquake engineering (PBEE), and the seismic performance of floating-roof tanks is evaluated from the perspective of probability. It is expected to provide a useful reference for the seismic design of floating-roof tanks.

2. Probabilistic seismic demand model

The probabilistic seismic demand model aims to establish a probabilistic relationship between structural demand \( D \) and seismic intensity measure through regression analysis. The probability of tank structure reaching or exceeding a certain limit state under a certain \( IM \) [9] is:

\[
P_f = P[D \geq C] \quad (1)
\]

where \( IM \) is intensity measure parameter, such as macroscopic seismic intensity, peak ground acceleration (PGA), spectral acceleration \( Sa(T,5\%) \) with 5% structural damping, etc.; \( C \) is seismic capacity of structure.

If \( D \) follows a log-normal distribution, median structural seismic demand \( m_D \) and \( IM \) follow a power exponential relationship.

\[
m_D = a (IM)^b
\]

\[
\beta_D = \sqrt{\frac{\sum_{i=1}^{N} (\ln(D_i) - \ln(m_D))^2}{N-2}}
\]

where \( \beta_D \) is log standard deviation, \( N \) is the number of nonlinear time analysis; \( D_i \) (\( i=1, 2, ..., N \)) is the \( i \)-th peak value of \( D \).

Taking logarithms on both sides of equation (2), the relationship between \( m_D \) and \( IM \) obeys a log-linear relationship. Seismic fragility is written using a log-normal distribution as

\[
P_f = 1 - \Phi \left( \frac{\ln(m_D) - \ln(m_C)}{\beta_D} \right) = \Phi \left( \frac{\ln(m_D) - \ln(m_C)}{\beta_D} \right)
\]

where \( \Phi[\cdot] \) is probability distribution function of a standard normal random variable, and \( m_C \) is median of seismic capacity corresponding to a certain limit damage state.

3. Description of the case Study

3.1. Modeling issues

The case is 10×10⁴ m³ storage tank, the site category is site II, the design seismic grouping is Group 1, and fortification intensity is 8. The diameter of tank is 80m, wall height is 21.6m, liquid filling height is \( H_w=20m \), thickness of courses from the bottom to the top is 32.5, 24.5, 21.5, 18, 15.5, 12, 12, 12, 12mm, respectively. Thickness of bottom plate is 20mm, and thickness of floating roof is 5mm. FEM of 10×10⁴ m³ tank is shown in Figure 1 and material parameters are set as in Table 1.
The floating-roof tank is unanchored, and liquid is considered as an irrotational, inviscid and incompressible ideal fluid. Contact is a nonlinear state, and system stiffness depends on the contact state. The contact problem is a difficult problem in structural analysis, which requires setting contact type, contact area, contact stiffness etc. The accuracy of contact setting directly affects solution results. After many attempts in this paper, the model converges. Two contacts are set in the model: Contact1 is set between tank bottom and concrete ground, as shown in Figure 1(b). The floating roof can run up and down in the tank, and Contact2 is set between seal material and tank wall, as shown in Figure 1(c).

### Table 1. Material parameters of tank model

| Material               | $\rho$ (kg/m$^3$) | $\mu$ | $E$ (N/m$^2$) | $\sigma$ (MPa) | $E_t$ (N/m$^2$) | $K$ (N/m$^2$) |
|------------------------|-------------------|-------|---------------|---------------|----------------|---------------|
| Tank wall              | 7800              | 0.3   | $2.06\times10^{11}$ | 4.9$\times10^8$ | $2.06\times10^9$ | -             |
| Floating roof          | 7800              | 0.3   | $2.06\times10^{11}$ | -             | -              | -             |
| Concrete base plate    | 2550              | 0.2   | $2.8\times10^{10}$ | -             | -              | -             |
| Sealing materials      | 1800              | 0.47  | $7.8\times10^6$   | -             | -              | -             |
| Liquid                 | 1000              | -     | -              | -             | -              | $2.0\times10^9$ |

The liquid sloshing period of storage tank in the literature [10] is calculated as:

$$T_w = \frac{K_s}{\sqrt{D}}$$  \hspace{1cm} (5)

The sloshing period is 11.001s and the sloshing frequency is 0.0909Hz. The fundamental frequency of the liquid sloshing in FE modal analysis is 0.0912Hz, and FEM matches the calculated value of specification equation, which verifies the validity of FEM.

To further verify the reliability of FEM calculation results, simplified mechanical model (SMM) of tank proposed in the literature [11] was used for the calculation of seismic response, and seven ground motion records from site II were selected, and PGA was adjusted to 0.2g. The comparison with FEM is shown in Table 2. Seismic response of FEM is close compared with SMM of seismic analysis of storage tank, which also indicates that FEM is dependable.

#### 3.2. Selection of ground motion records

Earthquakes are highly stochastic, including a series of uncertainties such as source mechanism, site effects and intensity. Seismic fragility analysis of tank in this paper uses 22 far-field ground motion records recommended by the Applied Technology Council (ATC) -63, and the ground motion records used are from PEER's NGA (Next Generation Attenuation) database. PEER uses the equivalent shear wave velocity $V_{s30}$ at 30 m below ground as the index for classifying the site soil category, which is different from the way China code defines the site soil category, so it is necessary to convert $V_{s30}$ into the shear wave velocity of the site soil corresponding to China code [12], as shown in Table 3.

| Number | Sloshing wave height (m) | Base shear ($10^6$N) | Bending moment ($10^9$N·m) |
|--------|--------------------------|----------------------|---------------------------|
|        | FEM | SMM | FEM | SMM | FEM | SMM |
| 1      | 0.031 | 0.058 | 0.56 | 0.65 | 1.58 | 1.93 |
| 2      | 0.140 | 0.184 | 0.66 | 0.82 | 1.88 | 2.43 |
| 3      | 0.062 | 0.091 | 0.57 | 0.76 | 1.62 | 2.25 |
| 4      | 0.067 | 0.075 | 0.59 | 0.51 | 1.64 | 1.51 |
| 5      | 0.180 | 0.174 | 0.83 | 0.45 | 2.28 | 1.31 |
### Table 3. Correspondence of site classification in PEER and Chinese seismic code

| China Codes | PEER(m/s) | Site I | Site II | Site III | Site IV |
|-------------|-----------|--------|---------|----------|---------|
|            | $V_{S30}>510$ | $260< V_{S30}<510$ | $150< V_{S30}<260$ | $V_{S30}<150$ |

### 4. Results & Discussion

The main failure modes of storage tanks are divided into the following four categories: liquid overflow, circumferential tensile damage of tank wall, tank wall instability and uplift of bottom sheet. The failure modes and seismic damage guidelines are shown in Table 4.

#### Table 4. Failure modes and seismic failure guidelines for storage tanks [3]

| Failure modes | Limit state equation | EDP | Fitting function | $R^2$ |
|---------------|----------------------|-----|------------------|-------|
| Liquid overflow | $h_a - [h] = 0$ | ln(EDP) = 0.07042 + 0.99812 ln(PGA) | 0.5629 |
| Tensile damage | $\sigma_t - [\sigma] = 0$ | ln(EDP) = 3.83037 + 1.02931 ln(Sa(T1)) | 0.9796 |
| Instability | $\sigma_y - [\sigma_y] = 0$ | ln(EDP) = 5.99403 + 0.16884 ln(PGA) | 0.7736 |
| Bottom uplift | $L - [L] = 0$ | ln(EDP) = 3.96735 + 0.91226 ln(PGA) | 0.9538 |

In this paper, four limit states (LS) of basic intact (LS1), slight damage (LS2), moderate damage (LS3) and severe damage (LS4) are used, and they classify the structure into five damage states of basic intact (DS1), slight damage (DS2), moderate damage (DS3), severe damage (DS4) and complete damage (DS5).

Seven PGA (0.05g, 0.10g, 0.15g, 0.20g, 0.30g, 0.40g and 0.80g) were selected in the range of 0.1-1.0g, and ground motion input was normalized, and 154 nonlinear dynamic time analyses were performed. PGA was used as IM, and sloshing wave height, circumferential stress, bottom vertical compressive stress and uplifting force were used as engineering demand parameters (EDP) under four failure modes, and probabilistic seismic demand model parameters of storage tank structure under different failure modes were obtained based on the log-linear assumption fitting.

As seen in Table 5, when PGA is selected as IM, the fitting results of sloshing wave height are poor, and the fitting goodness of circumferential stress, bottom vertical compressive stress and uplifting force are good. Three EDPs and PGA can well obey the logarithmic linear relationship. Seismic fragility curves and damage state probability of these three failure modes are shown in Figure 2 and Figure 3, respectively. When Sa(T1) is selected as IM, the fitting result of sloshing wave height is ideal. This is because fundamental sloshing period of liquid is much longer than that of structure. Considering the first-order periodic spectrum acceleration of liquid, the sloshing characteristics of liquid can be better reflected. So, Sa(T1) is a desirable choice for linear fitting of sloshing wave height. Seismic fragility curves and damage state probability are shown in Figure 4 and Figure 5.
As can be seen from Figure 2, with the increase of PGA, LS exceeding probability of tank failure mode gradually increases, the slope of fragility curve increases and then decreases, and performance level of structure gradually develops from intact to severe damage, each LS exceeding probability shows different degrees of increase, and structural fragility curve shows a flattening trend with the severity of structural damage state. When PGA is less than 0.1g, i.e., the seismic intensity is VII degree and below, LS1 exceeding probability is below 20%, which can ensure the basic intact seismic performance standard. When PGA is between 0.1-0.2g, LS1 exceeding probability of circumferential tensile damage and instability of the tank wall is 40%, but bottom uplift is 75%, which can no longer guarantee the basic intact seismic performance standard. When PGA reaches 0.3g, LS2 exceeding probability is 93% in the failure mode of bottom uplift, and structure cannot be kept in good condition. In 0.2-0.4g, circumferential tensile damage is dominated by the basic intact state, and tank wall instability is dominated by the medium damage state, and LS2 exceeding probability of instability is 66.9% and LS4 exceeding probability is 52.9%. Bottom uplift is dominated by severe damage, and LS4 exceeding probability is 90%. When PGA is 0.4g and above, LS4 exceeding probability of circumferential tensile damage increases significantly, and LS4 exceeding probability of instability and bottom uplift reaches more than 90%.

From literature [10], PGA of frequent, design-based, and rare earthquakes are 0.16g, 0.45g and 0.90g for the example of storage tank structure in this paper. Figure 3 shows the damage state probability of each failure mode when PGA reaches the level of frequent, design-based, and rare earthquakes. When ground motion intensity reaches frequent earthquake, damage state probability of circumferential tensile damage and instability in DS1 is much greater than other damage states probability. DS1 probability of base uplift is 50%, which is greater than other damage states probability. When ground motion intensity reaches design-based earthquake, DS1 probability of tank structure decreases, and DS2 and DS3 probability increases significantly, and DS5 probability of base uplift increases significantly. When ground motion intensity reaches rare earthquake, DS5 probability of each failure mode increases significantly, which indicates that the damage state level of tank structure gradually deepened. According to DS of failure mode, base uplift > instability > circumferential tensile damage. For unanchored tanks, base uplift and instability are the most important failure modes. Liquid overflow can cause floating roof damage, but not catastrophic, which is secondary failure mode.
5. Conclusion
The FEM of 10×10^4 m³ vertical floating-roof tank is established, and dynamic response is calculated by inputting ground motion in this paper. EDP with different failure modes is used as performance parameter of structure, and the relationship between EDP and PGA is established to analyze seismic fragility of tank structure, and the following conclusions are obtained.

- The probabilistic seismic demand model for floating-roof tank is established by taking PGA as IM, considering sloshing wave height, circumferential stress, vertical compressive stress, and uplifting force as EDP, but for sloshing wave height, Sa(T₁) as IM is an appropriate choice, instead of PGA.
- Seismic fragility analysis shows that base uplift > instability > circumferential tensile damage > liquid overflow according to the damage state of failure mode. For unanchored tanks, base uplift and instability are the most important failure modes.
- The damage states exceeding probability of vertical floating roof tank under different seismic intensity is calculated in the framework of PBEE. The study provides reference for seismic design of storage tanks from a probabilistic perspective.

Acknowledgements
This study is one of the phased achievements of the National Natural Science Foundation project "Research on Comprehensive damping Technology of important equipment in Petrochemical Industry" (51878124).

References
[1] SUN Jiangang. (2002) Research on seismic response control of vertical storage tanks. Harbin: Institute of Engineering Mechanics, CEA.
[2] Farshad Berahman, Farhad Behnamfar. (2007) Seismic Fragility Curves for Un-Anchored On-Grade Steel Storage Tanks: Bayesian Approach. Journal of Earthquake Engineering, 11:166-192.
[3] SUN Jiangang, ZHANG Ronghua, JIANG Feng. (2009) Numerical simulation analysis on the seismic fragility of storage-tank. Journal of Harbin Institute of Technology, 41: 138-142.
[4] WEI Lijun, WANG Xiangyang, LUO Aimin, et al. (2017) Investigation on seismic vulnerability of storage tanks based on Probit-Bayes method. Journal of Safety Science and Technology, 3: 17-21.
[5] Mehran S. Razzaghi, Sassan Eshghi. (2015) Probabilistic Seismic Safety Evaluation of Precode Cylindrical Oil Tanks. Journal of Performance of Constructed Facilities, 29: 04014170.
[6] GB/T 50761, (2018), Standard for seismic design of petrochemical steel equipments. Beijing.
[7] SUN Jiangang, WANG Xiangnan, ZHAO Changjun. (2010) Theoretical study on seismic isolation of storage tanks, Journal of Harbin Institute of Technology, 42: 639-643.
[8] SHENG Feng, HUANG Lei. (2017) Research of equivalent mechanics simplified model of liquid storage tank. Nuclear Power Engineering, 38: 85-89.
[9] LÜ Dagang, LIU Yang, YU Xiaohui. (2019) Seismic fragility models and forward-backward probabilistic risk analysis in the second-generation performance-based earthquake engineering. Engineering Mechanics, 36: 1-11+24.
[10] GB 50341, (2014), Code for design of vertical cylindrical welded steel oil tanks. Beijing.
[11] SUN Jiangang, CUI Lifu, HAO Jinfeng, et al. (2013) The simplified mechanical model and the seismic response for isolation tank with floating roof. Journal of Harbin Institute of Technology, 45: 118-122.
[12] JI Kun, WEN Ruizhi, REN Yefei. (2017) Ground motion recordings selection for seismic design code. Journal of Building Structures, 38: 57-67.