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SEISMIC EVALUATION OF FLEXIBLE STEEL WATER STORAGE TANKS

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Cylindrical steel liquid storage tanks are widely used for water supply and industrial chemicals. The seismic response of these tanks differs from buildings as it stores liquid with different hydrodynamic characteristics. Steel tanks can be exposed to severe damages during earthquakes such as elephant's foot buckling, diamond shape buckling, roof damage and failure of anchor bolts. This research investigates the seismic behavior of flexible steel water storage tanks using an analytical method. A series of parametric analyses are conducted for a typical liquid storage tank with different geometry properties and soil conditions. The effects of storage tank height, wall thickness, and subsoil type are investigated and their effects on the seismic response of the tank are evaluated and discussed. The results indicate that the soil type (representing shear wave velocity and shear modulus of the soil) has a profound impact on the base shear, overturning moment and hoop stress in the flexible tanks.

Keywords: Flexible steel tanks, Analytical modeling, Seismic design, Fluid-structure interaction.

1 INTRODUCTION

Steel storage tanks are considered a significant part of the industry and are widely used for water supply, storage of industrial chemicals, and power plants. Due to their importance, the storage tanks should be designed to withstand severe earthquakes. The seismic response of steel storage tanks is different from buildings because it stores liquid. The hydrodynamic pressure will apply to the tank wall, roof, and foundation differently, such as sloshing motion and hydrodynamic hoop stress. These can damage tanks during earthquakes causing elephant's foot buckling, diamond shape buckling, roof damage and failure of the support system (Phan and Paolacci 2018).

In this paper, the seismic behaviour of the steel storage tanks is investigated. The analytical method proposed in the Seismic Design of Storage Tanks of New Zealand Society for Earthquake Engineering was adopted to examine a case study storage tank (NZSEE 2009). A MATLAB code was developed based on the analytical approach and a series of parametric studies was conducted to evaluate the seismic response of the case study tank.

2 BACKGROUND

The seismic design of steel liquid storage tanks is usually based on the spring-mass model. When a liquid storage tank is subjected to horizontal seismic action, the liquid experiences horizontal acceleration.

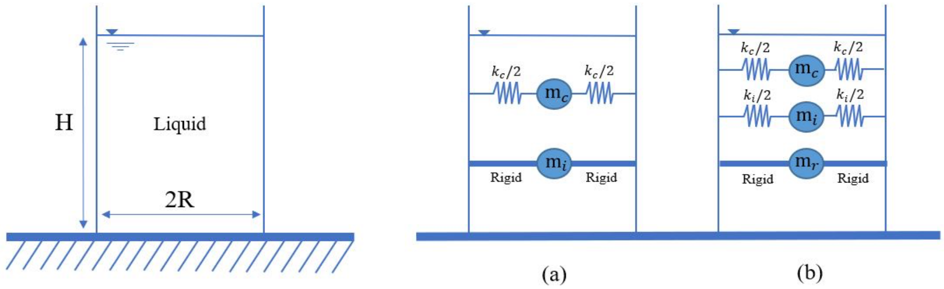

Figure 1. Spring-mass model for (a) rigid and (b) flexible cylindrical liquid storage tanks (horizontal earthquake).

Figure 1(a) shows a two-spring-mass model for the rigid cylindrical tank subjected to horizontal seismic action. The lower liquid mass is known as impulsive mass (m_i) that is rigidly attached to the tank wall. The upper liquid mass is known as convective mass (m_c) that is flexibly attached to the tank wall. The convective mass is attached to the tank wall with flexible springs stiffness (k_c) (Rawat *et al.* 2020).

Figure 1(b) shows, a three-spring-mass model for the flexible cylindrical tank subjected to horizontal seismic action. The top liquid mass is known as convective mass (m_c) that is mainly applied by sloshing motion. The middle liquid mass is known as impulsive mass (m_i) that accelerates along with the wall and induce impulsive pressure on the tank wall. The base liquid mass is known as rigid mass (m_r) that is rigidly attached to the tank wall. The impulsive and convective masses are attached to the tank wall with stiffness (k_i and k_c). The damping constants for the impulsive and convective masses are c_i and c_c (Rawat *et al.* 2020).

When a liquid storage tank is subjected to vertical seismic action, the liquid is subjected to vertical acceleration. The total fluid mass (m_l) in the rigid tank is rigidly attached to the tank base while the total fluid mass (m_l) in the flexible tank is attached to the shell base by a spring representing wall flexibility. The analytical processes proposed in the Seismic Design of Storage Tanks (NZSEE 2009) for calculating (1) base shear, (2) overturning moment and (3) hoop stress in the tank are adopted in this study.

The horizontal base shear components are given by the following equations in Eq. (1-6):

$$V_1 = C_d(T_1)m_1 g \tag{1}$$

$$V_r = C_d(\breve{T}_0)[m_0 - m_f]g \tag{2}$$

$$V_f = C_d(\breve{T}_f)[m_f + m_w + m_t]g \tag{3}$$

$$V = \sqrt{(V_f + V_r)^2 + V_1^2} \tag{4}$$

$$C_d(T_i) = C(T_i)k_f(\mu, \xi_i)S_p \tag{5}$$

$$C(T_i) = C_h(T_i)ZR_u N(T_i, D) \tag{6}$$

where V_1, V_r and V_f are the shear forces for convective mode, rigid impulsive mode, and flexible impulsive mode respectively and V is the total base shear. T_1 is the period of the first convective mode, $\breve{T}_0$ is the period of impulsive mode for the tank-foundation system, $\breve{T}_f$ is the period of the first impulsive mode, $k_f(\mu,\xi_i)$ is the correction factor (ductility and level of damping), S_p is the structural performance factor (taken as 1), m_1 is the convective mass, m_0 is the impulsive mass for rigid tank, m_f is the flexible impulsive mass, m_r is the rigid impulsive mass, m_w is the wall mass, and m_t is the roof mass.

The overturning moments are calculated using the following equations in Eq. (7-10):

$$M_1 = C_d(T_1)m_1 g h_1 \tag{7}$$

$$M_r = C_d(\breve{T}_0)[m_0 - m_f]gh_0 \tag{8}$$

$$M_f = C_d(\breve{T}_f)[m_f h_f + m_w h_w + m_t h_t]g \tag{9}$$

$$M_{OT} = \sqrt{(M_f + M_r)^2 + M_1^2} \tag{10}$$

where, M_1, M_r and M_f are the overturning moment for convective mode, rigid impulsive mode and flexible impulsive mode respectively and M_{OT} is the total overturning moment. h_1 is the height of first convective mode mass, h_0 is the height of rigid impulsive mass, h_f is the height of flexible wall impulsive mass, h_w is the height of center of gravity of wall mass, and h_t is the height of center of gravity of roof mass.

The hoop stress is calculated by a non-dimensional method as follows given in Eq. (11) and Eq. (12). It includes hydrostatic ($N_{\theta h}$), convective ($N_{\theta 1}$), impulsive ($N_{\theta i}$) and vertical ($N_{\theta v}$) hoop forces.

$$N_\theta = N_{\theta n} RP \tag{11}$$

$$f_h = \frac{N_\theta}{t_w} \tag{12}$$

where, $N_{\theta n}$ is the non-dimensional hoop force, R is the radius of the tank, P is the hydrostatic pressure at the base ($\gamma_l H$), P is the pressure for convective stress resultant, or the pressure for impulsive stress resultant or the pressure for vertical stress resultant, f_h is the hoop stress and t_w is the thickness of tank wall.

3 PARAMETRIC STUDIES

Parametric analyses were conducted based on the change of three primary parameters including the required fill height (H), wall thickness(t_w) and foundation soil types. The benchmark parameters were provided as shown in Figure 2 and Table 1.

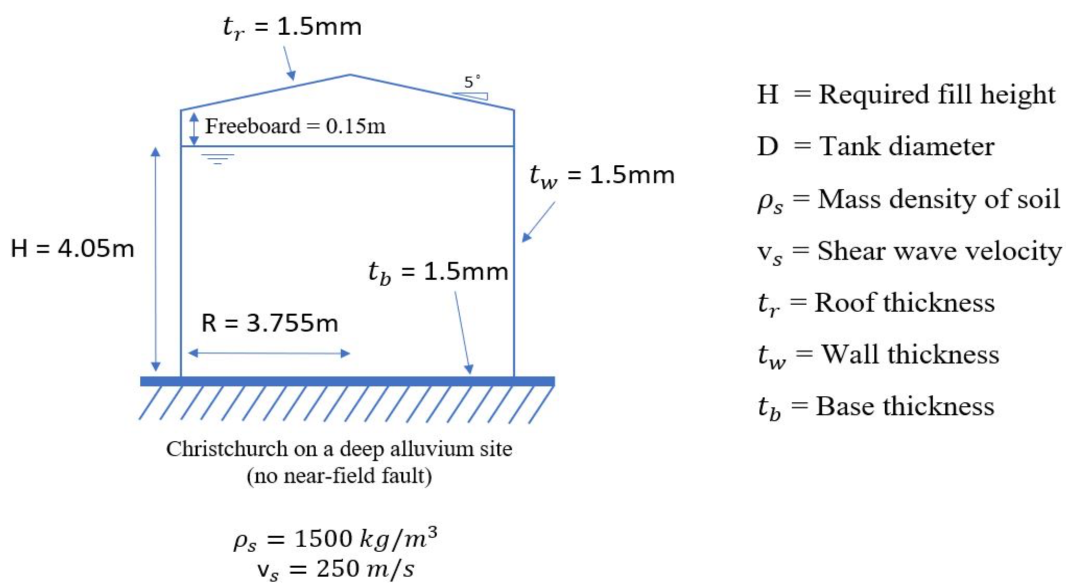

Figure 2. Illustration and properties of a case study tank used for parametric analyses.

The case study tank is classified as flexible considering the thickness of the tank is only 1.5mm. Based on the parameters above, and using the relevant equations, the base shear, overturning moment, and maximum hoop stress were calculated.

Table 1. Benchmark tank properties and dimensions.

Parameter	Value	Parameter	Value
Steel yield strength (MPa)	300	Specific gravity (liquid)	1 (water)
Steel tensile strength (MPa)	400	Hazard factor (Z)	0.3
Steel Young's modulus (GPa)	200	Probability of exceedance	1/500
Poisson's Ratio (Steel)	0.25	Displacement ductility factor (μ)	2 (impulsive coefficient)
Shear modulus of foundation (MPa)	94	Displacement ductility factor (μ)	1 (convective & vertical coefficient)
Poisson's ratio of foundation	0.33		

4 ANALYSIS OF RESULTS

4.1 Effect of Tank Height and Thickness

Figure 3 shows the results for different heights of the tank, while other parameters are fixed as the benchmark parameters (as per Figure 2 and Table 1). The base shear, overturning moment, and maximum hoop stress significantly increases with the increase in tank height. 100% increase in tank height resulted in 173% increase in base shear, 432% increase in overturning moment and 97% increase in maximum hoop stress.

The proportion of seismic masses is determined according to the height to radius ratio (*H/R*). When *H/R* is less than 1 (or classified as rigid behavior), flexible impulsive mass (m_f) is equal to 0 and rigid impulsive mass (m_0) is equal to the impulsive mass of the rigid tank (m_r). When H/R increases, the impulsive mass (m_0) increases logarithmically while the convective mass (m_1) decreases logarithmically. Therefore, the base shear and over-turning moments of the tank increases when the tank height increases.

Non-dimensional hoop forces ($N_{\theta n}$) are determined according to the height (H), radius (R) and wall thickness (t_w) of the tank. Non-dimensional hoop forces ($N_{\theta n}$) and the pressures (P) increase with an increase of tank height Therefore, the change of tank height has a significant impact on the hoop stress of the tank.

Figure 3 shows the seismic responses for different thicknesses of the tank, while other parameters are kept constant as per the benchmark parameters. It can be observed that the hoop stress decreased significantly with an increase in tank wall thickness. 100% increase in tank wall thickness resulted in 50% decrease in hoop stress.

4.2 Effect of Foundation Soil Type

Figure 4 shows the tank seismic response for the different foundation soil types (B, C and D), while other parameters are kept fixed as per the benchmark parameters (see Figure 2 and Table 1). Base shear and overturning moment gradually increase with decrease in shear velocity and shear modulus of soil; however, the maximum hoop stress show a decreasing trend.

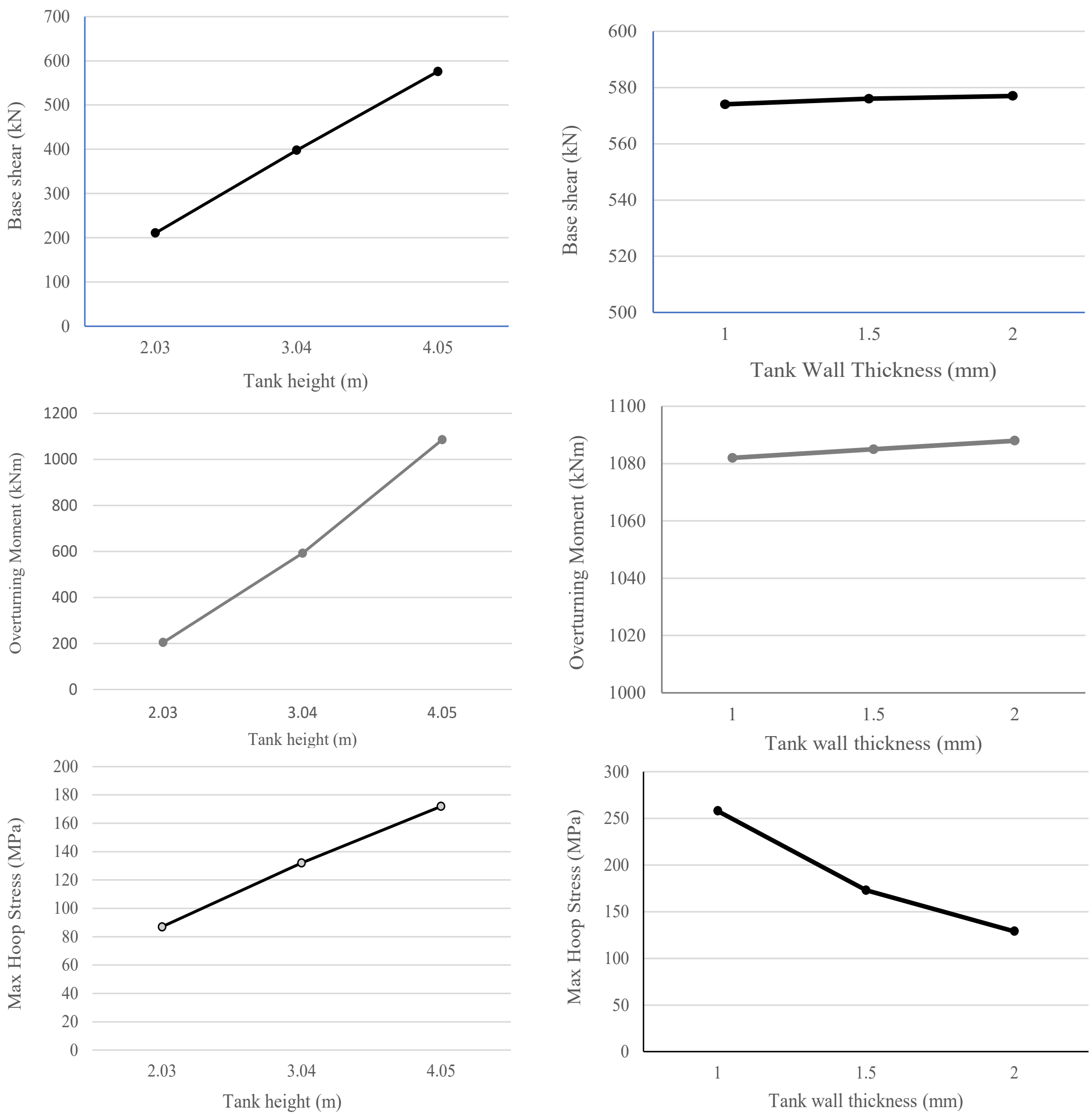

Figure 3. Effects of tank height and thickness on base shear, overturning moment and maximum hoop stress.

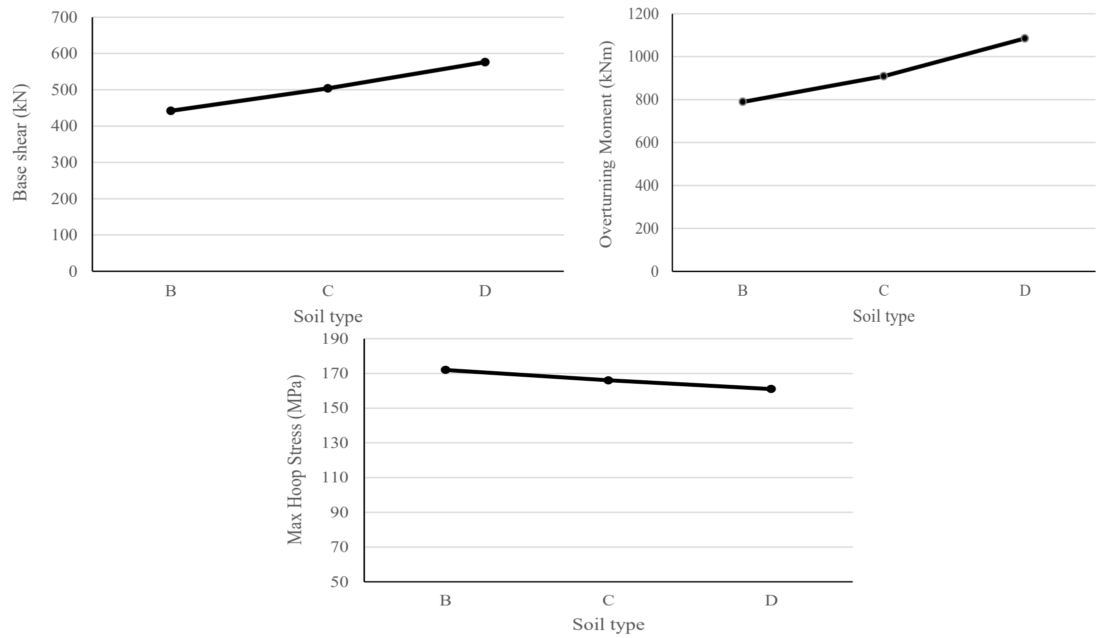

Figure 4. Effects of soil type on seismic response of the tank.

5 CONCLUSIONS

Three primary seismic response parameters including the base shear, overturning moment and maximum hoop stress were investigated for a case study steel tank using a series of parametric analyses. The results show that the height of the tank has a significant impact on seismic responses. Base shear, overturning moment and maximum hoop stress significantly increase when the tank height increases. The tank wall thickness, however, has a very minor effect on Base shear and overturning moment as expected, but it has a significant effect on the maximum hoop stress.

The foundation soil types (which represent different shear wave velocity and shear modulus of the soil) significantly impact the seismic response. Spectral shape factor depends on soil type. This factor increases in softer soils (the soils with low shear wave velocity). Furthermore, the damping factor decreases with the increase in shear wave velocity. Therefore, when the subsoil is classified as soft soil, the base shear and overturning moment increase. However, the hoop stress slightly decreases in softer soils.

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