Parametric Study of Soil Structure Interaction on Liquid Containing Concrete Tanks Based on a Modified Version of the NBCC 2015, ACI 350.3-06 and ASCE 41-06.

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ABSTRACT

Limited guidance is provided to the Canadian engineering community with respect to the seismic design and analysis of wastewater treatment plant (WWTP) facilities, especially pertaining to the soil-structure interaction (SSI) of liquid-containing tanks. Current Canadian standards do not provide explicit design methodologies for such non-building structures. Risks associated with the poor performance or the failure of these structures need to be carefully considered as structural failures can have life safety, plant operation, and environmental impacts. Most WWTP facilities in Canada are constructed near existing bodies of water where soil characteristics are generally less than ideal. Rigid bodies, such as heavily reinforced concrete tanks, can develop large base displacements from deformation of the underlying soil. The design assumption of fixity at the base may result in good structural performance of the concrete elements, but can greatly underestimate the overall system behavior and displacement if SSI is not considered. This paper investigates the SSI of square concrete liquid-containing tanks with the underlying soil to predict the tank's behaviour and better understand its performance during seismic events. A parametric study is performed on tanks of varying dimensions on soils of varying stiffness. Seismic loads are based on the ACI 350.3-06 analysis methodology for liquid-containing structures and adapted for a Canadian application. The dynamic analysis results are calibrated to a modified version of the NBCC 2015 equivalent static force procedure. Equivalent soil spring properties are modelled using ASCE 41-06 formulas for varying soil types and tank sizes. The study aims to understand the impact that SSI has on the performance of liquid-containing tanks during seismic events in order to establish more efficient and tailored designs in future Canadian standards.

Keywords: Rectangular concrete liquid storage tanks, soil-structure interaction, convective mode, impulsive mode, seismic response, non-building structures.

BACKGROUND

In Canada, no code or standard exists for the seismic design of liquid-containing concrete tanks. The seismic design and analysis of liquid-containing tank is generally completed using the National Building Code of Canada (NBCC) [1], but the NBCC does not provide explicit methodologies for the design and analysis of non-building structures such as liquid-containing tanks. The types of loading in non-building structures can significantly differ from building-type structures, as in the case of liquid-containing structures. In order to apply the provisions of the NBCC, the structural engineer must categorize tanks within a Seismic Force-Resisting System (SFRS), which is not representative of the tank's actual response to seismic events. To avoid this issue, many Canadian structural engineers choose to design liquid-containing tanks according to the American Concrete Institute Standard 350.3 *Seismic Design of Liquid-Containing Concrete Structures and* Commentary (ACI 350.3-06) [2]. This standard provides a procedure to determine the seismic loading on liquid-containing structures based on impulsive and convective vibration modes, which more accurately represent the tank's response to a seismic event.

Although the above-ground behaviour of tanks is relatively well understood, the interaction of liquid-containing structures with the underlying soil is not well defined in the available codes and standards. The soil-structure interaction (SSI) of liquid-containing tanks is especially important for wastewater treatment plant (WWTP) facilities, which commonly utilize concrete tanks for process and storage of liquids. Most WWTP facilities in Canada are constructed near existing streams and bodies of water, where soil characteristics are often problematic due to high water tables and soft soil deposits. Due to the lack of guidance on SSI in available codes and standards, structural engineers often assume fixed-base systems when designing tanks, therefore neglecting the structure's interaction with the underlying soil in dynamic conditions. This approach is consistent with the dynamic model of a liquid-containing tank rigidly supported on the ground, as outlined in ACI 350.3-06 [2].

The fixed-base assumption is a conservative assumption when calculating design seismic base shears, but this assumption will also underestimate the overall system displacements. Dynamic forces applied to rigid bodies, such as heavily reinforced and robust concrete tanks, on soft soils can cause large displacement at the base from soil displacements, which would not be considered in a fixed-base analysis.

Liquid-containing tank failure is generally not governed by structural failure, but by the inability to contain the liquids. Pipes and fixtures are often connected to liquid-containing tanks and may be the weak links in the structure if the tank displacement is greater than the displacement limit of the pipes and fixtures. The underestimation of the displacements of the tank subjected to seismic loading, due to the fixed-base assumption, could lead to pipe failure near the inlets and outlets and may result in an overall failed system. Performance of a WWTP facility is also highly dependent on a carefully tuned hydraulic gradient. The overall performance of the plant is not only related to the performance of each component, but on the process as a whole. Permanent deformation or displacements of a tank will result in an impaired performance of the plant.

The purpose of this paper is to investigate the interaction between liquid-containing tanks and the supporting soil and explore the impact of the fixed-base assumption on the design and system behaviour of liquid-containing tanks.

APPLICATION OF LITERATURE

The ACI 350.3-06 was developed specifically to help engineers determine the seismic demands on liquid-containing concrete tanks. It divides the weight of the tank contents into two components based on Housner's [3] equations for modeling the dynamic behaviour of liquid-containing tanks: impulsive and convective. The impulsive component is associated with the lower portion of the contained liquid and corresponds to the portion of the liquid within the tank that behaves rigidly with the structure, in addition to the tanks self-weight. The convective component is representative of the portion of the liquid that undergoes active movement or sloshing behaviour. ACI 350.3-06 defines the locations of the convective and impulsive centres of gravity based on the tank's liquid width-to-height ratio and the tank's aspect ratio (η) [2]. Three different tank sizes were developed for the parametric study: a slender tank ($\eta = 0.5$), a base tank ($\eta = 0.75$), and a squat tank ($\eta = 1.5$). Each tank is modelled based on its aspect ratio and assumes 610 mm thick concrete walls and a square 1220 mm thick concrete foundation. The properties outlined in Table 1 remained constant throughout the study. In order to compare similar magnitude of loading, the volume of water was fixed as 288 m^3 and the tank dimensions were varied to suit the different aspect ratios.

Table 1. Tank Properties.

Concrete Strength (f'_c)	**Concrete Unit Weight (γ_c)**	**Tank Wall Width (t_w)**	**Foundation Thickness (t_f)**	**Liquid Volume (V_L)**	**Liquid Unit Weight (γ_L)**
35 MPa	23.56 kN/m^3	0.61 m	1.22 m	288 m^3	10 kN/m^3

The dimensional properties of each tank are outlined in Table 2.

Table 2. Tank Types and Dimensions (All Water Volumes Equal to 288 m^3).

Tank Type	**Liquid Height (H_L)**	**Tank Width (B)**	**Aspect Ratio ($\eta = B/H_L$)**
Slender	10.5 m	5.2 m	0.5
Reference	8 m	6 m	0.75
Squat	5.0 m	7.6 m	1.5

SSI is represented with springs of varying stiffness to account for a range of different soil types. The ASCE 41-06 [4] outlines numerous methods to analytically represent soil springs, two of which were selected for this parametric study. Method 2 and 3, as per ASCE 41-06 categorization, are both based on Winkler's spring models. Method 2 provides distributed vertical stiffness properties for the end zones (each representing by 1/6th of the base width) and the middle zone of shallow bearing foundations that are not rigid with respect to the supporting soil (refer to Figure 1).

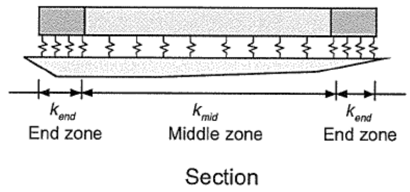

Figure 1. Vertical Stiffness Modelling using Method 2 (from ASCE 41-6) [4]

Equations 1 and 2 are used to calculate the soil stiffness properties using Method 2.

$$k_{2,end} = \frac{6.83G}{(1-\nu)}(l) \tag{1}$$

Where $k_{2,end}$ is the soil stiffness (kN/m) at each end zone of the foundation width used in Method 2, G is the soil's shear modulus (MPa), ν is Poisson's Ratio (unitless), and l is the tributary length of the spring (m).

$$k_{2,mid} = \frac{0.73G}{(1-\nu)}(l) \tag{2}$$

Where $k_{2,mid}$ is the soil stiffness for the middle zone of the foundation width (kN/m) used in Method 2.

Method 3 provides uniform spring coefficients for shallow bearing foundations that are flexible relative to the supporting soil. These springs are distributed uniformly along the foundation. Equation 3 is used to calculate the soil stiffness properties using Method 3.

$$k_3 = \frac{1.3G}{B(1-\nu)}(l) \tag{3}$$

Where k_3 is the unit subgrade spring coefficient for Method 3 (kN/m) and B is the foundation's width (m).

Although Method 2 can be used in combination with rotational soil springs, these were not included in the study for comparison purposes since Method 3 does not consider rotational springs within its procedure and, given the relative meshing of the vertical springs acting at a distance from the point of rotation at the base, the vertical springs were assumed to provide the overall rotational stiffness for the system.

For the purpose of this study, three different soils were selected based on similar studies for buildings and tanks [5] [6]. These soil types display a variety of different responses to the dynamic loading applied. The soil properties used in the parametric study are identified in Table 3.

Table 3 Soil Properties.

Spring Type	**Representative Soil Type**	**Poisson's Ratio (υ)**	**Young's Modulus (E)**	**Shear Modulus (G)**	**Tank Type**	**Stiffness (kN/m)**		
						Method 2 ASCE 41-06 (k_2)		**Method 3 ASCE 41-06**
						k_{mid}	**k_{end}**	**k_3**
Soft	Saturated Clay	0.5	10 MPa	57.7 MPa	Slender	2,126	19,890	3,786
					Reference	2,433	22,770	4,333
					Squat	3,066	28,680	5,460
Medium	Unsaturated Clay	0.4	50 MPa	19.9 MPa	Slender	9,490	88,790	16,900
					Reference	10,860	101,600	19,350
					Squat	13,690	128,100	24,370
Stiff	Dense Sand-Gravel	0.3	150 MPa	3.33 MPa	Slender	26,280	245,900	46,800
					Reference	30,080	281,500	53,570
					Squat	37,900	354,600	67,500

DYNAMIC MODELLING

The water tanks were modelled using SAP2000 by Computers and Structures, Inc. [7]. 2-D analysis models were created for three tanks of varying aspect ratios: a slender tank, a reference tank, and a squat tank. All models were created according to the tank properties and dimensions identified in Tables 1 and 2 above and were created following the procedure outlined in ACI 350.3-06 for the dynamic modeling of a liquid-containing tank rigidly supported on the ground [2]. The weight of the oscillating fluid that produces convective inertia was modelled as a load connected to the tank walls using equivalent springs. The weight of the water causing the impulsive seismic inertia was modelled as rigidly attached to the tank walls. Refer to Figures 2 and 3.

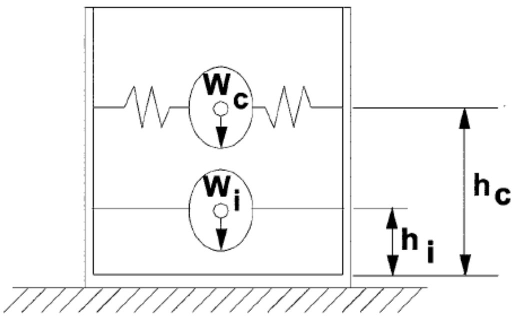

Figure 2. Dynamic Model of a Liquid-Containing Tank (from ACI 350.3-06) (XXX)

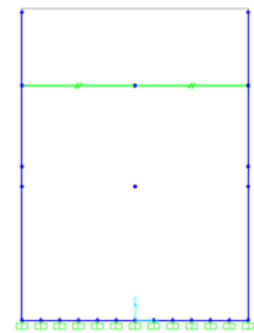

Figure 3. Model Used During the Parametric Study (Fixed Base)

The modal response spectrum analysis were performed using the uniform hazard response spectrum for a Site Class E in Ottawa, Ontario for the impulsive modes of vibration [1]. The convective hazard was estimated using the ACI 350.3-06 and modified for 0.5% damping [2]. The convective and impulsive modal analyses were performed separately and referenced the appropriate response spectra values. Refer to Figure 4 for the response spectrum curves.

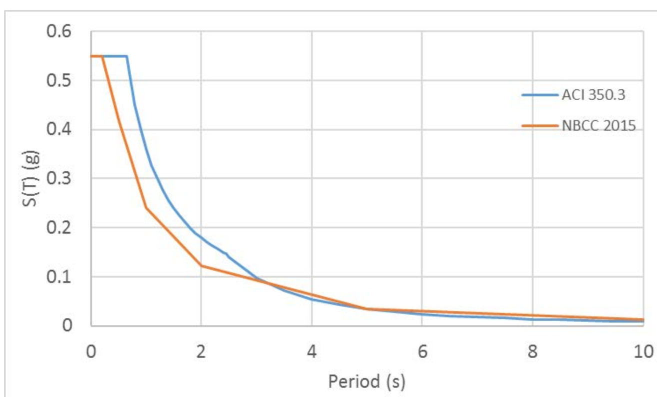

Figure 4. Response Spectrum Curves.

VALIDATION

The reference tank model with a fixed base was validated using hand calculations using ACI 350.3-06 [2] and a modified version of the NBCC 2015 [1] equivalent static force procedure. For the purpose of the study, the importance factor (I) as well as both the convective and impulsive response modification factors (R_i, R_c) were set equal to 1.0, whereas in actuality they should be set equal to 1.5, 1.0 and 2.0, respectively. Therefore, elastic values are discussed herein.

Based on the dimensional properties of the tank, the convective period (T_c) can be computed according to Equation 4 whereas the impulsive period (T_i) is dependent on the flexural stiffness (k) of the wall and impulsive mass (m_i), as shown in Equation 5. The convective and impulsive loads (P_c, P_i) are a function of their appropriate weights (W_c, W_i, W_w) and period-dependent seismic response coefficients (C_c, C_i). The impulsive load and moments are the result of the lateral inertia force due to the tank walls and of the impulsive water mass combined.

$$T_c = \frac{2\pi}{\lambda}\sqrt{B} \tag{4}$$

$$T_i = 2\pi\sqrt{\frac{k}{m_i}} \tag{5}$$

$$P_c = \frac{C_c \cdot I \cdot W_c}{R_c} \tag{6}$$

$$P_i = P_w + P'_i = \frac{C_i \cdot I \cdot W_i}{R_i} + \frac{C_i \cdot I \cdot (\varepsilon \cdot W_w)}{R_i} \tag{7}$$

$$V = \sqrt{{P_c}^2 + {P_i}^2} \tag{8}$$

Both loads are applied at their appropriate centres of gravity (h_c, h_i, h_w) based on the tank's dimensions and allow for the computation of the base shear and base moments (V, M_c, M_i) using the square root sum of squares method. The overturning moment (M_o) used in the validation process included the effects of the tank bottom and supporting structure.

$$M_c = P_c \cdot h_c \tag{9}$$

$$M_i = P_i \cdot h_i + P_w \cdot h_w \tag{10}$$

$$M_o = \sqrt{{M_c}^2 + {M_i}^2} \tag{11}$$

The results of the hand calculations were compared to the modelled version for the fixed-base tank and are displayed in Table 4. As noted in the table, the percentage of error between the hand calculations and the results obtained from the analysis model varies from -1.0% to 3.1%.

Table 4. Validation of Hand Calculations with Fixed-Base Analysis Model.

	Impulsive Period (Ti)	**Impulsive Base Shear (Vi)**	**Impulsive Moment (Mc)**	**Convective Period (Tc)**	**Convective Base Shear (Vc)**	**Convective Moment (Mc)**
Hand Calculations	0.205 s	2,610 kN	9,909 kN·m	2.765 s	65 kN	407 kN
Fixed-Base Analysis Model	0.203 s	2,584 kN	9,888 kN·m	2.768 s	67 kN	416 kN
% Error	-1.0%	-1.0%	-0.2%	0.1%	3.1%	2.2%

PARAMETRIC STUDY

In order to understand the overall impact of soil springs on liquid-containing tanks, a parametric study was performed by varying the aspect ratios of the tanks (slender tank, reference tank, and squat tank) and implementing soils spring values for both ASCE 41-06 Method 2 and Method 3. A total of 21 models were analyzed. A summary of the parameters used for the parametric study is included in Figure 5.

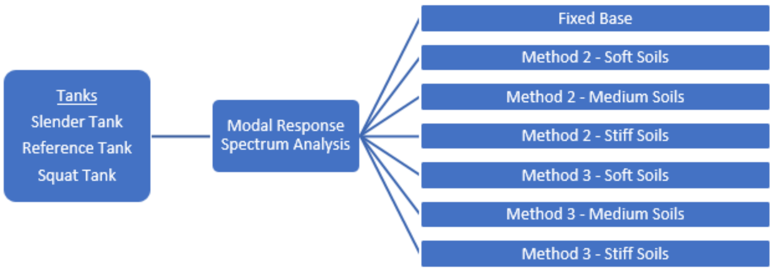

Figure 5. Summary of Parameters Used in the Parametric Study

ANALYSIS RESULTS

The modal results of the parametric study for the reference tank are presented in Figure 6. These modal ratios apply to all tanks but only the results of the reference tank have been plotted for clarity.

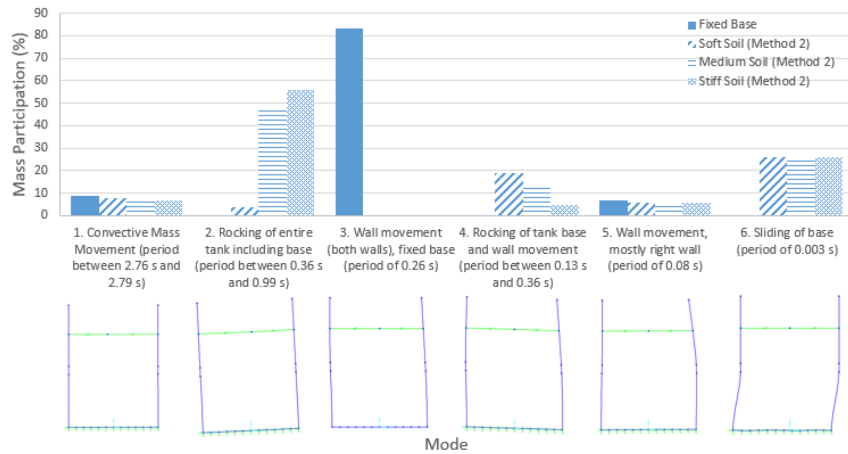

Figure 6. Typical Impulsive Modal Results of the Parametric Study for the Reference Tank

The results from the modal response spectrum analysis for the three tank aspect ratios and seven soil condition are plotted in Figures 7 to 10. It should be noted that the settlements plotted in Figure 9 only include the soil deformation due to the seismic loading and not the combination of seismic and gravity loadings.

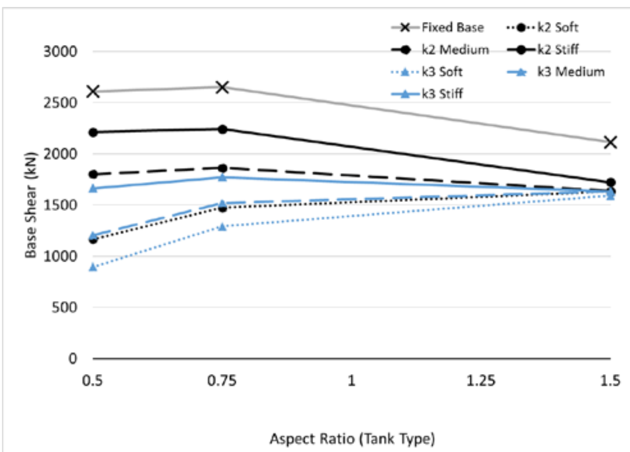

Figure 7. Base Shear vs. Tank Type

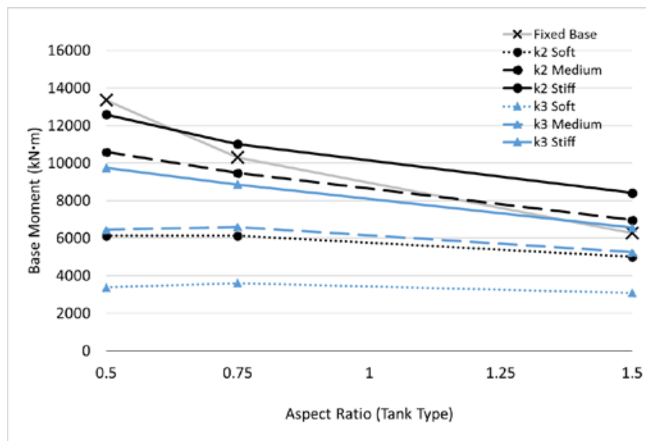

Figure 8. Moment at Base vs. Tank Type

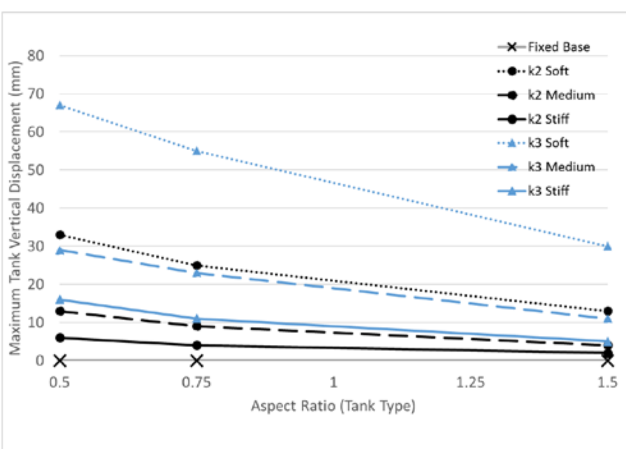

Figure 9. Maximum Tank Dynamic Vertical Displacement vs. Tank Type

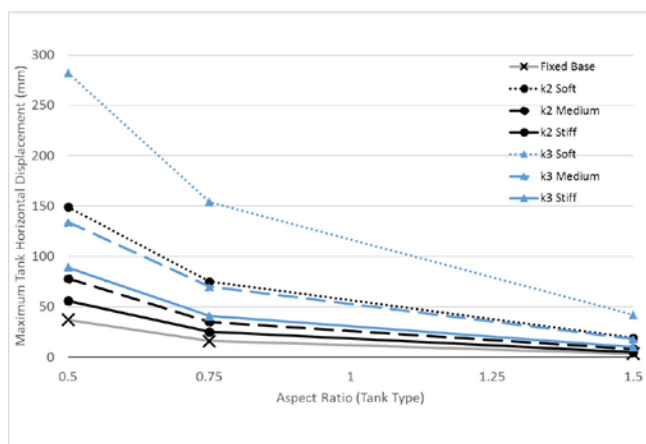

Figure 10. Maximum Wall Horizontal Displacement vs. Tank Type.

As illustrated in Figures 11 and 12 below, the soil stiffness has little impact on the convective base shears and moments. The impulsive base shears and moments for the slender and reference tanks, on the other hand, are significantly impacted by the soil stiffness, with greater base shears and moments for structures on stiffer soils. Soil stiffness has little impact on the impulsive base shears for the squat tank.

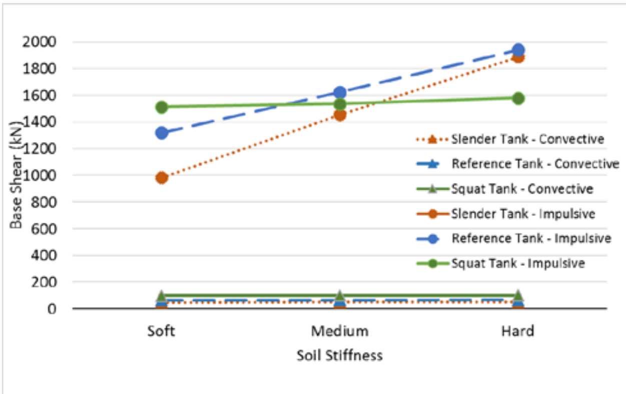

Figure 11. Impulsive and Convective Base Shear vs. Soil Stiffness

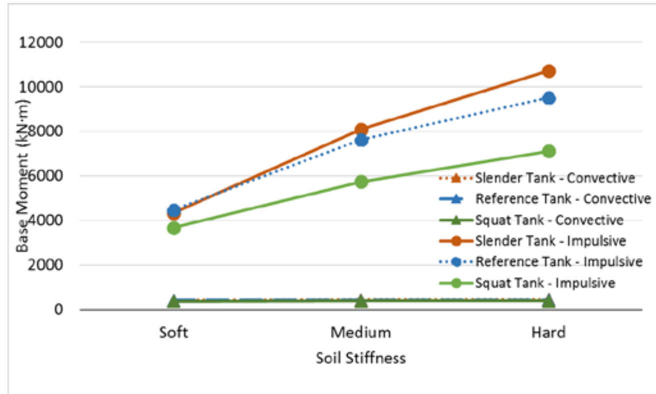

Figure 12. Impulsive and Convective Base Moment vs. Soil Stiffness

DISCUSSION

Based on the results of this analysis, lower soil stiffness (i.e. soft soils) decrease the seismic base shear demand on the structure. The difference is especially noticeable for the slender tank and the reference tank. For the squat tank, the impact of the soil conditions on seismic base shear is smaller.

The consideration of SSI increases both vertical and horizontal seismic displacements of the tank. The maximum vertical displacements obtained when considering SSI varied between 2 mm and 67 mm, whereas the vertical displacement of the fixed-base model was null. The tank's maximum horizontal displacement varied between 3 mm and 37 mm when using the fixed-base model. When considering SSI, the horizontal displacements increased to between 5 mm and 282 mm. For both the horizontal and vertical displacements, greater displacements occurred in the slender tank and with the softer soils.

The use of a fixed-base model tends to be an overestimation of the seismic base shears, but an underestimation of the seismic deflections. This can lead to a problematic design where the pipes cannot accommodate the actual deflection that may be experienced by the tank during a seismic event. In addition, structural separations between the liquid-containing tank and adjacent structures can be underestimated, which could lead to damage due to impact between the structures during the seismic event. If realistic post-disaster settlements and movements are not accounted for in the process hydraulic profile, critical plant operations could be jeopardized after a seismic event if the tanks are still structurally sound.

Consideration of the SSI is increasingly important when the tank is more slender. This is associated with the increase in impulsive component of the contained water mass and overturning demand on the foundation, which increases the displacement of the base when springs are introduced. The highest variability in the results is associated with the aspect ratio of 0.5.

The soil stiffness values calculated using Method 3 produced significantly larger deflections and smaller base shears than those calculated using Method 2. Given the relative stiffness of the foundation system in concrete tanks, the use of Method 2 may be a more realistic representation of the soils behaviour, especially at higher displacements. The method used to determine the soil stiffness must be verified based on the site conditions, relative stiffness's, and specific application in close coordination with a knowledgeable geotechnical engineer.

When tanks were placed on springs, the system transitioned from a quasi-single-degree-of-freedom system (SDOF for convective, impulsive) of freedom to a multi-degree-of-freedom system. SSI vibration modes such as rocking were observed in most models, especially in softer soils and slender tanks. The fixed-base model does not capture the SSI mode which were found to have an important mass participation. This results in longer vibration period, the participation of multiple modes, as well as lower base shears and overturning moment.

It should be noted that the convective and impulsive water masses used in the parametric study were determined following the dynamic modelling procedure in ACI 350.3-06, which was adapted from Housner's model for the behaviour of water tanks with a fixed base. The impact of the soil stiffness on the modal behaviour of the water tanks could also impact relative the proportion of water mass associated with the impulsive and convective modes as well as their reference heights. This warrants further study.

The parametric study was performed using a modal response spectrum analysis. This type of analysis uses mode superposition to determine the behaviour of a structure to a response spectrum curve. Modal combination was performed using the square root sum of the squares of the peak response quantities in each mode of vibration. The results of the modal response spectrum analysis are therefore maximum response quantities that are not a function of time. This method does not account for the modal behaviour of the structure with time and can overestimate the seismic base shears and displacements.

Performing a time history analysis could further refine the results from the modal response spectrum analysis and may better identify when the different modes are activated and participating in the behaviour of the structure. Nonlinear properties for the soil could be implemented and may also impact the system behaviour. In addition, a better representation of the contained liquid should be considered.

CONCLUSIONS

The objective of this study was to examine the effect of SSI on seismic analysis of liquid containing concrete tank structures. It is well understood that a fixed-based assumption leads to larger design loads for the superstructure. In the case of concrete tanks, the overall behaviour and performance objective is not strictly limited to the structure and its ability to contain liquid, but the operation of the overall system (piping, process hydraulic profile).

The parametric study confirmed that assuming a fixed-base tank for analysis results in higher seismic loading, but underestimates the system behaviour, deflections, and potentially the demand on pipes and fixtures.

The design of liquid-containing tanks needs to carefully consider the soil conditions and their effect on the behaviour of the structure and system when subjected to seismic loading. As demonstrated in the study, slender tanks and tanks constructed on soft soils are especially sensitive to the impact of SSI on their behaviour. Site-specific geotechnical and design parameters are generally required to properly account for SSI behaviour.

The ACI 350.3-06 approach for estimating the convective and impulsive modes may not properly represent a system when it is placed on springs. Additional SSI modes were observed to be dominant with large mass participation ratios at longer periods, especially for softer soils and slender tanks.

During the parametric study, linear springs were used to model the soil behaviour. Further analysis using nonlinear springs could be performed to investigate the impact of soil yielding on energy dissipation, damping, mode shapes, base shears, and deflections. The models were generally sensitive to soil parameter (Method 2 vs Method 3), especially in lower aspect ratios (slender tanks). This emphasizes the importance of to having a qualified geotechnical engineer working closely with the structural engineer in developing site-specific soil spring models and properties.

Performance objectives of tanks in WWTP facilities are not simply defined by the ability of the tanks to contain liquid after an event, but in their ability to support the process. This needs to be carefully considered whenever a post-disaster design objective for operational performance is required. This is especially important when considering the performance of process piping and the impact of deflections on the facility’s hydraulic gradient.

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