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Article

Evaluation of Soil-Structure Interaction on the Seismic Response of Liquid Storage Tanks under Earthquake Ground Motions

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Abstract: Soil-structure interaction (SSI) could affect the seismic response of structures. Since liquid storage tanks are vital structures and must continue their operation under severe earthquakes, their seismic behavior should be studied. Accordingly, the seismic response of liquid storage tanks founded on half space soil is scrutinized under different earthquake ground motions. To better comparison, the six considered ground motions are classified based on their pulse like characteristics, into two groups, named far and near fault ground motions. To model the liquid storage tanks, the simplified mass-spring model is used and the liquid is modeled as two lumped masses known as sloshing and impulsive, and the interaction of fluid and structure is considered using two coupled springs and dashpots. The SSI effect, also, is considered using a coupled spring and dashpot. Besides, four types of soils are used to consider wide variety of soil properties. To this end, after deriving the equations of motion, the MATLAB programming is employed to obtain the time history responses. Results show that although the SSI effect leads to decrease the impulsive displacement, overturning moment and normalized base shear, the sloshing (or convective) displacement is not affected by such effects due to its long period.

Keywords: liquid storage tanks; soil-structure interaction; seismic response; earthquake ground motions

1. Introduction

Liquid storage tanks are important structures which have key role in human lives. It is clear that in designing of such structures, all factors that affect seismic responses of these structures should be considered. One of these factors is soil-structure-interaction (SSI). The SSI affects earthquake ground motions, characteristics of structures and also soil properties. Accordingly, depending on the period of structure, the seismic response of structure could either increase or decrease. Several studies showed that the SSI effect is more important for massive structures such as tall buildings, bridges and liquid storage tanks which could cause to suspend their performance [1,2]. The most popular and relatively accurate model to represent the soil-structure-interaction is the substructure method which considers the soil as coupled springs and dashpots [3, 4].

Liquid storage tanks behave differently from common structures such as buildings, bridges, etc., due to fluid-structure-interaction. Housner's mass-spring model [3] was a first approximate model to obtain the seismic responses of rigid cylindrical liquid storage tanks. In the Housner's model [3], the whole liquid is divided into two parts; a portion of liquid which excites independently of tank wall near the free surface is named as "Convective" and the other part of liquid exciting unison with tank wall is named "Impulsive". By increasing the tank's geometries, Haroun and Housner [4] modified the Housner's model to consider the flexibility of tank's wall; in their presented model, the liquid is divided into three portions; convective and impulsive masses which are attached to the tank's wall through springs and dashpots and the rigid mass which is attached to the tank's wall rigidly. Matlhotra *et al.* [5] have proposed a simplified model by considering higher modes of impulsive mass with the first impulsive modal mass and higher mode of convective mass with the first convective modal mass. Bagheri *et al.* [6] studied the seismic responses of liquid storage tanks under near-fault ground motions; such earthquake ground motions have long-period components that may affect the long-period sloshing motion of liquid [6]. The effect of earthquake characteristics on seismic responses of base isolated liquid storage tanks is also studied by Bagheri and Farajian [7], who showed that the pulse-like earthquake-ground motions could cause excessive displacement in base isolation and therefore the impact could be occurred.

The SSI effect on seismic response of liquid storage tanks has been studied by several researchers. Veletsos and Tang [8] proposed a method to consider the SSI; they proposed to modify the impulsive mass frequency and damping to consider the SSI effect and their research has shown that the SSI has no special effect on convective mass displacement. Larkin [9] obtained the responses of steel and concrete liquid storage tanks considering SSI effect, and found that SSI affects the shear force and overturning moment specially on soft soils. Foundation embedment effects on behavior of elevated tanks were studied by Livaoglu and Dogangun [10], who concluded that embedment in soft soil significantly affects the tank roof's displacement. Livaoglu [11] shown that decreasing the stiffness of the soil leads to reduction of the base shear and impulsive displacement; on the other hand, sloshing displacement is not considerably affected due to SSI, embedment and wall flexibility [11].

In this paper, the effect of SSI on seismic response of liquid storage tanks is studied under earthquake ground motions in time domain. Accordingly, after solving the equations of motion in time domain, the peak responses are obtained and compared with the ones without considering SSI.

2. Structural Model of the Fluid-Tank-Soil System

A simplified model is implemented here to model the fluid-tank-soil interaction. Figure 1 shows a cylindrical liquid storage tank rested on a half space soil. As modeling of the interaction effects is complicated, the Malhotra's *et al.* theory [5] is used to considering the Fluid-Structure-Interaction (FSI), and the cone method [12] is employed to simulation of Soil-Structure-Interaction (SSI) effects. These models have been briefly described below.

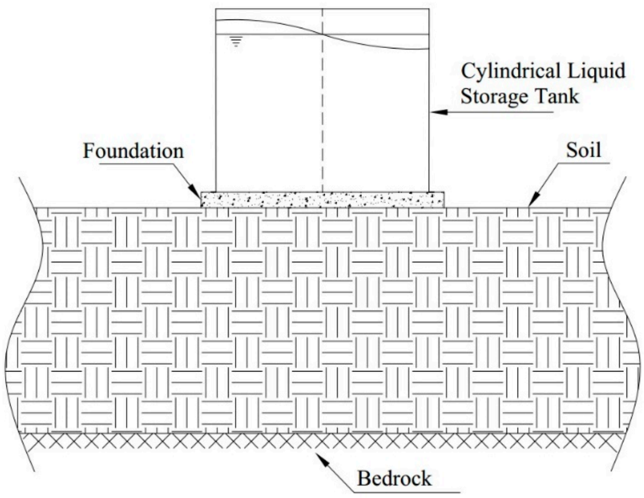

Figure 1. Liquid storage tank rested on half space.

2.1 Fluid-Tank System

The 3D finite element model of a liquid storage tank is usually complicated due to hydrodynamic interaction effects. Accordingly, the simplified mass-spring model of Malhotra *et al.* [5] is used in the present study. The geometry of a cylindrical tank is the liquid height (H), tank's

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radius (r), and equivalent uniform thickness of the tank wall (t) shown in Figure 2. According to Figure 3, the convective and impulsive masses (m_c and m_i) are connected to the tank's wall by springs and dashpots (k_c and c_c, k_i and c_i). The natural periods of the convective (T_c) and impulsive (T_i) of responses are [5]:

$$T_c = C_c \sqrt{r} \tag{1}$$

$$T_i = C_i \frac{H\sqrt{\rho_s}}{\sqrt{E\, t / r}} \tag{2}$$

where, ρ_s and E are the mass density of liquid and modulus of elasticity of tank's wall, respectively. The coefficients C_c and C_i, the relative convective and impulsive masses (m_c/m and m_i/m) and heights (h_c/H and h_i/H) are provided by Malhotra *et al.* [5]. The total liquid mass of tank filling with water is equal to ($\pi r^2 H \rho_w$). The corresponding stiffness and damping ratio of springs and dashpots associated with convective and impulsive masses are equal to:

$$k_c = m_c \times \omega_c^2 \tag{3}$$

$$k_i = m_i \times \omega_i^2 \tag{4}$$

$$c_c = 2\xi_c m_c \times \omega_c \tag{5}$$

$$c_i = 2\xi_i m_i \times \omega_i \tag{6}$$

where, ω_c and ω_i are frequency of convective and impulsive responses. The damping ratio of convective and impulsive mode (ξ_c and ξ_i) is 0.5% and 2%, respectively.

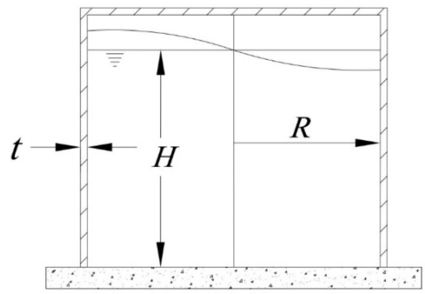

Figure 2. Geometry of liquid storage tank.

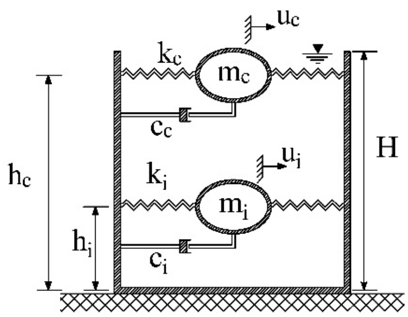

Figure 3. Simplified mass-spring model of Malhotra for fluid-structure-interaction.

2.2 Soil-Structurre System

Considering real conditions, a liquid storage tank resting on soil consists of a tank (structure) and an adjacent bounded soil called near-field soil and unbounded soil called far-field. Both near-field and far-field soils affect the seismic response of the structure.

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The soil-structure-interaction could be modeled using three proposed methods: i) Direct method by employing numerical methods, *such as finite element method (FEM), boundary element method (BEM), scaled boundary-finite element method (SBFEM)*, ii) Modifying the fixed base condition to take into account of SSI, where, in this model the effect of foundation embedment, layering and material damping was ignored, and iii) The substructure method which considers the soil by either dependent or independent frequency springs and dashpots which could be either used in time or frequency domain. In order to obtain the corresponding stiffness and damping, three methods could be used: i) The procedures presented in NIST GCR 12-917-21 [13], ii) Thin layer method which is used by SASSI software [14], and iii) Cone method proposed by Meek and Wolf [12]. Compared to other numerical methods, the cone model [12] has a simple numerical procedure and relative accurate response. In the cone method, the soil is modeled using springs and dashpots, and cones have translational, rotational and torsional behavior. Only the translational motion is considered in this paper due to its simplicity, and remaining motions are ignored.

Based on the cone method theory, when a homogenous semi-infinite domain is subjected to a static load (P_0), the components of the displacement field will vary along the depth in the shape of a truncated cone, as shown in Figure 4, for horizontal translational degree of freedom. The static stiffness of this truncated cone in a circular rigid foundation and equivalent circular foundation can be expressed by [15]

$$K_{Static} = \frac{8\rho v_s^2 r_0}{2-\upsilon} \tag{7}$$

where, ρ and v_s are mass density and shear velocity of the soil medium, r_0 is the radius of the equivalent circular foundation and υ is the Poisson's ratio. For dynamic problems, the stiffness of half-space in the cone model is frequency dependent and this static stiffness is used for calculating the dynamic stiffness $S(a_0)$ which is expressed by,

$$S(a_0) = K(k(a_0) + ia_0 c(a_0)) \tag{8}$$

in which, $k(a_0)$ is the dynamic spring coefficient, $c(a_0)$ is the dynamic damping coefficient and a_0 is the dimensionless frequency equaled to $\omega r_0/v_s$ with implementing excitation frequency ω. In this study, these frequency dependent stiffness and damping coefficients are calculated using CONAN computer program.

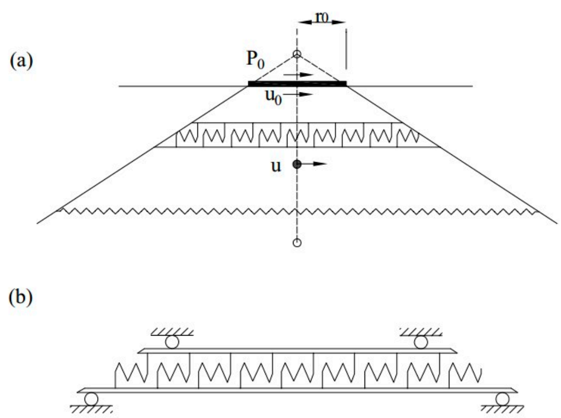

Figure 4. Translational truncated semi-infinite cone with horizontal motion, shear distortion and equilibrium of infinitesimal element, where rocking motion is prevented with; (a) infinite flexural rigidity and (b) rollers for horizontal motion.

In order to investigate the response of the structure due to various earthquakes on different soil conditions, four types of soil are considered, where, these soil properties are mentioned in Table 1; as it is clear from this table, soil S1 is known as a hard rock and by going to S4, the soils change to softer

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soil. As described, the cone method and CONAN program are used to evaluate the impedance functions of these four soil types by employing the soil characteristics.

Table 1. Properties of considered soils types.

Soil types	ζ_g	E (kN/m²)	G (kN/m²)	E_c (kN/m³)	γ (kN/m³)	υ	v_s (m/s)	v_p (m/s)
S1	0.05	7,000,000	2,692,310	9,423,077	20	0.30	1149.1	2149.89
S2	0.05	2,000,000	769,230	2,629,308	20	0.30	614.25	1149.16
S3	0.05	500,000	192,310	673,077	19	0.35	309.22	643.68
S4	0.05	35,000	12,500	75,000	18	0.40	82.54	202.18

2.3 Governing equations of motion

The equations of motion of the system of simplified model of liquid storage tank considering SSI effect, as shown in Figure 5, can be written as,

$$m_c\ddot{u}_c + c_c(\dot{u}_c - \dot{u}_f) + k_c(u_c - u_f) = -m_c\ddot{u}_g \tag{9}$$

$$m_i\ddot{u}_i + c_i(\dot{u}_i - \dot{u}_f) + k_i(u_i - u_f) = -m_i\ddot{u}_g \tag{10}$$

$$m_f\ddot{u}_f + c_c(\dot{u}_f - \dot{u}_c) + c_i(\dot{u}_f - \dot{u}_i) + c_s\dot{u}_f + k_c(u_f - u_c) + k_i(u_f - u_c) + k_s u_f = -m_i\ddot{u}_g \tag{11}$$

in which, u_c, u_i and u_f are convective, impulsive and foundation displacements relative to the bedrock, respectively and $\ddot{u}_g$ is the earthquake ground motion. The foundation mass is also represent by m_f. Other parameters are described in section 2.1.

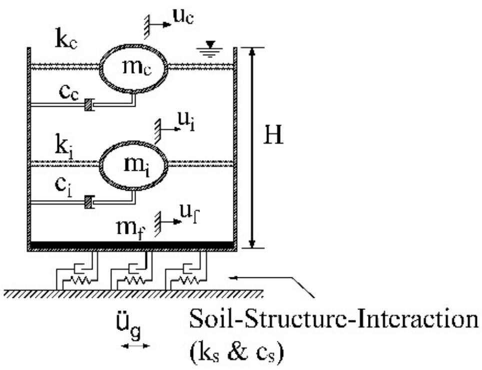

Figure 5. Simplified model of liquid storage tank considering soil-structure-fluid-interaction.

Using state-space method, a MATLAB routine is provided to solve the governing equations of motion. The numerical results will be mainly presented in terms of the convective and impulsive displacements relative to the foundation (x_c, x_i) according to Eqs. (12) and (13), free vertical surface displacement (d_x) according to Eq. (14), overturning moment (OM) and structural base shear (F_s) according to Eq. (15) and (16). The overturning moment and base shear are normalized by weight of the system.

$$x_c = u_c - u_f \tag{12}$$

$$x_i = u_i - u_f \tag{13}$$

$$d_x = 0.837R\,\frac{\omega_c^2(u_c - u_f)}{g} \tag{14}$$

$$OM = k_c \times x_c \times h_c + c_c \times v_c \times h_c + k_i \times x_i \times h_i + c_i \times v_i \times h_i \tag{15}$$

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$$F_s = k_c \times x_c + c_c \times v_c + k_i \times x_i + c_i \times v_i \quad (16)$$

3. Numerical Study

A parametric study has been done to evaluate the effect of SSI. For this purpose, a broad and a slender steel tank has been considered as a numerical study. The resulted seismic responses of tanks are compared with those of fixed ones. The geometric properties of the tank models are summarized in Table 2 and the resultant parameters of the equivalent mechanical models are listed in Table 3. The characteristics of selected earthquake ground motion records for time history analyses are tabulated in Table 4. These selected near-fault ground motions have been recorded close to faults and have revealed near-fault pulses.

Table 2. Properties of the Broad and Slender tanks used in this study.

Tank type	H (m)	R (m)	H/R	t (m)	E (GPa)	ρ (kg/m^3)
Broad	14.6	24.4	0.6	0.0203	200	1000
Slender	11.3	6.1	1.85	0.0058	200	1000

Table 3. Resultant parameters of the equivalent mechanical model for the Broad and Slender tanks.

Tank type	m_c/m	m_i/m	h_c/H	h_i/H	C_c (s/m$^{0.5}$)	C_i	T_c (s)	T_i (s)
Broad	0.608	0.392	0.557	0.400	1.65	7.08	8.15	0.253
Slender	0.245	0.755	0.727	0.444	1.48	6.07	3.66	0.157

Table 4. Selected earthquake ground motions for time history analyses.

No.	Earthquake	Station	PGA (g)
1	Chichi, Taiwán, 1999	NST-E	0.309
2	Chichi, Taiwán, 1999	TCU075-W	0.333
3	Imperial Valley, 1979	6617 Cucapah	0.309
4	Imperial Valley, 1979	5155 EC Meloland	0.314
5	Northridge, 1994	90014 Beverly Hills	0.617
6	Northridge, 1994	24514 Sylmar	0.604

4. Results

In this section the effect of SSI on seismic responses of both broad and slender liquid storage tanks is studied.

For example, Figure 6 depicts the time history of considered responses of two broad and slender tanks mounted on soil type 4 under Chichi-NST-E ground motion in both without SSI and with SSI, respectively.

The peak responses of broad and slender tanks rested on various soil types under different ground motions are tabulated in Tables 5 to 12.

It is observed that the impulsive mass displacement, normalized overturning moment and normalized base shear are reduced due to SSI effect. SSI causes to shift the period of structure, therefore the responses get reduced. Such reduction will lead to better performance of these structures during earthquake events. On the other hand the convective mass displacement is slightly affected. This phenomenon is related to the fact that the convective response has relative long period and therefore the SSI has no special effect on this response.

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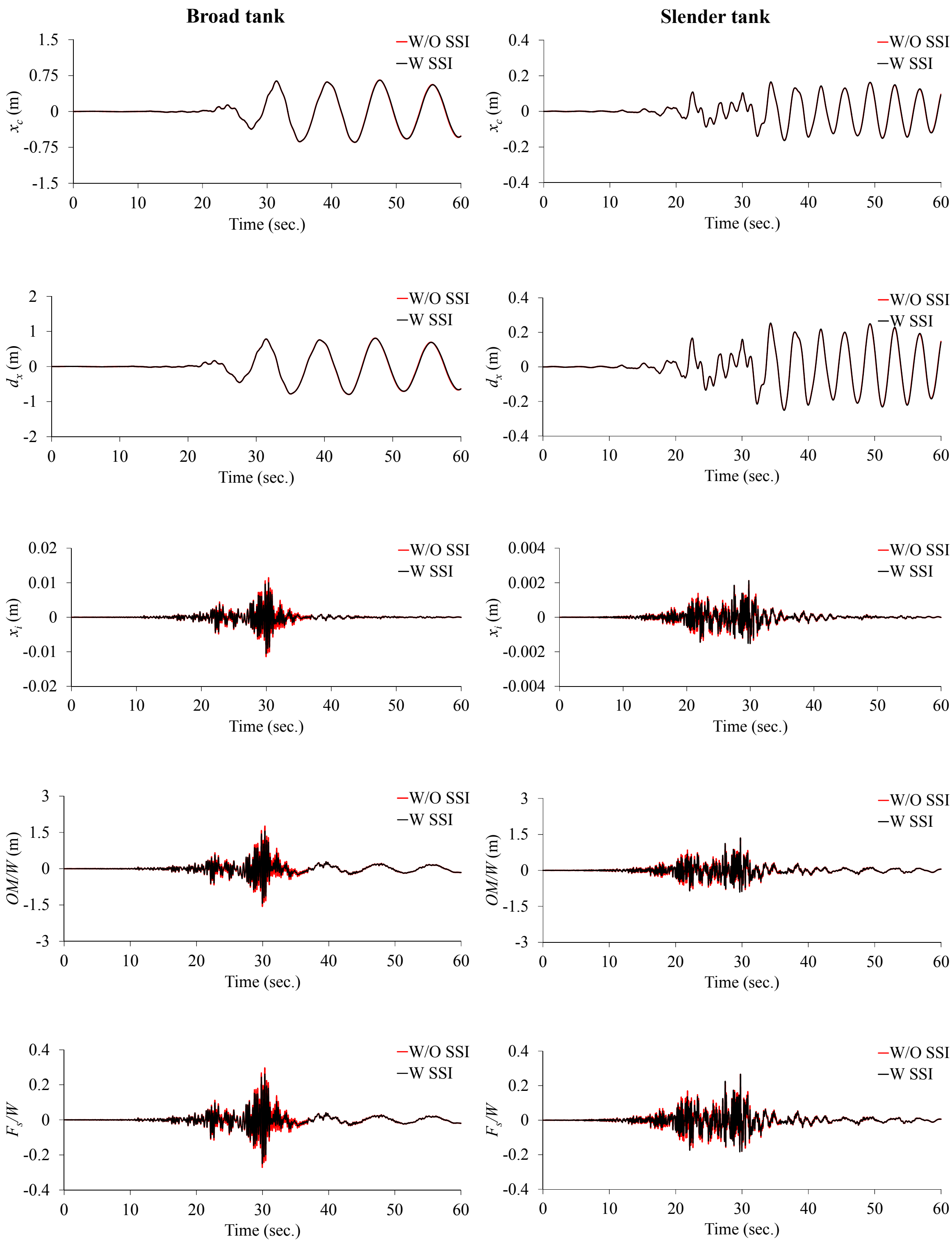

Figure 6. Time history of broad and slender tank under Chichi-NST-E ground motion rested on soil type 4.

Table 5. Peak responses of the broad tank on soil type 1.

Record No.	Tank Type	Condition	x_c (m)	d_x (m)	x_i (m)	*OM/W (m)*	F_s/W
1	Broad	w/o SSI	0.6259	0.7726	0.0102	1.544	0.2609
		w SSI	0.6259	0.7725	0.0102	1.526	0.2578
2	Broad	w/o SSI	1.4083	1.7382	0.0133	1.801	0.3145
		w SSI	1.4082	1.7381	0.0126	1.750	0.2958
3	Broad	w/o SSI	0.2738	0.3379	0.0070	1.033	0.1762
		w SSI	0.2738	0.3379	0.0072	1.037	0.1768
4	Broad	w/o SSI	0.3677	0.4539	0.0063	0.862	0.1491
		w SSI	0.3675	0.4536	0.0063	0.836	0.1463
5	Broad	w/o SSI	0.0951	0.1174	0.0260	3.766	0.6447
		w SSI	0.0951	0.1173	0.0257	3.711	0.6353
6	Broad	w/o SSI	0.1691	0.2087	0.0084	1.166	0.2021
		w SSI	0.1691	0.2087	0.0085	1.168	0.2023

Table 6. Peak responses of the slender tank on soil type 1.

Record No.	Tank Type	Condition	x_c (m)	d_x (m)	x_i (m)	*OM/W (m)*	F_s/W
1	Slender	w/o SSI	0.1320	0.2026	0.0041	2.572	0.5110
		w SSI	0.1320	0.2026	0.0041	2.572	0.5110
2	Slender	w/o SSI	1.4752	2.2636	0.0063	4.436	0.8281
		w SSI	1.4754	2.2638	0.0062	4.252	0.7913
3	Slender	w/o SSI	0.2612	0.4007	0.0096	5.866	1.1740
		w SSI	0.2612	0.4007	0.0094	5.821	1.1649
4	Slender	w/o SSI	0.5037	0.7729	0.0024	1.350	0.2748
		w SSI	0.5037	0.7729	0.0022	1.342	0.2732
5	Slender	w/o SSI	0.1303	0.1999	0.0092	5.735	1.1426
		w SSI	0.1304	0.2000	0.0090	5.609	1.1176
6	Slender	w/o SSI	0.4378	0.6718	0.0062	3.723	0.7522
		w SSI	0.4378	0.6718	0.0061	3.698	0.7473

Table 7. Peak responses of the broad tank on soil type 2.

Record No.	Tank Type	Condition	x_c (m)	d_x (m)	x_i (m)	*OM/W (m)*	F_s/W
1	Broad	w/o SSI	0.6264	0.7731	0.0225	3.304	0.5628
		w SSI	0.6264	0.7732	0.0213	3.127	0.5325
2	Broad	w/o SSI	1.4095	1.7396	0.0284	4.105	0.6959
		w SSI	1.4091	1.7391	0.0261	3.841	0.6539
3	Broad	w/o SSI	0.2739	0.3381	0.0175	2.522	0.4324
		w SSI	0.2739	0.3380	0.0176	2.526	0.4330
4	Broad	w/o SSI	0.3679	0.4540	0.0147	2.106	0.3573
		w SSI	0.3677	0.4539	0.0139	2.025	0.3434
5	Broad	w/o SSI	0.0961	0.1186	0.0648	9.319	1.5960
		w SSI	0.0959	0.1183	0.0604	8.717	1.4920
6	Broad	w/o SSI	0.1710	0.2110	0.0164	2.321	0.3999
		w SSI	0.1710	0.2110	0.0167	2.359	0.4059

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Table 8. Peak responses of the slender tank on soil type 2.

Record No.	Tank Type	Condition	x_c (m)	d_x (m)	x_i (m)	*OM/W (m)*	F_s/W
1	Slender	w/o SSI	0.1322	0.2029	0.0074	4.551	0.9072
		w SSI	0.1323	0.2030	0.0072	4.547	0.9063
2	Slender	w/o SSI	1.4791	2.2696	0.0090	6.053	1.1480
		w SSI	1.4790	2.2694	0.0089	5.848	1.1071
3	Slender	w/o SSI	0.2619	0.4019	0.0167	10.245	2.0470
		w SSI	0.2619	0.4018	0.0165	10.190	2.0359
4	Slender	w/o SSI	0.5049	0.7747	0.0034	2.111	0.4238
		w SSI	0.5050	0.7748	0.0035	2.099	0.4215
5	Slender	w/o SSI	0.1307	0.2005	0.0158	9.781	1.9492
		w SSI	0.1308	0.2006	0.0156	9.613	1.9156
6	Slender	w/o SSI	0.4390	0.6736	0.0099	6.042	1.2016
		w SSI	0.4389	0.6735	0.0098	5.934	1.1831

Table 9. Peak responses of the broad tank on soil type 3.

Record No.	Tank Type	Condition	x_c (m)	d_x (m)	x_i (m)	*OM/W (m)*	F_s/W
1	Broad	w/o SSI	0.6273	0.7744	0.0153	2.165	0.3732
		w SSI	0.6260	0.7726	0.0149	2.100	0.3620
2	Broad	w/o SSI	1.4338	1.7696	0.0222	3.612	0.5985
		w SSI	1.4329	1.7686	0.0218	3.551	0.5880
3	Broad	w/o SSI	0.2755	0.3401	0.0132	1.909	0.3264
		w SSI	0.2753	0.3398	0.0130	1.901	0.3249
4	Broad	w/o SSI	0.3690	0.4555	0.0124	1.871	0.3171
		w SSI	0.3679	0.4541	0.0122	1.851	0.3136
5	Broad	w/o SSI	0.0953	0.1177	0.0430	6.204	1.0624
		w SSI	0.0954	0.1178	0.0411	5.928	1.0151
6	Broad	w/o SSI	0.1848	0.2281	0.0228	3.316	0.5662
		w SSI	0.1847	0.2280	0.0226	3.309	0.5650

Table 10. Peak responses of the slender tank on soil type 3.

Record No.	Tank Type	Condition	x_c (m)	d_x (m)	x_i (m)	*OM/W (m)*	F_s/W
1	Slender	w/o SSI	0.1334	0.2048	0.0041	2.469	0.4955
		w SSI	0.1335	0.2049	0.0040	2.443	0.4902
2	Slender	w/o SSI	1.5005	2.3023	0.0055	4.113	0.7617
		w SSI	1.5000	2.3015	0.0054	3.818	0.7028
3	Slender	w/o SSI	0.2636	0.4045	0.0071	4.379	0.8764
		w SSI	0.2635	0.4044	0.0068	4.140	0.8286
4	Slender	w/o SSI	0.5143	0.7892	0.0034	2.014	0.4073
		w SSI	0.5144	0.7893	0.0032	1.995	0.4036
5	Slender	w/o SSI	0.1334	0.2048	0.0108	6.671	1.3313
		w SSI	0.1336	0.2049	0.0105	6.474	1.2921
6	Slender	w/o SSI	0.4434	0.6804	0.0072	4.437	0.8905
		w SSI	0.4431	0.6800	0.0070	4.288	0.8606

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Table 11. Peak responses of the broad tank on soil type 4.

Record No.	Tank Type	Condition	x_c (m)	d_x (m)	x_i (m)	*OM/W (m)*	F_s/W
1	Broad	w/o SSI	0.6568	0.8106	0.0114	1.765	0.2969
		w SSI	0.6475	0.7991	0.0099	1.406	0.2354
2	Broad	w/o SSI	1.5259	1.8833	0.0137	2.003	0.3286
		w SSI	1.5193	1.8751	0.0117	1.769	0.2990
3	Broad	w/o SSI	0.2755	0.3401	0.0097	1.356	0.2347
		w SSI	0.2734	0.3374	0.0093	1.318	0.2280
4	Broad	w/o SSI	0.4019	0.4961	0.0095	1.267	0.2219
		w SSI	0.4021	0.4963	0.0093	1.231	0.2157
5	Broad	w/o SSI	0.1417	0.1749	0.0273	3.933	0.6739
		w SSI	0.1418	0.1751	0.0235	3.395	0.5814
6	Broad	w/o SSI	0.3254	0.4017	0.0137	1.883	0.3271
		w SSI	0.3254	0.4017	0.0140	1.915	0.3325

Table 12. Peak responses of the slender tank on soil type 4.

Record No.	Tank Type	Condition	x_c (m)	d_x (m)	x_i (m)	*OM/W (m)*	F_s/W
1	Slender	w/o SSI	0.1633	0.2507	0.0021	1.351	0.2662
		w SSI	0.1632	0.2503	0.0021	1.351	0.2661
2	Slender	w/o SSI	1.8978	2.9119	0.0035	2.850	0.5001
		w SSI	1.8850	2.8923	0.0028	2.307	0.3875
3	Slender	w/o SSI	0.3377	0.5182	0.0054	3.323	0.6661
		w SSI	0.3365	0.5163	0.0047	2.870	0.5758
4	Slender	w/o SSI	0.6630	1.0174	0.0030	1.679	0.3413
		w SSI	0.6630	1.0174	0.0028	1.634	0.3321
5	Slender	w/o SSI	0.2115	0.3246	0.0056	3.496	0.6952
		w SSI	0.2115	0.3246	0.0048	3.014	0.5991
6	Slender	w/o SSI	0.7356	1.1286	0.0048	2.797	0.5756
		w SSI	0.7353	1.1282	0.0044	2.503	0.5142

From Tables 5 to 12, it is observed that the maximum values obtained for the reduction percentage of impulsive mass displacement, normalized overturning moment and normalized base shear are 13.2%, 20.3% and 20.7% for broad tank under Chichi-NST-E ground motion, and 20%, 19.1% and 22.5% for slender tank under Chichi-TCU075-W earthquake, when the liquid storage tank rested on soil type 4 (see Table 11 record no. 1 and Table 12 record no. 2). From all the data of Tables 5 to 12 (*for the 6 selected earthquake ground motions*), Figure 7 shows the mean reduction percentages of peak responses in broad and slender tank due to SSI effect. *(For the calculation of each mean reduction percentage, in those only very few specific cases in which there is amplification and not reduction because of the frequency content of the earthquake and the structure, those reduction percentages are taken negative).* Generally, as the shear velocity of medium soil decreases, aforementioned responses get more reduced. The mean reduction percentages of impulsive mass displacement, normalized overturning moment and normalized base shear are 7.6%, 8.3% and 7.9% for broad tank, and 10.4%, 9.9% and 10.5% for slender tank, when the liquid storage tank rested on soil type 4. According to Figure 7 the convective mass displacement and also free vertical surface displacement is only slightly reduced. This is due to long period of convective mass. However, for soil type 4, the SSI causes to reduce the convective mass displacement and also free vertical surface displacement, compared to the without SSI condition. This phenomenon is observed in both broad and slender tank.

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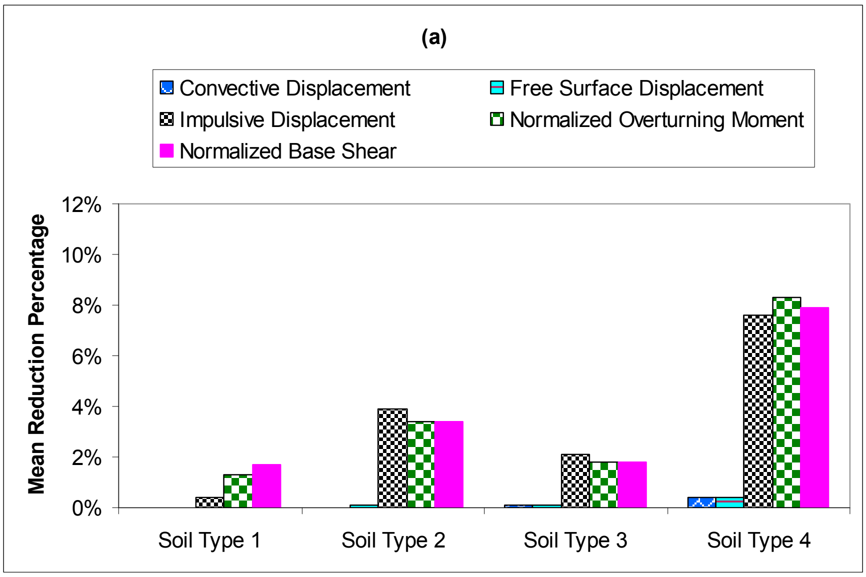

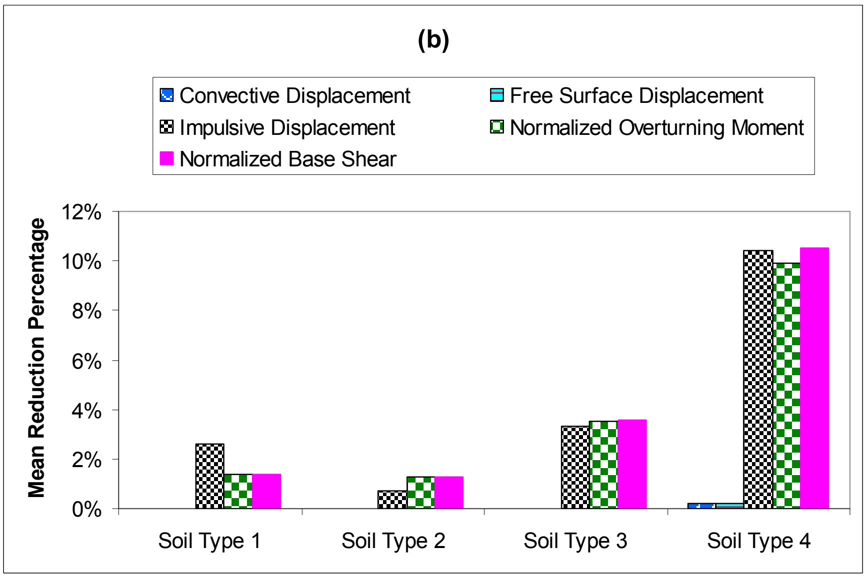

Figure 7.Mean reduction percentage of peak responses (a) broad tank (b) slender tank.

4. Conclusions

The seismic behavior of liquid storage tanks considering the SSI effect is evaluated in this paper. The substructure method is used to consider the SSI effect, and dynamic stiffness and damping are obtained using the cone method. Two types of tanks rested on four soil types are considered as the case study. Then the peak responses of these tanks, in both with and without considering SSI, under six earthquake excitations are compared. According to obtained responses, the impulsive mass displacement, normalized overturning moment and normalized base shear are reduced as the SSI effect is considered. However, for relative stiff soil this reduction is not considerable. But, for soft soil, the SSI effect could shift the fundamental period of impulsive mass and therefore the impulsive displacement and other dependent responses reduce.

Since convective mass has long period, the SSI did not considerably affect its seismic characteristics. Nevertheless, transition from relative stiff soil (S1) to softer soil (S4) could cause to shift the fundamental period of spectrum and therefore, the convective displacement is also reduced.

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