AN ANALYTICAL APPROACH FOR THE DETERMINATION OF BACKFILL EFFECTS ON RECTANGULAR DRINKING WATER STORAGE TANKS

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Abstract

The present paper aims to examine how and to what extend the variation of the backfill soil properties may effect the frequencies and/or periods of the backfill-rectangular tank wall-fluid system. For this purpose, a simplified analytical model is developed to estimate the modal properties and frequencies of fluid-rectangular tank wall-backfill system by means of a simple and fast analysis procedure. In this procedure, the fluid interaction is considered by using Housner's two mass approximations, and the backfill interaction is taken into account by using mass-spring-dashpot system. Backfill soil behind the exterior wall of the tank interacts with wall in compression, but it is assumed that there is no interaction in tension. While the backfill-wall-fluid system consists of three degrees-of-freedom structure in compression situation between wall and backfill, aforementioned system consists of two degrees of-freedom structure in tension situation. Furthermore, the dynamic equations of motions of the above-mentioned systems are written and modal characteristics related to total system are obtained considering five different backfill soil types. Consequently, it is demonstrated that the proposed analytical model can be used to analyze the backfill-wall-fluid system and the findings obtained from this study show that backfill soil has considerable effects on the dynamic behavior of rectangular tank wall. However, backfill interactions do not affect the sloshing modes.

Keywords: *Backfill interaction, fluid interaction, mass-spring-dashpot system, compression, tension*

1. Introduction

The analyses of the interaction between a structure and backfill soil, and/or between a structure and fluid are of significant interest to civil engineers. Liquid storage tanks are an example of such a class of structures, in which the effects of fluid and backfill interactions may be significant. Despite their structural simplicity, the seismic response of tanks is a rather complicated problem. What makes that response so complicated is the dynamic interactions between both the tank wall and backfill soil, and the tank wall and fluid.

Liquid storage tanks form crucial links in the water supply network and are most susceptible to earthquakes. Depending on design conditions and load bearing mechanisms, the tanks are classified into different categories, e.g. rectangular tanks, elevated tanks, underground tanks, ground-level cylindrical tanks, etc. The seismic response of various types of tanks has been examined by a number of researchers in the past, either experimentally, analytically, or numerically. While most of these studies have concentrated on the ground-level cylindrical tanks, the behavior of rectangular tanks during seismic loading has been studied by a few researchers. A review of chronological developments pertaining to the analyses of water storage tanks can be found in various publications. The publications performed on both elevated tanks and rectangular tanks can be attained from Livaoğlu and Doğangün (2006) and Livaoğlu (2008), respectively. Furthermore, studies on dynamic behavior of rectangular tank considering backfill-wall-fluid interaction were carried out by Livaoğlu et.al., 2007; Çakır et.al., 2008; Livaoğlu et.al., 2009.

The effect of backfill soil pressure is important in a number of problems, such as retaining and sheet pile walls, basement walls etc. Earthquakes have unfavorable effects on lateral soil pressures acting on retaining walls or exterior walls of the tanks. Because backfill exerts large dynamic forces on walls and causes severe failures. The damage of the exterior wall is mainly associated with the movement and failure induced by strong earthquake motion and high seismic soil pressure. Hence, the assessment of seismic lateral soil pressures is of practical significance in most seismic designs of retaining walls. Discussion of the all the research work on the seismic soil pressure is extensive and is beyond the scope of this study. Rather, only some milestones that have influenced the design practice are described below. The pioneering work, currently known as the Mononobe-Okabe method (M-O), is developed by Okabe (1924) and Mononobe and Matsuo (1929). Since then, a great deal of research has been performed to evaluate its adequacy and to improve it. Seed and Whitman (1970) focused on limit-state design and they used modified Mononobe Okabe analysis, an extension of the Coulomb-Rankine sliding wedge theory. Many investigators have used elasticity principles and wave propagation theory to obtain the dynamic response of soil-structure systems and model the effects of wall-soil interaction with different approaches, assumptions and simplifications. Tajimi(1973), using a two dimensional wave propagation theory, calculated earth pressure on rigid basement walls. Scott (1973) analytically studied earth pressure on rigid retaining walls rotating about the base, and concluded that forces and moments were significantly higher than those calculated by M-O analysis. Nazarian and Hadjian (1979) reported on a survey of the literature in the area of earthquake-induced lateral soil pressures and identified the shortcomings of different approaches. Arias et.al. (1981) developed a model for the case of fixed, rigid walls under an arbitrary horizontal dynamic excitation, and compared the results with those of Wood(1973) and with other finite element solutions. Veletsos and Younan (1994a, 1994b) developed a simple approximate expression for simulating the dynamic pressures, the associate forces, and the responses induced by ground shaking on a straight, vertical rigid wall retaining soil with a semi-infinite, uniform viscoelastic layer of constant thickness. The solutions for frequency-dependent and frequencyindependent parameters were studied and compared with the results proposed by Scott (1973). The elastic constrained bars with distributed mass were used to represent the soil stratum in backfill. They concluded that Scott's (1973) model, which ignores radiational soil damping and considers the wall pressure to be proportional to the relative motions of the wall and the soil at the far field, does not adequately describe the action of the system and may lead to large errors. Veletsos and Younan (1997) continued and expanded their work. A solution technique was developed to compute the dynamic response of cantilever retaining walls that are elastically constrained against base rotation subjected to horizontal ground motion. Wu and Finn (1996) developed a simplified linear elastic analytical solution based on a modified shear beam model for the seismic pressures against rigid walls. Furthermore, displacements of the retaining walls may be induced during earthquakes. Then, a displacement-based design needs to be introduced. Thus, some researchers carried out displacement-based designs taking into account the permissible displacements of the wall (Richards and Elms, 1979; Siddharthan et. al.,1991; Rafnsson, 1991; Wu, 1999; Prakash et. al., 1996; Choudhury et.al., 2004).

From the above discussion, it can be stated that there is almost no investigation about the analysis of backfill-exterior wall of rectangular drinking water storage tank- fluid system under the combined actions of forces induced by fluid and soil interactions, and also a practical method for determining the behavior of backfill-rectangular tank wall-fluid system is significantly needed. Thus, the main purposes of this study are to develop a simplified analytical model to determine the modal properties and frequencies and/or periods of backfill-rectangular tank wall-fluid system and investigate how different backfill soil properties affect the behavior of rectangular tank wall.

2. Proposed Model For Backfill-Rectangular Tank Wall-Fluid System

Seismic behavior of fluid-rectangular tank-backfill system is a complex problem. The problem can simply be idealized as shown in Fig. 1. In this idealization, fluid is modeled with Housner's two mass representation (Housner, 1957;1963) and backfill is modeled with mass-spring-dashpot system.

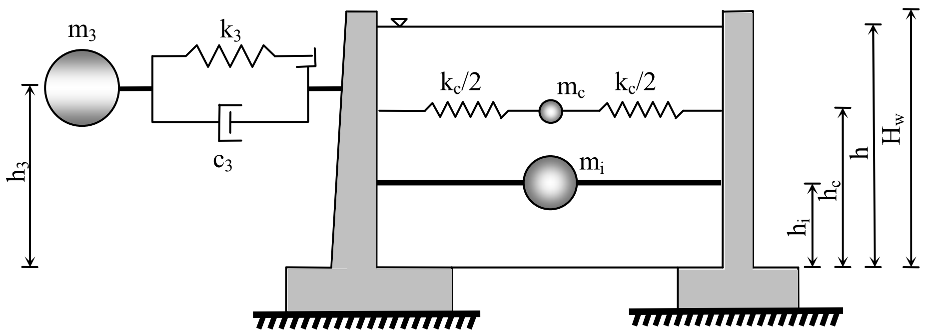

Figure 1. Proposed mechanical model for fluid-rectangular tank-backfill system

Housner (1957,1963) suggested that an equivalent impulsive mass (m_i) and a convective mass (m_c) should represent the dynamic behavior of a fluid. The heights of the convective (h_c) and impulsive (h_i) masses are given by Housner's model. The height h_3 which is necessary to determine the maximum base moment is equal to $(2/\pi)H_W = 0.637H_W$ where H_W is the height of wall (Veletsos, 1994b). Here, it is suitable to say that backfill soil behind the exterior wall of the tank interacts with wall in compression, but it is assumed that there is no interaction in tension. Thus, the simplified analytical models of backfill-rectangular tank wall-fluid system and rectangular tank wall-fluid system are shown in Fig.2 and Fig.3, respectively.

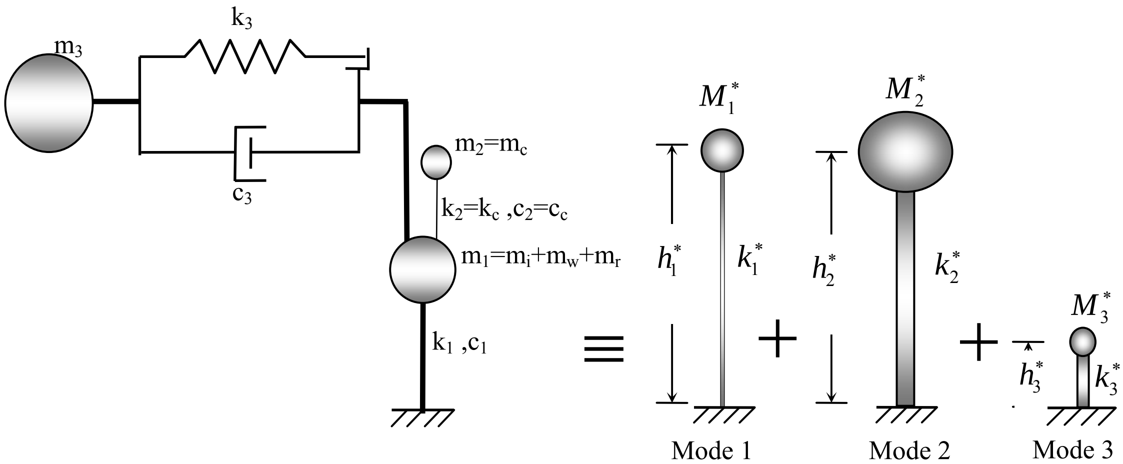

Figure 2. The mathematical model and modal representation of backfill-rectangular tank wall-fluid system.

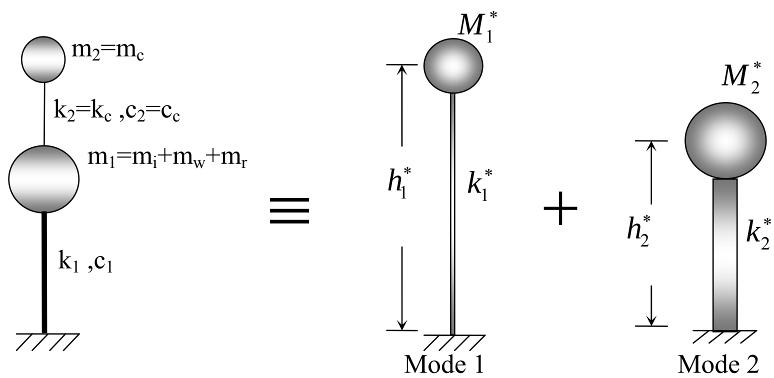

Figure 3. The mathematical model and modal representation of rectangular tank wall-fluid system.

To obtain a solution, the concerned design parameters, like stifnesses, masses and damping constants must be determined. The mass m_1 consists of the summation of impulsive mass (m_i), mass of wall (m_w) and effective mass of the roof (m_r). The mass m_2 is equal to convective mass (m_c) given by Housner's model. The mass m_3 is considered as effective backfill mass. The lateral stiffness of the exterior wall, k_1, can readily be determined as $k_1=12EI_{ort}/H_w^3$ since the roof slab is rigid [i.e., flexural

rigidity $EI_b=\infty$]. The stiffness k_2 is equal to convective stiffness (k_c) given by Housner (1957,1963). The stiffness k_3 is average shear stiffness for backfill soil which may conveniently be expressed as the product of the shear modulus of backfill (G) and reduced cross sectional area (F') of backfill. The reduced cross sectional area can be estimated as $F' = F/k'$ where F is the cross sectional area of backfill at average level, k' is a coefficient which can be taken as 1.2 for a rectangular cross sectional area. The c_1, c_2, c_3 are the damping values for impulsive mode, convective mode and backfill soil, respectively.
Considering the dynamic equilibrium of the backfill-rectangular tank wall-fluid system, basic dynamic equations can be written in matrix form:

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \\ \ddot{u}_3 \end{Bmatrix} + \begin{bmatrix} c_1+c_2+c_3 & -c_2 & -c_3 \\ -c_2 & c_2 & 0 \\ -c_3 & 0 & c_3 \end{bmatrix} \begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \\ \dot{u}_3 \end{Bmatrix} + \begin{bmatrix} k_1+k_2+k_3 & -k_2 & -k_3 \\ -k_2 & k_2 & 0 \\ -k_3 & 0 & k_3 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = \begin{Bmatrix} P_1(t) \\ P_2(t) \\ P_3(t) \end{Bmatrix} \tag{1}$$

Similarly, considering the dynamic equilibrium of the rectangular tank wall-fluid system, basic dynamic equations can be written in matrix form:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{Bmatrix} + \begin{bmatrix} c_1+c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{Bmatrix} + \begin{bmatrix} k_1+k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} = \begin{Bmatrix} P_1(t) \\ P_2(t) \end{Bmatrix} \tag{2}$$

where, (u_1,u_2,u_3), $(\dot{u}_1, \dot{u}_2, \dot{u}_3)$, $(\ddot{u}_1, \ddot{u}_2, \ddot{u}_3)$ are the displacements, velocities and accelerations of masses m_1, m_2, m_3, and $P_1(t), P_2(t), P_3(t)$ are the applied external forces. It is worth emphasizing that since the responses of sloshing displacement of fluid and lateral displacement and base shear forces were not calculated, and modal characteristics of the system were determined only, the data regarding both the damping matrix and the external forces were not discussed herein.

The obtained equations can be solved by not only direct integration techniques but also modal analysis technique. When one want to obtain the solution by modal analysis technique, modal properties such as effective modal masses, heights and stiffnesses should be computed from both three degree-of freedom and two degree-of-freedom systems. M_1^*, M_2^*, M_3^*; h_1^*, h_2^*, h_3^*; k_1^*, k_2^*, k_3^* are the effective masses, heights and stiffnesses of the first, second and third modes, respectively. These modal properties can be estimated using Eqs. (3) and (4) (Chopra, 2007).

$$M_n^* = \Gamma_n L_n^h = \frac{\left(L_n^h\right)^2}{M_n}; \qquad h_n^* = \frac{L_n^\theta}{L_n^h}; \qquad k_n^* = \omega_n^2 M_n^* \qquad (3)$$

where

$$M_n = \varphi_n^T m \varphi_n = \sum_{j=1}^{N} m_j \varphi_{jn}^2; \quad \Gamma_n = \frac{L_n^h}{M_n}; \quad L_n^h = \sum_{j=1}^{N} m_j \varphi_{jn}; \quad L_n^\theta = \sum_{j=1}^{N} h_j m_j \varphi_{jn} \qquad (4)$$

where N is the total mode number, φ_n is the mode vector of the **n**th mode, ω_n^2 is the eigenvalue of the **n**th mode.

3. Description of the rectangular tank system under consideration

In this study, the structural properties of the prismatic reinforced concrete rectangular storage tank with a container capacity of 8000 m^3, constructed in Erzincan (NE Turkey) in 1976, were considered. Both the front view and top view of the tank are given in Fig. 4. The rectangular tank under consideration has two main divisions. Dimensions of the tank and the other characteristics are shown in Fig. 5. In the analyses, Young's Modulus, Poisson's ratio and the weight of concrete per unit volume are taken to be 28000 MPa and 0.2 and 25kN/m^3, respectively. The liquid level is 2.5 m in the container. Soil conditions recommended in the literature are taken into account in the selection of the backfill soil types and their properties. The soil properties used in the analyses are shown in Table 1. The backfill-rectangular tank wall-fluid system considered in this study is shown in Fig. 6. The mechanical properties of considered tank were determined with in-situ non-destructive testing, and the structural properties of it were determined by making measurements on tank. Moreover, taking representative samples of soils from the field, the samples were tested in the laboratory, and it is determined that the backfill soil could be assessed in S2 soil class considered in this study.

Figure 4. The front view and top view of considered tank

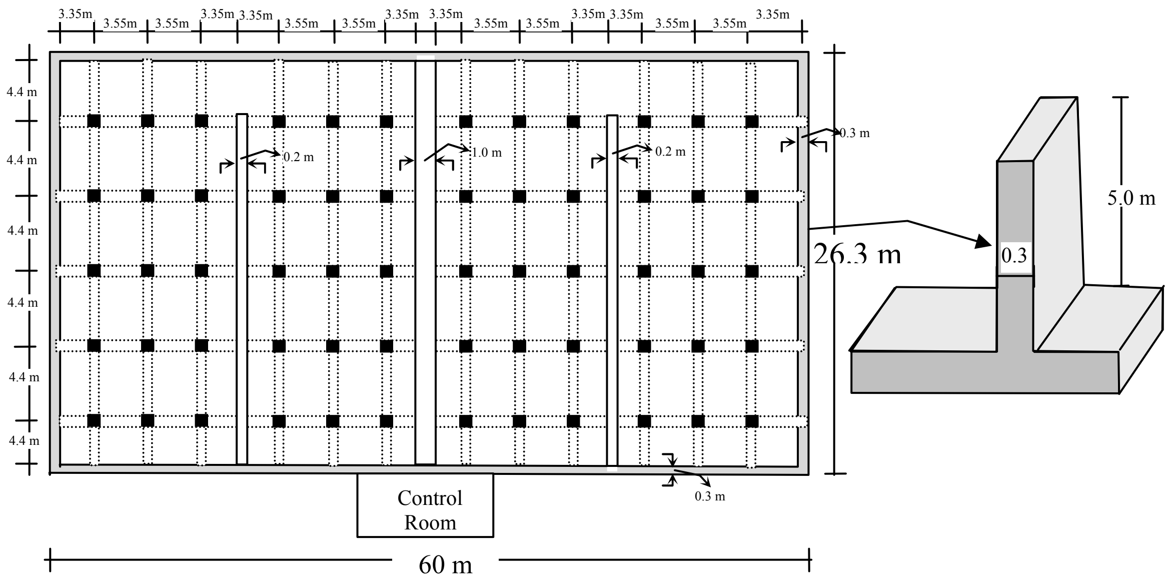

Figure 5. The dimensional properties of rectangular tank and exterior wall

Table 1. Data for considered backfill soil types

	Soil Types	S1	S2	S3	S4	S5
Soil Properties	E (MPa)	20	75	150	200	250
	ν	0.3	0.3	0.3	0.3	0.3
	G (MPa)	7.6920	28.8462	57.6923	76.9230	96.1538
	γ (kN/m^3)	19	18	18.5	19.5	20

E:Young Modulus; G:Shear modulus; ν :Poisson ratio; γ:unit weight

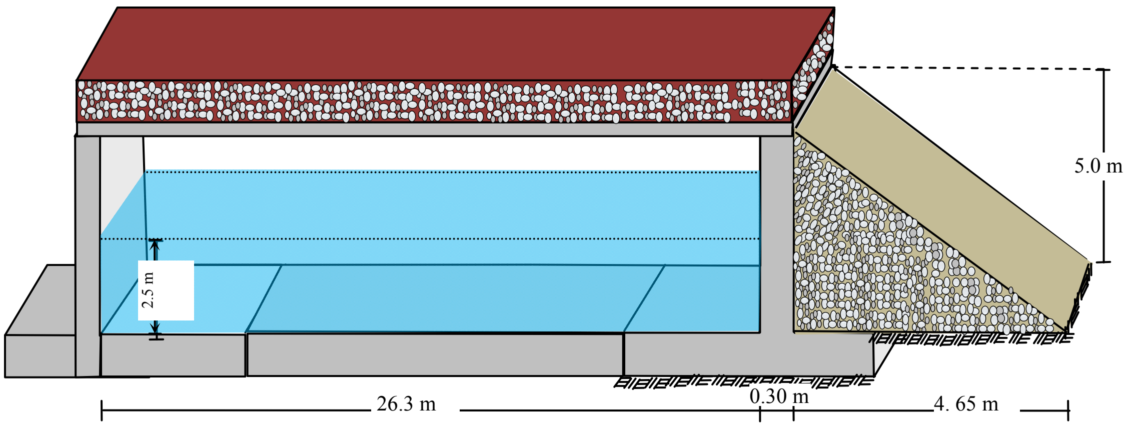

Figure 6. Backfill-rectangular tank wall-fluid system

4. Discussion of the analysis results

Considering five different backfill soil properties, the modal properties, periods and frequencies of the modes of proposed analytical model were determined via a computer program coded for seismic analysis of the backfill-rectangular tank-fluid system. The obtained frequencies are given in Table 2.

Table 2. Obtained frequency values for three modes

Backfill soil classes			S1	S2	S3	S4	S5
Frequencies (Hz)	Mode 1	f_c (Hz)	0.093	0.093	0.093	0.093	0.093
	Mode 2	f_i (Hz)	4.19	4.69	4.73	4.68	4.66
	Mode 3	f_3 (Hz)	9.17	16.39	22.63	25.58	28.30

When considering the effective modal masses, 92% of the total mass except for convective mass is represented by second mode and remained mass of the total mass is represented by third mode in S1 backfill soil conditions. In the other backfill soil conditions, however, almost all of the total mass except for convective mass is represented by second mode. Furthermore, 81% of the total water mass is represented by convective mode, and 11% of the total water mass is represented by impulsive mode in all backfill soil conditions.

Due to the absolute differences between the sloshing stiffness and the stiffness of the supporting system, it can be stated that the first mode represents the convective mode, and the second one represents the impulsive mode. The convective mode frequencies are obtained as almost the same for all the backfill soil conditions. The frequency values for all convective modes are obtained as 0.093 Hz. Thus, it can clearly be expressed that backfill interaction does not affect the sloshing mode. However, the obtained frequencies for impulsive modes can vary that if the backfill soil gets stiffer, the frequency of impulsive mode increases and the period decreases. For example, while the frequency value for S1 soil type is 4.19 Hz, the same value is 4.73 Hz for S3 soil type, and one can be said that backfill-wall interaction affects the system behavior so that the frequency deviation between S1 and S3 soil types may reach 13% increment. If the similar comparisons are made for third mode, it can be seen that the frequency values tend to increase with increasing backfill soil stiffness. Whereas the frequency value for S1 soil type is 9.17 Hz, the same quantity is estimated as 28.30 Hz for S5 soil type, and the frequency deviation may dramatically reach 209% increment It is possible to make similar comparisons on period values. Comparisons about periods of aforementioned modes are seen in Fig. 7.

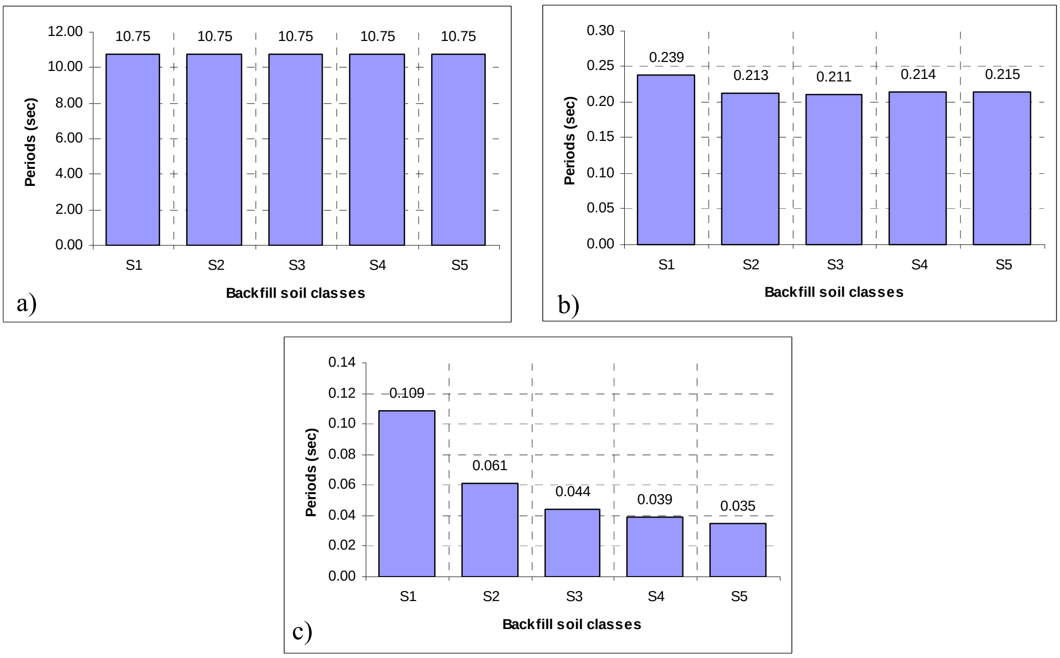

Figure 7. Comparison of the periods of a) the convective mode, b) the impulsive mode, and c) the third mode according to considered backfill soil classes

5. Conclusions

A simplified analytical model has been proposed for the determination of modal properties of backfill-rectangular tank wall-fluid system including backfill-wall and fluid-wall interactions for different backfill soil properties. Frequency values of convective modes estimated from analysis are not different for all conditions. So, the sloshing modes are not practically affected by backfill-wall interaction effects. However, the frequencies of impulsive mode generally change when the backfill soil gets softer. Thus, one can be said that variation of backfill soil stiffness may be more effective and influences the system behavior, and not to take into account the accurate backfill soil properties may cause underestimation or overestimation of the system response.

The proposed analytical model has capabilities of estimation the displacement response at the height of impulsive mass, sloshing displacements, base shears and overturning moments with less computational efforts. So, the proposed model will be solved soon after for the determination of aforementioned responses and the obtained results will be presented to literature.

Acknowledgment

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