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Research Article

AN OVERVIEW TO THE DYNAMIC BEHAVIOUR OF THE INVERTED T TYPE CANTILEVER RETAINING WALL TAKING INTO ACCOUNT SOIL STRUCTURE INTERACTION PHENOMENON

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ABSTRACT

The dynamic response of the cantilever retaining walls is affected by many factors such as the geometry of the wall, the earthquake frequency content, the wall flexibility, the backfill characteristics, and the soil structure interaction. Therefore, it may not be possible to analyse all aspects of the dynamic response of the cantilever retaining walls in spite of their simplicity. It is also well known that some unfavourable effects on the behaviour of the walls may impair the balance of the wall. In this context, the study aims to investigate the dynamic response of the T type cantilever retaining wall considering soil structure interaction. In line with this purpose, the soil structure interaction system is produced with a three dimensional finite element model. The seismic analyses are performed in time domain using C-OLC360 component of 1983 Coalinga earthquake, and four different foundation soil systems are used in these analyses. The elasto-plastic behaviour of the backfill and the foundation soil are represented with Drucker-Prager material model. In order to reflect the material damping of the system, Rayleigh damping is utilized considering mass and stiffness proportional dampings. In addition, the viscous boundary dashpot elements which consider the criteria of Lysmer and Kuhlemeyer for wave propagation, are placed around the boundaries of the numerical model. The results are examined in terms of both the stresses and displacements. The findings have revealed that the dynamic response of the T shaped cantilever retaining walls is considerably affected by the soil structure interaction.
Keywords: Cantilever retaining wall, soil structure interaction, geotechnical engineering, finite element method, damping.

1. INTRODUCTION

The retaining walls in daily life serve many purposes as the quay walls, bridge abutments, wing walls, sheet pile walls, braced cuts, mechanically stabilized earth walls, and exterior walls of the underground structures etc. These structures, which are generally used with the purpose of fulfilling the transportation and infrastructure requirements, are expected to remain functional in the post-earthquake period in earthquake-affected places. The studies reported by the many researchers show that the retaining walls are exposed to heavy damage or failure under the earthquake loads despite thought to have been properly designed against ground motions [1-7]. In this regard, it is clearly seen that the dynamic design of these structures has some mysteries, and

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there are still unresolved issues on dynamic behaviour. What makes that design so complex is the dynamic intera ctions between not only the wall and backfill soil but also the wall and foundation soil.

Due to both the interaction mechanism between backfill-subsoil-wall and the variability of soil characteristics, it is not easy to analyse all features of the seismic response of retaining walls accurately. Therefore, not only simplified seismic analysis procedures with some assumptions for soil, wall, and ground motion but also the comprehensive numerical models and experimental works, are commonly used for seismic analysis and design of retaining walls. Furthermore, the devastating effects of the earthquakes make the problem more complicated compared to the static design procedure for retaining walls.

The existing approaches for design and dynamic analysis of retaining walls can be classified into following three categories: 1) analytical limit state procedures (conventional methods) which assume that the structure can displace and/or rotate sufficiently at its base to induce a limit or failure state in the backfill, 2) analytical linear elastic or viscoelastic approaches, in which the wall is essentially rigid and the ground motion is of sufficiently low intensity so that the retained soil behaves as a linear elastic or viscoelastic material, 3) numerical methods of solution (intermediate case), in which the backfill behaves as a linear elastic or nonlinear elastoplastic material. Some of the contributions for these three areas are provided by Okabe [8], Mononobe and Matsuo [9], Seed and Whitman [10], Nadim and Whitman [11], Ghosh [12], Santhoskumar et al. [13], Jadhav and Prashant [14], Richards and Elms [15], Whitman and Liao [16], Steedman and Zeng [17], Zeng and Steedman [18], Pain et al. [19], Matsuo and Ohara [20], Wood [21], Arias et al. [22], Veletsos et al. [23], Wu and Fin [24, 25], Li [26], Younan and Veletsos [27], Papagiannopoulos et al. [28], Vrettos et al. [29], and Beskou et al. [30], Callisto and Soccodato [31], Al Atik and Sitar [32], Athanasopoulos-Zekkos et al. [33], Shrestha et al. [34], Osouli and Zamiran [35], Cakir [36, 37], Zamiran and Osouli [38], Chowdhury and Singh [39], Bakr and Ahmad [40] and Cattoni et al. [41]. Owing to the versatility of it, the third category, which also includes this study, allows to examine the stress and displacement responses of the interaction system. In addition, the modelling of the foundation soil and backfill system by the finite element procedure make it possible to consider the propagation effects of the earthquake waves moving from the bedrock. Within the framework of these considerations, the authors believe that it is appropriate to examine the soil-structure interaction influences with finite element method.

When investigated the previous studies on retaining structures mentioned above, it is seen that most of them are concerned with the determination of earthquake-induced soil pressures. However, the topic of soil-structure interaction effects on the seismic behaviour of cantilever retaining walls has been the subject of relatively fewer studies. This study aims to investigate the dynamic response of the T type cantilever retaining wall considering soil structure interaction phenomenon. In this context, the dynamic analyses have been performed in time domain through the finite element model, and in these analyses, four different foundation soil systems have been used. The results have been presented in terms of both the peak displacements taken from the wall top and the stresses obtained from the critical sections. Furthermore, the changes of the displacements along the wall height have been shown.

2. PROBLEM DEFINITION AND MATHEMATICAL MODEL

As can be seen from the literature, the dynamic response of the retaining walls is investigated based on the approaches referred above. The corresponding solution methods, however, include many assumptions in terms of the problem definition. Two groups of evaluations, based on fixed base and flexible soil conditions, are carried out in this study. In the first assessment, the finite element model of the backfill-wall system are verified by an analytical model developed under fixed base assumption (Figure 1) through modal analysis. This way is commonly preferred due to ease of use and effective results in terms of calculating cost. In this context, this paper, at first, considers the fixed base approach to verify the finite element model. In the second one, dynamic analysis of the cantilever retaining wall is performed considering soil structure interaction by finite element method.

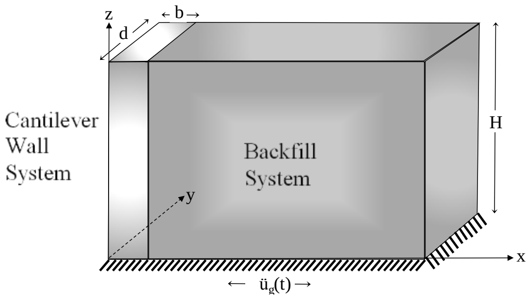

Figure 1. Wall-backfill system considered for mathematical model

Soil structure interaction is a very complex problem by nature. It would be useful to see this problem as a simple mathematical model using well-known basic approaches. In accordance with this purpose, the authors define the mass-spring-dashpot system using backfill mass and stiffness properties proposed by Veletsos and Younan [42]. But, it needs to emphasize that Veletsos and Younan approach does not take into account the mass of the rigid wall. Mathematical model is shown in Figure 2.

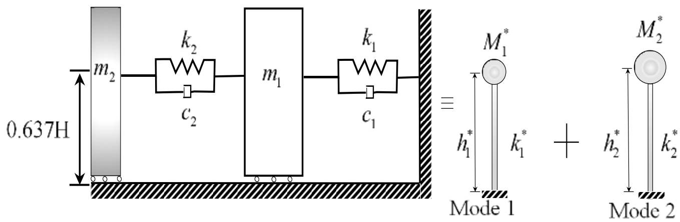

Figure 2. Mathematical model of wall-backfill system considered

Spring-dashpot-mass model includes two masses and stiffness values. Undamped vibration modes of the mathematical system can be easily selected knowing related some physical and mechanical parameters of the wall and backfill system. Mass of the backfill system is defined as m_1 and it is considered as follows:

$$m_1 = 0.543\psi_\sigma \rho H^2 \tag{1}$$

where ρ and H refers to the mass density and height of the backfill, respectively. Additionally, $\psi_\sigma, \psi_0, \psi_e$ expressions are defined as follows:

$$\psi_\sigma = \frac{\psi_0^2}{\psi_e};\ \psi_0 = \sqrt{\frac{2}{1-\nu}};\ \psi_e = \sqrt{\frac{2-\nu}{1-\nu}} \tag{2}$$

These equations are functions of Poisson's ratio (ν). The backfill stiffness is represented with k_1, and it is equal to

$$k_1 = m_1 \frac{\pi^2 G}{4H^2 \rho} = 1.339\psi_\sigma G \tag{3}$$

where G is the shear modulus of the soil.

The wall mass is introduced by m_2, and the wall lateral stiffness is represented as $k_2 = 3EI / H^3$ where E, I and H are Young's Modulus, the section inertial moment and height of the wall, respectively. Furthermore, material dampings of the wall and backfill have been defined with c_1 and c_2 in the analytical model, respectively.

If the mathematical model, which has two degrees of freedom, is subjected to external forces, the dynamic motion equation can readily be formed using D'Alembert's principle. The dynamic equation is defined as follows:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{Bmatrix} + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} = \begin{Bmatrix} P_1(t) \\ P_2(t) \end{Bmatrix} \tag{4}$$

where the acceleration, velocity, and displacement expressions of backfill and wall are defined as $(\ddot{u}_1, \ddot{u}_2), (\dot{u}_1, \dot{u}_2), (u_1, u_2)$, respectively.

Forces trying to move the masses due to the ground motions is stated as $P_1(t)$ and $P_2(t)$. It is important to state here that only the mass and stiffness matrix are considered because undamped modal analysis is done at this stage.

The formed matrix form of the equation is solved by using modal analysis procedure. In this context, the modal parameters such as effective modal masses (M_1^*, M_2^*), effective stiffnesses (k_1^*, k_2^*) and effective heights (h_1^*, h_2^*) can be determined. The parameters can be found as follows:

$$M_n^* = \Gamma_n L_n^h = \frac{\left(L_n^h\right)^2}{M_n}; \quad h_n^* = \frac{L_n^\theta}{L_n^h}; \quad k_n^* = \omega_n^2 M_n^* \tag{5}$$

$$M_n = \phi_n^T m \phi_n = \sum_{j=1}^{N} m_j \phi_{jn}^2; \quad \Gamma_n = \frac{L_n^h}{M_n}; \quad L_n^h = \sum_{j=1}^{N} m_j \phi_{jn}; \quad L_n^\theta = \sum_{j=1}^{N} h_j m_j \phi_{jn} \tag{6}$$

where N, ϕ_n and ω_n^2 expressions define the total mode number, the **n**th mode vector and eigenvalue, respectively.

3. FINITE ELEMENT MODEL AND VERIFICATION UNDER FIXED BASE CASE

The numerical model is established with the help of solid elements and viscous boundaries. Considered wall height is H=7 m. The thickness and length of the wall are 0.4 m and 1 m, respectively. The wall and backfill have the same height. The widths (the dimensions in the y direction) of the cantilever wall and backfill are 1 m. The backfill length is considered as 10H (in the x direction). Young's Modulus, Poisson' s ratio and weight per unit for the wall and backfill in modal analysis is 30000 MPa; 35 MPa, 0.2; 0.35, 25 kN/m^3 and 18 kN/m^3, respectively. Figure 3 shows the schematic representation of the developed finite element model with fixed-base.

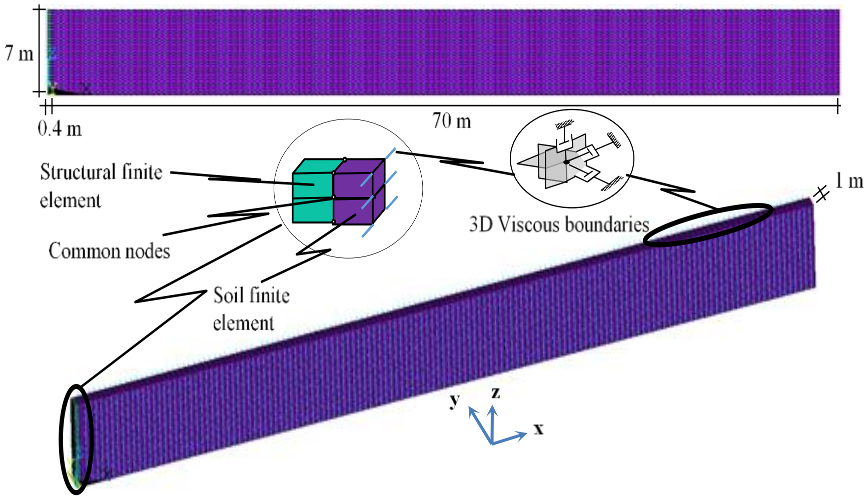

Figure 3. Schematic representation of the finite element model under fixed base

The finite element models formed for dynamic analysis can be verified by many methods such as laboratory tests, modal tests or analytic models. The wall-backfill finite element model is verified using analytic model described above. The modal equations performed for spring-dashpot-mass system are solved by the code written by the authors. The analysis results are shown together with calculated mass and stiffness parameters in Figure 4. Analytic model shows that the backfill mode is represented with 73% of the total effective mass, and the backfill mode frequency is 3.157 Hz. On the other hand, the wall mode is represented with 27% of the total effective mass, and its frequency is calculated as 2.161 Hz.

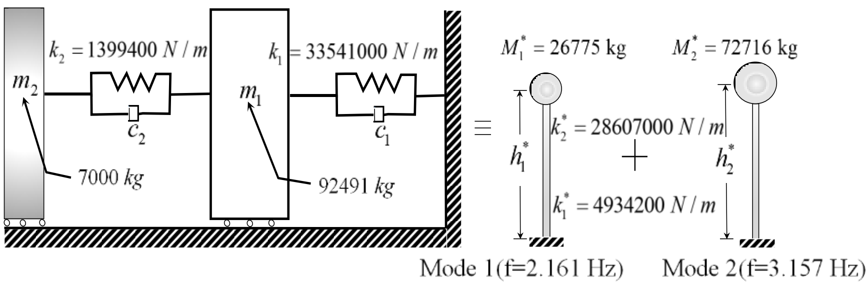

Figure 4. Input and output parameters obtained for modal analysis

The modal analysis is performed considering elastic material responses in this study. Furthermore, it is worth emphasizing that the numerical model is extended to its most general and comprehensive case, and the viscous boundaries and nonlinear properties considered in the FEM are for properly determination of the seismic behaviour of the system during time history analysis. Accordingly, mode shapes and frequencies of the model are presented in Figure 5.

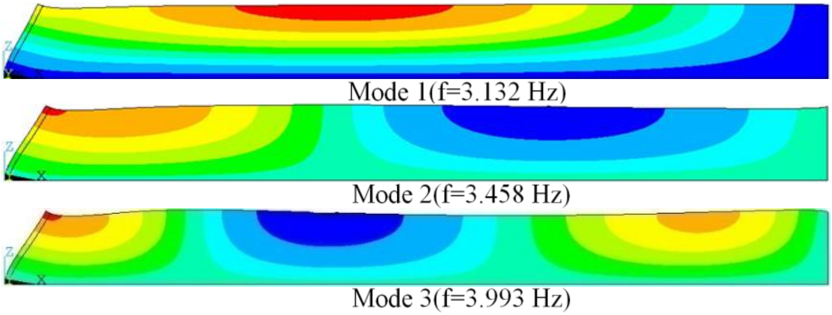

Figure 5. Mode frequencies and mode shapes obtained from FEM

The results of the finite element model is coherent with those of the analytic model. It is important to note that the modes obtained from the finite element model are the coupled system's modes because the backfill and wall junction interface has been modelled as a common face to compare the result with the analytical model's results. Due to the perfectly bonding, the backfill strongly dominates the modal behaviour in the finite element model. In this connection, since the first mode in the finite element model corresponds to the second mode in the analytical model, there is a clear agreement between them. The related mode frequency is 3.132 Hz in the finite element model while it is 3.157 Hz in the analytical model. The results obtained from the two approaches are presented in Table 1.

Table 1. The results acquired from the proposed models

Model Type	Mode Number	Mode Frequency (Hz)
Analytic Model		
	First Mode	2.161
	Second Mode	3.157
Finite Element Model		
	First Mode	3.132
	Second Mode	3.458
	Third Mode	3.993

4. SOIL STRUCTURE INTERACTION MODEL AND ITS PROPERTIES

The finite element method can produce realistic results due to the fact that it permits calibration in accordance with both field and laboratory tests. Moreover, it is very useful in terms of considering of the effects such as the nonlinear behaviour of the material, the system damping and propagation of the earthquake wave. These effects directly affect the structural dynamic behaviour in examining the soil structure interaction problem.

Figure 6 shows the soil structure interaction system consisted of the foundation soil, backfill soil, and the cantilever retaining wall. The cantilever wall has a base slab which has 0.65x5.35 m dimensions, and the widths of the front and back consoles are 1.50 m and 2.80 m, respectively. The wall height is 7.65 m from the bottom to top. The vertical stem is H=7 m where the section narrows from 1.05 m up to 0.35 m, and the backfill width is 6 m. The whole system is created with the solid elements by using ANSYS 13.0 software [43]. For the cantilever wall, SOLID65 element is preferred which can be used with or without rebar, and has properties of the cracking under the tension and crushing under the compression. This element includes eights nodes having three degrees of freedom at nodal x, y, z directions. In the foundation and backfill systems, SOLID45 element is used which can reflect plasticity, creep, swelling, stress stiffening, large deflection, and large strain properties. It is defined by eight nodes having three degrees of freedom at nodal x, y, z directions. COMBIN39 elements, which can show nonlinear behaviour, are used to reflect the discrete behaviour of the interface where the wall and backfill systems encounter. The debonding or bonding behaviour of the wall is provided with force deflection relations defined on the nonlinear springs.

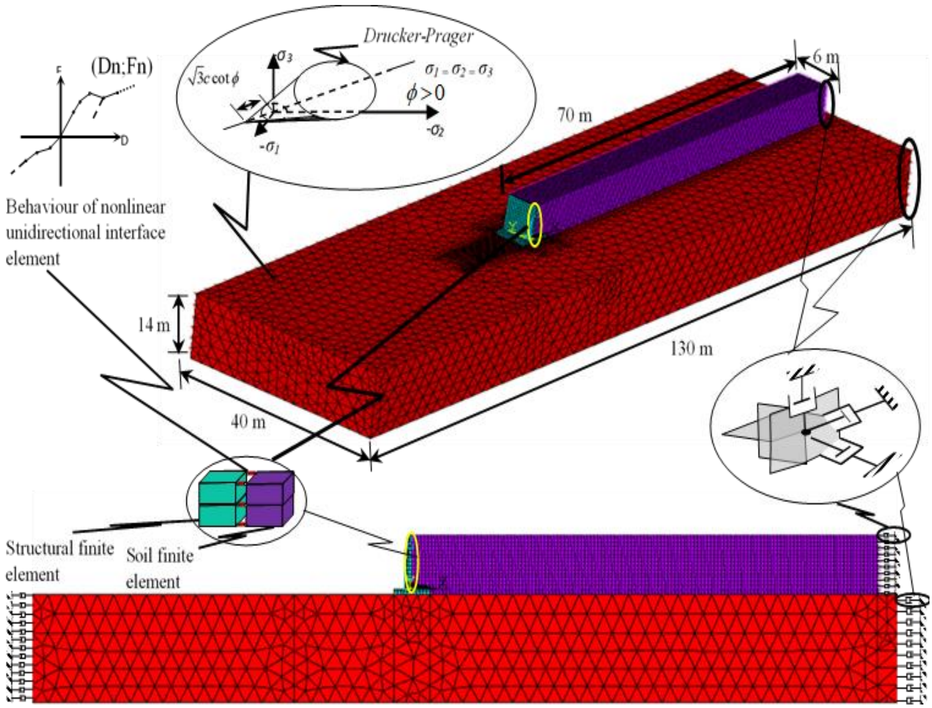

Figure 6. Schematic representation of the soil structure interaction system

One of the most important points in terms of the realism of the results is to accurately reflect the characteristics of the semi-infinite soil medium in modelling. Because this soil medium with infinite volume in reality, has a limited volume here, the dimensions of the soil systems should be taken large enough. If infinite soil medium is not defined as a soil volume having sufficient dimensions or a soil volume limited with dampers, the system energy is trapped inside the model and the moving waves in the soil medium are reflected back without damping from the boundaries. In this regard, the lengths of both the foundation and the backfill soils are designed considering the critical distance of 10H [44]. Moreover, viscous dampers, which take into account the Lysmer and Kuhlemeyer criteria [45], are placed at the boundaries of soil to get rid of reflection effects of the earthquake waves, and to imitate the far field behaviour. The elastoplastic material behaviour is provided with Drucker-Prager yield criteria for the foundation soil and backfill systems. It is a well-known fact that soil materials exhibit complex behaviour under seismic motions. Idealizations are, thus, usually necessary to develop simplified mathematical constitutive laws for practical solutions. Various models can be found in the literature, and most of them are complex and require many parameters. Therefore, the simple elastic-perfectly plastic material models are often used in practical applications. The relative simplicity of the Drucker-

Prager model, which may reflect some characteristics of soil response with only three parameters, explains why this model is commonly used.

5. SOIL PROPERTIES AND SEISMIC LOADING DETAILS

The seismic analyses are performed in time domain as a full transient by using Newmark method. In these analyses, C-OLC360 component of 1983 Coalinga earthquake having 3.63 m/s^2 peak acceleration is used. The record taken from PEER ground motion database [46] is regulated at 0.05 s intervals before using. The regulated record is presented in Figure 7. The material dampings are represented by Rayleigh damping in the analyses. The damping ratio is 5% for both structure and soil.

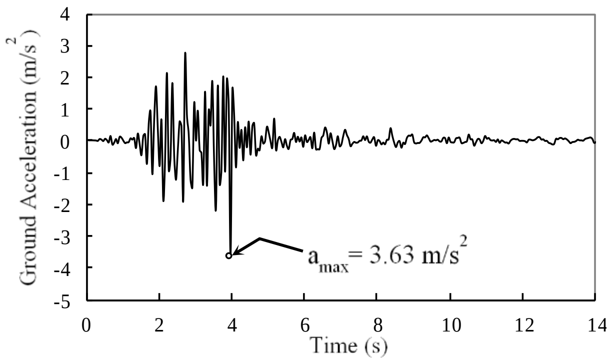

Figure 7. 1983 Coalinga earthquake record

The mechanical and physical properties of the four different ground systems used in this parametric study are presented in Table 2. Additionally, the same backfill properties are used in all seismic analyses. The properties of the wall are as follows: Young's Modulus: 30000 MPa, Poisson's ratio: 0.20, weight per unit volume: 25 kN/m^3. The corresponding parameters for the backfill system are taken as 100 MPa, 0.30 and 18 kN/m^3, respectively. Furthermore, the internal friction angle and cohesion value of the backfill system are considered as 35º and 5 kPa.

Table 2. The properties of the considered foundation soil systems

Soil System	E, kN/m^2	G, kN/m^2	ν	ϕ(°)	ψ(°)	γ, kN/m^3	V_s, m/s	V_p, m/s
S1	500000	192308	0.30	35	0	19	318.14	595.19
S2	150000	57692	0.30	35	0	19	174.25	326.00
S3	75000	27778	0.35	35	0	18	124.23	258.60
S4	35000	12963	0.35	35	0	18	84.86	176.66

E: Young's Modulus, G: Shear Modulus, ν: Poisson's ratio, ϕ: Internal friction angle, ψ: Dilatancy angle, γ: Weight per unit volume, V_s: Shear wave velocity, V_p: Compressional wave velocity

6. RESULTS AND DISCUSSIONS

In Table 3, the wall responses and their occurrence times are shown. While the peak displacements are taken from the wall top, the peak stresses are calculated at the critical sections of the cantilever wall in x, y, z directions. These peak responses are found at the nodes selected from front and back faces of the wall. If Table 3 is examined, it can be seen that the peak displacements and stresses of the wall may considerably change depending on the soil structure interaction. In addition, it is seen that this interaction changes not only the dynamic peak responses of the wall but also their directions.

Table 3. The peak stresses and relative horizontal displacements, and their realization times

Soil System	S1		S2		S3		S4	
Responses	t (s)	Value	t (s)	Value	t (s)	Value	t (s)	Value
u_t (m)	4.00	-0.0004	3.90	0.0016	3.95	0.0033	3.95	0.0048
$S_{z(\text{back corner})}$ (MPa)	4.00	0.1663	2.80	-0.4687	3.90	-0.5598	2.85	-0.4419
$S_{y(\text{back corner})}$ (MPa)	4.00	0.0267	2.80	-0.0835	3.90	-0.1047	2.85	-0.0924
$S_{x(\text{back corner})}$ (MPa)	4.00	0.0973	2.80	-0.3707	3.90	-0.4941	2.85	-0.4377
$S_{z(\text{back midpoint})}$ (MPa)	4.00	0.1287	2.80	-0.4655	3.95	-0.5904	2.85	-0.4839
$S_{y(\text{back midpoint})}$ (MPa)	4.00	0.0481	2.80	-0.1876	3.90	-0.2442	2.85	-0.2239
$S_{x(\text{back midpoint})}$ (MPa)	4.70	0.0807	3.90	-0.4009	3.95	-0.5557	2.85	-0.5139
$S_{z(\text{front corner})}$ (MPa)	4.00	-0.1857	2.80	0.5370	3.90	0.6591	2.85	0.5526
$S_{y(\text{front corner})}$ (MPa)	4.00	-0.0086	2.80	0.0215	3.90	0.0259	2.85	0.0226
$S_{x(\text{front corner})}$ (MPa)	4.00	-0.0858	2.80	0.2040	3.50	0.2416	2.85	0.2236
$S_{z(\text{front midpoint})}$ (MPa)	4.00	-0.1208	2.80	0.4324	3.95	0.5479	2.85	0.4350
$S_{y(\text{front midpoint})}$ (MPa)	4.00	-0.0263	2.80	0.0762	3.90	0.0849	2.85	0.0639
$S_{x(\text{front midpoint})}$ (MPa)	4.70	-0.0364	2.80	0.1262	3.95	0.1478	3.55	0.1198

u_t: Maximum lateral top displacement of the cantilever wall; t: Time; S_z, S_y, S_x (back corner): Stresses estimated on the backface (backfill side) of the cantilever wall in z, y and x directions, respectively; S_z, S_y, S_x (back midpoint): Stresses estimated on the back face of the cantilever wall in z, y and x directions, respectively; S_z, S_y, S_x (front corner): Stresses estimated on the front face of the cantilever wall in z, y and x directions, respectively; S_z, S_y, S_x (front midpoint): Stresses estimated on the front face of the cantilever wall in z, y and x directions, respectively.

The interaction effects on seismic response of cantilever retaining wall are displayed and discussed comparatively below. The forces acting on the critical section of the retaining wall take an important place in evaluating the dynamic behaviour of the retaining walls. Accordingly, some examples are presented in Figure 8 to evaluate the change of the peak stresses over time.

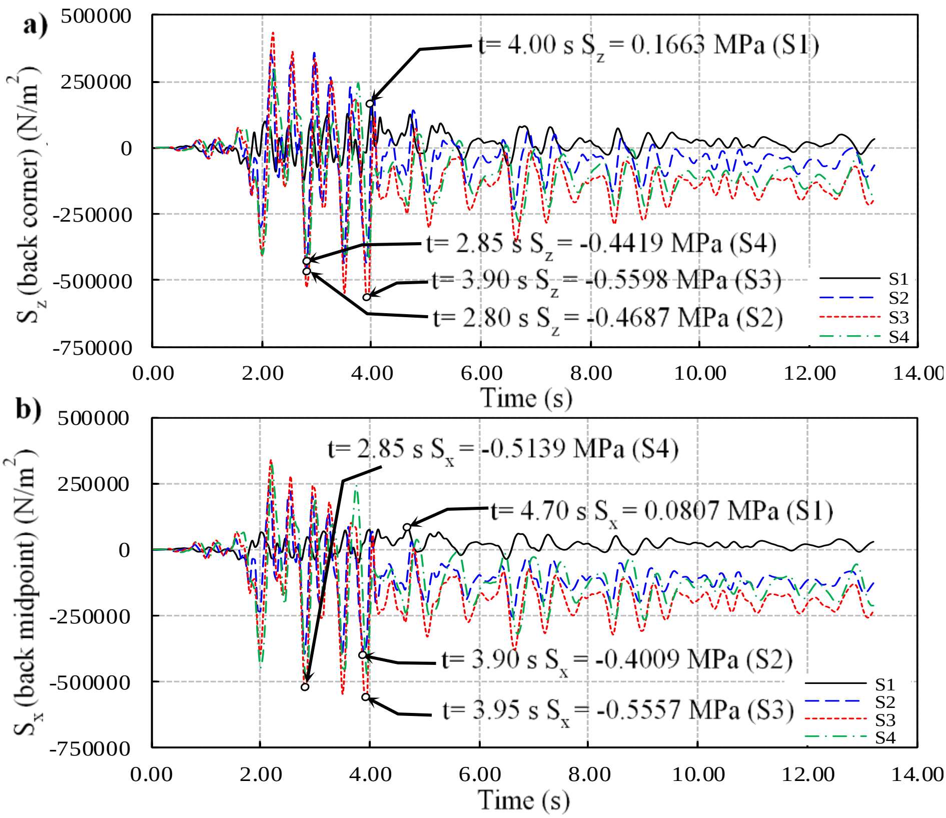

Figure 8. The peak stress-time history obtained from a) back corner of the wall in z direction b) back midpoint of the wall in x direction

The peak responses in Figure 8 are compared depending on the soil-structure interaction. For example, Figure 8a shows that while the peak stress value in the S1 foundation soil system is 0.1663 MPa, the same values in the S2 and S3 foundation soil systems realize as 0.4687 and 0.5598 MPa levels, respectively, with increments of 182% and 237%. It is important to state that while the peak response in the S1 foundation system realize as tension, the direction of these responses changes as pressure in S2 and S3 foundation soil systems. Another example to the variation of both magnitude and direction of the stress is presented in Figure 8b, where while the peak response of the cantilever retaining wall for S1 foundation soil system is 0.0807 MPa as tension, the same values in S2 and S3 foundation soil systems, as pressure, realize at 0.4009 MPa and 0.5557 MPa levels, respectively, with the increments by 396% and 589%. Furthermore, if Figure 8a is examined in terms of the occurrence times of the peak response, it can be seen that while the realization time of the peak response in S1 soil system is around 4 s, these times in S2, S3 and S4 foundation soil systems are around 2.80 s, 3.90 s, 2.85 s, respectively. The occurrence times of the peak responses in Figure 8b exhibit the similar trend under different soil conditions, and the realization times of the peak responses change. As seen in both examples, the soil structure interaction affects the peak responses of the wall, and the realization times of these responses.

Another way of examining the dynamic behaviour of retaining walls is to reveal the change in the relative displacements as shown in the Figures 9 and 10. When the peak relative displacements are considered from Figure 9, it is seen that the wall on S1 foundation soil system exhibits the most rigid behaviour compared to the softer foundation soil systems like S2, S3, and S4.

Furthermore, it can be stated clearly that the wall relative displacements increase due to the decrement in the foundation soil stiffness. This trend can also be seen in the time history of the wall top displacement from Figure 10. While the peak displacement value for S1 foundation soil system is 0.0004 m with a movement away from the backfill, the peak responses of S2 and S3 foundation soil systems arise as 0.0016 m and 0.0033 m with the increments of 300% and 725% as action toward backfill. The realization times of the peak displacements are about 3.90-4.00 s in all foundation soil systems.

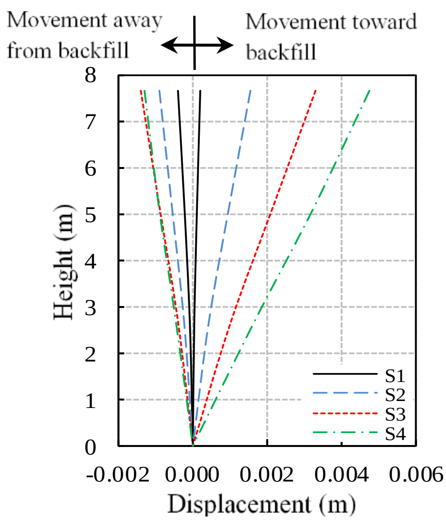

Figure 9. The relative horizontal displacement obtained along the cantilever wall height

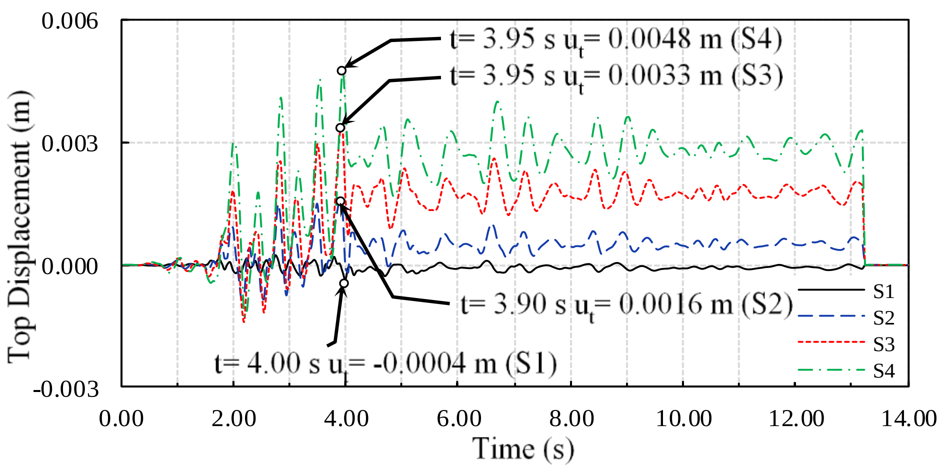

Figure 10. Time history of the horizontal top displacement of the cantilever retaining wall

7. SUMMARY AND CONCLUSIONS

This paper investigates the dynamic response of the T type cantilever retaining wall considering soil structure interaction, and aims to shed light on some aspects for the designers and researchers. In this context, the soil structure interaction system under consideration consists of the foundation soil, backfill soil and the cantilever wall. The full transient dynamic analyses are performed under the selected earthquake record. Both the stresses on the critical section of the wall and the horizontal displacements obtained from the wall top are examined in terms of the response magnitudes and occurrence times. In addition, the relative displacements along the wall height are interpreted depending on the change in soil system stiffness.

The results indicate that both the stresses and relative displacements of the wall can vary significantly depending on the foundation soil flexibility, and thus the remarkable output achieving from the comparisons is that the variation of the local ground conditions notably affects the wall response. Local ground conditions affect the amplitude and frequency content of the ground motion so that they may tend to act as a filter for earthquake waves by attenuating the motion at certain periods and may tend to amplify it at the other periods. So, it is obvious that the seismic response of the cantilever wall is governed by the complex interaction phenomena between the properties of the wall, the soil, and the ground motion characteristics. For the reasons mentioned above, these structures, which can be very sensitive to the dynamic loads, should not be constructed with typical project, and the design must be carried out with site-specific analyses.

While the analysis results reveal the essential features of dynamic soil-wall interaction, more examples are needed to generalize the results, and investigation of the different wall configurations are required.

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