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Tunnel-Soil-Structures Interaction Effect due to Seismic Loading

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Keywords:

Dynamical interaction, Superficial structure, Underground structure, Seismic loading, Finite element method

Abstract

In this work, the effect of the dynamical interaction between the superficial and the underground structures is studied under an impact of seismic loading. Finite element Plaxis^{2D} code$^{©}$ under conditions of plane strain is used successfully. The material behaviour of the soil, the superficial structures and the tunnel is assumed to be fully elastic and are modeled with 15-nodes triangular element. The present study shows that increasing the number of neighboring structures and decreasing the separation distance between them can significantly reduce the seismic responses amplitudes of the superficial structures and the tunnel, especially in the case of soft soils. This reduction can reach up 35%. These results can be taken into consideration in the study and construction of realistic projects, especially sensitive ones.

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1 INTRODUCTION

Soil-structure interaction (SSI) is an important research topic in earthquake engineering, which has received great attention for several decades. As a branch of the SSI, structure-soil-structure interaction (SSSI) has been a key research topic in recent years. It is an interdisciplinary field of activity, which lies at the intersection of structural and soil dynamics and mechanics, earthquake engineering, geophysics and geomechanics, materials science, numerical methods and various other technical disciplines [1]. The widespread damage within urban centres has highlighted the need for a better understanding of the seismic SSSI, especially given population growth and increasing urbanization [2]. In reality, the correct and ideal prediction of the dynamic behaviour of the responses of heterogeneous media in interaction between them is difficult because of the difference in their physical and mechanical properties on the one hand and the large dimensions on the other hand. This difficulty leads to the appearance of complex equations that require an enormous volume of calculations for solving them. Several works have been carried out in order to study the effect of this phenomenon between surface, underground and surface-underground structures by using frequently the finite element method (FEM) [3-7]. Other methods have been also used successfully as the boundary element method (BEM) and the hybrid method (FEM-BEM) [8]. In addition, a series of experimental tests on centrifuge models and in situ have been carried out for validating the numerical results [9]. The sensitivity of the SSSI to the pre-seismic initial conditions, in particular the foundations inclination, settlements and also their subsequent evolution due to successive earthquakes has been studied. The effects of the physical and mechanical characteristics of the structures and the soil, the position and the number of the adjacent structures as well as the distance of the separation between them were also taken into account in many studied cases. On the other hand, the type of applied dynamical impact (surface traffic, underground traffic, rotating machine, earthquake...) and its location as to the studied structures systems play a major role in determining the behaviour of the dynamic response [10, 11]. Most of the works in the literature confirm the importance of accurately describing and modelling the surrounding urban environment in structure-soil-structure interaction analyses, in order to understand the future influence of increasing urbanization on seismic hazard in populated areas. The presented results of these works indicate that the proximity of structures can significantly modify the behaviour of the dynamic response of these structures, however, these studies do not clearly indicate in which circumstance the effect of SSSI must be considered. Several researchers mention the negative effects of SSSI, other researchers indicate the positive effects of SSSI on the response of the structures. Nevertheless, numerous researchers note that the effect of SSSI can increase or decrease the response of the structures depending on the circumstances considered [8, 10-14]. For exemple, the presence a tunnel under a building can have a significant effects on the interaction between the tunnel, soil, and structure. The influence of tunnel depth showed through an increase in the differential settlement, the horizontal displacement and the inter-story drift when the tunnel is shallow. These effects disappears when the tunnel or building is farther away from each other [15]. The flexibility of surrounding soil affects dynamic responses characteristics of the tunnel and structures as their responses can be amplified [8, 14, 16-18]. On the other hand, some studies shown that tunneling has a direct effect on the rate of structural displacement and increases the structural response. The presence of surface structures considerably altered the tunnelling-induced soil response. The structure-to-tunnel position notably influences the magnitude of soil displacements and causes localised phenomena such as embedment of structure corners. Also, the behavior of the structure is affected by the position of the structure at the ground level and the position of the tunnel and this should be considered during the design phase of the structures [17, 19]. The present work is carried out for studying numerically the dynamical interaction effects between superficial structures and a tunnel under the impact of a seismic loading with considering the influence of the soil rigidity, the density of the adjacent structures and the distance between them.

2 FINITE ELEMENT ANALYSIS

Under conditions of plane strain, a numerical modelling study is carried out by using the finite element Plaxis^{2D} code$^{©}$. The behaviour of the soil and the structures is assumed to be perfectly elastic. The behaviour model is characterized by the Young's modulus E, the shear modulus G, the Poisson's coefficient υ and the bulk modulus K, where the relationship between them are given as following:

$$G = \frac{E}{2(1+\upsilon)} \tag{1}$$

$$K = \frac{E}{3(1-2\upsilon)} \tag{2}$$

For all cases studied in this work, a model of deformation plane with 15-nodes triangle elements is used (Fig. 1). The common nodes of the soil-structures and soil-tunnel interaction areas are considered perfectly rigid (without interface elements).

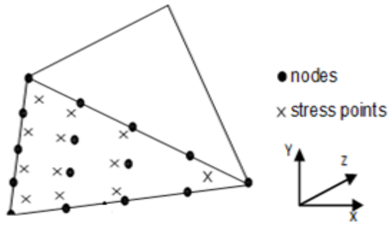


Figure 1. 15-nodes triangle element

The modelling is carried out by the FEM based on the following dynamic equation:

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{F\} \tag{3}$$

Where, [M], [K] and [C] are successively the mass matrix, the stiffness matrix and the damping matrix. $\{U\}$, $\{\dot{U}\}$, $\{\ddot{U}\}$ and $\{F\}$ are the vectors of the displacement, the velocity, the acceleration and the loads. In the finite element formulations, [C] matrix is often formulated as a function of the mass and the stiffness matrix (Rayleigh damping):

$$[C] = \alpha_R[M] + \beta_R[K] \tag{4}$$

In the Plaxis code, the Rayleigh damping formulation is implemented and the values of α_R and β_R can be estimated with the system of equations:

$$\alpha_R + \beta_R\omega_{ni} = 2\omega_{ni} \tag{5}$$

Where, is the damping ratio and ω_{ni} are two natural frequencies of the studied element. In this work, the two first natural frequencies $\omega_1 and\ \omega_2$ of the ground can be calculated as follows:

$$\{\omega_1 = (V_s/2H)\ \ \omega_2 = (3V_s/2H) \tag{6}$$

here, V_s and H are the shear wave and layer depth of the soil.

To solve numerically the equation (3), the implicit time integration scheme of Newmark is used. This method is more complicated but it produces a more reliable and more stable calculation process. To determine the accuracy of the numerical time integration and obtain a stable solution, the coefficients of Newmark α_N and β_N have to satisfy the following condition [20]:

$$\{\ \alpha_N \geq \frac{1}{4}(\frac{1}{2} + \beta)^2\ \ \beta_N \geq 0.5 \tag{7}$$

In all this study the values α_N= 0.3025 and β_N = 0.6 are used, but other combinations are also possible [21]. To resolve the reflecting wave's problem, the viscous absorbent boundaries method is used [22] where the increase of the normal and the shear stress components at the boundaries are absorbed by a vertical and a horizontal dampers as following (Fig. 2):

$$\{\ \sigma_n = -a\rho V_P\dot{u}_x\ \ \tau = -b\rho V_s\dot{u}_y \tag{8}$$

Where, ρ, V_P, V_S, $\dot{u}_x$ and $\dot{u}_y$ are respectively; the materials density, the velocity of pressure and shear waves, the horizontal and the vertical velocities. The coefficients of relaxation $c_1 = 1$ and $c_2 = 0.25$ are taken in this study in order to improve the effect of absorption, this values are reasonable to absorb the waves at the boundaries.

3 CASE STUDIES RESULTS AND DISCUSSIONS

3.1 Effect of the density of structures

To study the density effects of the superficial structures on the tunnel-soil-structures interaction due to seismic loading, the model as it is presented in figure (2) is taken with varying the soil stiffness. This model consists of a tunnel situated in a homogenous half-space. Set of two rigid massive blocks are added; the first one to the right and the second one to the left. 4 sets of structures are added one by one (Fig. 2). All structures are identical. The distance between structures is taken: d = 6 m, except the two first structures where the distance is equal to 10 m for all cases. The depth of the tunnel is taken: h= 4 m. The tunnel and structures concrete characteristics are taken as: $E_c = 3\times10^7$ kN m^{-2}, $\upsilon_c = 0.25$ and $\rho_c = 2000$ kg m^{-3} [23, 24]. For the soil, three cases are adopted where the characteristics are successively varied as follows; shear wave: V_s= 800 m s^{-1}, 400 m s^{-1} and 200 m s^{-1}, mass density: $\rho_s = 2200$ kg m^{-3}, 2200 kg m^{-3} and 2000 kg m^{-3}, Poisson's ratio: $\upsilon_s = 0.30$, 0.30 and 0.40 [25]. The accelerogram of Parkfield earthquake is adopted in this study. The characteristics of this earthquake are presented in the figure (3). The boundary dimensions are chosen based on a sensitivity analysis up to reach stable analysis. The boundary conditions are taken fully fixed at bottom and horizontally fixed at laterals borders.

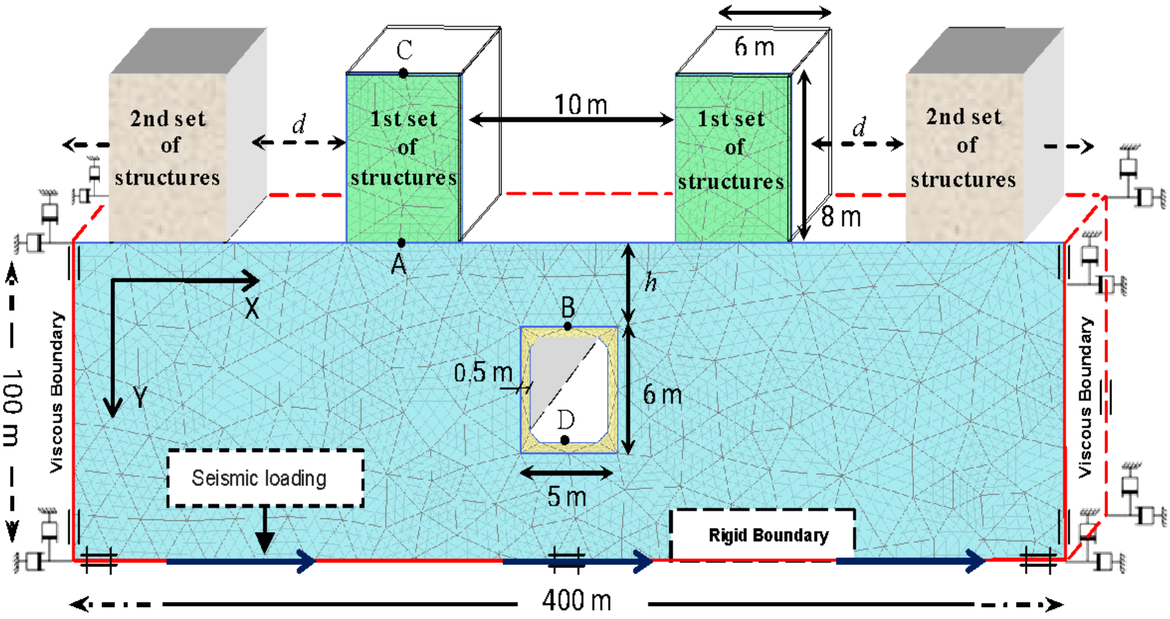
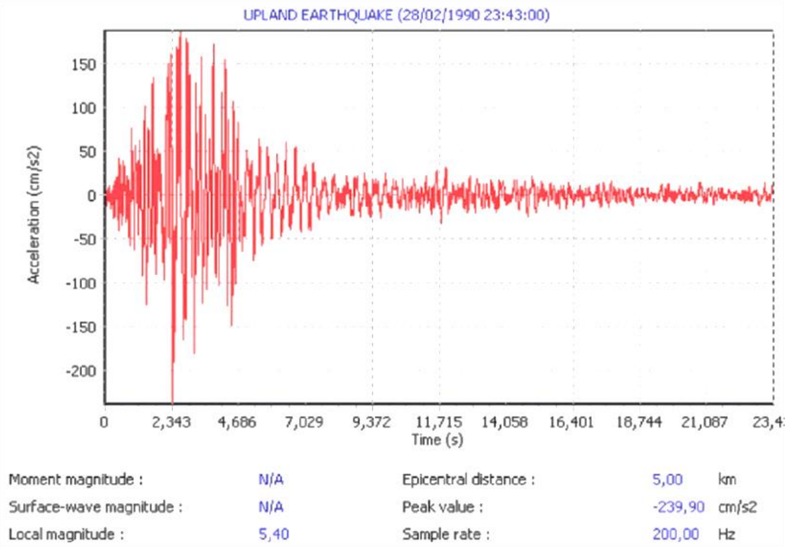


Figure 2. Geometry and meshing of the tunnel-soil-structures system by FEM

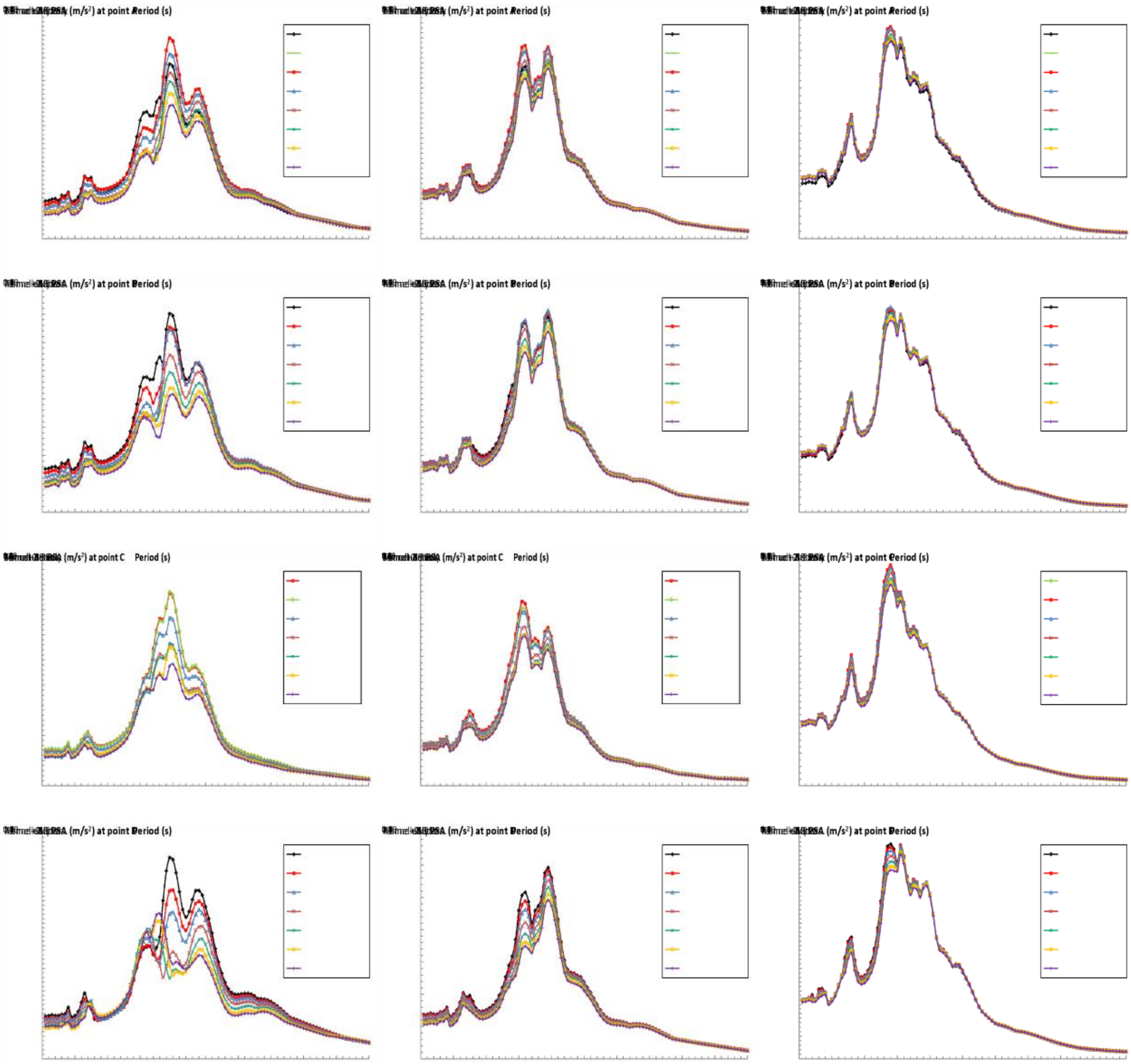


Moment magnitude : N/A
Surface-wave magnitude : N/A
Local magnitude : 5,40
Epicentral distance : 5,00 km
Peak value : -239,90 cm/s2
Sample rate : 200,00 Hz

Figure 3. Characteristics of Parkfield earthquake

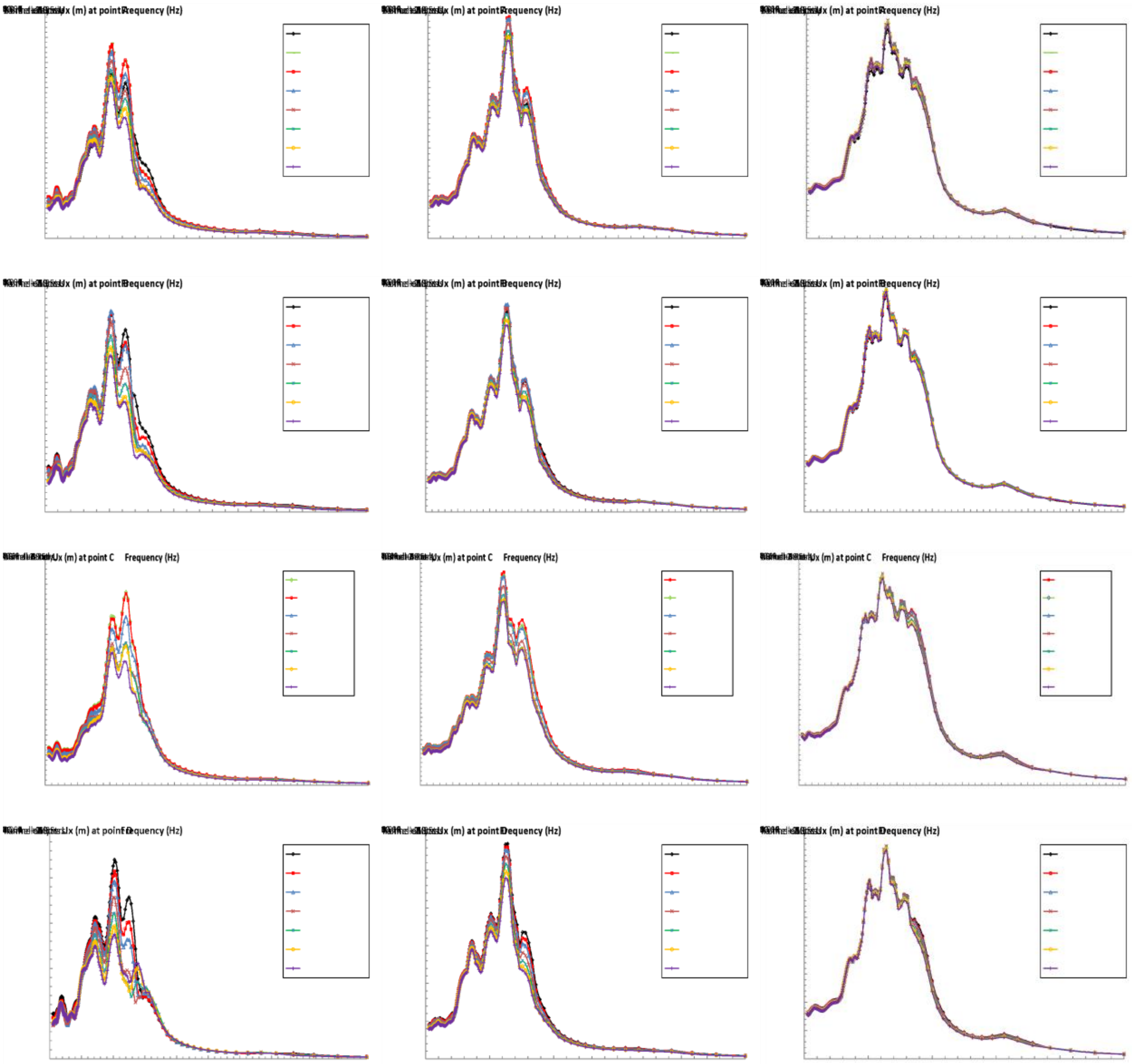
Figures (4) and (5) present the responses of the tunnel-soil-structures system due to seismic loading. These curves show that the responses of the system are influenced by the variation in the number of adjacent structures and the stiffness of the ground. It is noted that when the number of surface structures increases, the responses of the structures (points A and C) and of the tunnel (points B and D) are significantly deamplified. The magnitude of this deamplification is also governed by the soil type where it increases as soil stiffness decreases. For soft soil, the reduction in responses produced by the increase in the number of structures can reach up 35% compared to the case of a single structure. In the stiff soil case this reduce can reach up 22%. On the contrary in the very stiff soil case where it does not exceed 8%. In addition, beyond 8 added structures, the values of the deamplification converge towards stability. This behaviour is more apparent in the case of stiff soil. On the surface of the ground at point A, it can be noticed that the response is amplified compared to the case without structures if the number of structures added is less than 6, beyond that, the response is deamplified until stability.

In addition, it is also observed in this study that the presence of the tunnel has no obvious effect on the response of the structures (point A and C).



(a) V_s = 200 m/s *(b)* V_s = 400 m/s *(c)* V_s = 800 m/s

Figure 4. Pseudo-acceleration response spectrum of the tunnel-soil-structures system



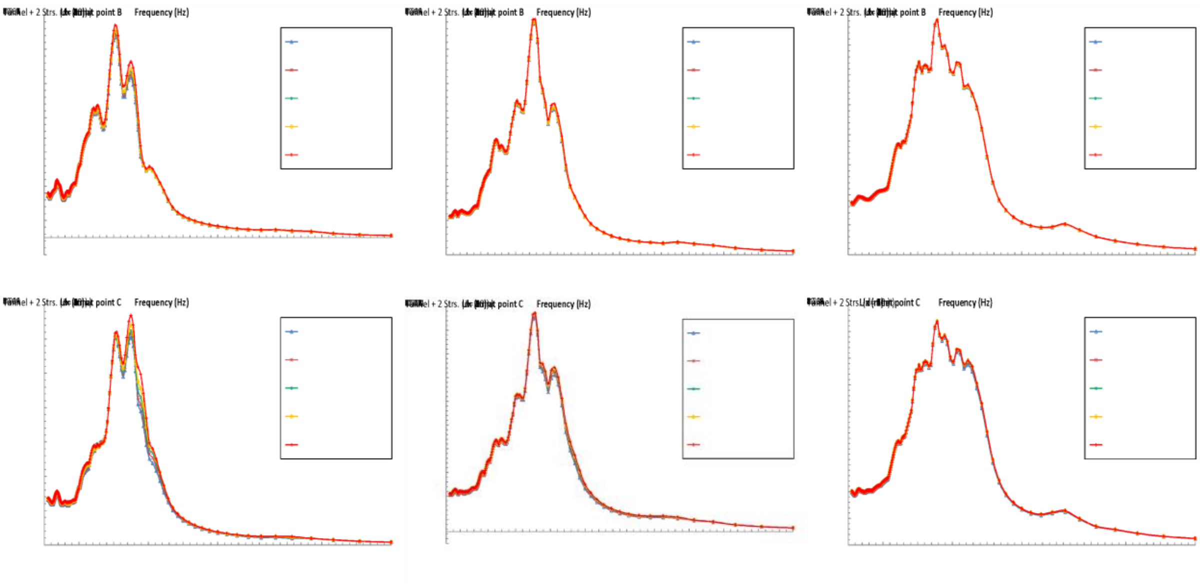
(a) V_s = 200 m/s *(b)* V_s = 400 m/s *(c)* V_s = 800 m/s

Figure 5. Horizontal displacements of the tunnel-soil-structures system

3.2 Effect of the distance between the adjacent structures

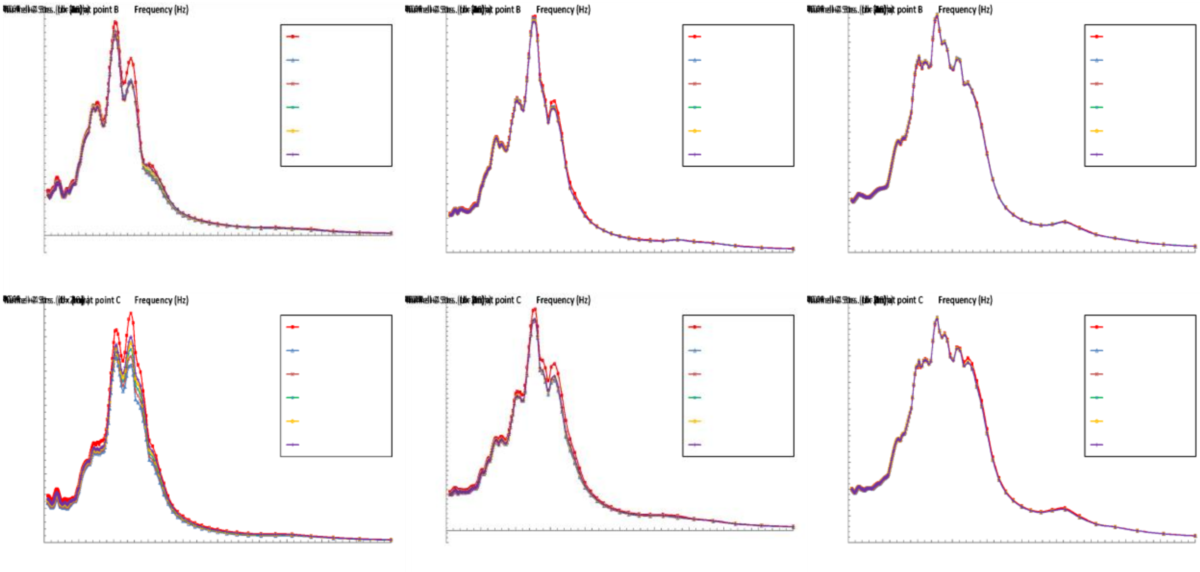
In this part of the study, the distance effect between adjacent structures is studied under a seismic loading impact. The cases of two and four neighboring structures are adopted. The same characteristics of the ground, the tunnel and the structures mentioned in subsection (3.1) are taken to study these cases. For the two adjacent structures case, the distance between the structures are successively taken: *d* = 2 m, 4 m, 6 m, 8 m and 10 m. Figure (6) presents the horizontal displacements at the summit of the first structure (point C) and the tunnel (point B) with varying stiffness of the ground. In this figure, it can be observed that the decrease of the distance between the two structures reduces the tunnel and the structures responses. In the soft soil case and for *d* = 2 m, the reduction in the responses can reach up to 10 % in comparison with the stiff and very stiff soil cases.

In the case of four neighbouring structures, the distance values are successively taken: *d* = 2 m, 4 m, 6 m, 8 m and 10 m except between the first two structures where the distance is equal to 10 m. In figure (7) where the distance is decreased, the system responses are reduced. The shape of this reduction is more observable at the summit of the structure (point C). Particularly, in the soft soil case, the reduction can reach up to 17 % in *d* =10 case. By comparing with the case of presence only two structures, it is remarked that this reduction can reach up to 26 %.



(a) V_S = 200 m/s *(b)* V_S = 400 m/s *(c)* V_S = 800 m/s

Figure 6. Horizontal displacements of the tunnel-soil-structures system



(a) V_S = 200 m/s *(b)* V_S = 400 m/s *(c)* V_S = 800 m/s

Figure 7. Horizontal displacements of the tunnel-soil-structures system

4 CONCLUSION

In this work, the interaction effect between the superficial and the underground structures on the seismic responses behaviour is numerically studied with varying the soil stiffness, the number and the distance between the superficial structures. Consequently, the results show that the behaviour of the seismic responses of the studied system (Tunnel-Soil-Structures) is significantly influenced by the soil nature, the density of the adjacent structures as well as the separation distance between them. The increase in the number of neighboring structures and the decrease in the separation distance between them can remarkably reduce the seismic responses of the superficial structures and the tunnel. This attenuation can reach up 35% in the case of soft soil, 22% in the stiff soil case and 8% for the very stiff soil case.

Note

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Author Contributions

Abderrahim ACHOURI: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing
Mohamed Nadir AMRANE: Conceptualization, Methodology, Investigation, Writing - Review & Editing, Supervision

All authors read and approved the final manuscript.

Conflict of interest

No conflict of interest was declared by the authors.

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