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EFFECT OF STRUCTURES DENSITY AND TUNNEL DEPTH ON THE TUNNEL-SOIL-STRUCTURES DYNAMICAL INTERACTION

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Abstract: This paper studies the presence effects of two or more adjacent structures on the tunnel responses and vice versa due to surface and underground traffic loads. The study is numerically carried out by using Finite element Plaxis^{2D} software©. The obtained results demonstrate that the dynamical interaction between the tunnel and the structures is significantly influenced by varying the number and distance between the adjacent structures, the depth of the tunnel and the location of the traffic load. These results can be considered and used in realistic and practical cases and also to help build efficient and more comfortable construction projects.

Keywords: Dynamical interaction, Structures density, Tunnel depth, Traffic loads, Plaxis^{2D} software©, Finite element method

1. Introduction

In recent years, several construction projects of the superstructure and infrastructure (building structures, equipment structures, underground and surface traffic systems, etc.) were realized to contain the rapid explosion of population in the world and solve the problem of traffic in cities. This rapid development reduces the distance between the different types of structures and creates dynamical interaction between them, where this interaction adversely affects people [1]. This phenomenon is caused from the waves generated by the motions of different types of transportation and transmitted through the ground to the nearby structures [2]. To study the effects of the Soil-Structure Interaction

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(SSI) and Structure-Soil-Structure Interaction (3SI) on the behavior of the significant structures (nuclear building, etc.) [3]-[6]. Several research works are carried out by using different complex methods as the analytical methods [7], the Finite Element Method (FEM) [8], [9], the Boundary Element Method (BEM) [2], [10], hybrid numerical methods as the FEM-BEM [11], [12] and the Scaled Boundary-Finite Element Method (SBFEM) [13] or the Symmetric Galerkin Boundary Element Method (SGBEM) [14]. Sophisticated software like ANSYS, ABAQUS and FLAC are also used successfully to study numerically this phenomenon [15]-[18]. A successful design of urban traffic systems involving the road traffic at the ground surface level and the railway traffic in tunnels is a very difficult task due to the dynamical interaction phenomena between the components of the system [5], [19]. This interaction is related to several factors as: the material and geometrical characteristics of the system, the distance between all components, the nature of the ground, the type of the structures [7], [9], [13] and [20].

In the present work dynamical study of the Structure-Tunnel-Structure Interaction (STSI) is carried out by taking into account the effect of the number and distance between the structures, the depth of the tunnel and by the location of the traffic impact.

2. Numerical modeling and validation

In this work, a numerical modeling study carried out by using the finite element Plaxis^{2D} software$^{©}$ under plane strain conditions. The linear fully elastic behavior is taken for the soil and the structures. The behavior model is characterized by the Young's modulus E, the shear modulus G, the Poisson's coefficient v and the bulk modulus K, where the relationship between them are given as following:

$$G = E/2(1+v), \tag{1}$$

$$K = E/3(1-2v). \tag{2}$$

In all studied examples, the soil and the structures are modeled by using the 15-nodes triangle element. The soil-structures interaction area is considered fully rigid, hence the interface element is not considered. In the numerical implementation of dynamics, the implicit time integration scheme of Newmark is used. This method is based on two equations which are presented below:

$$u^{t+\Delta t} = u^t + \dot{u}^t.\Delta t + \left(\left(\frac{1}{2} - \alpha\right).\ddot{u}^t + \alpha.\ddot{u}^{t+\Delta t}\right).\Delta t^2, \tag{3}$$

$$\dot{u}^{t+\Delta t} = \dot{u}^t + \left((1-\beta).\ddot{u}^t + \beta.\ddot{u}^{t+\Delta t}\right).\Delta t, \tag{4}$$

where u, $\dot{u}$ and $\ddot{u}$ are respectively; the displacement, the velocity and the acceleration of the considered point, t is the time of the considered step, Δt is the time step, α and β are the integration constants of Newmark. The coefficients α and β are expressed as a function of the numerical dissipation parameter γ as follows:

$$\alpha = \frac{(1+\gamma)^2}{4}, \tag{5}$$

$$\beta = \frac{1}{2} + \gamma, \tag{6}$$

where the value of γ belongs to the interval [0, 1/3] [21].

For this study the values $\alpha = 0.3025$ and $\beta = 0.6$ correspond to $\gamma = 1/10$ are used, where these values make it possible to ensure very low numerical damping and stable results, other combinations are also possible as long as α and β satisfy the following conditions [22]:

$$\alpha \geq 1/4\left(\frac{1}{2} + \beta\right)^2, \tag{7}$$

$$\beta \geq 0.5. \tag{8}$$

As it was proposed by Lysmer and Kuhlmeyer, the increase of the normal and shear components of the stress at the boundaries due to the reflecting waves are absorbed by dampers as following [19], [23]:

$$\sigma_n = c_1 \rho V_P \dot{u}_x, \tag{9}$$

$$\tau_n = c_2 \rho V_s \dot{u}_y, \tag{10}$$

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. c_1 and c_2 are the dimensionless coefficients of relaxation (viscosity coefficients) that have been introduced in order to improve the effect of the absorption. According to [23], the choice of $c_1 = c_2 = 1$ (standard viscous boundary) provides maximum wave absorption when the boundary is achieved for perpendicular impinging waves, defining the case of efficiency boundary conditions (non-reflecting conditions). Other values effects of c_1 and c_2 are also studied by White et al. [24] as a function of the Poisson's coefficient. As a result, these values are exact only for 1D propagation of body waves. For 2D and 3D cases, perfect absorption depends on angles of wave incidence and because the presence of shear waves, where the damping effect of the absorbent boundaries is not sufficient without relaxation. For this reason $c_1 = 1$ and $c_2 = 0.25$ are recommend, where the experience gained until now shows that this values results in a reasonable absorption of waves at the boundary [22], hence these values are used in this study.

To compare and validate the accuracy of the present numerical modeling results, the same material and geometrical characteristics taken by Estorff et al. [5] is adopted. A soil-tunnel system is taken as it is shown in *Fig. 1*. The material characteristics of the soil are: $E_S = 2.\ 66\times10^5$ kN m^{-2}, $\upsilon_s = 0.33$ and $\rho_s = 2000$ kg m^{-3}, for the tunnel concrete: $E_t = 3\times10^7$ kN m^{-2}, $\upsilon_t = 0.25$ and $\rho_t = 2000$ kg m^{-3}. The depth of the tunnel is taken $h = 4$ m. Two traffic and unit loads are adopted; the first applied on the over ground at point A (P^A) and the second inside the tunnel at the point C (P^C), these loads are distributed separately on two meters. The mesh coarseness is taken fine near the tunnel and medium in the rest.

The adopted system is studied firstly under an impact of applying surface traffic load, secondly under an impact of the underground traffic load. *Fig. 2a* and *Fig. 2b* present the vertical displacements at points A, B and C due to surface and underground traffic loads. The good convergence between the present modeling results and Estorff work [5] can be remarked. In addition, the used values of the integration constants of Newmark (α = 0.3025 and β = 0.6) and the dimensionless coefficients of relaxation (c_1 = 1 and c_2 = 0.25) ensures practically a very low numerical damping, stable results and reasonable absorption of waves at the boundary. The values effects of these coefficients are clearly shown in *Fig. 2a* and *Fig. 2b* for the two loading cases, where the vertical responses behavior carried out by the present modeling is a bit smoother than the results of Estorff [5].

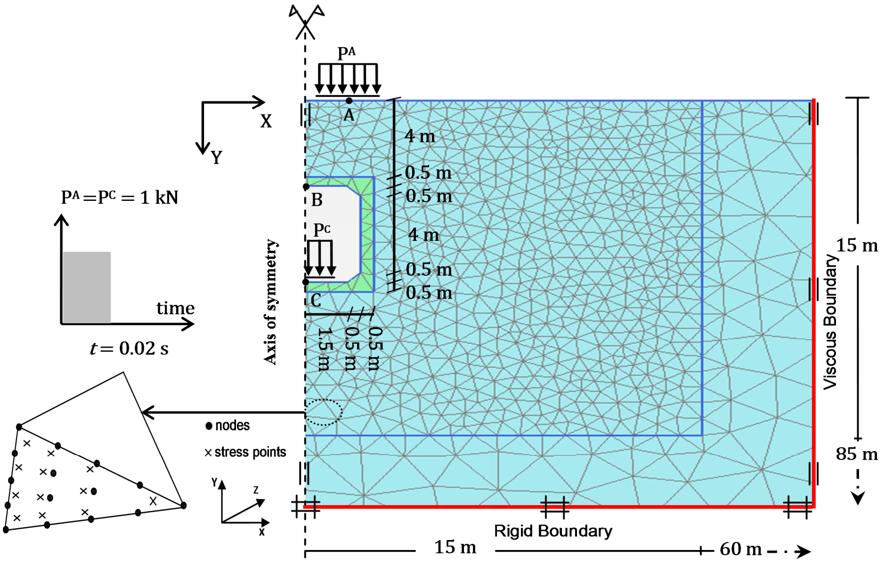
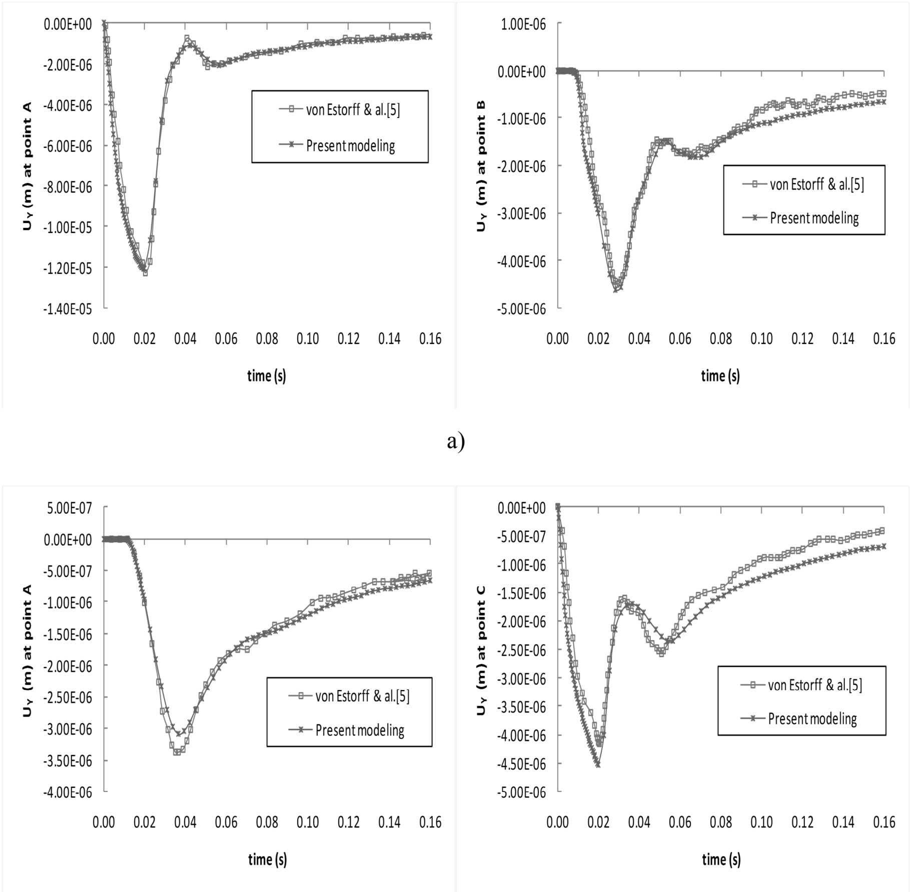


Fig. 1. Geometry and meshing of the half-space-tunnel system by FEM (present study)

3. Parametric study and discussions

3.1. Effect of structures density

In this studied case, the effect of the density of the surface structures on the tunnel is studied; the same geometrical and material properties of the ground and the tunnel are taken as in section 2 where set of two structures 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. 3*). Three cases of distance between structures are separately taken: d = 2 m, 4 m and 6 m except the two first structures where the distance is equal to 10 m for all cases. The loads are applied in first on the base of the tunnel, in second step on the over ground. In the underground traffic load case at point B (*Fig. 4*) it can be remarked, firstly that when 0.02 s ≤ t ≤ 0.036 s the response at the summit of the tunnel is amplified for all added structures cases. Secondly; if 0.045 s ≤ t ≤ 0.056 s this response is amplified when over than 2 structures are added (i.e. no effect for 2 added structures case).



a)

b)

Fig. 2. Vertical displacement due to: a) surface traffic load (P^A); b) underground traffic load (P^C)

Finally, where 0.065 s ≤ t ≤ 0.09 s the response is amplified for all added structures with less magnitude in the case of 2 structures. In the surface traffic load case at point B (*Fig. 5*), when 0.02 s ≤ t ≤ 0.08 s the response is clearly amplified 2.5 times comparing to the non-existing structures case. For the effect on the structures (*Fig. 4* and *Fig. 5*) at point A, in the same previous temporal bands, the amplification of the magnitude at the base of the structure due to surface or underground traffic loads is clearly stated. It is easily remarked that the number of four structures gives the greatest amplification, where the amplification magnitude due to the surface load case is more than the underground load case. Moreover, the *Fig. 4* and *Fig. 5* show also that the effects of the structures density on the responses of the structures and the tunnel are significantly influenced by varying the distance (*d*) between the adjacent structures. The amplification due to the augmentation of the number of structures decreases where the distance (*d*) increases for the two loading cases. The decreasing tendency of this amplification converges to the two structures case.

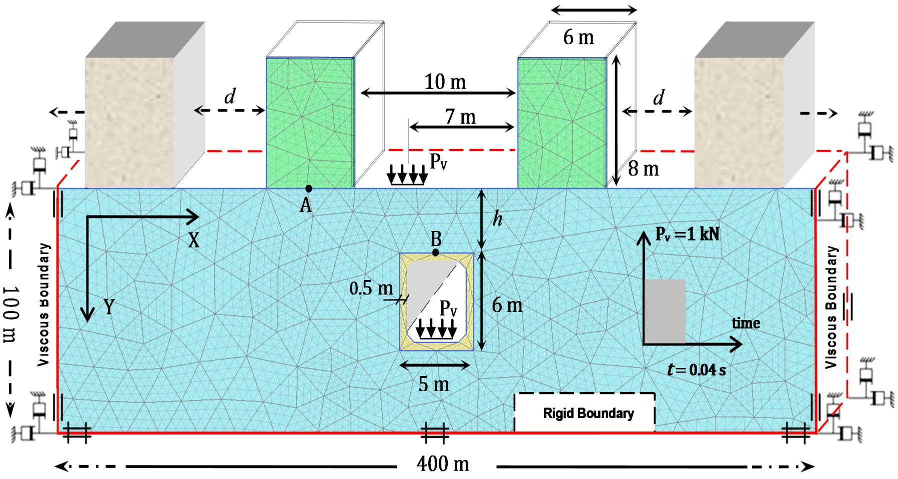


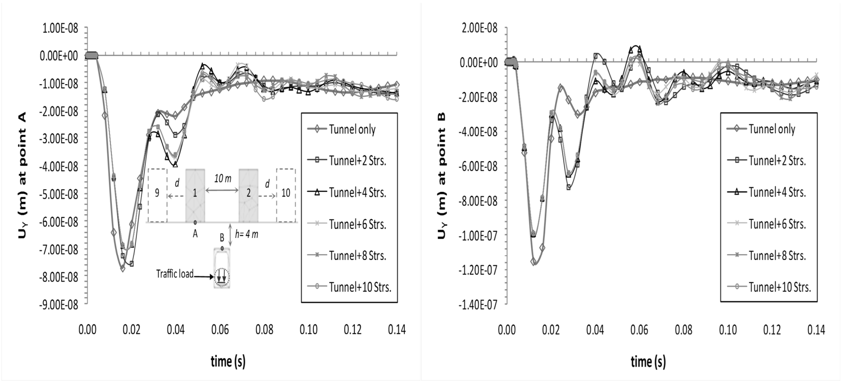
Fig. 3. Geometry and meshing of the structure-tunnel-structure system by FEM (present study)

3.2. Effect of the distance between the structures

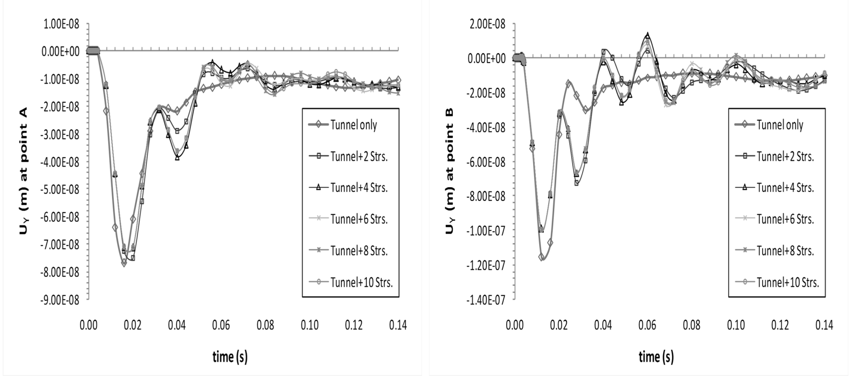
The objective of this case study is to determine the necessary distance that eliminates the dynamical interaction effects between adjacent structures subjected separately to surface and underground traffic impacts. To study the effect of distance between structures, the case of four structures is considered according to the results in subsection 3.1, where the distance values are successively taken: d = 2 m, 4 m, 6 m, 8 m, 10 m and 110 m except between the two first structures where the distance is equal to 10 m. In *Fig. 6* and *Fig. 7* tendencies of amplification are conserved at each points A or B for the two loading cases except the case of vertical displacement at B due to underground traffic load. In the two studied loading cases this effect is non-significant for the distance between two structures over than 110 m; it converges to the 2 structures case.

3.3. Tunnel presence and depth effect

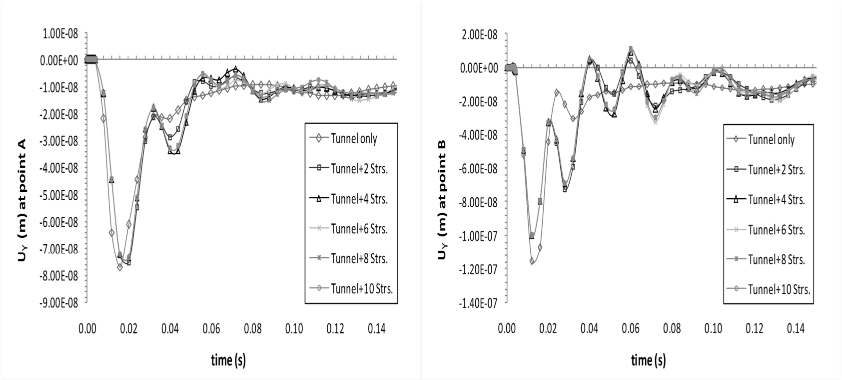
According to subsections 3.1 and 3.2 for the number of structures (4 structures) and for the realistic distance case (d = 6 m), the tunnel presence and the depth effects are studied.



a) *d* = 2 m

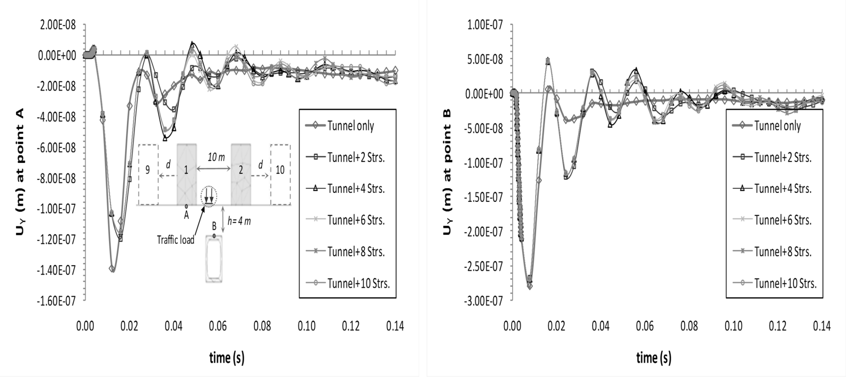


b) *d* = 4 m

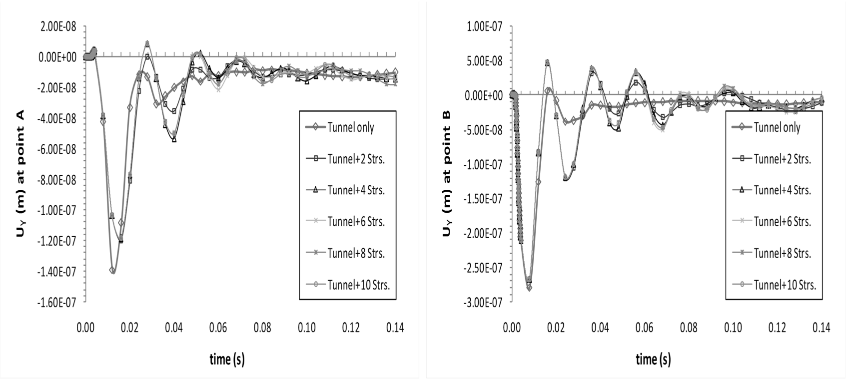


c) *d* = 6 m

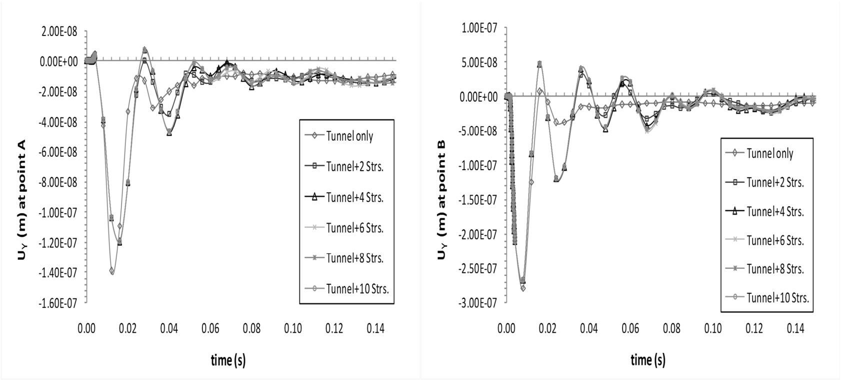
Fig. 4. Vertical displacement due to underground traffic load



a) $d = 2$ m



b) $d = 4$ m



c) $d = 6$ m

Fig. 5. Vertical displacement due to surface traffic load

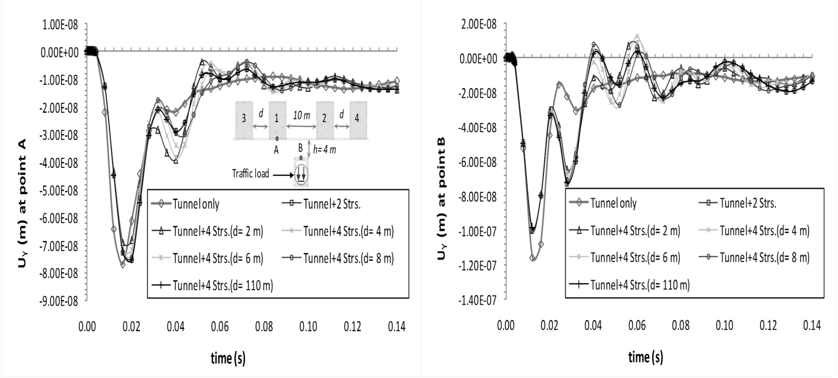


Fig. 6. Vertical displacement due to underground traffic load

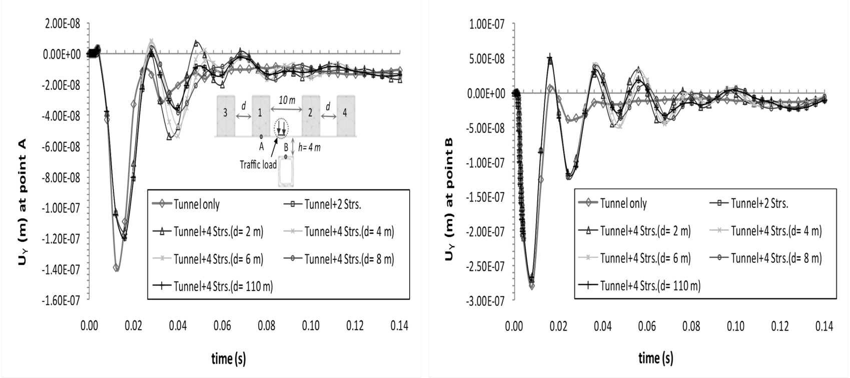


Fig. 7. Vertical displacement due to surface traffic load

The same material characteristics in subsections 3.1 and 3.2 with four identical structures are taken (*Fig. 3*). The distance between adjacent structures is taken: $d = 2$ m except the two first structures where it is equal to 10 m for all cases. The depth of the tunnel (h) in the soil is taken successively equal to 4 m, 8 m, 12 m, 16 m and 20 m. The loads are applied in first on the base of the tunnel, in second step on the over ground. At point A *Fig. 8* shows that the presence of the tunnel increases the vertical responses of structures, this augmentation decreases proportionally when the tunnel depth increases, over 16 m the response of structures due to surface load stabilize to those for non-existing tunnel values. At point B (*Fig. 8*) and at points A and B (*Fig. 9*) the effects of the tunnel depth save the same tendency as at point A (*Fig. 8*). It should be remarked firstly that; the maximum amplitude of the tunnel and the structures responses due to underground load case is less than the surface load case. Secondly, for the two loading cases the depth of 4 m gives the maximum amplifying. Finally, for the surface load case the depth effect of the tunnel is insignificant on the response of the structure at point A (*Fig. 8*).

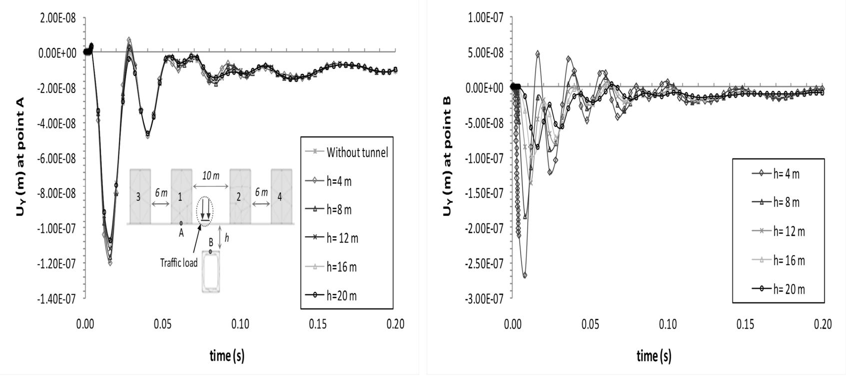


Fig. 8. Vertical displacement due to surface traffic load

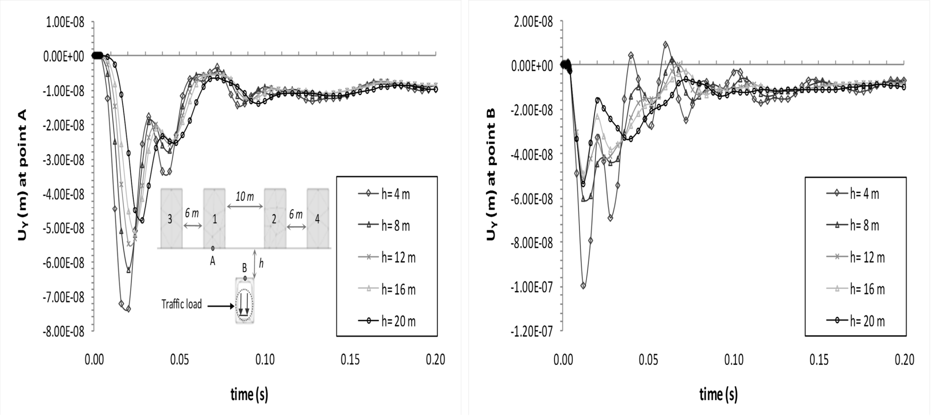


Fig. 9. Vertical displacement due to underground traffic load

4. Conclusion

A 2D numerical modeling is carried out to study the effects of structures density and tunnel depth on the structure-tunnel-structures interaction (STSI) due to traffic loads. The accuracy of the present study results is established by comparing with previous works. As results, it is concluded that:

The modeling of the 3SI and the STSI by using the finite elements Plaxis^{2D} software$^{©}$ can be easily performed, efficient and rapid in comparing with analytical methods and other software; hence the sophisticated strategies and software are not always necessary to study such phenomena. The presence of the underground structure below the surface structures increases the dynamic responses. The increase of the distance between the tunnel and the structures reduces the effect of the dynamical interaction on their responses. The density of structures located on the over ground influences clearly on the responses of the structures near the tunnel and also on the response of the tunnel, this effect increases where the distance between the adjacent structures and the depth of the tunnel decreases and vice-versa. On the other hand, the tendency of the structures density effect corresponds to the location of the traffic load. As conclusion it should be remarked; the responses of the tunnel present three successive states (reduction, amplification and stabilization) for both solicitation cases. At the base of the near left structure, the responses present two states (amplification in a large temporal domain before stability) when load is applied at the over ground. In the underground applied load case, two separate states can be remarked (amplification in two separate temporal domains before stability). This study states clearly that real cases can be extracted to be used in real projects of cities in horizontal and vertical extensions (present study case).

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