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Non-Linear Numerical Modeling of the Interaction of Twin Tunnels-Structure

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Abstract**—**Structures on the ground surface bear impact from the tunneling-induced settlement, especially when twin tunnels are constructed. The tunneling influence on the structure is considered as a critical issue based on the construction procedure and relative position of tunnels. Lebanon is suffering from a traffic phenomenon caused by the lack of transportation systems. After several traffic counts and geotechnical investigations in Beirut city, efforts aim for the construction of tunneling systems. In this paper, we present a non-linear numerical modeling of the effect of the twin tunnels constructions on the structures located at soil surface for a particular site in Beirut. A parametric study, which concerns the geometric configuration of tunnels, the distance between their centers, the construction order, and the position of the structure, is performed. The tunnel-soil-structure interaction is analyzed by using the non-linear finite element modeling software PLAXIS 2D. The results of the surface settlement and the bending moment of the structure reveal significant influence when the structure is moved away, especially in vertical aligned tunnels.

Keywords**—**Bending moment, construction procedure, elastic modulus, relative position, soil, structure location, surface settlement, twin tunnels.

I. Introduction

LEBANON is one of the small countries that are suffering from traffic. Unfortunately, despite of all the efforts in establishing new areas adapting the most recent improvements, Lebanese area will not be capable of bearing these developments with the increasing population rates [1]. The search for quick solutions can be presented by creating latest maze of traffic reducer systems which are twin tunnels. By the help of traffic management center, it was proven that the highest traffic counts are presented at Verdun-Beirut city [2]. Consequently, a full geotechnical investigation is pulled to find out the type of soil, soil's parameter, rocks, underground water presence, and other underground obstacles.

Many researches elaborated the influence of twin tunnels on the soil and structures. These studies took several doors for analysis, some established the effect of the soil type on the construction [8], and others highlighted the field of relative tunnel positions and construction procedure [6]. These researches continued to study the interaction of twin tunnels with soil and structures as well [4]. However, almost no thorough studies have taken into consideration the effect of variation of the structure's parameters and positions on the soil displacement induced stresses in the tunnels, and the bending moments subjected to the structure.

This paper presents analysis of the interaction between twin tunnels and the superstructure with a particular interest of structure's location, construction procedure and relative position. For this, a parametric study is conducted for the investigation of the influence of these factors on the soil settlement and induced moment on the structural frame from the construction. The numerical modeling and analysis are performed on two configurations of twin tunnels: aligned – horizontally and vertically using PLAXIS 2D.

II. Numerical Modeling

Analyses are conducted by using the finite element method. The soil behavior is described by using an elastic perfectly plastic constitutive relation based on the associated Mohr-Coulomb criterion. The soil domain of length=40D (D=tunnel diameter) and depth=7D is modeled after mesh generation [4]. The mesh used in all the modeling is the same and it contains 2453 triangular 6-nodes elements and it is refined in the critical region of the construction (see Fig. 1). The superstructure is represented by a frame of 4 m height and a 6 m longitudinal span supported by two footings which are 2 m wide. The structure's mid span is to be centered above the tunnels and subjected to a uniform factored load q_u=16 kN/m^2.

The two configurations are shown in Figs. 2 (a) and (b). In vertical alignment, the variation of the structure's location is accomplished based on changing S (S is the distance from the central tunnels' axis to the mid span of the super structure). In the meanwhile, in horizontal alignment, structure is located in two different places: at an equivalent distance from the two tunnels and above the left tunnel in a way, its mid span is collinear with the central soil domain's axis and central tunnels' axis, respectively. Concerning the boundaries conditions, the displacements are considered in both directions at the bottom, while zero horizontal displacement is imposed at lateral boundaries. Table I summarizes the properties of the soil and lining used in the studies revealing the type of soil in Beirut [3]. The soil corresponds to sandy soil, and the coefficient of the lateral stress (K_0) is equal to 0.5.

The models include the use of a lining thickness equals 0.5 m, and tunnels' diameter is 7.5 m located at a depth which is equal to 2.5D. In addition, the Young's Modulus of soil, E, increases with the depth according to:

$$E\,(z) = E_0\,(P_m/P_0)^{0.5} \qquad (1)$$

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where P_m denotes the mean stress at depth z, E_0 is constitutive parameter, which corresponds to the Young's Modulus with the mean pressure $P_m = P_0$. This expression takes into account the variation of the Young's Modulus with the mean pressure, which increases with the depth due to the soil self-weight.

TABLE I
PROPERTIES OF BOTH THE SOIL AND LINING MATERIALS

Material	Eo (Mpa)	Poisson's Ratio	Cohesion (kPa)	Friction Angle (Deg.)	Dilatancy Angle (Deg.)	Unit Weight (kN/m^3)
Soil	30	0.35	0.3	34	4	18
Lining	30,000	0.25				25

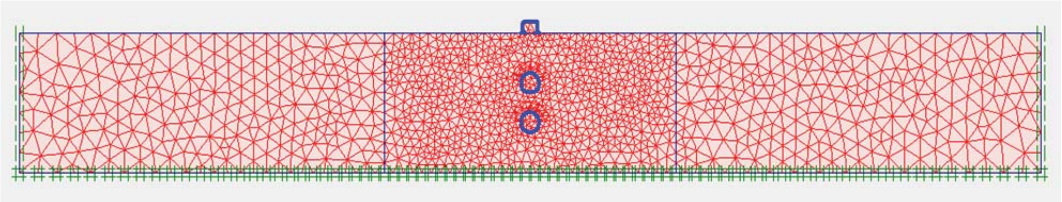

Fig. 1 Mesh of a vertically aligned tunnels with a super structure

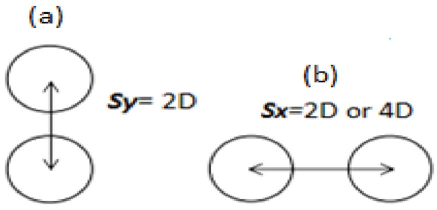

Fig. 2 (a) vertically aligned tunnels (b) horizontally aligned tunnels

The finite element modeling of construction of twin tunnels is carried out as follows: the first tunnel is constructed by using the convergence-confinement method with a stress release factor α=0.5 [5], [6]. This factor corresponds to the ratio of the stress release before lining installation. Secondly, construction of the second tunnel is performed by using also the convergence-confinement method, as for the first tunnel with a stress release factor α=0.5 [5], [6]. This factor applies for the stresses exercised around the tunnel after the excavation of the first tunnel. The reference cases of the construction procedure represent the construction of the upper tunnel and the left tunnel first in the vertically and horizontally aligned twin tunnels, respectively.

A. Construction Procedure and Relative Position Influence

The shape of the settlement curve with the absence of a structure is noticed to be a smooth parabolic shape without any sudden sharp increase or decrease. However, this changes when a structure is presented, and a sharp increase under the foundation due to the concentrated load subjected on the soil domain occurs.

The construction order shows a critical influence in the vertical twin tunnels only. The results established reveal that the case of construction procedure referred to as reference case leads to higher settlement and internal forces compared to the inverted case by approximately 5%. Conversely, the construction of horizontally aligned tunnels is not dependent on the order beyond Sx=2D [7]. At Sx=2D, very slight increase about 2% is noticed in the reference case.

According to Young's modulus, the elastic modulus increases with depth, thus more stiffness is acquired due to the compaction state. In fact, excavation in a stiffer domain first will result in less surface settlement compared to the excavation of the upper tunnel first. On the other hand, the slight decrease in the maximum surface settlement when a structure is present is due to the compaction of the soil under the structure's foundation after its settlement.

Many numerical analyses show that both the settlement pattern and amplitude depend on the distance between tunnels [6]. The maximum soil settlement is observed for the configuration with close tunnel Sx=2D. 4D spaced tunnels shows a decrease in the surface settlement by approximately 30% compared to that of 2D spaced tunnels. High surface settlement is due to the interlocking of induced stresses from the construction of tunnels. As a result, unlike the 4D spaced tunnels, the surface settlement curve of tunnels with Sx=2D is similar to a single tunnel.

The bending moment subjected to the structure in both configurations shows the same results while varying the construction order.

In general, the surface settlement and the bending moment in twin tunnels are more critical than in a single tunnel configuration. When Sx increases, the critical lateral excavation zone increases causing higher moment at the mid span of the structural frame (see Fig. 3).

B. Structure's Location Influence in Vertical Alignment

In Fig. 4, the structure is located at distance S that varies between (0, 3, 7, 10, 20, 30, and 60 m).

The surface settlement in S=3m is not symmetrical anymore due to the change of the footing's position. Compared to S=0, the settlement is decreased on the right side sharply by around 36% due to stress release on the right side because the right footing is at a distance 3 m away from the central tunnel axis. However, the settlement on the left side to which the structure is moved witnesses a maximum surface settlement that is greater than that in S=0 m by about 4%. This increase can be correlated to the concentrated load subjected by the left footing. When X/D=28 (middle of the soil domain) the surface settlement of Case 2 (S=3 m) increases by 21% from that of Case 1 where S=0 m.

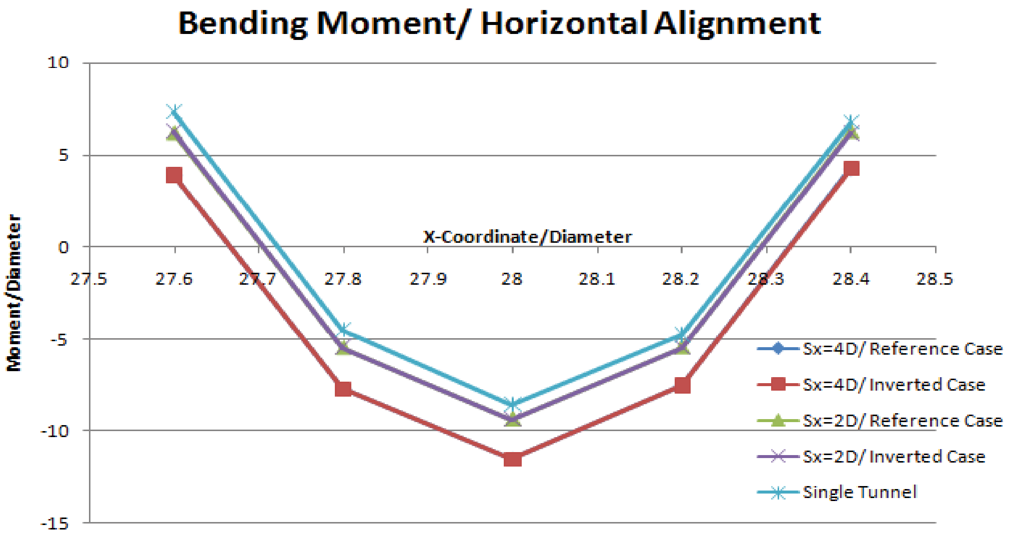

Fig. 3 Variation of bending moment as a function of relative position of tunnels and construction order in horizontal alignment

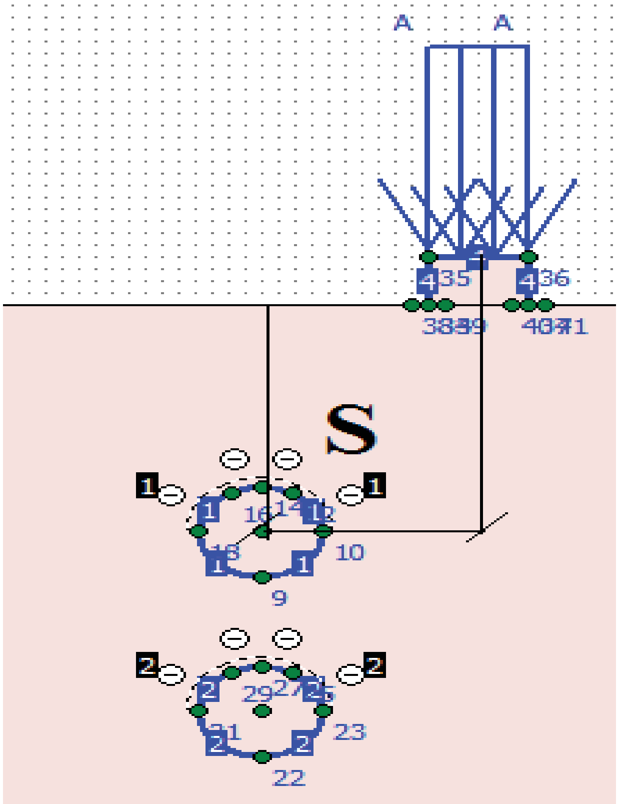

Fig. 4 Variation of structure's location by distance S in vertically aligned tunnels

The situation changes beyond S=3 m, a decrease in the maximum surface settlement occurs as a result of shifting the structure far from the excavation region. The stresses induced in the critical excavation region from the structure vanish gradually reaching a constant surface settlement beyond S=60 m. The maximum surface settlement in S=20 m decreases by 33% compared to S=0 m and approximately same decrease is noticed at X/D=28 (see Fig. 5). Consequently, the maximum surface settlement in this case is about 7% lower than that of a single tunnel and a structure at S=0.

Regarding the bending moment, the maximum mid span negative moment increases gradually as S increases. Beyond S=20 m, it starts increasing slightly by around 4% reaching 48% at S=30 m and then drops by 39% when S is equal to 60 m. At the same time, the positive moment subjected to the columns of the frame undergoes a gradual decrease as S increases. At S=60 m, it shows a decrease by approximately 29% compared with S=0 m (see Fig. 6).

It is clearly identified that the location of the structure has a big influence on the tunnels' construction. The structure is subjected to a symmetrical moment when it is at S=0 which results in a smaller negative mid span moment compared to S=3 m, 7 m, 10 m, and 20 m… The uniform displacement of the structure when S=0 m leads to a minimum mid span moment. At the same time, far locations of the structure threaten the occurrence of differential settlement. This contributes to the fact that the structure is under a higher rotational effect which results in an increasing mid span moment to a distance is approximately equal to 3D.

C. Structure's Location Influence in Horizontal Alignment

In horizontal alignment of twin tunnels, structure is located in two different places of 2D spaced tunnels; Case a: at an equivalent distance from the two tunnels and Case b: above the left tunnel in such a way its mid span is collinear with the central tunnels' axis (see Fig. 7). The maximum surface settlement is the same in both cases. However, at X/D=28 in case b after the left shift, the surface settlement decreases by around 7% (see Fig. 8). The sharp increase is noticed to be in both cases under both footings of the structure. The surface settlement will decrease gradually as the structure is located far away from the middle of the soil region. This is expected because the structure is found in a region not totally subjected to the stresses induced from the construction.

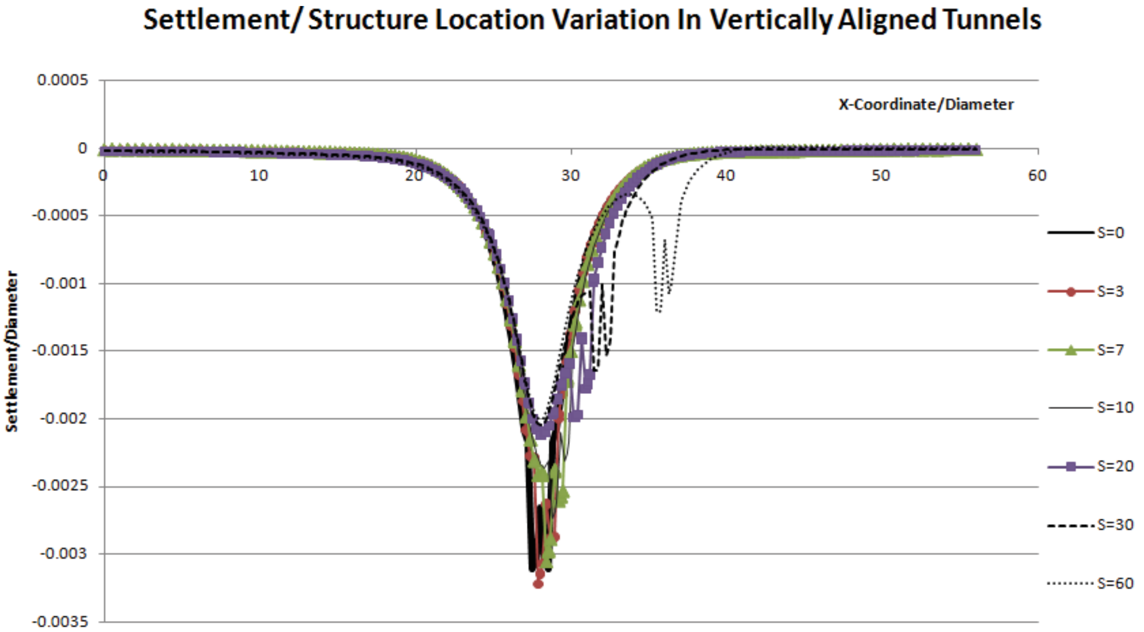

Fig. 5 Variation of surface settlement as a function of changing the structure’s location in vertically aligned tunnels

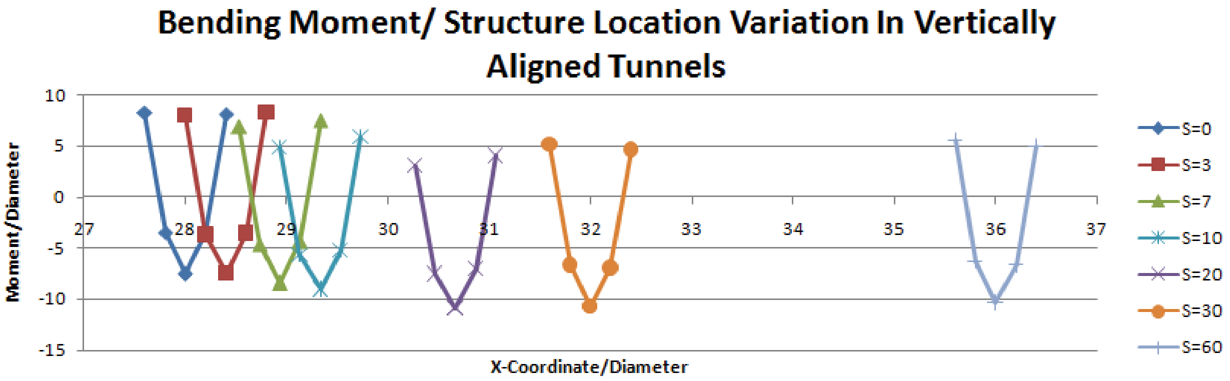

Fig. 6 Variation of bending moment as a function of changing the structure’s location in vertically aligned tunnels

By comparing the bending moment subjected on the structural mid span in case b with case a, it is noticed that there is a decrease by around 3% (see Fig. 9). The mid span bending moment increases when the structure is between the critical excavation region. The free distance between the two tunnels causes the soil particles to move and gradually fill in escaping from the induced internal stresses in the tunnels. Thus, this will cause two opposite moments on the columns of the frame resulting in high negative moment on the mid span. Bending moment of Case b shows an increase on the columns of the frame by about 10% compared to case a. In Case b, the subjected bending moment is approximately similar to the case of a single tunnel.

III. CONCLUSIONS

This paper includes a numerical analysis of the construction of twin-tunnels with a particular focus on the influence of both the construction procedure and geometric configuration on the soil settlement and internal forces with the presence of a super structure. This paper also represents the effect of structure’s location on the construction of vertically and horizontally aligned structures.

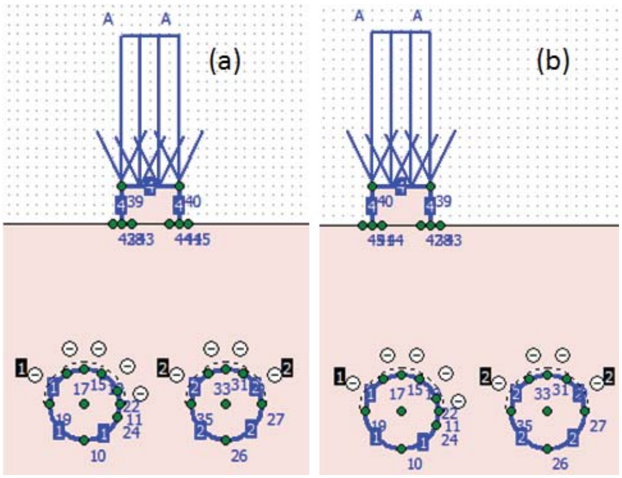

Fig. 7 Two cases of variation of structure’s location in horizontally aligned tunnels

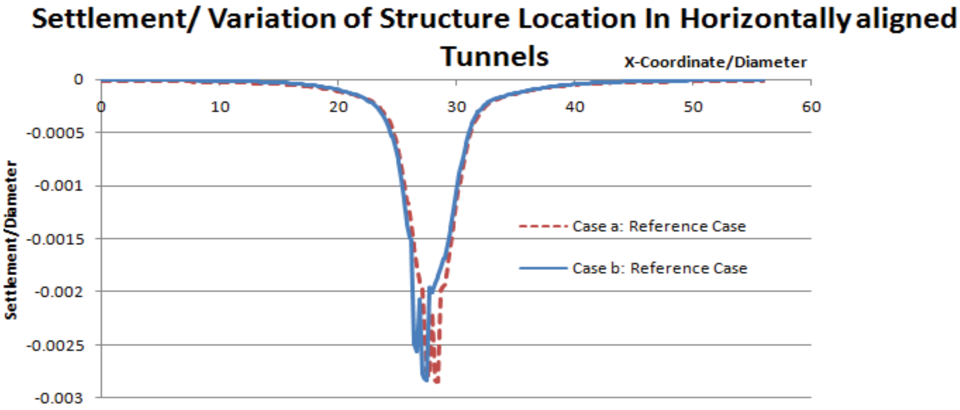

Fig. 8 Variation of surface settlement as a function of variation of structure location in horizontally aligned tunnels

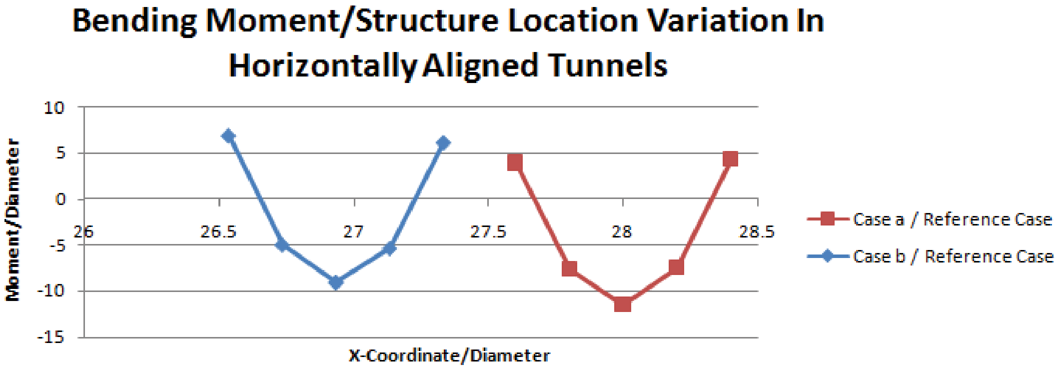

Fig. 9 Variation of bending moment as a function of variation of structure location in horizontally aligned tunnels

The comparative study shows that the construction procedure affects the soil settlement of the vertical twin tunnels. The construction of the upper tunnel at first leads to higher settlement, compared to the obtained by the construction of the lower tunnel at first in the vertical alignment. The highest soil settlement is obtained for vertical aligned tunnels, while horizontal aligned tunnels cause the lowest settlement without being affected by the order of construction beyond 2D. The maximum soil settlement is observed for the configuration with close tunnel Sx=2D.

The design of twin-tunnels must take into consideration other constraints like the damage accommodated by the adjacent super structure. The numerical modeling shows that surface settlement is minimal as long as the structure is located far from the central domain axis. In this case, special attention should be taken into consideration when dealing with a super structure located at a distance ranges from 0D to 3D from the vertical twin tunnels' central axis. In 4D spaced horizontal tunnels, the structure's mid span is subjected to a higher bending moment compared to 2D spaced ones. This explains the increase of the mid span moment when the structure is between the two tunnels due to diminished excavation's region.

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