Parametric study of twin tunnel under seismic loads for Cairo Metro Line No. 4

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ABSTRACT
The damage of tunnel induced by intense earthquake is obviously important. Thus, more attention has been paid to the tunnel destruction induced by earthquake. So far, there are few studies conducted on the influence of earthquake dynamic loads on horizontal twin tunnels. In this research, a systematic analysis of horizontal twin tunnels of Cairo Metro Line No. 4 was performed using finite element model by the commercial software PLAXIS 2D and under static and earthquake dynamic loads using the Dahsour Earthquake 1992 time real history. Both static and dynamic analyses in this research have taken into account the effect of the soil structure interaction on the static and dynamic performance of horizontal twin tunnels. Also, a parametric study had been performed on the horizontal twin tunnels of Cairo Metro Line No. 4 under different parameters, which included the tunnel’s depth \((d)\), the distance between twin tunnels \((S)\), and the surrounding soil stiffness \((E)\). Results showed that both static and dynamic analysis are expected to be governed by soil structure interaction. Also, the studied parameters are very important in tunnel design under static and dynamic loads, especially the distance between twin tunnel, where these types of twin tunnels were excavated by TBM machine.

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Introduction

Most urban underground structures are constructed in shallow and soft grounds and thus are prone to seismic disturbances. Such structures, depending on their use, are of great importance in terms of long-term safety. If the construction site of large underground structures such as public transport tunnels is very soft or loose, their seismic behavior should be estimated \([1–3]\). In the past decades, many studies were concentrated on the consequence of single tunnel excavation in terms of surface and subsurface movements \([1–4]\).
On the other hand, the case of twin tunnels is nowadays very common in many metroprojects around the world because twin tunneling is particularly favored when developing underground transportation systems all over the world [5,6]. Interactions between closely spaced tunnels were studied in the past using a variety of approaches: physical model tests [7], numerical modeling [8–12], and empirical and analytical methods [13–18]. The physical modeling to predict, as well possible different construction settings adopted during the second excavation, generally alters the expected ground movements due to the construction of a new one, often leading to a non-symmetric final settlement trough. Numerical methods demonstrate a valuable tool to analyze this class of problems, overcoming the limitations related to the empirical methods. In several cases, a detailed investigation can only be fulfilled adopting a three-dimensional (3D) solution, which permits to calculate for any construction scheme, including the case of twin tunnels, for any kind of surface structure and its relative position with respect to the tunnels’ axes. However, the validity of such methods is strongly affected by different factors [19], the correct simulation of the tunnel excavation sequence [20] and the details of the structural modeling [21]. Extensive surveys of the papers submitted for the session on numerical and physical modeling of tunnels were provided by Jacobsz [22].

However, the most recent studies improved the knowledge of tunnel–structure interaction and the effects of operation parameters on the settlement, the interactions of twin tunnel construction parameters and adjacent structures were not considered simultaneously. In this paper, the interaction between twin tunnels subjected to dynamic loads has been studied using numerical finite element method (FEM) by commercial software PLAXIS 2D. The main purpose of this study was to provide a numerical model which would allow to evaluate the interaction behavior of mechanized twin tunnels. Thus, the structural forces induced in the lining of circular twin tunnels and ground displacement surrounding the two tunnels were evaluated taking into account the soil structure interaction (SSI) and the dynamic performance of the horizontal twin tunnels of Cairo Metro Line No. 4. In addition, a parametric study has been performed under different parameters, which include the tunnels depth (d), the distance between twin tunnels (S), and the surrounding soil stiffness (E). Finally, the above analysis results were discussed at the end of this paper.

Effects of dynamic loading on twin tunnels

Understanding the behavior of underground structures during earthquake events is one of the most interesting challenges in geotechnical engineering. While tunnels are generally enforced better than above ground structures during earthquakes, damage to some of these important structures during
previous earthquake events, that is, the 1995 Kobe, Japan earthquake, the 1999 Chi Chi, Taiwan earthquake, the 1999 Bolu, Turkey earthquake, the 2014 Valparaiso, Chile earthquake, and recently the 2015 Illapel, Chile earthquake, highlights the need to account for seismic loading in the design of underground structures. Earthquake effects on underground structures lead into two groups: (1) ground shaking, and (2) ground failures such as liquefaction, fault displacement, and slope instabilities [23]. Ground shaking implies to the vibration of the ground induced by seismic waves that propagate through the earth’s crust. Figure 1 shows the ground response due to the various types of seismic waves: (i) Body waves travel within the earth’s material (P waves and S waves), (ii) Surface waves travel along the earth’s surface (Rayleigh waves or Love waves, see Figure 1. Owen and Scholl [24] asserted that the behavior of an underground structure during seismic event can be approximated to that of an elastic beam subject to deformations imposed by the surrounding ground.

Three types of deformations express the response of underground structures to seismic motions (see Figure 2):

- Axial compression/extension,
- Longitudinal bending,
- Ovaling/racking.

Axial and curvature deformations in horizontal or near horizontal tunnel occur because of wave propagation parallel or at an angle to the axis of tunnel (Figure 2 a, b). On the other hand, Ovaling or racking deformations are due to wave propagating perpendicular or near perpendicular to the axis of tunnel (Figure 2 c, d) [24].

Figure 1. Ground response to seismic waves [30].
Case study: Greater Cairo Metro Line No. 4

The Greater Cairo Metro Line No. 4 passes under the River Nile in Egypt land. Phase No.1 of line No. 4 will extend from El-Malek El-Saleh station on line No. 1 to Remaya square station. It will meet the route of line No. 2 in Giza station. The study area for Greater Cairo Metro Line No. 4 starts from Station No. 1 (El-Malek El-Saleh) and extends up to Station No. 6 (Madkor Station) as shown in Figure 3 [25–27].

Recently (NAT) [26] suggested twin tunnel system in a part of metro line No.4, as shown in Figure 4 (b). In this study, the analysis of this system as well as single tunnel system, as shown in Figure 4 (a), will be presented. The proposed cross section by the contractor for twin tunnels shows that the outside diameter is 6.40 m and lining segment thickness 0.30 m. Also, cross section of single tunnels shows that the outside diameter of the tunnel is 9.10 m and lining segment thickness is 0.50 m. Therefore, the two proposed systems along with the geological cross sections and different configuration of tunnels are shown in Figures 4 and 5 [25].

Single tunnel system: For the proposed system, single tunnel starts from station No.1 to station No.5. In this paper, the numerical analysis of single
Tunnel will be between station No.3 and station No.4 (Section No.1), as shown in Figures 4 and 5.

Twin tunnel system: Horizontally aligned twin tunnels are widely used for tunnel configuration in urban metro projects. But, vertical aligned twin tunnels are used between station No.3 and station No.4 because there is a narrow street between these two stations. For that, diagonally aligned twin tunnels are used to connect the vertical and horizontal alignment, as shown in Figure 4.

Figure 3. General layout of Greater Cairo Metro Line No. 4 (phase no.1) [26].

Figure 4. Geological cross sections and different configuration of tunnels [26].
The numerical analysis of twin tunnels in this research will include only the horizontal alignment between station No.5 and station No.6 (Section No 4). Geometrical configurations for the case study are mentioned above and clearly demonstrated in section No 4 of Figure 4.

**Numerical modeling**

In this study, Finite Element Analysis was conducted using PLAXIS [35] Finite Element program. In PLAXIS program, a 2-D plane strain model were used for soil modeling and 2-D beam elements for tunnel lining modeling. To simulate
the soil behavior, 15-node triangular element was used. Standard earthquake boundaries have a convenient default setting to generate standard boundary conditions for earthquake loading. These boundaries consist of a combination of absorbent boundaries and prescribed displacements, velocities or accelerations. The vertical boundaries were taken relatively far away from the tunnel. It is constituted by a rectangular domain 120 m wide and 55 m high, in order to place far enough the lateral boundaries as shown in Figure 6.

The Mohr-Coulomb constitutive model was used for the soil. The wave velocities Vp and Vs have been calculated related to the stiffness parameters E and n. The material damping (Rayleigh) in the soil is generally caused by its viscous properties, friction and the development of plasticity. The Rayleigh damping term is assumed to be proportional to the mass and stiffness of the soil material. The Rayleigh parameters $\alpha$ and $\beta$ were assumed 0.01 and 0.01, respectively. The damping coefficient C is assumed to be proportional to the soil mass M and stiffness K by means two coefficients $\alpha$ and $\beta$. The damping coefficient C is obtained by next matrix equation.

$$C = \alpha M + \beta K(1.0)$$

The time integration scheme (Newmark) parameters were setting for the iterative procedures to determine the numeric time integration according to the implicit Newmark scheme. The dynamic model analysis uses a different time parameter than other types of models. These times are time stepping, time interval, and realized end time.

In numerical computation, the earthquake loading was often imposed as an acceleration time history at the base of the model. Load multiplier from data file of the 1992 Dahsour Earthquake was considered for 2D analysis using PLAXIS [28].

The time integration scheme (Newmark) adapted in the analysis are constant and assumed as $\alpha = 0.3025$ and $\beta = 0.60$. The wave absorption coefficients were used with constant values, where $C1 = 1$ for dissipation in the direction normal to the boundary and $C2 = 0.25$ in the tangential direction. The soil Rayleigh damping parameters $\alpha$ and $\beta$ were assumed with constant value 0.01 and 0.01, respectively. The time interval for the duration of the earthquake loading was 40 s, and the time increment was chosen 1 s.

**Material parameters**

The geological formations along the bored tunnel are typical Cairo Nile Alluvial Deposits as shown in Figure 4, section No. (4) and five main units are recognized as follows: Fill, Top Clay, Dense Sand, Very Dense Sand and Bottom Clay.
Geotechnical parameters are based on the geotechnical investigation report [25]. The soil parameters are given in Table 1. The water table was at the ground surface.

The tunnel lining is from concrete and the properties of concrete segment are shown in Table 2.

**The characteristics of dynamic load**

On October 12, 1992, a significant earthquake (Mb = 5.8) had occurred southwest of Cairo near the Dahsour region, about 25 km SW of downtown Cairo, at the coordinates 29.77°N, 31.07°E, the focal depth of this event was 23 km. This event is the largest instrumentally recorded earthquake near Cairo in a heavily populated area. It was the first disastrous event to have occurred in this region since the 1847 event, after a lapse of 145 years [29].

The synthetic ground motion generated by the author has been used as earthquake acceleration file at bedrock level. The author generated the synthetic ground motion using SMSIM-program for simulating ground motions, seismological model by Boore [30]. The strong motion data simulated the 1992 Dahsour earthquake with (Mb = 5.8). Figure 7 shows the synthetic time histories of the 1992 Dahsour Earthquake at bedrock level.

In numerical computation, the earthquake loading was often imposed as an acceleration time history at the base of the model. Seismic action was considered for 2D analysis using PLAXIS, load multiplier from data file (Dahsour 1992) was scaled to 0.3 g, which represents an acceleration of moderate earthquake motion of the parametric study in this paper. The magnification of propagated wave was not considered in this study.

**Analysis of output results**

The purpose of this study is to evaluate the behavior of horizontal twin tunnels under static and earthquake dynamic loads. This study can set new guidelines for the design phase of an underground structure for the further parametric study. The evaluation is done by modal analysis, with a numerical model of the tunnel, based on the finite element method. Parameters to be analyzed: – the straining actions of the twin tunnel lining under static and dynamic loads also the max displacement of the twin tunnels for acceleration = 0.3 g.

The results of the analysis of the models show a significant increase in the internal forces that act on the lining. Furthermore, the deformations in the segmental lining increase with the effect of the dynamic loads. Table 3 shows a parametric study using Dahsour earthquake time history scaling at 0.3 g to indicate and comparatively results the effect of the seismic excitation on the
stability and safety of the TBM tunneling for the increase in the internal forces in lining and its deformations. First row presents a construction simulation that the left tunnel was first constructed, second row presents the effect of the static loads after the construction of the right tunnel. Third row presents the dynamic effect on both tunnels. It can be noted that, the earthquake excitation has large effect on the time history of shearing forces and bending moments. The results of the dynamic load for the internal forces and deformation may be observed in Figure 8.

**Parametric study analysis under earthquake dynamic load**

Four parameters were studied in these analyses of Cairo Metro Twin Tunnels under earthquake dynamic load using the time history of Dahsour earthquake 1992 scaling to 0.3 g, which represents the study of moderate earthquake effect of different parameters and under moderate earthquake dynamic load. These parameters include the following:

**The Clear Distance between Twin Tunnel (S):** At 1D horizontal distance, 2D, 3D, and 4D where D is the diameter of single tunnel.

**Twin Tunnel Crown Depth (d):** At 2D, 3D, 4D, and 5D where D is the diameter of single tunnel.

**The Surrounding Soil Stiffness (E):** Where it is represented for two different types of surrounding soil with different stiffness the Clay increasing gradually from top clay to bottom clay (E1, E2 and E3) and the Sand increasing gradually from dense sand to very dense sand (E1, E2, and E3).

**The distance between twin tunnel (S)**

In this section, the effect of the clear spacing between twin tunnels on the displacements and the straining actions due to static and dynamic load was investigated. Figure 9 (a-d) shows the effect of spacing between tunnels on the extreme values of static and additional values from seismic load (0.3 g) of displacements, axial loads, shear force, and bending moments.

From this figure, we can deduce that increasing the spacing S between tunnels decreased the value of static displacements by 8% from S = 1D to 3D then stay almost constant till 4D. Shear forces and bending moments values decreased by around 5% from 1D to 4D. The axial forces remain

The axial forces remain almost unchanged or additional dynamic values, it was noticed that the shear forces will increase from 150% of its static value for S = 1D to 70% for S = 4D with the same pattern of decreasing with spacing. While bending moment values increased 120% of its static value for S = 1D; then, this rate is reduced with S till attending an increase of 30% of static value for S = 4D.
From this figure, we can conclude that the recommended spacing between horizontal twin tunnels should be more than about 2.5D to decrease the effect of interaction between tunnels for the reduction of the additional straining actions due to static and seismic loads.

**Twin tunnel depth (d)**
Next, the static and additional dynamic effect of the depth of the crown of tunnels on the straining actions of tunnels lining was studied, changing the depth (d) from 2D to 5D where D is the tunnel diameter in meters. From Figure 10 (a-d), we can deduce that: Max deflection of tunnels increased slightly by 5% with the depth increase but the values for dynamic force were about 30 times the static values for 0.3 g earthquake.

Axial forces increased linearly with the depth to double the values from 2D depth till 5D depth for static loads, the effect of dynamic loads is barely noticeable.

Shear forces decreased with depth for static and dynamic loads, but the increased values for seismic force (0.3 g) was about 180% for 2D depth then reduced to 58% to 5D depth.

Finally, for bending moments, values for static loads oscillated with depth to increase to the double the value from 2D depth to 5D depth. The increase in bending moments for seismic loads varied from 180% for 2D depth to 25% for 5D depth.

From Figure 10, we can conclude that the rate of increase in shear force and bending moment for dynamic loads is decreased noticeably after about 3.5D depth.

**The surrounding soil stiffness (E)**
In this section, the effect of surrounding soil stiffness on the displacements and straining actions of twin tunnel due to static and seismic load(0.3 g).

*The surrounding soil stiffness (E), soil type is clay.* From Figure 11 (a-d), we can deduce that increasing the stiffness of surrounding clay from (E) from 10 to 30 MPa decreased the straining actions on the twin tunnel for static load. But the additional values from seismic load (0.3 g) increased with the increase of clay stiffness. The additional values of displacements for the dynamic loads varied from 20 to 600% while the axial loads remained unchanged. The additional shear and bending moments due to dynamic loads varied from 4% to 9%.

*The surrounding soil stiffness (E), soil type is sand.* From Figure 12 (a-d), we can deduce that increasing the stiffness of surrounding sand (E) from 50 to 100 MPa decreased the straining actions on the twin tunnel for static load. But the additional values from seismic load (0.3 g) increased with the
increase in sand stiffness. The additional values of displacements for the dynamic loads was 230% while the axial loads remained unchanged. The additional shear and bending moments due to dynamic loads varied from 10% to 35%.

We can deduce that increasing soil stiffness has good effect in reducing straining actions for twin tunnels subjected to static loading but increased slightly straining actions for twin tunnels subjected to dynamic loads for the scope of tunnels and soils studied in this research.

**Conclusion**

In this study, the behavior of horizontal twin tunnels under static and earthquake dynamic loads was evaluated to set new guidelines for the design phase of underground structures for the studied parameters. The evaluation is done by modal analysis based on the finite element method using PLAXIS software. According to the case studied, the following conclusions can be drawn:

1. The excavation sequence has an important effect on the straining actions of horizontal twin tunnels, the second tunnel has increased values for shear forces and bending moments.
2. The clear distance between horizontal twin tunnels is recommended to be more than about 2.5D to neglect the effect of interaction between tunnels and to reduce the additional straining actions due to static and seismic loads. From the studied case, we can notice that the rate of

| Table 1. Geotechnical soil parameters [25]. |
|------------------------------------------|
| Unit Weight g (kN/m³) | Young Modulus E (MPa) | Poisson Ratio N | Fition Angle r₀ | Cohesion Cu (kPa) |
| Fill                      | 18                         | 10          | 0.35  | 27            | 0             |
| Dense Sand                | 20                         | 75          | 0.29  | 36            | 0             |
| Very Dense Sand           | 20                         | 100         | 0.28  | 38            | 0             |
| Top Clay                  | 19                         | 8.5         | 0.40  | 20            | 8.5           |
| Bottom Clay               | 19                         | 30          | 0.40  | 20            | 20            |

| Table 2. Properties of concrete segment [25]. |
|---------------------------------------------|
| Property                                | Value                   |
| Design Standard Strength (MPa)            | Fcu = 50                |
| Modulus of Elasticity, Ec(MPa)            | 31,500                  |
| Poisson Ratio (n)                        | 0.20                    |
| Unit Weight of Concrete (kN/m³)           | 25                      |
The increase of displacements and internal forces is reduced considerably when the clear distance between twin tunnels reaches 2.5D.

(3) For practical reasons, the clear distance between horizontal twin tunnels could be less than the recommended value of 2.5D, but the effect of interaction of tunnels should be taken into consideration. Increasing the distance between tunnels from 1D to 4D decreases the static responses up to 8% and the dynamic response up to 70%.

(4) The values of tunnels displacements for static and dynamic loads and axial forces for static loads, increase considerably with the increase of tunnels depth but the rate of increase is halted noticeably after about 3.5D depth. On the other hand, we can conclude that the rate of increase of shear force and bending moments for dynamic loads is decreased noticeably after about 3.5D.

(5) Increasing the depth of the crown of tunnels from 2D to 5D increased the maximum deflection of tunnels by 5% and decreased the straining actions for static loads. While the rate of decrease for dynamic loads in shear and bending was 50% and 40%, respectively.

(6) For the scope of tunnels and soils studied in this research, we can deduce that increasing soil stiffness has good effect in reducing displacements and internal forces for twin tunnels subjected to static loading. But, for dynamic loads, displacements rapidly increase and internal forces increase slightly with growing value of soil stiffness.

It is recommended for future studies to use 3D analysis and to use extensive parametric studies to cover all aspects concerning twin tunnels. Also, it is advisable to include the effect of pore water pressure into the effect of ground water level on tunnels.

**Table 3.** Lining stress and total displacement for the left and right Tunnel of Cairo Metro Line No. 4 Twin Tunnels.

| Dahshour Earthquake Time History Scaling | Left Tunnel | Right Tunnel |
|------------------------------------------|-------------|--------------|
|                                          | Total disp (m) | Axial Force (KN/m) | Shear Force (KN/m) | Bending (KN/ m) | Total disp (m) | Axial Force (KN/m) | Shear Force (KN/m) | Bending (KN/ m) |
| Static Excavate                        | 0.0030       | −1210        | 30.55         | −48.69          | 0              | 0              | 0              | 0              |
| Left Tunnel                             | 0            | −1210        | 30.55         | −48.69          | 0              | 0              | 0              | 0              |
| Static Excavate Right Tunnel            | 0.0047       | −1210        | 29.39         | −46.53          | 0.0047         | −1210         | −29.95         | −47.55         |
| Static Excavate Left Tunnel             | 0.1522       | −1190        | −43.21        | 56.69           | 0.1512         | −1180         | 64.56          | 77.77          |
| Static Excavate Right Tunnel            | 0.0047       | −1210        | 29.39         | −46.53          | 0.0047         | −1210         | −29.95         | −47.55         |
| Static Excavate Left Tunnel             | 0.1522       | −1190        | −43.21        | 56.69           | 0.1512         | −1180         | 64.56          | 77.77          |
| Static Excavate Right Tunnel            | 0.3 g        | −1190        | −43.21        | 56.69           | 0.1512         | −1180         | 64.56          | 77.77          |

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Figure 7. The synthetic time histories of the 1992 Dahsour Earthquake at bedrock level.
Figure 8. Dynamic total displacement and straining action of left and right Tunnel of Metro Twin Tunnel Line No. 4 at 0.3 g.
Figure 9. Effect of spacing $S$ on the straining actions of twin tunnels.
Figure 10. Effect of Twin Tunnel Crown Depth $d$ on the straining actions of twin tunnels.
Figure 11. Effect of the surrounding soil stiffness (E) (MPa), Type of Soil Clay on the straining actions of twin tunnels.
Figure 12. Effect of the surrounding soil stiffness (E) (MPa), Type of Soil Sand on the straining actions of twin tunnels.
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