Seismic Analysis of Urban Tunnel Systems for the Greater Cairo Metro Line No.4

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ABSTRACT
The objective of the study is to investigate the influence of seismic analysis of tunnel systems (single and twin tunnels). The seismic analysis is significant for tunnel projects in urban cities to avoid the collapse of tunnels in this crowded city due to displacements generated as a result of earthquake waves. A case study is The Greater Cairo metro line No.4, Phase No.1. To evaluate the influence of seismic waves on single and twin tunnels, four cases were simulated, the first case of a single tunnel and three cases of twin tunnels. For more serious understanding of the issue of seismic waves on twin tunnels, the horizontal, vertical and diagonal alignment are analyzed. Total displacement was presented for tunnel systems. Moreover, induced internal forces in tunnel lining have been computed. The paper presents a two-dimensional model using numerical simulations by PLAXIS program. Based on the calculated result, a higher displacement occurs in tunnel lining during the earthquake. The maximum change of internal forces during an earthquake occurs in shear force, then bending moment. Moreover, the normal force of tunnel lining is less affected by seismic actions.

KEYWORDS: Seismic analysis, Tunnel systems, internal forces, numerical analysis, displacement

INTRODUCTION

The reason for construction of tunnels in crowded cities is to limit traffic congestion in the streets. Therefore, we must take care when designing such facilities, this is because its collapse caused many problems which affected the surrounding buildings and alarm the population in these cities. Seismic waves are one of the main reasons for the collapse of tunnels, although tunnels less effective against earthquakes compared to above-ground structures. Damage of tunnels as a result of seismic loads Because of many reasons, including strong ground shaking and difficulty earthquakes analysis for the designer who makes it neglects loads of earthquakes in the design.

Mohammad and Akbar (2005) studied the interaction between the ground and tunnel lining during earthquake excitation and found that Effect of earthquake on tunnel–ground interaction depend on various parameters including peak acceleration, intensity and duration of earthquake and the relative rigidity between tunnel and ground. Increasing structural dimensions of lining in static design cannot always be a reliable method against earthquake loading, because this would increase
the rigidity of lining and therefore, would increase the effect of earthquake loading. (Ulas and Gopal, 2010) discussed a model study on the effects of input motion on the seismic behaviour of tunnels, they found that the magnitude of the maximum input acceleration plays a crucial role on the maximum and residual lining forces, which the tunnel experiences. (Sahoo and Kumar, 2014) concluded that an increase in the magnitude of the earthquake acceleration leads to a significant increment in the magnitude of internal compressive pressure. (Liu and Song, 2005) found that the increase in buried depth improved the safety of the underground structure against earthquake damage. (Asheghabadi and Matinmanesh, 2011) used finite element seismic analysis and found that existence of tunnel amplifies the seismic waves on the soil surface and the maximum amplification occurs on the interface of the tunnel and soil. (Park et al., 2009) simulated tunnel response under spatially varying ground motion, they found that the spatially variable ground motion causes longitudinal bending of the tunnel and can induce substantial axial stress on the tunnel lining. The effect can be significant at boundaries at which the properties of the ground change in the longitudinal direction. (Cheng et al., 2014) studied the seismic response of fluid–structure interaction of undersea tunnel during bidirectional earthquake and concluded that the vertical displacement of the lining structure is greater than its horizontal displacement. (Manofis et al., 1995) concluded that the seismically induced stress state in a buried pipeline is more pronounced in the case of transverse vibrations than in the case of longitudinal vibrations.

Shahrour et al. (2010) analyzed elastoplastic analysis of the seismic response of tunnels in soft soils and concluded that the plastic deformations induce an important reduction in the seismic-induced bending moment in the tunnel, while the soil dilatancy moderately affects the bending moment in the liner. (Azadi and Hosseini, 2010) presented an analyses of the effect of seismic behaviour of shallow tunnels in liquefiable grounds and found that reduction of the frequency from 3 Hz to 1 Hz caused the axial force, shear force, and bending moment of the tunnel lining to increase 19%, 115% and 131%, respectively. Also, they concluded that reduction of the loading frequency causes the pore pressure to increase in the area below the tunnel and since the loading amplitude decreases 50%, the bending moment reduces to 12.7%. In this regard, when the loading amplitude increases 2.5 times, the maximum bending moment becomes 1.28 times more than that in the reference model.

Shong-loong and Meen-wah (2011) concluded that the deeper the location of the tunnel, the less the tunnel lining is affected by the effect of earthquake. (Hatzigeorgiou and Beskos, 2010) concluded that the damage in the liner increases with decreasing rock strength and liner thickness. (Sahoo and Kumar, 2012) examined seismic stability of a long unsupported circular tunnel and found that the failure zones around the periphery of the tunnel becomes always asymmetrical with an inclusion of horizontal seismic body forces. (Gomes, 2013) investigated the effect of stress disturbance induced by construction on the seismic response of shallow bored tunnels, he concluded that stress disturbance due to tunnel construction may significantly increase lining forces induced by earthquake loading. (Azadi, 2013) studied the seismic behaviour of urban tunnels in soft saturated soils, he concluded that the bending moment induced in the tunnel lining increases and then decreases about 33% during cyclic loading. (Hosseini et al., 2010) concluded that increasing the stiffness of the support system can increase the effect of the seismic loads. (Abdel-Motaal et al., 2013) presented mutual seismic interaction between tunnels and the surrounding granular soil and concluded that the maximum exerted straining actions in tunnel lining are directly proportional to the relative stiffness between tunnel and surrounding soil (lining thickness and soil shear modulus). Moreover, it is highly affected by the peak ground acceleration and the tunnel location (embedment depth).
BACKGROUND

Study area

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 extend up to Station No. 6 (Madkor Station) (Fig. 1).

Figure 1: General Layout of Greater Cairo Metro Line No. 4 (Phase No.1)
Source: JICA. Project document (2010)

<table>
<thead>
<tr>
<th>Soil layers</th>
<th>Fill</th>
<th>Dense Sand</th>
<th>Very dense Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>18 (Bulk)</td>
<td>20.00</td>
<td>20.00</td>
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<tr>
<td>Saturated unit weight, $\gamma_{sat}$ (kN/m$^3$)</td>
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<td></td>
<td></td>
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<tr>
<td>Angle of internal friction $\phi$</td>
<td>$27^\circ$</td>
<td>$36^\circ$</td>
<td>$38^\circ$</td>
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<tr>
<td>Young’s modulus, $E$ (MPa)</td>
<td>10</td>
<td>75</td>
<td>100</td>
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<tr>
<td>Poisson ratio ($\mu$)</td>
<td>0.35</td>
<td>0.29</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Source: JICA Preparatory study (2012)
PROBLEM DEFINITION AND DOMAIN

Recently (NAT) suggested twin tunnel system for metro line No.4, as shown in Fig. 2 (b). In this study, the analysis of this system with another system proposed by the authors which is a single tunnel system, as shown in Fig. 2(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 show that the outside diameter of the tunnel is 9.10 m and lining segment thickness is 0.50 m. Therefore the studied problem consists of two proposed systems (single and twin tunnels) as shown in Fig. 2(a) and Fig.2 (b).

### Single tunnel system

For 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 Fig.2 (a).

### Twin tunnel system

Horizontally aligned twin tunnels are a 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 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 Fig.2 (b). The numerical analysis of twin tunnels will be for vertical alignment between station No.3 and station No.4 (Section No.2), diagonal alignment between station No.4 and station No.5 (Section No.3) and horizontal alignment between station No.5 and station No.6 (Section No.3), as shown in Fig.2 (b).

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**Table 2:** Soil parameters for clay layer

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Top clay</th>
<th>Bottom clay</th>
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<tr>
<td>Saturated unit weight, ( \gamma_{sat} ) (kN/m(^3))</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Undrained shear strength ( C_u ) (kN/m(^2))</td>
<td>8.50</td>
<td>20.00</td>
</tr>
<tr>
<td>Undrained Young’s modulus, ( E ) (MPa)</td>
<td>8.50</td>
<td>30.0</td>
</tr>
<tr>
<td>Angle of internal friction ( \varnothing )</td>
<td>20(^\circ)</td>
<td>20(^\circ)</td>
</tr>
<tr>
<td>Poisson’s ratio (( \mu ))</td>
<td>0.40</td>
<td>0.40</td>
</tr>
</tbody>
</table>

*Source: JICA Preparatory study (2012)*

**Table 3:** Properties of concrete segment

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Standard Strength (MPa)</td>
<td>( f_{cu}=50 )</td>
</tr>
<tr>
<td>Modulus of elasticity, ( E_C ) (MPa)</td>
<td>31500</td>
</tr>
<tr>
<td>Poisson ratio (( \mu ))</td>
<td>0.20</td>
</tr>
<tr>
<td>Unit weight of concrete/(kN·m(^{-3}))</td>
<td>25.0</td>
</tr>
</tbody>
</table>
Figure 2 (a): Proposed single tunnel system

Figure 2 (b): Proposed twin tunnel system

Figure 3: Geological cross sections and different configuration of tunnels.
NUMERICAL ANALYSIS PROCEDURE

In this study, Finite Element Analysis was conducted using PLAXIS 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. The finite element model is plotted in Fig. 4. It is constituted by a rectangular domain 120m wide and 55 m high, in order to place far enough the lateral boundaries.

![Finite element model](image)

**Figure 4:** Boundary conditions of bottom, surface and vertical boundaries of a two-dimensional model

**Choice of input acceleration time history**

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 (earthquake 28/2/1990). The duration of the dynamic analyses was truncated as 10 sec. Fig.5, shows the graphical acceleration time-history that was applied in the analysis as an input data file from the PLAXIS library.
RESULTS AND COMPARISONS

To evaluate the influence of seismic waves on single and twin tunnels, four cases were simulated, the first case of a single tunnel and three cases of twin tunnels. For more serious understanding of the issue of seismic waves on twin tunnels, the horizontal, vertical and diagonal alignments are analyzed. The recording points are tunnel invert and crown, and the left and right edges (points) of the tunnel.

Effect of seismic waves on single tunnel

Using the finite element code PLAXIS with our data file (earthquake 28/2/1990), total displacement, shear force, the normal force and bending moment are obtained, in order to investigate the single tunnel failure during the seismic activity, as shown in Fig.6 - Fig.9.

Fig. 6. Indicates the time history of total displacement registered at the invert, crown, left and right points of single tunnel. It can be seen that the total displacement change randomly during seismic wave. Moreover, total displacement up to 62% of maximum displacement at the first third of the earthquake duration, then stops suddenly and then up to the maximum displacement at the mid-time of the earthquake action. In addition to, Change the displacement during the earthquake is about 100% with respect to the average value. Fig. 7 Shows the time history of the shear force registered at the maximum shear force points. It observed that, Change the shear force during the earthquake is about 9.0% with respect to the average value. Also, Change the bending moment and normal force during the earthquake is about 4.0% and 1.0% respectively, with respect to the average value, as shown in Fig.8 and Fig.9.
Fig. 6: Time history total displacement for single tunnel.

Fig. 7: Time history shear force for single tunnel.

Fig. 8: Time history of lining bending moment for single tunnel.

Fig. 9: Time history of lining normal force for single tunnel.
Effect of seismic waves on horizontal alignment (twin tunnels)

Fig. 10. Indicates the time history of total displacement registered at the invert, crown, left and right points of horizontal twin tunnels, Change the displacement during the earthquake is about 100% with respect to the average value. Fig.11. Shows the time history of the shear force registered at the maximum shear force points. It observed that, the shear force change randomly during seismic wave. Moreover, shear force up to maximum value at the third time of the earthquake duration. In addition to, Change the shear force during the earthquake is about 17% with respect to the average value. Also, Change the bending moment and normal force during the earthquake is about 8.0% and 4.0% respectively, with respect to the average value, as shown in Fig.12 and Fig.13.

Fig.10: Time history total displacement for twin tunnel.  
Fig.11: Time history shear force for twin tunnel.

Fig.12: Time history of lining bending moment for twin tunnel.
Effect of seismic waves on vertical alignment (twin tunnels)

Fig. 14 and Fig. 15, Indicates the time history of total displacement registered at the invert, crown, left and right points of vertical twin tunnels, Change the displacement during the earthquake is about 100% with respect to the average value. Fig. 16 and Fig. 17, Shows the time history of the shear force registered at the maximum shear force points, Change the shear force of top and bottom tunnel during the earthquake is about 4.0% and 3.0% respectively, with respect to the average value.

Also, the difference in the normal force of top and bottom tunnel during the earthquake is about 0.50% for both tunnels, with respect to the average value, as shown in Fig. 18 and Fig. 19. Moreover, Change the bending moment of top and bottom tunnel during the earthquake is about 1.50% and 1.0% respectively, with respect to the average value, as shown in Fig. 20 and Fig. 21.
Fig. 16: Time history shear force for top tunnel.

Fig. 17: Time history shear force for bottom tunnel.

Fig. 18: Time history of lining normal force for top tunnel.

Fig. 19: Time history of lining normal force for bottom tunnel.

Fig. 20: Time history of lining bending moment for top tunnel.
Effect of seismic waves on diagonal alignment (twin tunnels)

Fig. 22 and Fig. 23 indicate the time history of total displacement registered at the invert, crown, left and right points of diagonal twin tunnels, in order to investigate the diagonal twin tunnels failure during the seismic activity. Change the displacement during the earthquake is about 100% with respect to the average value. Fig. 24 and Fig. 25 show the time history of the shear force registered at the maximum shear force points, change the shear force of top and bottom tunnel during the earthquake is about 10.0% and 4.0% respectively, with respect to the average value. Also, Change the normal force of top and bottom tunnel during the earthquake is about 2.0% and 1.0% respectively, with respect to the average value, as shown in Fig. 26 and Fig. 27. Moreover, Change the bending moment of top and bottom tunnel during the earthquake is about 4.0% and 2.0% respectively, with respect to the average value, as shown in Fig. 28 and Fig. 29.

Fig. 21: Time history of lining bending moment for bottom tunnel.

Fig. 22: Time history total displacement for top tunnel.

Fig. 23: Time history total displacement for bottom tunnel.
**Fig. 24:** Time history shear force for top tunnel.

**Fig. 25:** Time history shear force for bottom tunnel.

**Fig. 26:** Time history of lining normal force for top tunnel.

**Fig. 27:** Time history of lining normal force for top tunnel.

**Fig. 28:** Time history of lining bending moment for top tunnel.
CONCLUSION

2D finite element model is used to simulate the seismic action on tunnel system. Therefore, the total displacement of tunnel lining was obtained. Moreover, the bending moment, shear force and normal force of tunnel lining were computed. Based on the calculated result, it can be seen that:

1) For tunnel systems, higher displacement occurs in tunnel lining during the earthquake, the total displacement change randomly during seismic wave. Moreover, the maximum displacement occurs at the mid-time of the earthquake action and displacement stops suddenly at the third time of earthquake. In addition to, the displacement during the earthquake is about 100% with respect to the average value.

2) For tunnel systems, maximum change in lining internal forces (bending moment, shear force and normal force) occurs at third time of earthquake duration and this the same time that displacement stops suddenly.

3) According to study conditions, horizontal twin tunnels is the most affected by seismic action, then diagonal twin tunnels and single tunnel. In addition to, vertical twin tunnels is less affected by seismic action compared to other systems.

4) According to study conditions and for tunnel systems, the maximum change of internal forces during earthquake occurs in shear force, then bending moment. Moreover, the normal force is less affected by seismic actions.

5) The left and right tunnel of horizontal twin tunnels, were affected by earthquake with the same value.

6) The bottom tunnel of vertical and diagonal twin tunnels, is less affected by earthquake than top tunnel.

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REFERENCES


