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EFFECT OF DAMPING ON THE BEHAVIOR OF TUNNEL LINING UNDER SEISMIC LOADS

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The study of the dynamic behavior of underground structures, such as transportation tunnels, pipe lines, or … etc. to dynamic loads like moving loads, blasting, vibrations, or seismic loads is an engineering problem of dynamic soil-structure interaction. Numerical models for soil-tunnel have been considered as an important design tools for many years. The accuracy of the results obtained depends on the knowledge of the input data for the tunnel and the surrounding soil. One of the most important problems in numerical modeling of dynamic problems related to input data is how you can simulate the effect of damping in soil-tunnel model. So, it is therefore clear that unless some techniques for simulation of damping effect are provided, shortage results would be inevitably produced due to shortage in input data. The aim of this study is that how to simulate the damping effect on the soil-tunnel models to represent the real behavior of the models. This paper studies the effect of damping on the behavior of soil-tunnel models under dynamic loads in time domain by using the FEM. There are many types of damping coefficients are studied in this analysis. It can be concluded that damping should be taken into consideration to represent the real behavior of soil-tunnel models. For application of this study, Cairo Metro Tunnel- Line 2, was chosen.

KEYWORDS: *Tunnels, Finite Element Method, Soil-Structure Interaction, Damping, Seismic loads, Displacements, Stresses.*

1. INTRODUCTION

The existing puplic transport facilities of Greater Cairo (Egypt), coud no longer cope adecuately with the demand generated by enormous growth and population expansion. It was therefore decided that an underground metro network should be constructed along the major routes of transportation, running on the surface in suburbs, and through tunnels in the urban core of Cairo. The proposed system consists of three lines, as shown in **Fig. 1.** For application of this study, Cairo Metro Tunnel- Line 2, was chosen. It is the first urban line connecting Shubra El-Khiema railway station on the east bank of the river Nile at north, with Giza railway station on the west bank of the river Nile. This line is 18.3 Km long. It is planned that the line is executed using a full-face shield Tunnel Boring Machine, TBM, except for some portions, where the cut-and-cover method is more applicable, Mansour [1]. The study of the dynamic behavior

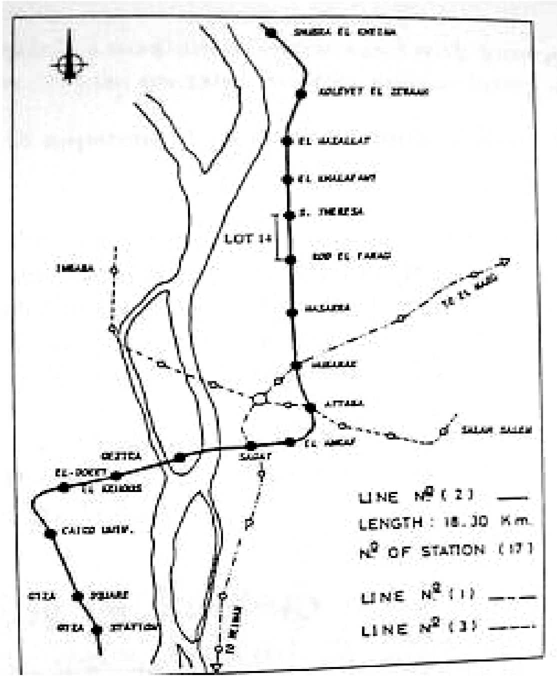


Figure 1: Layout of Cairo metro project, (after Mansour, [1])

of underground structures such as transportation tunnels under earthquake loads is an engineering problem of dynamic soil-structure interaction and has been of considerable interest to geotechnical engineers. Even through in engineering practice tunnel design often considers only static or quasi-static (e.g. creep) loading conditions. A non-negligible research effort has been devoted to investigate their behavior in dynamic conditions. Dynamic analysis and design of tunnels for earthquake loading requires the proper evaluation of the forces which may act upon them; Constantopoulos *et al.* [2]. He mentioned that the strains in flexible tunnels are considered to be equal to the strains in the surrounding soil and the tunnel stresses are computed by combining the appropriate tunnel section properties with the corresponding strains. The designing of the tunnel lining is usually done with the help of a 2D numerical analysis using finite element of finite different method which is able to more efficiently simulate the modeling of the excavation steps. The structure is divided into two parts, tunnel lining, called concrete tunnel lining, and the surrounding soil. Since the concrete lining is not an independent structure, the choice of the finite element model for concrete was mainly limited by two factors; the first being that the elements should be able to combine with the 2D plane strain elements used for soil, and the second that the used finite element mesh must not be very fine in order to prevent the calculating time from being too large. Because of these constrains, different types of approximations were used in the existing models. The concrete lining was modeled using a normal plane strain element similar to that used for the surrounding soil but with a concrete modulus of elasticity; Parreira *et al.* [3]. Other models used a two-nodded element; Aydan *et al.* [4], while still others used a beam element; Adachi [5]. These models for a concrete lining are not accurate since they take into consideration only the axial and shear forces.

The BEAM 6 element provides an acceptable solution for the finite element modeling problem, as it considers all possible deformations of the lining. The advantages of this element are that it can describe the real behavior of the lining as an arched frame, it can combine with 2D finite elements used for soil, and the number of elements required to model the lining with an acceptable accuracy is very small. Many investigations have used BEAM 6 elements for lining; as mentioned by Sezaki *et al.* [6], Swoboda *et al.* [7], and Moussa [8]. The accuracy of the dynamic analysis greatly depends on the size of the elements, the grading ratio, time step and the frequency of the applied dynamic load. Discretization dispersion occurs when the finite element model does not accurately represent the dynamic response of the continuum. Also, excitation frequency components above the fundamental frequency of the model cause spurious oscillations about the analytical solution; Ta *et al.* [9]. One of the problems in numerical modeling of dynamic soil-tunnel interaction which is related to input data is how you can simulate the effect of damping in soil-tunnel model. So, it is therefore clear that unless some techniques for simulation of damping effect are provided, shortage results would be inevitably produced due to shortage in input data.

The aim of this study is that can simulate the damping effect on the soil-tunnel models to represent the real behavior of the models. This paper studies the effect of damping on the behavior of soil-tunnel models under dynamic loads in time domain by using the Finite Element Method. There are many types of damping coefficients are studies in this analysis such as mass and or stiffness-proportional damping and Rayleigh damping. Another important thing in the dynamic analysis is the initial stress field. Oreste [10] studied the importance of initial stress effects on the static conditions of the final lining of a tunnel.

2. MODELING OF TUNNEL LINING

The tunnel lining was modeled with a 2D BEAM 6 element which has six nodes, each having two degrees of freedom. The element nodes are arranged to form three pairs, each pair having two nodes connected by a rigid truss element, as shown in **Fig. 2**. The stiffness matrix of a BEAM 6 element was developed by Swoboda [11]. Also, the mass matrix of a BEAM 6 element, lumped or consistent, was introduced by Swoboda *et al.* [12].

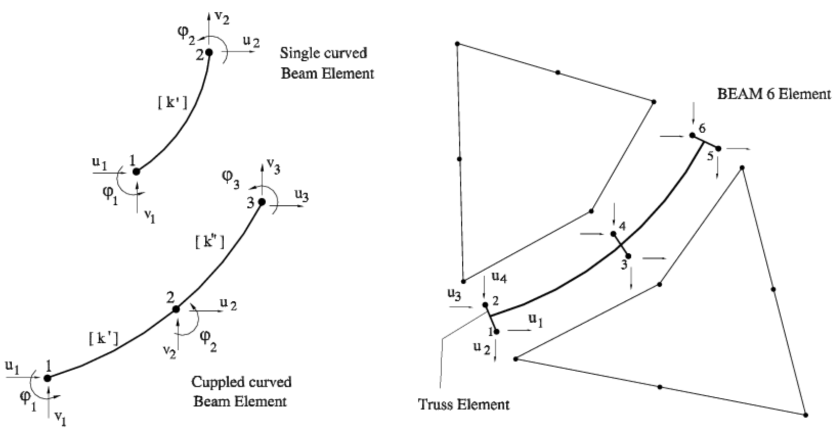


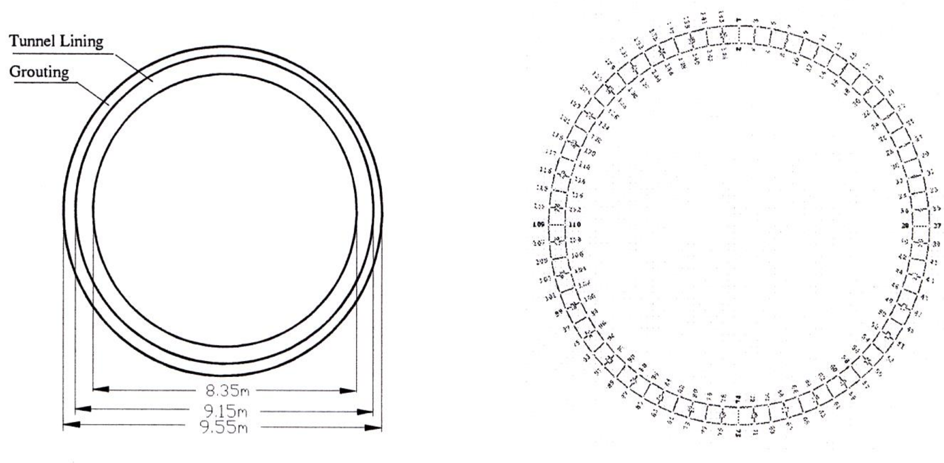
Figure 2: Combined action between BEAM 6 and LST elements (after Swoboda [11])

3. CAIRO METRO TUNNEL

Tunnel line-2 of Cairo Metro, Egypt, at Km 4.234, was chosen for application of a 2D model of soil-tunnel interaction. It is focused on the first phase of line 2 which include a 7 kilometer shield driven tunnel, going from Khalafawy station to Sadat station, and executed by using a full face TBM applying slurry method, to support the tunnel face during excavation.

4. STATIC AND DYNAMIC ANALYSIS MODEL

A finite element model for soil and tunnel lining for soil-tunnel interaction model was built. The model has a length of 59.0 m and a height of 43.0 m including a tunnel. The soil and grouting were modeled with 2D elements, called an LST element, (Linearly Varying Strain Triangular Element), whereas, the tunnel lining was modeled with 2D BEAM 6 elements. Calculations are carried out on the assumption that the tunnel lining is perfectly bonded to the surrounding soil. On the contrary, the disadvantage is the assumption of a rigid base for the stratum. Nevertheless, this is not a serious restriction because it is always possible to choose a depth that large enough to simulate the presence of an underlying half-space. In effect, a rigid basement is fully reflective, i.e., no energy can be transmitted into the bedrock via the refraction of the outgoing waves from the overlaying stratum, Aviles *et al.* [13]. The cross section of the tunnel opening is a circle has 8.35 m inner diameter, 9.15 m outer diameter, and 0.40 m lining thickness as shown in **Fig. 3**. This study was performed using the finite element method. Analysis of displacement, internal forces and stresses in tunnel lining and around the tunnel was carried out using a 2-D plain strain finite element taking into consideration the linear elastic behavior of the lining and the ground material as mentioned by Hasan, *et al.* [14].



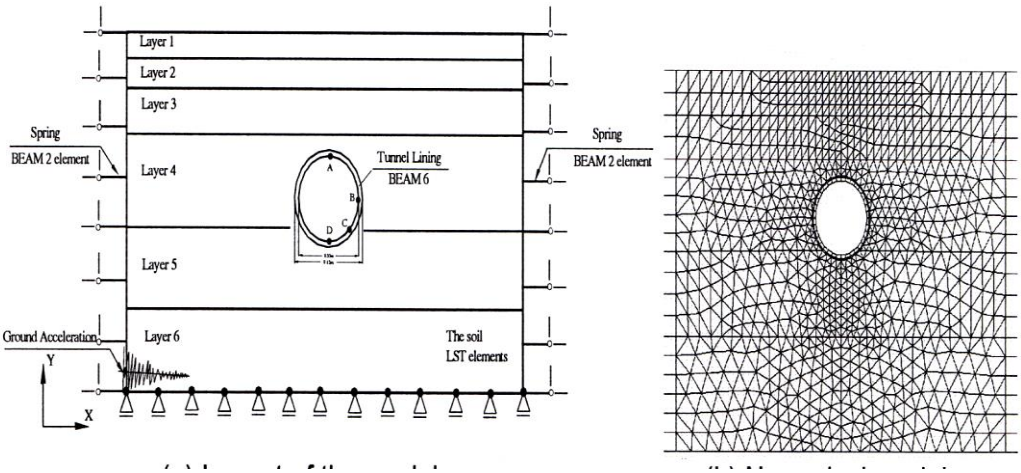
(a) Cross-section (b) Element and joint numbering

Figure 3: Cairo metro tunnel, line 2.

The results of static analysis and dynamic analysis will be shown in this study. The material constants such as modulus of elasticity (E), Poisson's ratio (v), density (γ), angle of internal friction (ϕ), cohesion (C)□and compressive strength (F_c) for different elements of the model are shown in **Table 1**. The layout of the model used in static and dynamic analysis is shown in **Fig. 4-a**. This model includes springs on both sides as lateral boundary conditions. The finite element mesh is shown in **Fig. 4-b**. The cross-sectional area for springs was taken 0.30 m^2 and has a length of 2.0 m in each side.

Table 1. Material constants of the model.

Material constant	Soil Layer 1	Soil Layer 2	Soil Layer 3	Soil Layer 4	Soil Layer 5	Soil Layer 6	Conc. Lining	Gro-uting	Spri-ngs
E (KN/m^2)	6.0E6	9.0E6	36.0E6	80.0E6	95.0E6	16.0E7	33.5E9	1.1E9	8.0E6
v	0.40	0.40	0.35	0.30	0.30	0.30	0.18	0.29	0.35
γ (KN/m^3)	18.0	18.5	19.0	20.0	20.0	20.0	25.0	22.0	19.5
ϕ	20.0	20.0	30.0	35.0	35.0	37.0	-	00.0	35.0
C(KN/m^2)	50.0	00.0	00.0	00.0	00.0	00.0	-	00.0	00.0
F_c (Mpa)	-	-	-	-	-	-	100.0	-	-

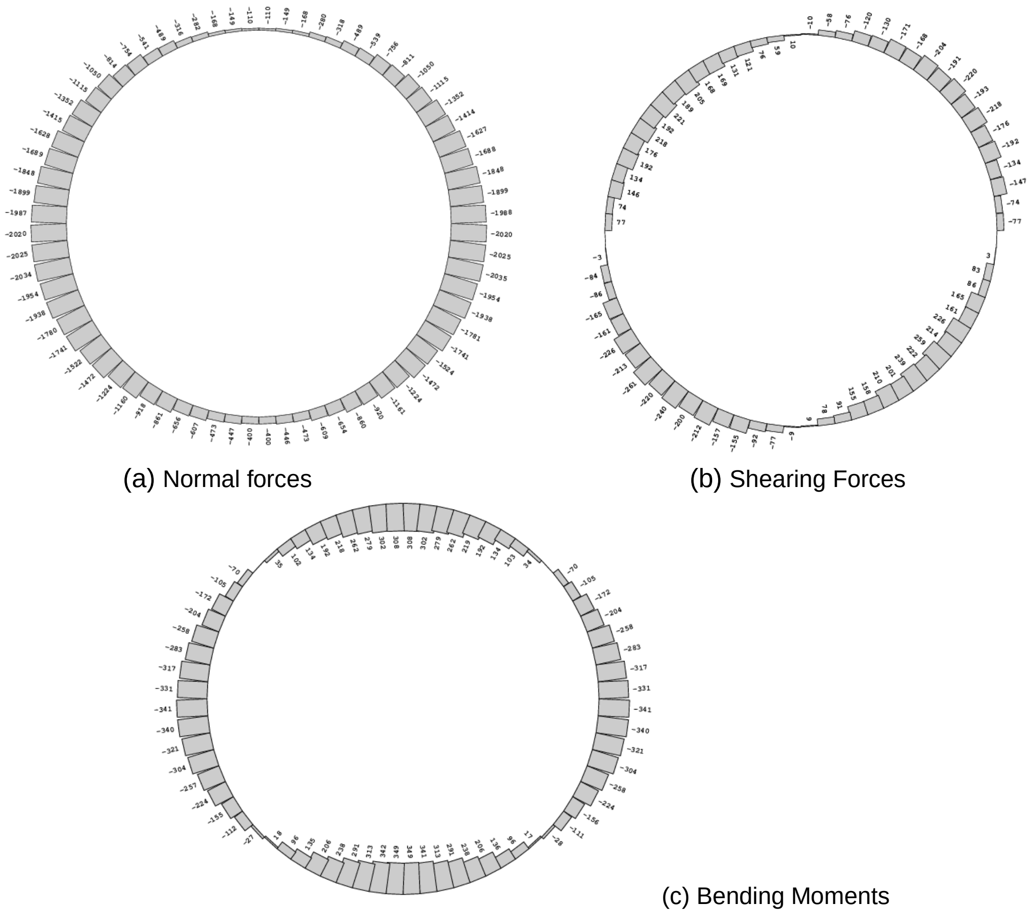


(a) Layout of the model (b) Numerical model

Figure 4: Static and dynamic analysis model

5. RESULTS OF STATIC ANALYSIS

In this analysis, finite element method was used to simulate soil-tunnel interaction model. The proposed 2D numerical model used in static analysis after excavation is shown in **Fig. 4**. A technique of dead weight method has been used in this analysis. The static solution was performed in plane strain analysis. The distribution of normal forces, shearing forces and bending moments in tunnel lining is shown in **Fig. 5-a,b,c**, respectively.



(a) Normal forces (b) Shearing Forces

(c) Bending Moments

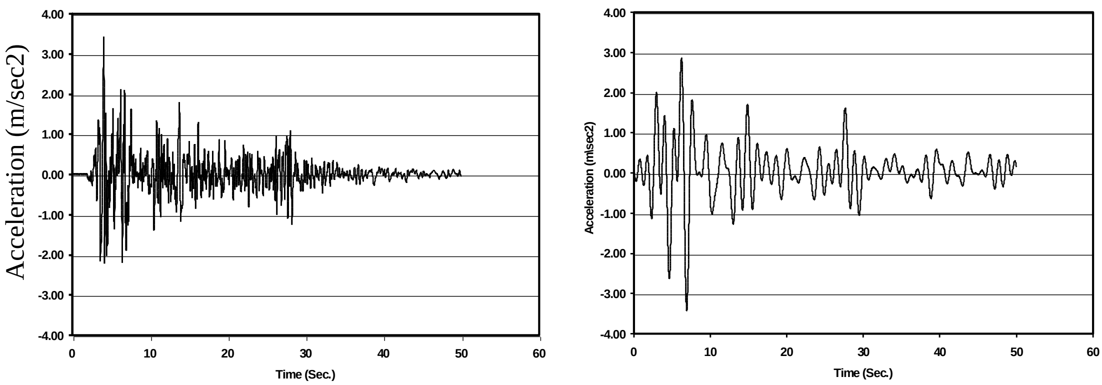
Figure 5: Internal forces in tunnel lining due to static analysis

6. DYNAMIC ANALYSIS

Two things are essentially needed to conduct some analysis of the earthquake response of a soil-tunnel interaction system: a physical modeling of the system and the input mechanism to it. Physical modeling of the system includes the selection of an appropriate finite element for the soil and the tunnel lining, also, mesh size and time step. Input mechanism includes the definition of an appropriate ground motion history. Once a suitable seismic excitation has been established, the calculation of stresses and strains can be carried out.

6.1. Earthquake Input Mechanism

The model used in dynamic analysis was excited by rigid-base translation, with El Centro earthquake accelerations. A reduction in its frequency to equal 1.0 Hz was done. The vertical acceleration, in y-direction, was selected as two-thirds of the values for the horizontal one. The time increment, Δt, was chosen 0.1 Sec. **Figure 6** shows the time history of acceleration of El Centro earthquake, (May, 1940).



(a) Original (b) After Cut-off Frequency

Figure 6: El Centro earthquake, (May, 1940)

The dynamic equilibrium equations can be expressed as:

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=-[M]\{\ddot{U}_g\} \tag{1}$$

Where [*M*], [*C*] and [*K*], are the mass, damping and stiffness matrices, respectively. $\{\ddot{U}\}$, $\{\dot{U}\}$ and $\{U\}$ are the relative acceleration, relative velocity and relative displacement vectors, while $\{\ddot{U}_g\}$ is the acceleration of ground. The analysis is carried out via direct time integration using Newmark method. The damping matrix is obtained as :

$$[C] = a[M] + b[K] \tag{2}$$

Where *a* and *b* are constants and can be obtained from damping ratio ξ as shown in equation (3), Xiansheng *et al.* [15]

$$a = \frac{2}{3}\xi \qquad b = \frac{1}{3}\xi \tag{3}$$

ξ can be obtained from the layered half-space as follows

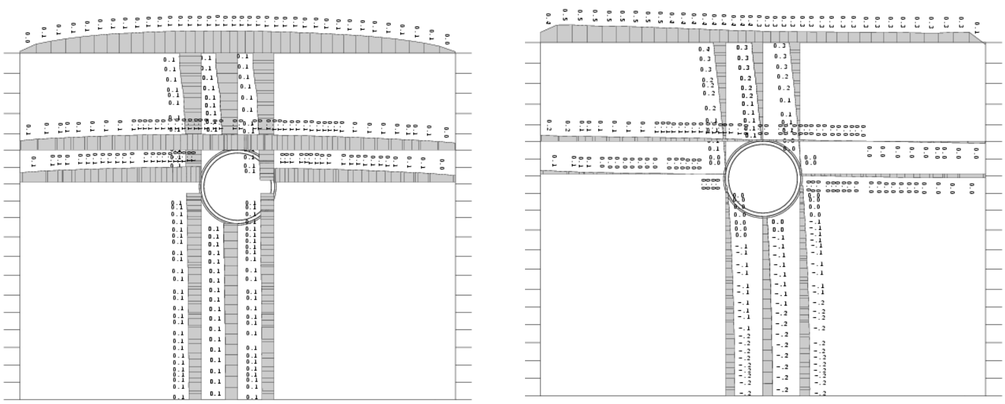
$$\xi = \frac{\sum \eta_i h_i}{H} \tag{4}$$

Where η_i is the damping value, h_i is the thickness of *i-th* layer, and *H* is the total thickness of layers.

The effect of damping has been taken into consideration. Mass-proportional damping has a larger influence on the lower mode frequencies than those of the higher modes. On the other hand, the stiffness-proportional damping has a larger influence on the higher mode frequencies, Muravyov *et al.* [16].

6.2. Results And Discussions Of Dynamic Analysis

The additional horizontal displacements of soil-tunnel model due to earthquake excitation are plotted after 6.9 Sec. in **Fig. 7**. It can be seen that, the effect appears in zone surrounding the tunnel opening, where in the case of analysis with damping effect results in values less than those obtained from other case without damping effect.

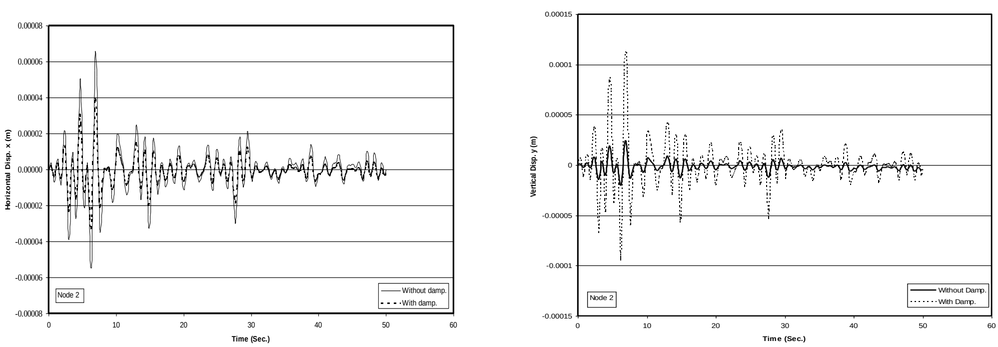


a) Without damping effect b) With damping effect

Figure 7: Horizontal displacement (mm) of soil-tunnel model after 6.9 Sec.

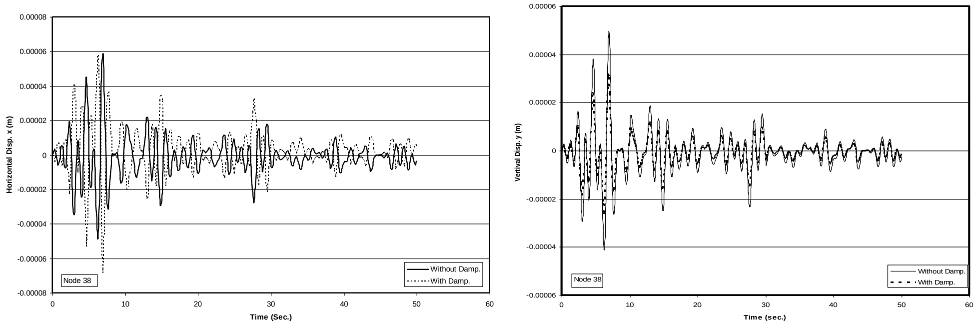
The time history of horizontal displacements in tunnel lining for nodes ***A, B*** and ***C*** which corresponding to joint numbering **2, 38** and **58** due to earthquake excitation were plotted in **Figures 8, 9** and **10,** respectively.

This study considered the effect of damping on the behavior of tunnel lining and found that the energy waves can be absorbed, so there are no reflection waves back to the model. Also, It can be found that, the effect of damping clearly appears in horizontal displacements, especially for nodes **2** and **58**, whereas, a little effect appears in node **38**. In the case of the vertical displacements for all nodes, the damping effect appears small or negative effect. Also, it can be noted that**,** the crown of tunnel lining, node **2**, has been affected more than other nodes.



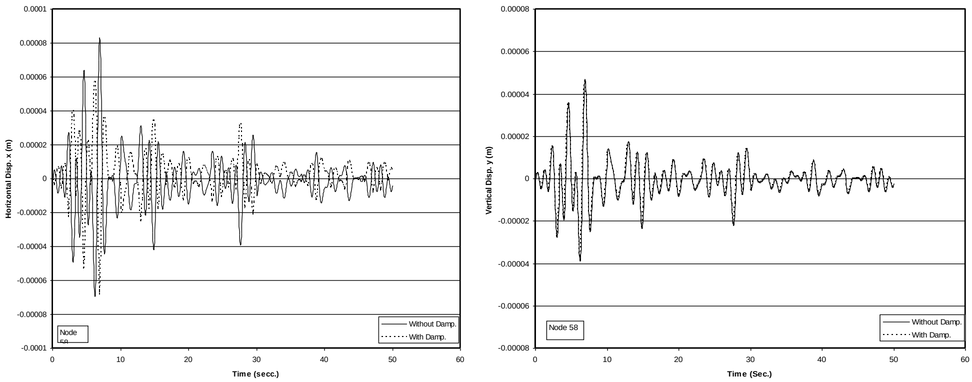
a) Horizontal displacement b) Vertical displacement

Figure 8: Time history of displacement for node 2 (tunnel lining)



a) Horizontal displacement b) Vertical displacement

Figure 9: Time history of displacement for node 38 (tunnel lining).

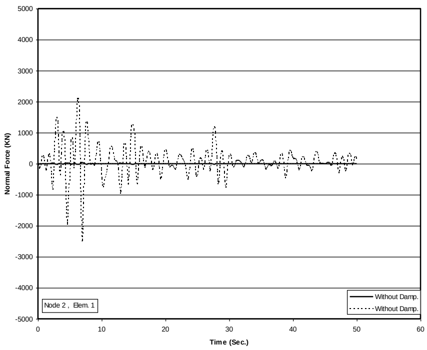


a) Horizontal displacement b) Vertical displacement

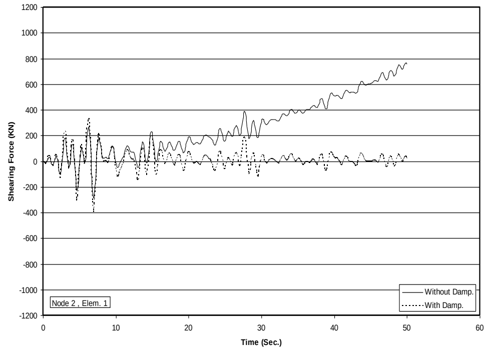
Figure 10: Time history of displacement for node 58 (tunnel lining)

The time history of additional internal forces due to earthquake excitation for nodes **2, 38** and **58** in tunnel lining were calculated and plotted as shown in **Figures 11,** 12 and 13, respectively. It can be noticed that, the damping has large effect on time history of shearing forces and bending moments, especially for node **2** as shown in **Figures 11- b** and **11-c,** whereas, the damping increases the additional normal forces on node 2 as shown in **Figures 11- a,** and this valid until 10 Sec excitation , after that time the damping effect decreases the internal forces. On the other hand, node **38** has a little effect with damping, as shown in **Fig. 12.** Whereas, node **58** has largely affected by damping like node **2**, as illustrated in **Fig. 13**.

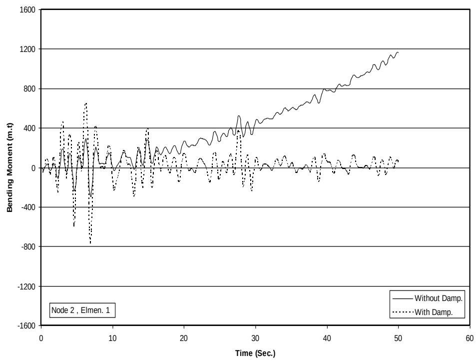
The distribution of additional normal forces, shearing forces, and bending moments in tunnel lining due to dynamic analysis after 6.3 sec and 6.9 sec were plotted in **Figures 14** to **19**.



a) Normal forces

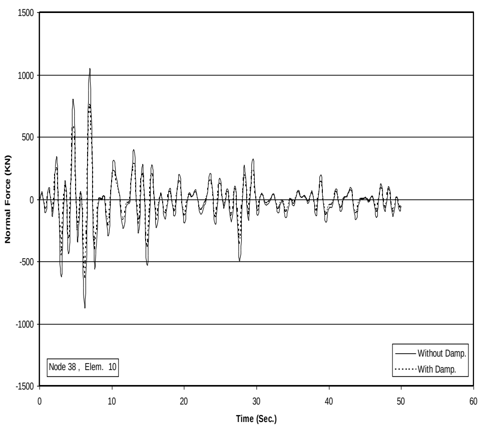


b) Shearing forces

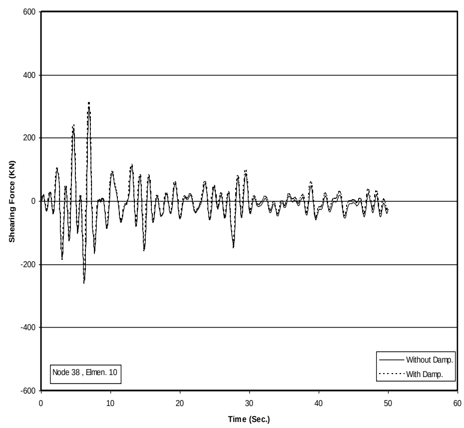


c) Bending moments

Figure 11: Time history of forces for node 2 (tunnel lining).



a) Normal forces



b) Shearing forces

Figure 12: Time history of forces for node 38 (tunnel lining)

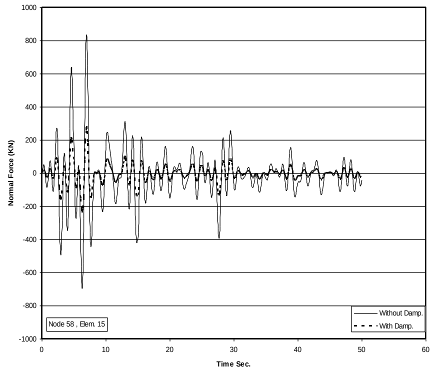
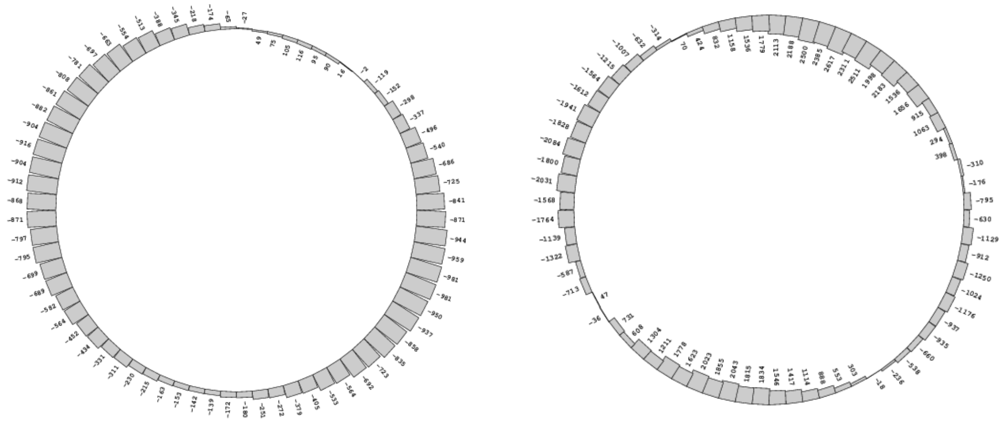
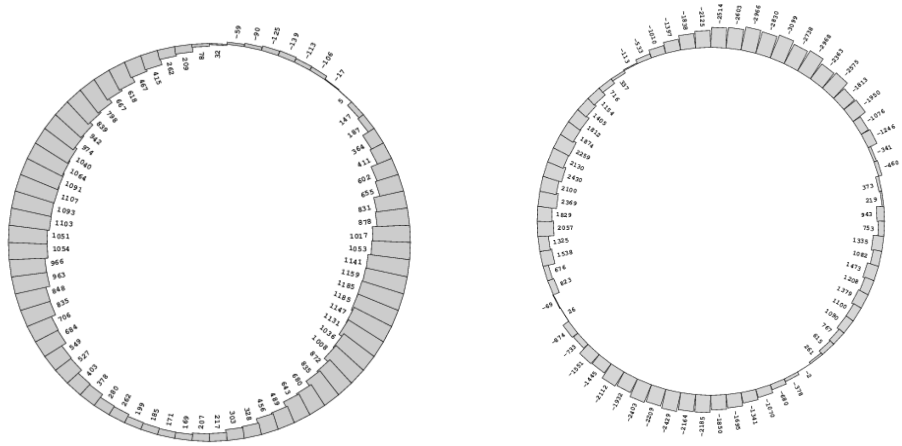


Figure 13: Time history of normal forces for node 58 (tunnel lining)



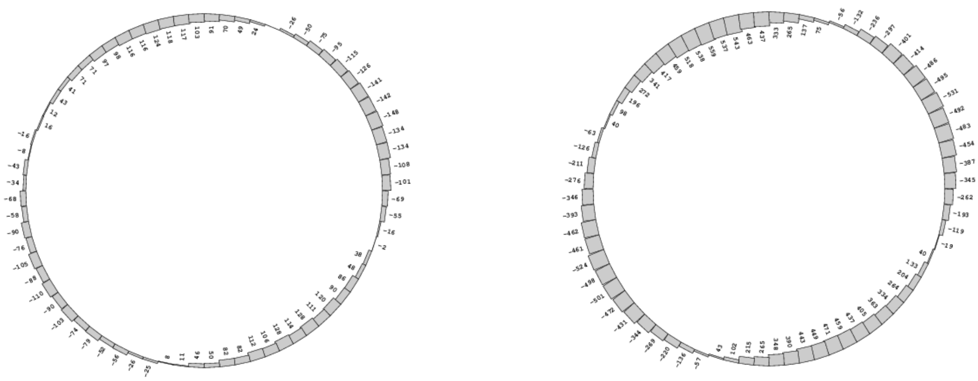
a) Without damping effect b) With damping effect

Figure 14: Normal forces in tunnel lining after 6.3 sec.



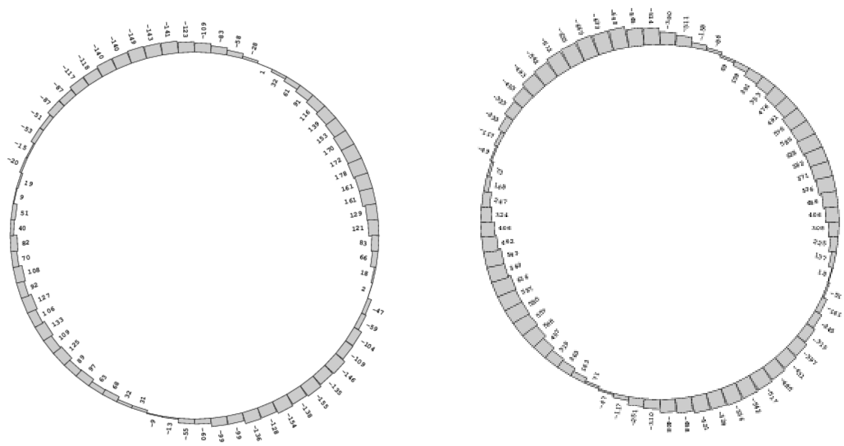
a) Without damping effect b) With damping effect

Figure 15: Normal forces in tunnel lining after 6.9 sec.



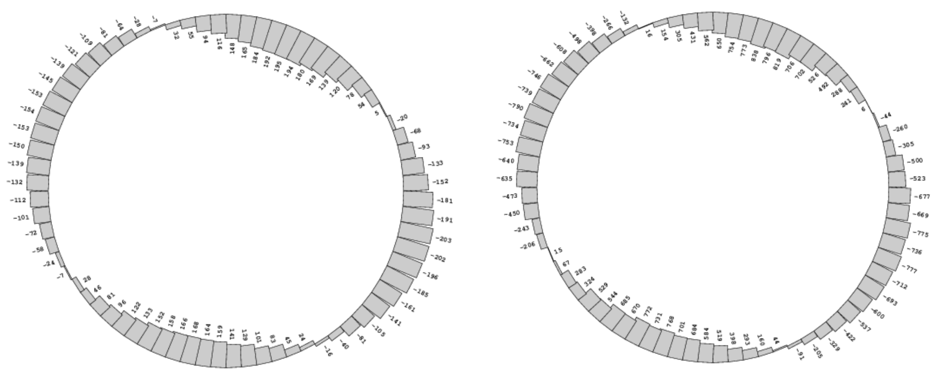
a) Without damping effect b) With damping effect

Figure 16: Shearing forces in tunnel lining after 6.3 sec.



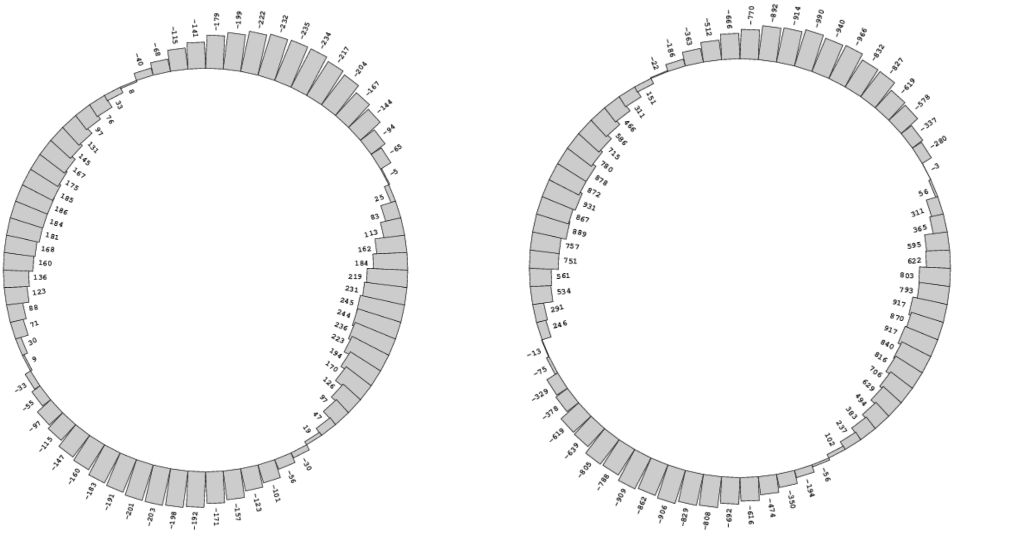
a) Without damping effect b) With damping effect

Figure 17: Shearing forces in tunnel lining after 6.9 sec.



a) Without damping effect b) With damping effect

Figure 18: Bending moments in tunnel lining after 6.3 sec.



a) Without damping effect b) With damping effect

Figure 19: Bending moments in Tunnel Lining after 6.9 sec.

It can be shown that the static analysis gives in tunnel lining only compression normal forces, whereas, in the case of dynamic analysis gives normal forces changed from compression to tension and vice versa and have values approximately from 0.58 to 1.0 times the forces obtained from static analysis. In the case of static analysis, the node ***B*** has maximum value of normal force. In dynamic analysis without damping effect, the nodes pass through inclined lines from center such as nodes **50**, and **122** have maximum values of normal forces, whereas, in the case of damping effect nodes **14** and **82** have maximum values of normal forces. Also, the crown node ***A*** and bench node ***B*** are less affected by earthquake than other nodes as illustrated in **Figures 14** and **15**. In dynamic analysis, the additional shearing forces in tunnel lining obtained from case of damping effect is more than these values obtained from case of without damping effect and have values approximately twice time those obtained from static analysis as illustrated in **Figures 16** and **17**. Also, the shearing forces have changed between negative and positive at the same position. For additional bending moments obtained from dynamic analysis, in the case of without damping effect, the values are approximately 0.8 times these obtained from static analysis. Whereas, in the case of damping effect these values are 3.0 times these obtained from static analysis, as shown in **Figures 18** and **19**. It can be noticed that, from the beginning of excitation to 10 Sec., the additional bending moments obtained from seismic load have been increased when taking into consideration the damping effect, after that the additional bending moments have been decreased.

7. CONCLUSIONS

The present study is concerned with the effect of damping on the behavior of tunnel lining under seismic loads. A careful numerical study is carried out by using the finite element method to analyze the additional internal forces in tunnel lining obtained from 2D soil-tunnel interaction plain strain finite element model.

Based on the numerical results obtained from static and dynamic analysis, the following conclusions can be drawn:

(1) The static analysis gives in tunnel lining only compression normal forces, whereas, in the case of dynamic analysis gives normal forces changed from compression to tension and vice versa and have values approximately from 0.58 to 1.0 times those obtained from static analysis.
(2) The crown node ***A*** and bench node ***B*** are less affected by earthquake than other nodes.
(3) In dynamic analysis without damping effect, the nodes pass through inclined lines from center such as nodes **50**, and **122** have maximum values of normal forces, whereas, in the case of damping effect nodes **14** and **82** have maximum values of normal forces.
(4) At the same position, the shearing forces changed between negative and positive at the same position.
(5) For additional bending moments obtained from dynamic analysis, in the case of without damping effect, the values are approximately 0.8 times these obtained from static analysis. Whereas, in the case of damping effect these values are 3.0 times these obtained from static analysis.
(6) The present study considered the effect of damping on the behavior of tunnel lining and found that the energy waves can be absorbed, so there are no reflection waves back to the model.

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تأثير التخميد على سلوك جسم نفق تحت تأثير أحمال الزلازل

تستخدم الأنفاق بكثرة كحل أساسى فى البلاد المزدحمة بالمرور. حيث تعتبر الأنفاق من المنشات الهامة والحساسة. و لأمان هذه المنشآت يجب أن تتم دراستها وتحليلها إستاتيكياً و ديناميكياً. إن دراسة السلوك الديناميكي للمنشات الأرضية أحد الماهيم الهندسية للتفاعل بين المنشأ والتربة. و لذلك فان النماذج العددية لتمثيل التداخل بين المنشآت الأرضية والتربة من الأمور المهمة و التي يتم البحث فيها منذ سنوات عديدة. و تعتمد دقة النتائج على معرفة كيفية إدخال البيانات الصحيحة للتربة والنفق و كذلك كيفية اختيار العناصر المحددة المناسبة.

فى هذه الدراسة تم تمثيل التربة بالعناصر المثلثية(LST) ذات الستة نقاط كل واحدة لها درجتين من حرية الحركة الانتقالية , أما النفق فتم تمثيله بعناصر الكمرة السداسية (BEAM6) و التي لها ستة نقاط كل واحدة لها درجتين من حرية الحركة الانتقالية. من المسائل الهامة فى التحليل الديناميكي للتداخل بين النفق والتربة هي كيفية تمثيل مصفوفة التخميد للتربة والنفق (Damping matrix) و ذلك لوجود أكثر من مادة مختلفة الخواص. أيضاً يهتم هذا البحث بدراسة تأثير التخميد على سلوك النفق تحت تأثير أحمال الزلازل.

وقد استخدمت في هذا البحث طريقة العناصر المحددة كطريقة عددية وذلك في مدى التحميل المرن. ويشمل البحث دراسة تحليلية لكل القوى المتولدة داخل جسم النفق مثل القوى العمودية وقوى القص وعزوم الانحناء ، وكذلك الإزاحات الأفقية والرأسية. تم اختيار مترو أنفاق القاهرة – الخط الثاني كتطبيق على هذه الدراسة.

وقد أظهرت نتائج التحليل العددي أن التحليل الاستاتيكى يعطى قوى عمودية ضغط فقط, في حين أن التحليل الديناميكي يعطى قوى عمودية تتغير بين الشد و الضغط و أن قيمها تتراوح بين 0.58 إلى 1.0 من القوى العمودية الاستاتيكية. وقد وجد أن النقط التي تقع على الخطوط الرأسية أو الأفقية من مركز النفق مثل نقطة A و B أقل تأثرًا بأحمال الزلازل من تلك التي تقع على الخطوط المائلة. أيضاً وجد أن تأثير التخميد يغير مواضع النقط التي بها أقصى قوى قص. كما أوضحت النتائج أنه عند إدخال تأثير التخميد فإن قوى القص تتغير من موجب إلى سالب و بالعكس عند نفس النقطة . لهذا يجب فحص وتدقيق للقوى الناتجة من التحليل الديناميكي و أخذها في الاعتبار عند التصميم الإنشائي حتى لا يكون هناك قصور في التصميم.