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Nonlinear Seismic Analysis for Circular Tunnels In Stratified Soil

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ملخص البحث

اثناء انتشار موجات القص الزلزالية , تتعرض الانفاق لتشكلات بيضاوية والتي تولد عزوم انحناء وقوي محورية اضافية علي جسم النفق. في الحالات التي تكون فيها التربة حول النفق طبقية ومختلفة في الخواص الجيولوجية، تكون التشكلات في مقطع النفق اكثر حدة مما يؤدي الي تضاعف في القوي الزلزالية المتولدة في النفق. هذا البحث يقدم دراسة عن تاثير الطبقية في التربة حول جسم النفق علي السلوك الزلزالي تحت احمال موجات القص الزالزالية. كذلك تحدد الدراسة قيم الزيادة في القوي الزلزالية مع الاخذ في الاعتبار سلوك التربة اللدن. ويتضمن البحث دراسة بارمترية لمعرفة الحالة الحرجة لمكان وجود الاختلاف في طبقات التربة بالنسبة للنفق. تم عمل نماذج تحليل ثناعية الأبعاد باستخدام طريقة العناصر المحدودة وتطبيق الأحمال الزالزالية الديناميكة مع الاخذ في الاعتبار سلوك الاحتكاك اللدن بين سطحي التربة والنفق. بينت الدراسة وجود تأثير هام لطبقية التربة علي نتائج القوي الزلزالية المتولدة فى جسم النفق، مما يستلزم اخذها في الاعتبار اثناء التصميم الزلزالى للأنفاق.

ABSTRACT

During propagation of the seismic Shear waves, the tunnels are subjected to ovaling deformations which induce incremental bending and thrust forces in the tunnel liner. In cases where the soil is made of stratified layers, tunnel liners take sharper deformed shapes and experience magnified bending moments and thrust forces. This paper investigates the effect of the soil stratification on the seismic behavior of circular tunnels under S-waves loading. It also addresses the seismic forces magnifications in Non-linear soil analysis and worst case scenario for the soil layers interface location. A series of 2D finite element models are subject to earthquake time histories and the system is analyzed accounting for tunnel/soil interface frictional-slippage conditions. The study showed that soil stratification has a great effect on the tunnel seismic forces that needs to be considered in the seismic analysis and design of tunnels.

KEYWORDS: Soil Stratification, Seismic S-Waves, Circular Tunnel, Earthquake Loads

1. Introduction

Propagating of seismic Shear-waves in a direction normal to the tunnel longitudinal axis, results in ovaling deformations of the tunnel lining cross-section [1]. The ovaling deformations are critical for tunnels sections design and it can cause failure for the tunnel liner [2]. Normally, in the design for underground structures assume that tunnels are embedded in single homogeneous soil layer even when the soil has slight differences in the geotechnical properties. Tunnels may be excavated or constructed in stratified ground with variable stiffness. In such case, seismic behavior of the tunnels should be investigated. Previously studies highlighted the importance of the effect of the stratified soil on the tunnel seismic response under transverse P-waves [3]. These studies highlighted the importance of the soil stratification effect on the tunnel design. It was found that tunnel lining forces increased up to 3 times when the layers interface crossing the tunnel lining [3].

Utilizing nonlinear soil properties and dynamic analysis can produce more realistic results for the seismic response for the tunnel [2]. In this study, the effect of the soil stratifications on the seismic forces of circular tunnels- under seismic S-waves produced by applying seismic horizontal acceleration time history in the ground is investigated. Soil nonlinear properties adopting different Plasticity models were included in the study. Also the frictional contact behavior and the separation at the tunnel/soil interface during earthquake deformations was considered to capture more features of the real soil structure interaction behavior. It worth mentioning that the coefficient of friction between the soil and tunnel is an import parameter for the seismic response [4] and shall be adopted in the analysis.

2. Model Description

2-D finite element analysis for circular tunnels embedded in multi-layered soil conditions was carried out. ABAQUS/Standard finite element code [5] was employed for the analyses, as it possess several contact simulation techniques.

Figure 1 describes the basic model geometry and the applied pressure loading. Elastic beam element (type= B21) was adopted to model the tunnel liner. Elastic plane strain element (type= CPE4) were used to model the soil medium. Top Boundary in the model is restrained in Vertical and horizontal direction. Bottom Boundary in the model is restrained in the vertical direction only. The time history Accelerations were assigned at the bottom boundary in the horizontal direction.

Tables from 1 to 5 summarizes the soil properties and the geometric properties of the tunnel used in the analysis models. Mohr coulomb and Drucker Prager failure criterion model has been adopted in many studies in earthquake analysis for tunnels [2, 6, 7, 8].

Single, two and three different layer properties were assigned to the soil medium. The soil types were classified as follows:
Soil Type (A), represents the soft layer with nonlinear properties
Soil Type (B), represents the stiff layer with nonlinear properties
Soil Type (C), represents the very stiff layer with nonlinear properties
Soil Type (D), represents rock layer with nonlinear properties
Soil Type (Ae), represents the soft layer with elastic properties only
Soil Type (Be), represents the stiff layer with elastic properties only
Soil Type (Ce), represents the very stiff layer with elastic properties only
Soil Type (De), represents rock layer with elastic properties only

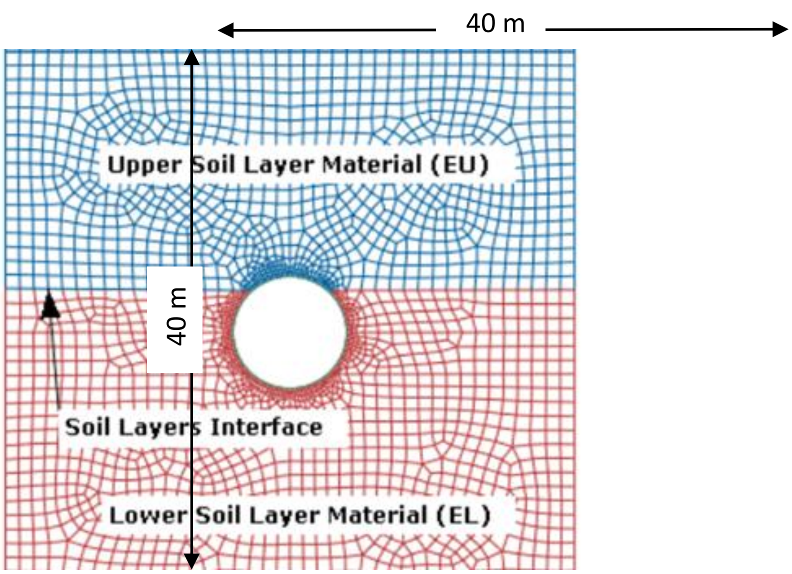

Figure1. Finite element model: elements meshing and input S-wave load

Table (1) : Input data of tunnel liner

Liner Properties	
Modulus of elasticity, E_l	19 GPa
Tunnel radius, r	4.0 m
Poisson ratio, ν_l	0.2
Thickness, t	0.35 m

Table (2) : *Input data of Soil type (A) Modified Drucker Prager Soil Model parameters* [9]

Modulus of elasticity Es	60 MPa
Poisson ratio, ν_l	0.33
Density	1900 Kg/m^3
dilatation	0 Degree
Friction angle	50.19 Degree
Void ratio	0.6
Initial effective stress	200 000 Pa
Flow stress ratio	1

Drucker Prager Strain Hardening

Stress (Pa)	**strain**	**Stress (Pa)**	**strain**
2.00E+05	0	3.00E+07	0.001225
5.00E+06	0.000787	5.00E+07	0.00135
1.00E+07	0.000957	6.00E+07	0.001395
2.00E+07	0.001126		

Table (3) : Input data of Soil type (B) Cam Clay Model B Parameters [10]

Modulus of elasticity Es	182 MPa
Poisson ratio, ν_l	0.28
Density , ρ	1923 Kg/m^3
cohesion	10 kPa
Friction angle	44.56
Cap eccentricity	0.4
Initial yield	0
Flow stress ratio	1
Transition Surface	0.05

Yield stress (Pa)	**Volumetric strain**
35000	0
70000	0.0017
103000	0.0032
1030000	0.045

Table (4) : Input data of Soil type (C) Drucker Prager Model Parameters [11]

Modulus of elasticity Es	938.4 MPa
Poisson ratio, ν_l	0.38
Density	1700 Kg/m^3
Cohesion	250 kPa
Friction angle	22 degree
Dilatation angle	6 degree

Table (5) : Input data of Soil type (D) Drucker Prager with hardening strain Model Parameters [12]

Modulus of elasticity Es	2200 MPa
Poisson ratio, ν_l	0.30
Density	1960 Kg/m^3
Yield Stress	20 GPa
Stress Flow Ratio k*	1
Friction angle	50 degree
Dilatation angle	5 degree

The normal behavior was defined by implementing a hard contact formulation with separation allowed between the tunnel outer surface and soil surface. Dynamic implicit analysis has been performed for all models with initial, minimum, and maximum time increments of 10^{-6}, 10^{-12}, and 10^{-2}, respectively.

Most of metro tunnels specifically in Egypt are shallow tunnel. So another set of models similar to the described above were created with additional step of analysis for the geostatic stresses in the soil. The top boundary in the model was changed to free joints. Lateral loads at the side boundaries were applied during earthquake action to support the earth pressure loads (See Figure 2). The Burial Depth in these models is 20m from the ground surface to the tunnel spring line.

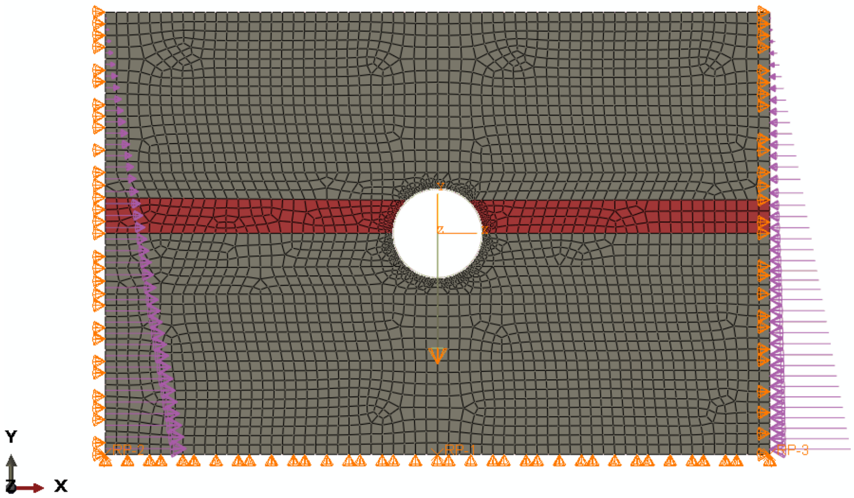

Figure 2. Finite element model: Applied Lateral Loads for Shallow Tunnels

3. Analysis Models Using Earthquake Time History Analysis

All analysis models were performed under the application of earthquake time history Horizontal acceleration for KOYNA earthquake (See Figure 3) magnitude of 6.5 on the Richter/' scale on December 11, 1967. The soil media in this set of analysis was enlarged to be 60m width by 40m height in order to achieve more accurate models.

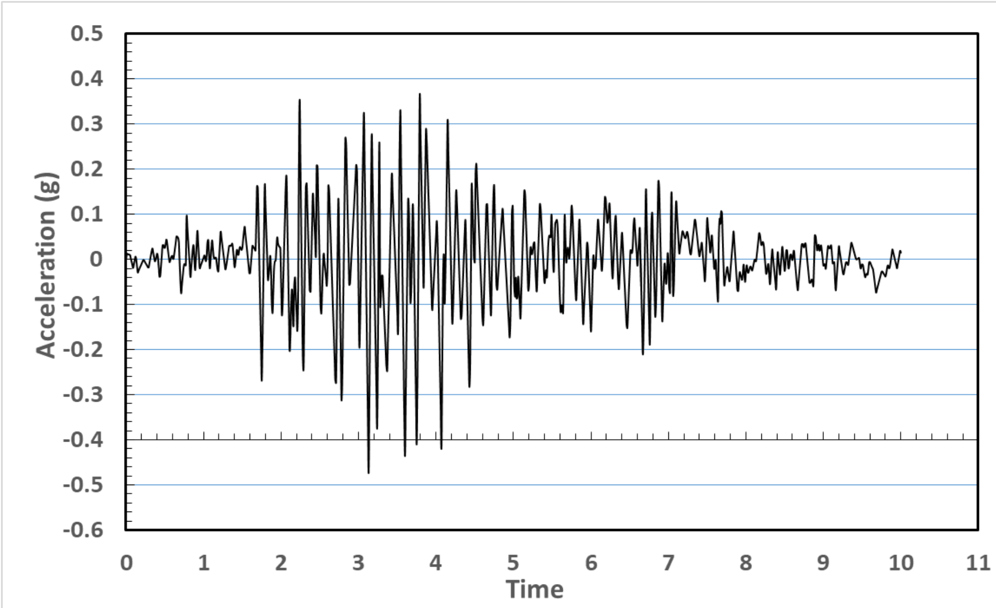

Figure 3. KOYNA Earthquake Horizontal acceleration

4. Results and Discussion

The results are divided into two groups, one for the linear soil materials which are listed in Table 6 and the other one for the nonlinear soil material are listed in Table 7 .
From the results shown in Table 6, it can be shown that the bending moments have small change against the soil type while thrust forces are increases as the soil stiffness increased. The results from Double layered ground are greater than results given from the softer soil material with magnification almost double for the bending moments and 3 for the thrust forces. The results from the Three layers ground Models (refer to Figure 4) are larger than the single layered ground by approximately 3 times for bending moment and 10 times for the thrust forces. With reference to Figure 5, it can clearly noticed be that, the deformations are sharp in case of stratified ground.

Table (6): Numerical results in terms of maximum thrust forces and Bending moments					
Number of Soil Layers	**Layers interface Location**	**Lower Layer**	**Upper Layer**	**Bending Moment M_{max}**	**Thrust Force N_{max}**
Single	-	***Ae***	***Ae***	***260***	***82***
Single	-	***Be***	***Be***	***313***	***80***
Single	-	***Ce***	***Ce***	***295***	***97***
Single	-	***De***	***De***	***321***	***251***
Double	crown	De	Ae	207	321
Double	Spring line	De	Ae	389	444
Double	Invert	De	Ae	355	250
Double	**Spring line**	**De**	**Be**	**511**	**636**
Double	Spring line	De	Ce	460	570
Three	**Spring line**	**De-Be**	**Be-De**	**1191**	**2247**

Notes: -Values are represented in KN.m and KN per running m of liner perimeter

-Ae, Be, Ce, De are refers to soil type elastic material

From the results shown in Table 7, it can be shown that the seismic forces have variable values against the soil type depend on the nonlinear displacement and plastic behavior around the tunnel. The results from Double layered ground are greater than results given from the softer soil material with magnification almost double for the bending moments and 3 for the thrust forces. The results from the three layers ground models are larger than the single layered ground by approximately 8 times for bending moment and 7 times for the thrust force. From Figures 6 and 7. It can be noticed that, the tunnel liner deformed shape is sharper in nonlinear soil material model. From the tables it can be concluded that, generally the soil layers interface when it crossing the tunnel at the spring line it gives the worst scenario for the seismic forces and deformations. The existing of soft layer between two hard soil layers produce the maximum seismic forces in the tunnel liner.

Table (7): Numerical results in terms of maximum thrust forces and Bending moments					
Number of Soil Layers	**Layers interface Location**	**Lower Layer**	**Upper Layer**	**Bending Moment M_{max}**	**Thrust Force N_{max}**
Single	-	***A***	***A***	***260***	***84***
Single	-	***B***	***B***	***173***	***151***
Single	-	***C***	***C***	***527***	***468***
Single	-	***D***	***D***	***321***	***251***
Double	Spring line	D	B	360	429
Double	Spring line	C	B	283	273
Three	**Spring line**	**D-B**	**B-D**	**2442**	**1730**

Notes:-Values are represented in KN.m and KN per running m of liner perimeter

-A, B, C, D are refers to soil type Non-linear material

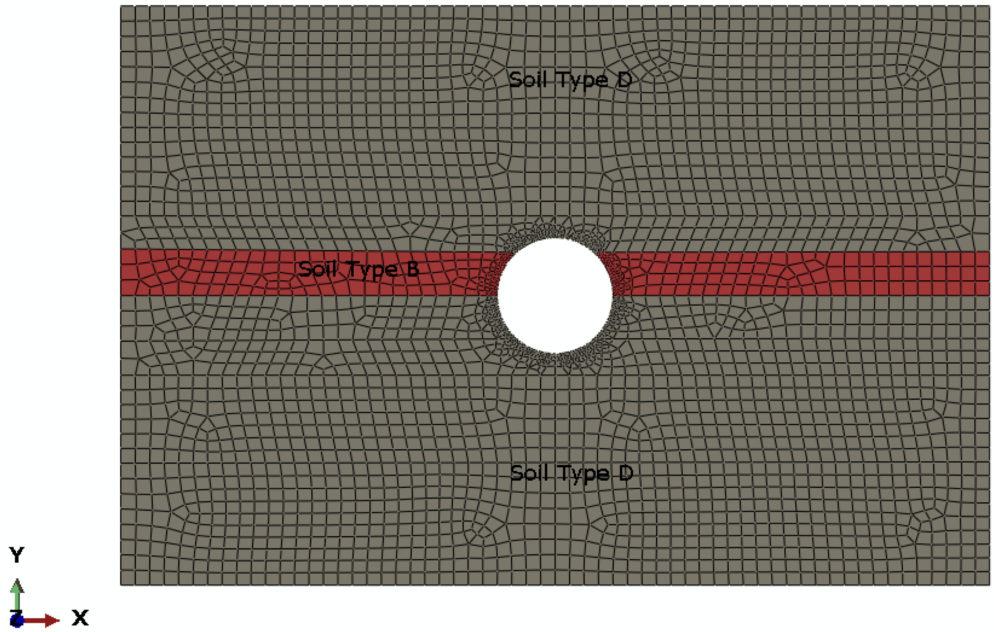

Figure 4. Soil Stratification for FEM DBD. Intermediate softer layer crossing the tunnel

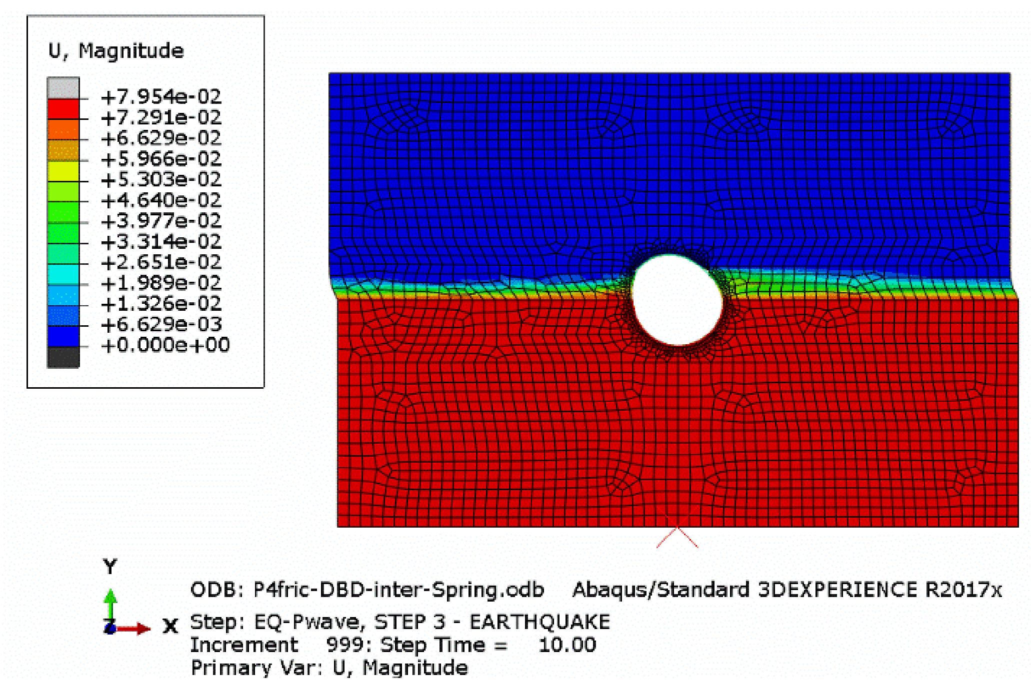

Figure 5. Lateral deformations for FEM DBD. Intermediate softer layer crossing the tunnel

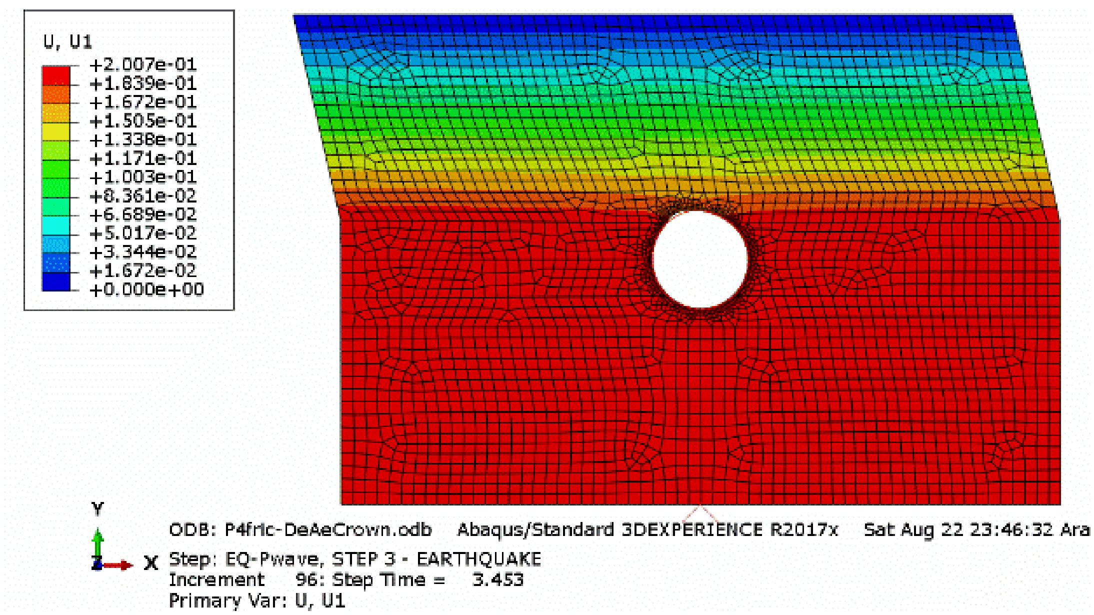

Figure 6. Lateral deformations for Dynamic Finite element Analysis (Rock lower Layer / Soft Soil Upper Layer) linear materials

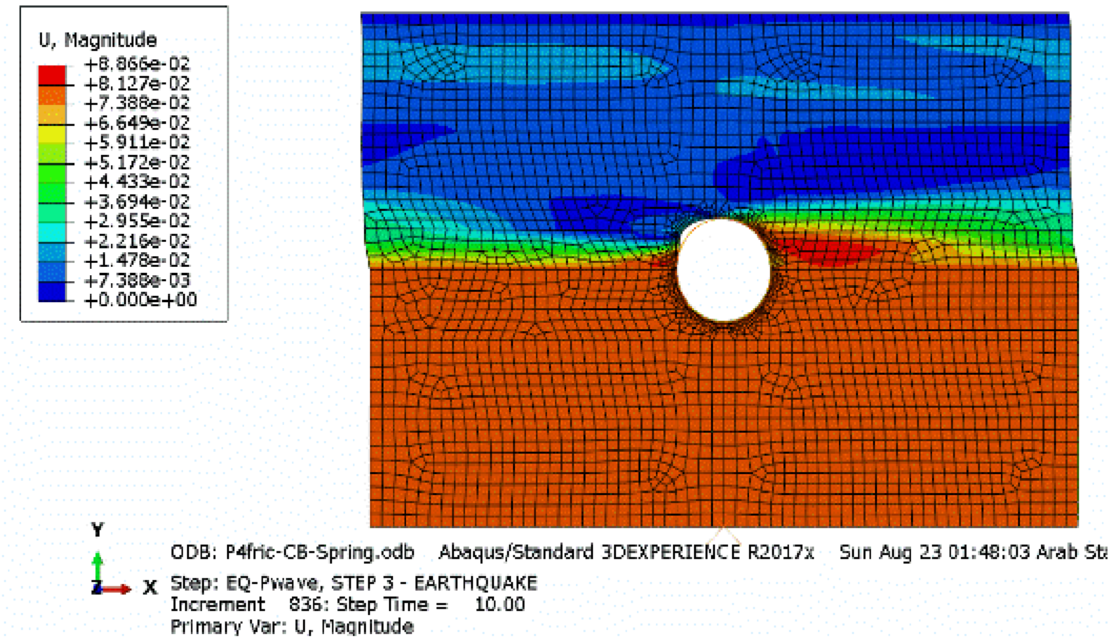

Figure 7. Lateral deformations for Dynamic Finite element Analysis (Stiff lower Layer / Soft Soil Upper Layer) Non-linear Soil Properties

In shallow tunnel models, the initial geostatic stress in the ground and the initial contact pressure on the tunnel face were simulated by adding Geostatic step in ABAQUS model prior to Earthquake Step. Moreover, the upper supports in the top boundaries were cancelled in these analyses to simulate the behavior of shallow tunnels. In Table 8, the first three rows are resulted from the nonlinear soil properties while the last three row are resulted from analysis for the elastic soil materials. From the table, it can be noticed that, bending moments resulted from nonlinear soil models are larger than bending moments resulted from elastic materials, whereas thrust forces are less than their correspondents for single layers only.

The envelope forces come from the multi-layer model with nonlinear material properties are with considerable magnification for the bending moment that reaches 6.5 times to the single layer material B. The thrust forces increased by 30% from the single layer to the multi-layer model. Figure 8 shows graphically the difference in bending moments for the shallow tunnel models with nonlinear soil properties of single layers B and D against multi layers (D soil for lower and upper + B soil for the intermediate layer). It is evident from the curves that, the multi-layer model gives maximum bending moment larger than bending moment from the single layer models by almost 6 times.

Table (8): Numerical results in terms of maximum thrust forces and Bending moments Shallow tunnels					
Number of Soil Layers	**Layers interface Location**	**Lower Layer**	**Upper Layer**	**Incremental Bending Moment M_{max}**	**incremental Thrust Force N_{max}**
Single	-	*B*	*B*	*66*	*1338*
Single	-	*D*	*D*	*4*	*428*
Three	Spring line	D-B	B-D	**423**	**1763**
Single	-	*Be*	*Be*	22	1550
Single	-	*De*	*De*	4	711
Three	Spring line	De-Be	Be-De	46	748

Notes:-Values are represented in KN.m and KN per running m of liner perimeter

-A, B, C, D are refers to soil type with non-linear properties

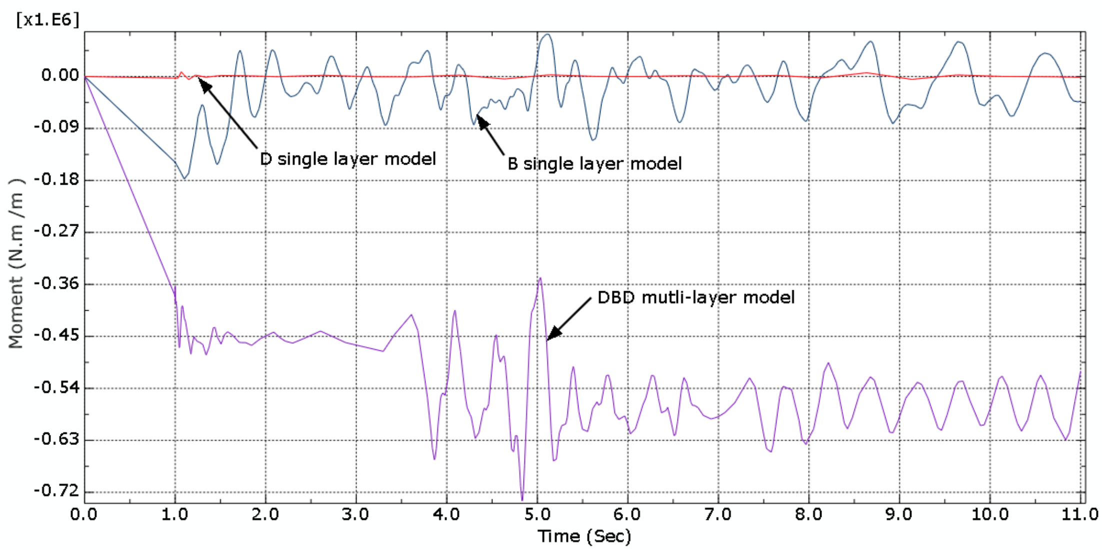

Figure 8. Results for bending moments from Single Layer vs Multi-layer model considering n~~N~~on-linear Soil Properties and Shallow tunnel simulation

5. Conclusions

In this study, the seismic performance for circular tunnel constructed in stratified ground and subject to vertically propagated shear-waves is investigated. From the study it can be concluded that:

1. Soil stratification has a great effect on the seismic behavior of tunnel liners. In particular, increases of up to 800% and 700% were observed for liner bending moments and axial forces, respectively.
2. The larger the stiffness differences between soil layers, the larger the magnification of tunnel liner seismic forces.
3. Numerical results showed that, the worst case scenario for the soil stratification takes place when the soil layers’ interface exists at the tunnel spring line.

4. For shallow tunnels, Soil stratifications have less effect on the seismic response of tunnels than for deep tunnels. For the latter case, lining bending moments and thrust forces were increased by up to 600% and 20%, respectively.

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