Dynamic analysis of two adjacent tunnels
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Abstract—Designing tunnel linings are usually performed accounting for the static cases of loading only, without considering the effect of earthqakes. Earthquake loads on tunnels are unpredictable due to the special nature of earthquakes. In this study, a numerical analysis using the finite element software ADINA is performed. The soil domain is presented as a plane strain problem with porous media formulation for the soil domain, and 2-node beam element to simulate the lining of the circular tunnels. In this study present the effect of, closer spacing results in larger interaction, comparison between the different tunnels lining thickness for the different soil types indicates slight increase in the normalized internal forces due to increasing the thickness and changing the soil type from stiff clay to hard clays resulted in significant reductions in the heave during construction and the consequent settlement due to the tunnel operation, with hard clays giving minimal heave and settlement values. The dynamic analysis results also show that slight differences between the different tunnels lining thickness began to be noticed as the clay stiffness increased. Designing for static loads only in tunnels may lead to catastrophic failure of such vital underground structures.

Index Terms—Tunnels, Finite Element Methods, ADINA Software, Clay Soil, Dynamic Analysis.

I. INTRODUCTION

Large-diameter tunnels are underground structures in which the length is much larger than the cross-sectional dimension. Tunnels are dug in different types of geo-materials varying from soft clay to hard rock. The method of tunnel construction depends on such factors as the ground conditions, the ground water conditions, the length and diameter of the tunnel drive, the depth of the tunnel, the logistics of supporting the tunnel excavation, the final use and shape of the tunnel and appropriate risk management [1]. There are three main shapes of highway tunnels; circular, rectangular, and horseshoe or curvilinear. The shape of the tunnel is largely dependent on the method of construction and the ground conditions. The finite element technique has a great versatility in analyzing one or two tunnels at different type of soil not including all soil types [2, 3, 4, 5, 6, 7, 8, and 9]. The dynamic effect on underground structure is important and can be grouped into two categories: (1) Ground shaking, and (2) Ground failure such as liquefaction, fault displacement, and slope instability. There are three types of deformations expressing the response of underground structures to seismic motions: (1) axial extension and compression, (2) longitudinal bending, and (3) ovaling/racking [10]. There are many methods used for the analysis of underground structures with the finite element method remained the most capable and versatile method of analysis of tunnels in different soil types under different loading conditions [11, 12, 13, 14, 15, 16, 17, 18, and 19].

II. THE FINITE ELEMENT METHOD

The numerical analysis is performed using the finite element software ADINA Version 8.5 (2011), [20]. The name ADINA stands for Automatic Dynamic Incremental Nonlinear Analysis. In order to satisfactorily model the Soil-Structure Interaction (SSI) effects under static and dynamic loading, ADINA employs the displacement and stress based finite element method. The soil domain is presented as a 2-D, 6-node triangle plane strain element with porous media formulation, Mohr-Coulomb soil model for the soil, and 2-node beam element to simulate the lining of the circular tunnels. The material of the lining is chosen to be of reinforced concrete with modulus of elasticity, Ec =2.1*10^10 N/m, using the repeatable side boundaries to model the soil domain side boundaries during the dynamic analysis [13].

III. PARAMETRIC STUDY

The studied parameters included different consistencies of clay modeled using Mohr-Coulomb soil model, with modulus of elasticity =10^10, 20^10, and 40^10 N/m^2, to model stiff clay, very stiff clay and hard clay soils, the center to center spacing of the two tunnels (D = 3d, 4d, 5d), in which d is the tunnel diameter, the chosen tunnel diameter is 10 m. The lining thickness t=0.03d is chosen for the analysis as shown in Fig. (1). There are four phases for static and dynamic analysis in ADINA software. The phases are put in order to simulate the sequenced loading of soil and tunnels construction and operation. The analysis is performed to compute the displacement and internal force in tunnels that took place in each phase of construction and loading. The first phase accounts for the effect of the soil own weight or the geostatic pressure, which took place due to consolidation of the soil under its own weight. This phase is followed by the construction phase in which the finite elements inside the tunnel zone is allowed to vanish (die) and the tunnel lining elements are allowed to exist (birth) employing the death/birth facility of the software. Slight heave is noticed at the soil surface due to removing the soil inside the tunnel, followed by settlements that took place due to placing the tunnel lining and operation process. The operation phase in which the traffic loads are placed inside the tunnel, and the surface traffic load are also applied at the ground surface as shown in Fig. (2). The fourth phase, the earthquake loads are applied to the tunnels during operation. The total time span of Northridge Earthquake is 59.98 sec., but the period of strong shaking is only 20 sec, which is accounted for in the dynamic
IV. NUMERICAL ANALYSIS AND RESULTS

Parameters chosen for the analysis are mainly the soil type, and distance between the two adjacent tunnels along with other parameters in the static and dynamic cases.

A. Effect of Different Parameters in the Static Analysis

The static case is composed of three phases. The total settlements which took place in the soil domain due to the consolidation under the soil own weights are considered the baseline for studying the effect of tunnel construction and operation phases. Fig. (5) shows colored contour shading of the settlements that took place during the first three phases.

Fig. (5): Settlements at Different Phases, with $D = 3d$, and $t = 0.03d$ in Very Stiff Clay Soil.

Fig. (6) shows the settlements that took place in the soil during the consolidation phase, the construction phase and the operation phase at the crown point for a distance between the two adjacent tunnels ($D$) is 3d, and the thickness of lining ($t$) is 0.03d in stiff clay soil. Fig. (6) also shows that slight heave took place due to the tunnel construction (excavation) process in which a stress relief took place due to removing the inner soil bounded by the tunnel lining. This slight heave is followed by settlement again due to loading the tunnel in the operation phase.

Fig. (6): Loading inside the Tunnels and at the Ground Surface.

Fig. (3): Displacement-Time History for Northridge Earthquake for the Whole Record (60 sec.) and the Period of Strong Shaking (20 sec.)

Fig. (4): Acceleration-Time History for Northridge Earthquake for the Whole Record (60 sec.) and the Period of Strong Shaking (20 sec.)
Table (1) shows the effect of varying the center to center spacing between tunnels on the normal force, shear force, and bending moment at the tunnel spring points during the static analysis. The computed results show very slight effect of varying the distance between the two tunnels on the normal forces for spring points. The shear forces at the spring point have significantly increased to almost 2.50 times of their original values when varying the tunnel spacing from 3 up to 5d. This behavior indicates that the distance between the tunnels along with the type of soil plays a major role in the values of the generated shear forces within the tunnel body. Regarding the bending moments, a moderate reduction of about 35% in the original bending moment value is noticed at the spring point in hard clays, with less reduction in very stiff, and then stiff clays. It should be noted that the underlined values are considered the base for normalizing the other computed values.

**Table (1): Effect of Distance between the Tunnels to Diameter Ratio in Displacements for Different Soil Types at the Spring Point.**

<table>
<thead>
<tr>
<th>Variation of distance between tunnels for a lining thickness of 0.03d</th>
<th>Internal force for tunnels in each Type of Clay</th>
<th>Normalized form of internal force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal force, kN</td>
<td>Shear force, kN</td>
</tr>
<tr>
<td>(a) Stiff clay</td>
<td>Max. N = 2299 kN, Min. N = 1445 kN</td>
<td>Max. Sh = 383 kN, Min. Sh =-445 kN</td>
</tr>
<tr>
<td>D = 3d</td>
<td>227</td>
<td>77</td>
</tr>
<tr>
<td>(b) Very Stiff clay</td>
<td>Max. N = 2650 kN, Min. N = 2050 kN</td>
<td>Max. Sh = 240 kN, Min. Sh =-277 kN</td>
</tr>
<tr>
<td>D = 4d</td>
<td>229</td>
<td>207</td>
</tr>
<tr>
<td>(c) Hard clay</td>
<td>Max. N = 2665 kN, Min. N = 2070 kN</td>
<td>Max. Sh = 145 kN, Min. Sh =-176 kN</td>
</tr>
<tr>
<td>D = 5d</td>
<td>229</td>
<td>207</td>
</tr>
</tbody>
</table>

**Fig. (8): Time-Displacement Behavior for Different Soil Types for D = 4d, t = 0.03d, at the Tunnel Crown Point.**
Changing the soil type from stiff clay to very stiff and hard clays resulted in significant reductions in the heave during construction and the consequent settlement due to the tunnel operation, with hard clays giving minimal heave and settlement values as shown in Fig (8). Larger soil stiffness is usually associated with lower heave and settlements.

B. EFFECT OF DIFFERENT PARAMETERS IN DYNAMIC CASE

1 Effect of the Center to Center Spacing on the Horizontal and Vertical Displacements

The effect of center to center spacing between two tunnels on the horizontal displacements that took place due to the dynamic action is presented in Fig. (9). Horizontal displacements of up to about 50 cm are noticed indicating the large amplification of the earthquake horizontal displacements as it goes up through the soil domain. The figure also shows that the mutual interaction of the two adjacent tunnels due to the earthquake loads is negligible. However, stiffer soils tend to noticeably amplify the induced earthquake movements, giving higher lateral displacements than softer ones. The soil surface horizontal displacement increased by about 65% from the original earthquake movement, as the maximum original earthquake lateral movement is about 30 cm. This will quantify the amount of soil movement amplification that took place as the earthquake waves moving upward into the soil domain.

![Figure 9: Horizontal Displacement-Time History for Different Soil Types due to Dynamic Load, for t = 0.03d at the Tunnel Crown](image)

![Figure 10: Effect of varying the center to center spacing between the two adjacent tunnels on the vertical displacements that took place during the earthquake all calculated at the ground surface.](image)
Fig. (10): Vertical Displacement-Time History for Different Soil Types due to Dynamic Load, for t = 0.03d at the Ground Surface.

2. Internal Force-Time History for Different Tunnel Spacing

The displacement-time history of the original earthquake motion, which is the actual input motion fed into the lower boundary of the finite element mesh representing the soil domain, as shown in Fig. (3). However, the acceleration-time history is associated with shorter time span and much faster variation and reversals in the acceleration values with time, as presented in Fig. (4). This trend assures that the normal, shear forces, and bending moments within the tunnel body are more dependent upon the tunnel mass rather than the tunnel stiffness. The equation of motion in dynamics is composed of three terms in which the mass is multiplied by the acceleration, the damping is multiplied by the velocity, and the stiffness is multiplied by the displacement. Dependency on the soil and tunnel stiffness will result in displacement like behavior; while depending on the soil and tunnel mass will result in acceleration like behavior.

Fig. (11) Shows the normal force-time history within the tunnel body at the spring for the different soil types, and tunnel thickness of 0.03d. Moderate to relatively large variation in normal forces are noticed in the spring point zone within the tunnel body. However, total reversal from compression to tension forces is not noticed altogether over the studied cases, and as will be noticed in the bending moment behavior. Thus, variation in normal forces is only one sided and their consequent effect on the overall tunnel body safety is not of great importance like the case of bending moments. Moreover, the initial static normal forces at the spring point are relatively higher than those computed at the crown point due to the positions of these points within the tunnel body.

Fig. (11): Normal Force-Time History for Different Soil Types Due to Dynamic Load, for t = 0.03d at the Spring Point.

Fig. (12) Show the effect of changing the center to center spacing between the two adjacent tunnels on the shear force-time history during the earthquake. As previously noted, and regarding the initial static shear force values, the variation of shear forces during the earthquake event is very large and should be considered in the analysis and design of the tunnel body. When compared with the initial static shear force value peaks reached about 3.5, 10 and 30 folds this value in stiff, very stiff, and hard clays respectively. Slight differences are noticed between the different tunnel spacing for all the studied cases. In fact these differences are not that high compared with the variation in shear force due to earthquake motion and static case. The maximum peak reached about 30% when D=4d relative to D=3d for different soil types. Knowing that the initial static shear forces are different, and the generated dynamic shear forces oscillate about a virtual line passing through that initial shear value. Nevertheless, the variation in shear forces due to the dynamic action is significant, and reversible. The figures also shows what looks like symmetrical shear force values in the spring and crown points, having the same initial static value but with different sign.

(a) Stiff clay

(b) Very stiff clay

(c) Hard clay
The variation of bending moment values with time during the earthquake at the spring point of the tunnel for different center to center tunnel spacing are presented in Fig. (13). The original static bending moments could be magnified up to 7 folds and down with the same amount for all soil types, which may lead to failure in the tunnel body. Reversals of bending moments with large values in both directions are noticeable herein. Varying the center to center spacing between the two tunnels does not show noticeable differences between the different chosen spacing during the dynamic event. However, in all cases, smaller tunnel spacing resulted in higher initial static bending moments, indicating that tunnel spacing of 3d or less is unfavorable regarding the induced flexural stresses due to the static analysis. Moreover, an acceleration dependent behavior is noticed in the variation of bending moments with time, as previously noted.

3 Effect of Soil Type on the Dynamic Behavior of Tunnels

There are an infinite number of possibilities when varying the soil type during the parametric study analysis. However, to keep this paper within a manageable volume, only one soil type is chosen, which is clay, but with three different consistencies, namely; stiff clay, very stiff clay, and hard clay. All the studied cases are performed while keeping the tunnel center to center spacing constant at D = 4d, and the tunnel thickness constant at t = 0.03d.

Fig. (14) Shows the effect of varying the soil type on the horizontal displacements at the ground surface between the two tunnels. The displacement time history follows the original horizontal earthquake displacement but with amplified values. Stiffer soils show earlier tracking of the input horizontal displacement indicating faster arrival of the earthquake waves into the ground surface. Relatively softer soils show somewhat delayed tracking of the input motion indicating slower wave arrival. Thus, stiffer soils tend to amplify and allow faster movement of the earthquake waves, and on the other hand, softer soils tend to slightly dampen the movement values and hinder is movement and propagation.

Downward vertical soil movement (settlement) and upward soil movement (heave) may take place during earthquakes. Starting at the previously calculated settlement value, the dynamic action caused continued settlements at the ground surface in all the studied soil types, as shown in Fig. (15). Depending on the soil stiffness, lower strength soils gave higher settlements and vice versa. As previously noted, permanent soil settlements below underground or above-ground structures may be large enough to cause cracks.
or even failure to such structures. One more time, depending on the actual soil and tunnel type, seismic activity in the tunnel area, and the importance of surface structures, a separate dynamic analysis should be performed to direct or redirect the design into the proper path.

Based on the results of the research, the following conclusions can be drawn:

1- During the dynamic analysis, reversals of bending moments with large values in both directions are noticed. This case should be considered in the analysis and design of tunnels to account for such flexural stress reversals on the tunnel section and reinforcements.

2- The variation of shear forces during the earthquake event is very large reaching about 3.5, 10 and 30 folds the static computed value in stiff, very stiff, and hard clays respectively. The variation is significant, reversible, and should be considered in the analysis and design of the tunnel body. The generated dynamic shear forces almost oscillate about a virtual line passing through that initial shear static value.

3- Moderate to relatively large variation in normal forces are noticed in both the spring and crown zones within the tunnel body. However, total reversal from compression to tension forces is not noticed allover all the studied cases. Thus, variation in normal forces is only one sided and their consequent effect on the overall tunnel body safety is not of great importance like the case of bending moments and shear forces.

4- The variation of bending moment, shear and normal forces with time follows the general trend of acceleration-time history, other than the displacement-time history of the original earthquake motion, which is the actual input motion fed into the lower boundary of the finite element mesh representing the soil domain. This may be trend assures that the normal, shear forces, and bending moments within the tunnel body are more dependent upon the tunnel and surrounding soil mass rather than the tunnel and surrounding soil stiffness.

5- Depending on the actual soil and tunnel type, seismic activity in the tunnel area, and the importance of surface structures, a separate dynamic analysis should be performed to direct or redirect the tunnel design and direction into the proper path.

6- Stiffer soils tend to amplify and allow faster movement of the earthquake waves, and on the other hand, softer soils tend to slightly dampen the movement values and hinder the earthquake wave movement and propagation.

**ACKNOWLEDGMENT**

This work is investigated at structural engineering department, Faculty of Engineering Zagazig University.

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