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# *Analytical and Numerical Solutions of Tunnel Lining Under Seismic Loading and Investigation of Its Affecting Parameters*

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***ABSTRACT***

Underground structures like tunnels are important elements of transportation, network, and service, which due to being surrounded by the ground and withstanding in situ stresses show different seismic behaviors in comparison with surface structures. This paper presents analytical solutions for seismic and static loads in circular tunnels and then they have been used to evaluate internal forces of lining for a section of Bangkok's urban tunnel. The problem is solved using numerical analysis of finite difference for both horizontal and vertical acceleration coefficients and the results were compared with analytical solutions' results. According to the results by increasing the horizontal seismic acceleration, the axial force and bending moment increases. And with increasing the depth of tunnel, the forces of lining increases but vertical acceleration of earth has small effect on stresses. For the in- situ stress coefficient, it has been seen that as the ratio is further more away from the number one, the created stress increases in the lining.

***KEYWORDS:***

Underground Structures, Theoretical Solution, Numerical Solution, Horizontal Acceleration Coefficient, In-situ Stress Ratio.

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## 1- INTRODUCTION

Tunnels generally have a better performance against seismic loads in comparison with surface structures, where until before 1995, they were not designed against dynamic loads. However, the earthquakes that occurred in 1990s caused severe damages to some of the tunnels. Thereafter, dynamic analysis of tunnels attracted the attention of researchers. In order to understand the behavior of tunnels under seismic loads, the tunnel does not need to undergo a certain accelerometer for its behavior to be evaluated. Because, it incurs a heavy cost. Instead, it is possible to apply the equivalent shear load on the boundaries of the desired area, then measure the distortion and ovalling deformation of the tunnel and accordingly obtain the forces exerted on the coating. This is the direction most scientists have gone through to achieve the coating force. For example, Einstein and Schwartz (1979) presented simple analytical solutions for bending force and moment in the tunnel coating exposed to static loads [2]. Wang (1993) together with Penzien and Wu (1998) proposed closed solutions for calculation of the forces in the tunnel coating subject to equivalent static transformation [7.8]. Hashash et al (2001 and 2005) reported a significant difference between the solutions by Wang and Penzien in the calculation of forces in the tunnel coating previously compared with a numerical method [3,4]. Bobet (2003) developed the static relations of Einstein and Schwartz to determine seismic loads in the coating of tunnels [1]. Another analytical solution focusing on PTTO was presented by Kyung-Ho Park in 2009 dealing with calculation of the relations between displacements and interactive forces of coating-soil using spring elasticity coefficient [5].

Here, a circular tunnel with a diameter of R subject to horizontal and vertical accelerations caused by seismic loads has been considered. In general, the state of tensions surrounding the tunnel can be stated as follows [6]. Where, $\sigma_v$ and $\sigma_h$ are horizontal and vertical tensions, respectively, $\tau$ is the shear tension, $k_v$ and $k_k$ are vertical and horizontal acceleration coefficients respectively, K is the lateral pressure coefficient of earth, $\gamma$ and is the average specific gravity of the Earth from the ground up to the depth of H. Through assuming elastic behavior and according to the principle of superposition, one can divide this state into two figures demonstrated below: state one (1) is equivalent to exertion of and loads (on behalf of the static loads) $\sigma_v$ and $\sigma_h$ state two (2) that is obtained directly from the earth horizontal acceleration, which is a representative of seismic loads.

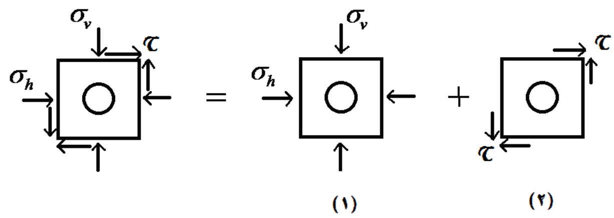


**Figure 1. SCEMATIC VIEW OF THE PROBLEM LOADING [6].**

Note that unlike the suggestion proposed above for the shear tension, in previous studies such as the solution by Penzien and Wu (1998) together with Hashash et al (2001,2005), this tension used to be obtained through shear strain of the $\gamma_c$ free field (Fig. 2).

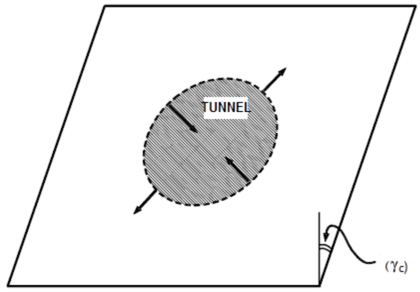


**Figure 2. FREE FIELD SHEAR STRAIN ($\gamma_c$)**

Where, $V_{max}$ is the particle shear wave velocity, $V_x$ is the earth shear wave velocity, $E_x$ is the environment Young module (soil), and $v_s$ is the Poisson coefficient of the environment (soil).

Regardless of the relation from which shear tension is extracted, the axial force and bending moment are eventually obtained through summing up the forces and bending moments of states (1) and (2):

Where, $T_s$ and $M_s$ are the axial force and bending moment in the static loading state. $T_s$ and $M_s$ are also the axial force and bending moment in the seismic loading state.

## 2- ANALYTICAL AND NUMERICAL SOLUTION OF THE BANGKOK SUBWAY (MODELING AND VALIDATION).

In order to evaluate the methods proposed in the previous sections, a section was considered from the subway tunnel, Blue Line, in Bangkok with soil profile properties indicated in Fig. 3. For this section, the forces developed in the coating including the axial force and bending moment in the static and dynamic states were investigated for different coefficient values of the earthquake vertical and horizontal acceleration. Since, the analytical relations, one cannot consider soil profile as layered, a set of average properties are used, according to Table (1).

Table 1. The soil properties in the analytical method

Preliminary assumptions of the modeling: 1. Flat strain conditions are applied. 2. The soil behavioral model and the concrete coating are linear elastic and massless.

For the modeling, finite difference method and FLAC2D software were used. In a model, first pressure tensions were exerted on to all of the external boundaries. Next, in another model, the shear tension was applied. The procedure of load exertion is provided in Fig. 4 and 5. Finally, the bending force and moment obtained from these two analyzers were summed together. The only slip-free conditions were considered between the tunnel coating and the surrounding soil. The properties of soil and 20 coating are provided in Tables 1 and 2. Fig. 6, 7, 8, and 9 demonstrated the bending forces and moments of the tunnel coating in two states of absence and presence of a vertical acceleration coefficient, when the tunnel is located 20 m deep in the ground.

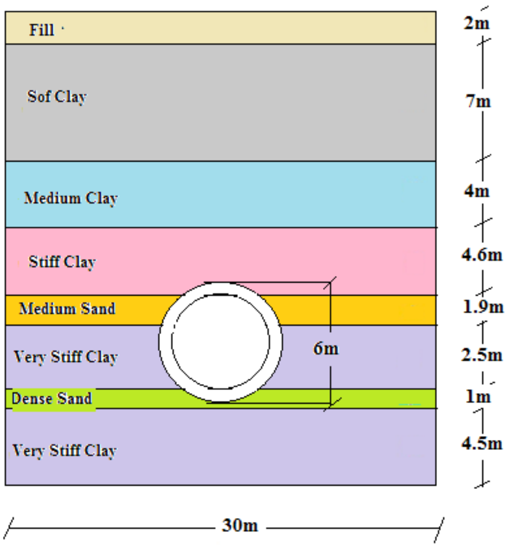


**Figure 3. THE PROFILE OF SOIL AND THE TUNNEL COATING.**

**Table 1. THE SOIL PROPERTIES**

| Layers | unit weight | Poisson's ratio | Young's modulus |
|---|---|---|---|
| | γ (KN/m$^3$) | $\nu_s$ | $E_s$ (MN/m$^2$) |
| Fill | 18 | 0.38 | 10.8 |
| Soft caly | 16.5 | 0.43 | 5 |
| Medium clay | 17.5 | 0.38 | 15.4 |
| Stiff clay | 19.5 | 0.46 | 34.4 |
| Medium sand | 19.5 | 0.46 | 110 |
| Very stiff clay | 20.5 | 0.44 | 66 |
| Dense sand | 19.5 | 0.44 | 150 |
| Very stiff clay | 20.5 | 0.44 | 66 |

**Table 2. THE PROPERTIES OF THE TUNNEL COATING**

| Poisson's ratio | unit weight | thickness | Allowable stress of concrete |
|---|---|---|---|
| $\nu_c$ | $E_c$ (MN/m$^3$) | t (m) | $f_c$ (KN/m$^2$) |
| 0.2 | 31000 | 0.3 | 30000 |

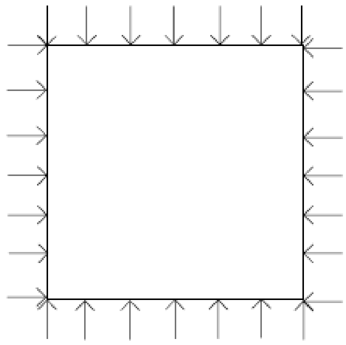

**Figure 4. STATIC LOADING**

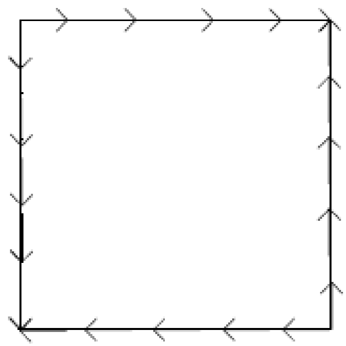

**Figure 5. SHEAR LOADING (SEISMIC)**

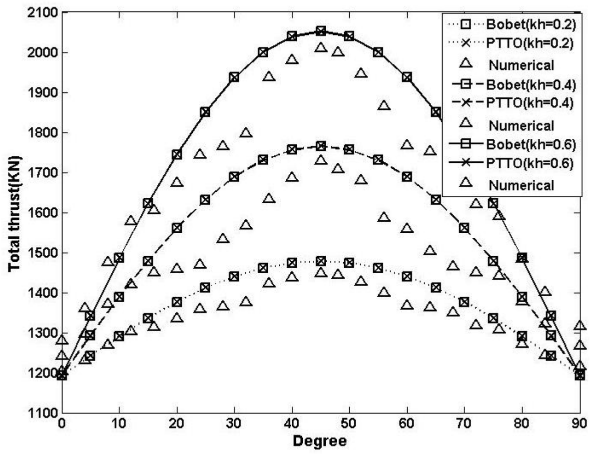


**Figure 6. DISTRIBUTION OF THE TOTAL AXIAL FORCE FOR DIFFERENT VALUES OF $k_k$ IN 20-M DEPTH.**

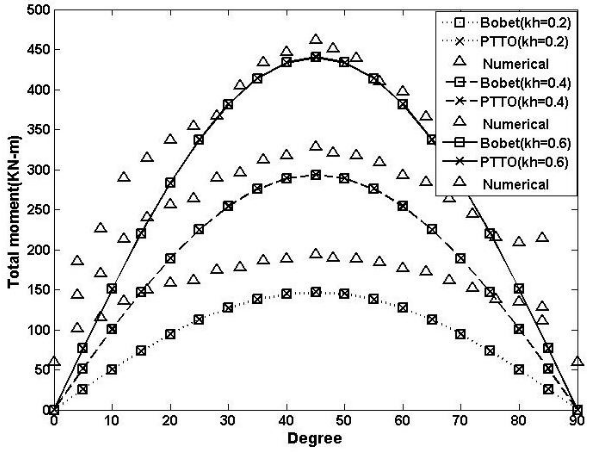


**Figure 7. DISTRIBUTION OF THE TOTAL BENDING MOMENT FOR DIFFERENT VALUES OF $k_k$ IN 20-M DEPTH.**

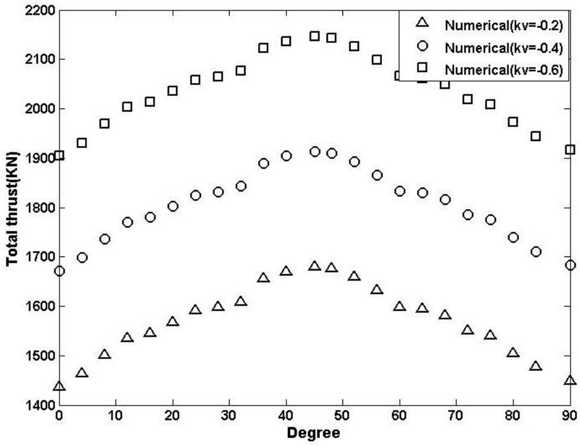


**Figure 8. DISTRIBUTION OF THE TOTAL AXIAL FORCE FOR CONSTANT VALUES OF $k_h$=0.2 AND DIFFERENT VALUES OF $k_v$ IN 20-M DEPTH.**

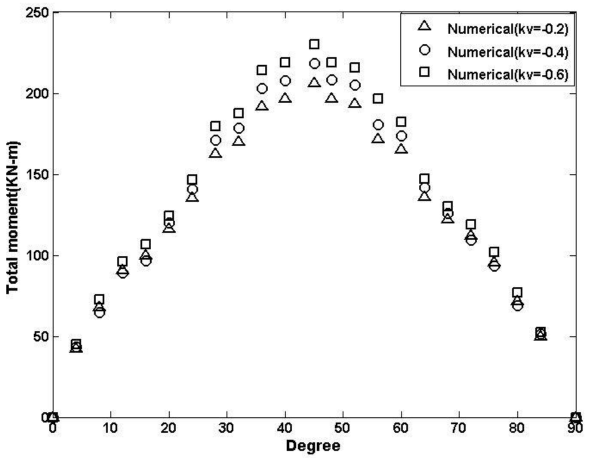


**Figure 9. DISTRIBUTION OF THE TOTAL BENDING MOMENT FOR CONSTANT VALUES OF $k_h$=0.2 AND DIFFERENT VALUES OF $k_v$ IN 20-M DEPTH.**

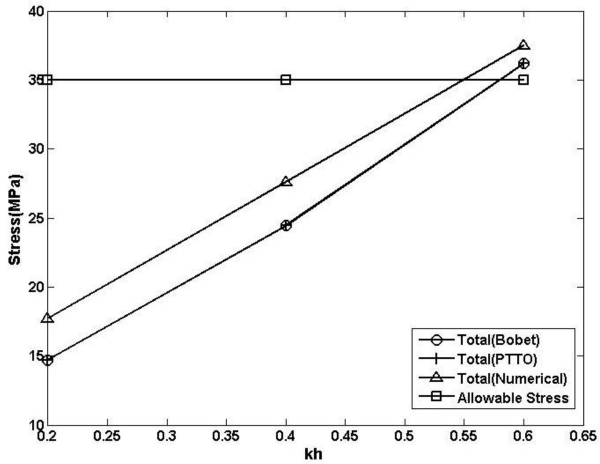


**Figure 10. THE MAXIMUM ENVIROMENTAL TENSION WITH DIFFERENT VALUES OF $k_h$ AT A DEPTH of 20 M.**

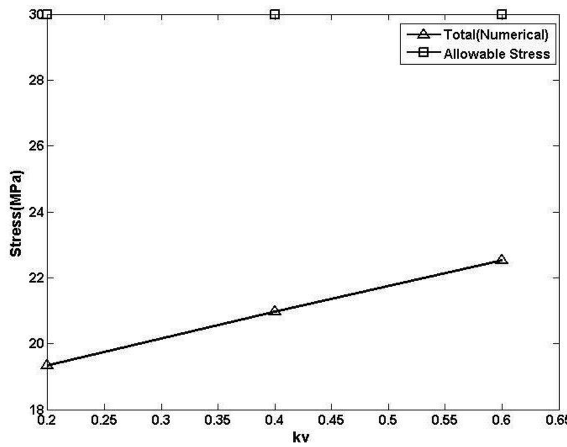


**Figure 11. THE MAXIMUM ENVIROMENTAL TENSION WITH CONSTANT VALUES OF $k_h$=0.2 AND DIFFERENT VALUES OF $k_v$ AT A DEPTH of 20 M.**

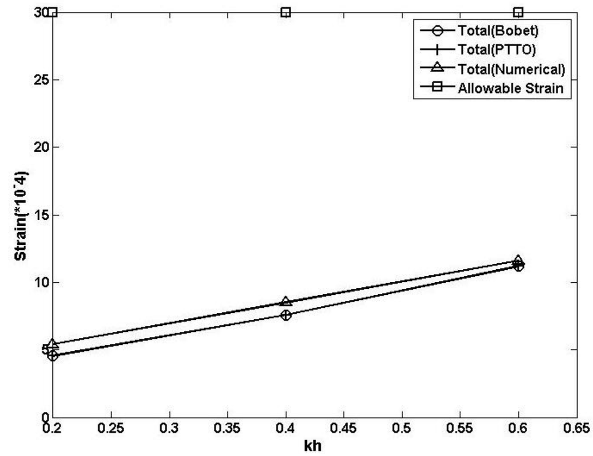


**Figure 12. THE MAXIMUM ENVIROMENTAL STRAIN WITH DIFFERENT VALUES OF $k_h$ AT A DEPTH of 20 M.**

According to Diagrams 6 and 7, a relatively good congruence can be observed between the analytical solutions and the numerical method. It is also seen that as the earthquake horizontal acceleration coefficient increases, so does the forces developed in the coating (axial force and bending moment). However, the vertical acceleration coefficient is effective only on the axial force, though these results are not unexpected

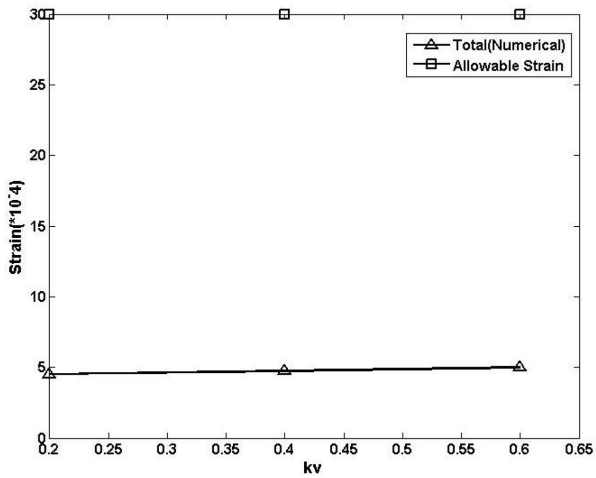


**Figure 13. THE MAXIMUM ENVIROMENTAL STRAIN WITH CONSTANT VALUES OF $k_h$=0.2 AT A DEPTH of 20 M.**

according to basic analytical relations.

On the other hand, one can obtain the environmental tensions and strains using the following relations:

Where, t is the coating thickness, $\sigma_\theta^1$ is the environmental tension, and $\varepsilon_\theta^1$ is the environmental strain.

Having obtained the tension and strain in the coating for different values of the influential factors in the problem and compared the allowable tension and strain, it is possible to achieve the preliminary estimation of the coating thickness or to investigate the potential failure of the coating for the current thickness. For example, for the considered problem, Fig. 10, 11, 12, and 13 reveal the value of these tensions and the strains along with the allowable values for the different potential horizontal and vertical acceleration coefficients.

According to these diagrams, as $k_h$ or the earthquake horizontal acceleration coefficient increases, the tensions approach rapidly to the allowable tension, where when this coefficients reaches 0.55, the tunnel coating is on the verge of failure. However, in this same state, the strains are still lower than the allowable limit. Given the criterion we want to use for the design of the coating and by knowing the maximum tolerated horizontal acceleration in the region, one can determine the preliminary thickness of the coating. Furthermore, considering the vertical acceleration, it is observed that for its different values, the tensions and strains are lower than the allowable limit.

## 3- CONCLUSION

At the beginning of the paper, the trend of the analytical solution of tunnels under situ horizontal, vertical and shear tensions was reviewed based on the elasticity theory and the amount of ovalling deformation of the tunnels' cyclic sections. Shear tensions are directly caused by the lateral movements of the earth representing the seismic loads. It was also stated that these basic relations can be used for preliminary estimation of the tunnel concrete coating thickness, though they have slight differences with each other. In order to show the applicability of these relations, we used them along with the numerical solution for specific sections of the Bangkok urban tunnel. We evaluated the effect of four factors of the earthquake horizontal and vertical acceleration, the tunnel placement depth, and the earth lateral pressure coefficient. It was observed that the earthquake horizontal acceleration and the tunnel placement depth are two important parameters in the value of the internal forces developed in the tunnel coatings. When they increase, the tensions easily reach the allowable tension threshold at which potential failure of the concrete coating can be expected. Two other important parameters are the earth vertical acceleration and the lateral pressure coefficient. The former has little effect on the tensions, but for the latter it was seen that the more distant this coefficient from the range of number one, i.e. the situ tensions away from the isotope state, then the tension developed in the coating grows.

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