THE RESEARCH OF THE EMERGENCY SITUATIONS CONSEQUENCES OVER THE ENVIRONMENT IN UNDERGROUND TRANSPORTATION

SEISMIC STABILITY OF METRO TUNNELS BY A FINITE ELEMENT PROGRAM

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Study the effect of earthquakes on the tunnel lining of shallow depths within the soft ground (like the Metro tunnels) can be of great. In the present study, the effect of some known earthquakes (as by their seismograms) is illustrated on some presumed tunnel cross sections to evaluate the seismic behaviour of the ground-lining system. The analyses are based on a known finite element program and the results are expressed by the deformations or strains and the stresses within the lining and the ground immediately close to tunnel perimeter.

Keywords: tunnel, earthquake, analyses, seismograms.

1. Introduction

Though it was assumed generally for a long time that the tunnels are stable against the earthquake motions, but the responses of several tunnels (with or without lining) showed that there are some particular places within the underground spaces in which some degrees of damages or even collapses may be expected due to some strong earthquakes (Iida et al., 1996, Wang et al., 2001, Kontogianni et al., 2003). For this reason, many analytical and experimental researches have been curried out during last 3 decades in which different aspects of this subject have been seriously discussed; as examples of some recently published papers on this topic can be referred to Wang (1993), Penzien (2000), Hashash et al. (2001), Uenishi et al. (2001), AFPS/AFTES (2001), Choi et al. (2002), Adme (2004) and Hashash et al. (2005).

In order to evaluate the effect of different variables on the lining response, or on the stability characteristics of tunnel lining due to occurrence of

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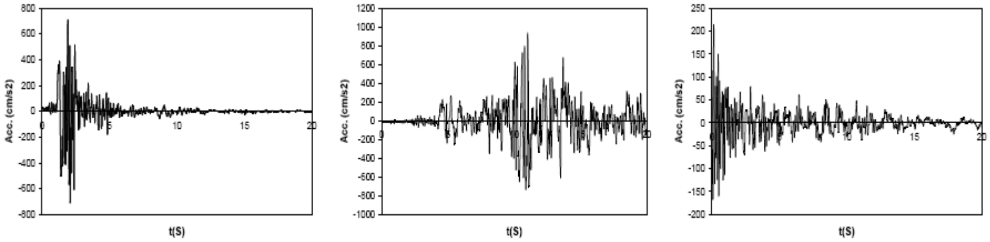
earthquake, an appropriate method is to perform some parametric numerical analyses. In the present article, the effects of some known earthquakes on some defined tunnel cross sections are studied. The relevant computations carried out by using a 2D finite element program (Plaxis) and applying the available three seismograms. The results can be classified in some main categories, from which only four aspects are chosen for presentation here: the effect of earthquake seismogram, the tunnel diameter, soil strength and the lining stiffness.

2. Computations and results

The domain of finite element mesh was selected as a rectangular of 600m length by 40m height with the adsorbing boundaries (based on Lysmer and Kuhlmeyer theory, 1969). The selected finite elements were 15 nodded triangles, and the interface elements for the tunnel- lining contacts. Three types of tunnel cross sections used: i.e. circular (normally 8m in diameter), square and horse shoe shape with different sizes. The depth of overburden in these analyses was 16m and the computations carried out under 70% (β coefficient as defined in plaxis) of total load applied on the lining for the static condition [1].

The seismograms of applied earthquakes (San Fernando in US, Naghan and Tabas in Iran) are shown in Fig. 1. Soil properties and lining characteristics are summarized in Table 1.



(a) Naghan (b) Tabas (c) San Fernando

Figure 1: Time history of three earthquakes

Table 1. Material Properties Examined in Finite Element Analyses

Material	γ (kN/m³)	*E* (MPa)	*c'* (kPa)	ϕ' (°)	ν	K_o	*t* (Cm)
Soil	20	60	60	30	0.3	0.5	-
Concrete lining	24	28000	-	-	0.15	-	30

Notes: γ=total unit weight; *E*=deformation modulus c'=soil cohesion; ϕ'=soil internal friction angle; ν=Poisson's ratio (both materials); K_o=lateral earth pressure coefficient; t=thickness of lining

Several computations carried out primarily to assure the reliability of results and to observe the effect of different variables. The variable parameters are mainly the type of cross section shape, the domain dimensions, soil properties and lining stiffness [2]. The results are expressed in terms of deformations and distortions of the tunnel perimeter, the axial force, the shear force and the bending moment inside the lining.

Seismograms are applied in time interval of 0.02 sec (for a total time of 20 sec) at the base of the soil layer (depth of 40 meter from the surface), while the attenuation coefficient is assumed to be 5% for all computations [3]. Though different types of illustrating the final results are available, but mostly the maximum values of the aimed quantities are extracted for comparisons, judgment and the discussion. Although there are many sets of results to be discussed, but in this article some relatively important results are shown [4]. An example of axial force distribution inside the thickness of lining around the opening perimeter is shown in Fig. 2 for two cases: without the earthquake conditions and with earthquake for the properties indicated in Table 1.

(a) static (b) dynamic

Figure 2. Comparison of axial force distribution around the lining perimeter for two cases

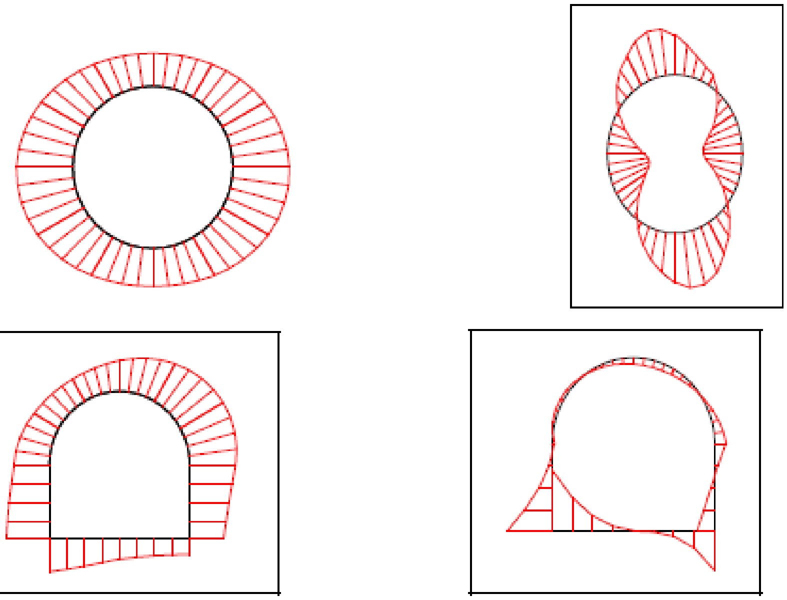
Also Table 2 illustrates the comparative quantities for three types of earthquakes. As it is expected, because of the difference between three earthquakes, the maximum amount of axial force, shear force and the bending moment occurred in the same lining are dependent on the magnitude and frequency content of the earthquake. These results correspond to the conditions of no slippage between the lining and the ground. It is well known that for different degrees of slippage we will get some other results. The results in table 2 indicate that by increasing the earthquake maximum acceleration, obviously the internal forces inside the lining ascend (compare lines 1, 3 and 4). Besides, two different seismograms with the same maximum acceleration results in different responses. This effect can be followed by comparing lines 2 and 3 in table 2.

Table 2. Comparison of calculated forces for three types of earthquakes

Line	Earthquake	T_{max} (kN)	V_{max} (kN)	M_{max} (kN.m)
1	San Fernando	31	9	14.72
2	San Fernando normalised to Naghan	181	58.23	112.41
3	Naghan	301	116.3	200
4	Tabas	491	253.52	389.2

Notes: T_{max}=Maximum axial force; V_{max}=Maximum shear force; M_{max}=Maximum moment

The influence of the shape of tunnel cross section on the axial force and the shear force in the lining occurs in due to Naghan earthquake is shown on Fig. 3.

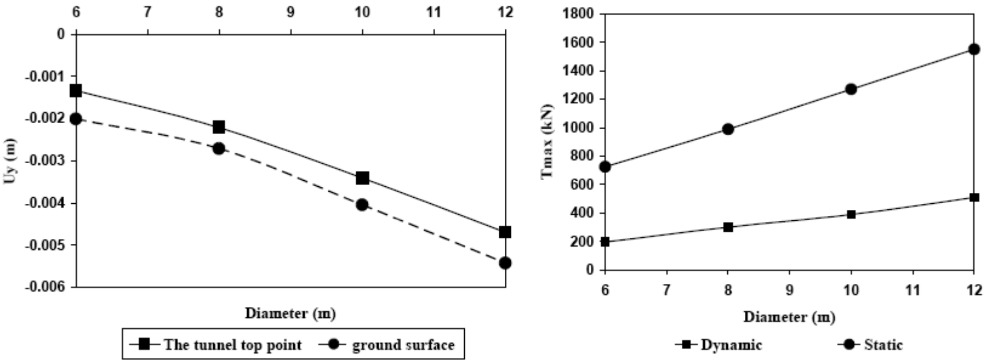


(a) Axial force

(b) Shear force

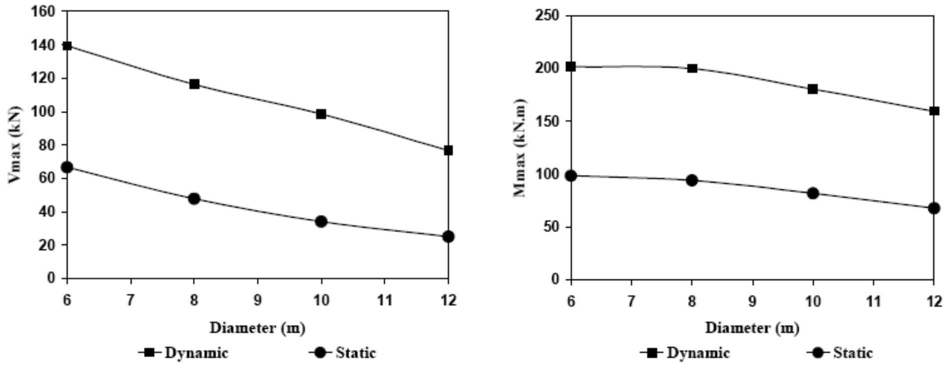
Figure 3. Comparison of axial force distribution and shear force distribution around the lining perimeter for two different shapes of cross section

The effect of tunnel diameter is another factor which can be interested in designing decisions. For this purpose tunnels with diameters of 6, 8, 10, and 12 meters inside the same ground conditions and the same lining properties (the properties as indicated in Table 1) were examined under the effect of Naghan earthquake. It is acceptable that if the thickness of lining is kept constant while the size of tunnel section becomes larger, because the relative stiffness of lining structure decreases, consequently the stresses within the lining change accordingly [5]. The effect of this parameter is illustrated in Figs. 4 to 5 for the vertical deformation of the tunnel top point and the ground surface (Fig.4a), for the maximum axial force inside the lining in the static and dynamic conditions (Fig. 4b). In Fig.5 the effect of tunnel diameter are shown for both static and dynamic conditions, For the maximum shear force inside the lining (Fig.5a) and for the maximum bending moment inside the lining [6] (Fig.5b).



(a) (b)

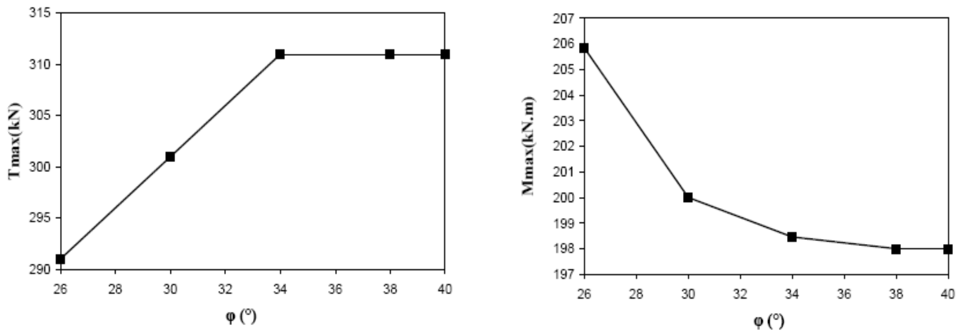
Figure 4. Effect of tunnel diameter on: a) vertical deformation and b) axial force in lining



(a) (b)

Figure 5. Effect of tunnel diameter on: a) shear force and b) bending moment of lining

It is of interest to know whether the ground properties can affect the earthquake response of the internal forces and moment inside the lining; and to what extent. For this reason some computations carried out with changing the friction angle and the cohesion of the surrounding soil. The results of relevant computations for the variation in friction angle are shown graphically on Fig.6. As can be concluded, because the friction angle is the major part of the ground strength, if its value is so small as the soil can yield, then the lining can response more freely compared to the case that the soil response behaves elastically. This difference in soil-lining response, results in the difference in the distribution of force and moment inside the lining for two mentioned cases.



(a) (b)

Figure 6. Effect of ground friction angle on: a) axial force and b) bending moment of lining

The influence of lining thickness is another section of this parametric study. Related to this topic, a flexibility coefficient has been defined (Penzien, 2000) as a function of lining thickness (and other properties):

$$F = \frac{E_m\left(1 - v_l^2\right)R^3}{6E_l I\left(1 + v_m\right)} \qquad (1)$$

Where E_m is the modulus of elasticity of the medium, I is the moment of inertia of the tunnel lining corresponds directly to the thickness (per unit width), R is the radius of the circular tunnel lining.

The relationship between this coefficient and the tunnel thickness is shown in Fig. 7 for a tunnel of 8 meter diameter. In Figs.8 to 9 the variations of computed values (from the present computations) of the internal forces and the bending moment as a function of the flexibility coefficient are illustrated in comparison to Penzien's solution (2000) and Wang's solution (1993) for the conditions of no slip between the lining and the ground [7].

These comparisons indicate that the results of PLAXIS agree well with the predictions by Penzien's and Wang's solutions for the moment and the shear forces, but for the internal axial force do not coincide with either of them.

However this comparison shows that Wang's solutions is much closer to the finite element results [8].

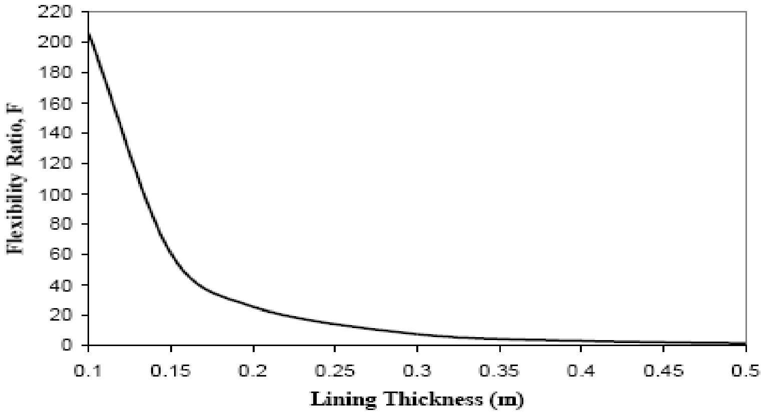
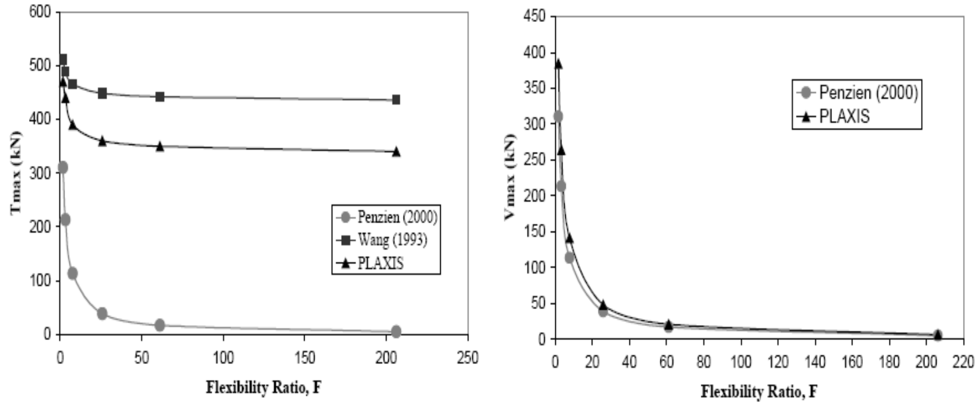


Figure 7. The relationship between flexibility ratio and the tunnel thickness

This means that the assumptions in his theory can probably agree more closely to the reality. For full slip cases all the curves resulted from the finite element and two mentioned theories are nearly coincided



(a) (b)

Figure 8. Comparison of a) Tmax and b) Vmax resulted from PLAXIS and closed form solutions (Wang (1993) and Penzien(2000)) in no slip condition

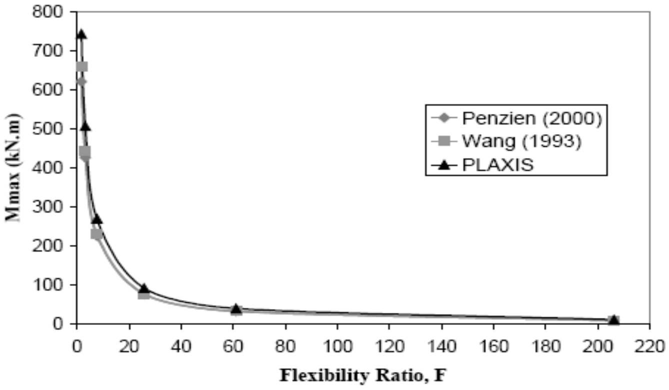


Figure 9. Comparison of Mmax computed by PLAXIS and closed form solutions (Wang(1993) and Penzien(2000)) in no slip condition.

3. CONCLUSIONS

The present study performed for understanding the effect of different variables on the earthquake response of the tunnels in shallow soft ground. The results indicate that all engineering factors can influence the results, but the significance of the effects is dependant on the earthquake maximum acceleration, and the type of the seismogram.

REFERENCES

[1]. *Z. Adme*, Analysis of NATM tunnel responses due to earthquake loading in various soils, 2004.

[2]. *I. Choi, J.S. Kim, J.M.,* Nonlinear earthquake response analysis of 2-D Underground, 2002.

[3]. *J.J. Schmidt, B. Yao,* Seismic design and analysis of underground structure. Tunnelling and Underground Space Technology", Vol.16, pp.247-293, 2001.

[4]. *H. Iida, T. Yoshida, N. Iwafuji,* Damage to Daikai subway station, 1996.

[5]. *Kontogianni, V.A. Stiros*, Japanese Geotechnical Society , pp.283 - 300, 2003.

[6]. *J. Earth*, Earthquakes and seismic faulting : Effects on tunnels, vol.12, pp. 153-156.

[7]. *Lysmer, J. Kuhlemeyer*, 1969. Finite dynamic model for infinite media.

[8]. *Uenishi, K. Sakurai, Mizoguchi,* PLAXIS: Finite element Package for Analysis of Geotechnical Structures. Delft, 2001