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The Seismic Behavior of Urban Tunnels in Soft Saturated Soils

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Abstract

Damages of the life lines were observed first in Nigata earthquake (1964) and then in the Alaska earthquake. After that, discussion about the earthquake effects on the underground structures became an important issue. Therefore, several studies were carried out about dynamic analyses of the underground structures. In Kobe earthquake (1995), most of the devastations happened in several urban subway. Taiwan earthquake (1999) is one of the examples of damages of underground structures in which many tunnels in the city center were highly damaged. 1999 Earthquake in Turkey is another example of subway structure damage in which highway tunnels were damaged severely. Also, several reports exist about the damages of large underground structures. Tangshan earthquake in china (1976) and Loma prieta earthquake in America (1989) are some examples of these kinds. Thus, many studies have been designed to focus on the effects of earthquake loading on the forces and displacements of underground structure. Gradual increments of excess pore pressure in soft saturated soil layers during earthquakes led to a decrease in the effective stress and this mechanism of underground structure seismic behavior has not been fully recognized; and despite the presence of several studies that have been conducted already, many others are still needed. So the present study strives to assess the effect of seismic behavior of urban tunnels as a life line in soft soils. In this paper the FLAC software has been used to model the pore pressure changes during earthquakes. The studies thus far have been focused on the impact of increasing the pore pressure and decreasing the effective stress in soft saturated soil on the tunnels constructed in this area.

Keywords: Life Lines; Tunnel; Soft Soils.

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1. INTRODUCTION

The damages resulting from seismic loading in soft saturated soils may cause underground structures to be buoyant and settle due to decreases in the bearing capacity and increases in the lateral earth pressure. For example, in Chi-Chi earthquake on 21th of September in 1999 in Taiwan, many surface structures such as bridges, roads and buildings were destroyed and some others were severely damaged (Chou et al., 2001) due to tilting and overturning. Several pieces of research and papers discussed the damages of small underground structures such as embedded pipes in soft soils (Hamada 1996, Koseki et al., 1997, O'Rourke et al 1991). Besides, few studies contain numerical and analytical methods (Wang et al., 1990) and experimental studies (Koseki et al.,1997, Ling et al 2003) performed on this topic. In these studies, uplifting the pipe lines are assessed in detail. Damages of large underground structures have also been reported. Regarding the case, Schmidt and Hashash report that some California tunnels in the Loma prieta earthquake (1989) became susceptible to buoyancy (Schmidt and Hashash 1998). Some researchers (Chou et al., 2001, Hashash et al., 2001, Hashash et al., 1998, Ohshima and Watanabe 1994, Stamos et al., 1995, John et al., 1987) such as Chou's have focused on this matter (Chou et al., 2001). Although there are few reports about damages to large underground structures, the rapid and extensive development of cities and their lifelines such as subways and underground structures, makes it quite necessary to investigate the effect of seismic behavior of soft saturated soils on these type of structures more extensively. Nigata (1964), Chubu-Nihonkai (1983), Luzon (1990), oki-Kushiro (1993) and oki-Hokkaido Nansei (1993) are the other examples of such cases (Japanese Society of Soil Mechanics and Foundation Engineering 1986, Japan Society of Civil Engineers 1993, Khoshnoudian 2002, Koseki et al., 1997, Matsumoto 1968).

When stresses and deformations of the tunnel lining increase, large deformations are observed in the area. Thus, improving the surrounding area of the tunnel, the stresses and deformations can be controlled and their magnitudes can be reduced to an allowable limit. As a part of the analysis of these forces and displacements, seismic loading effects are considered when designing underground structures, and so the equations are measured under small strains. Thus, the real results in surrounding tunnels and underground structures cannot be expressed by applying these equations when large strains due to some phenomena such as liquefaction occur. Therefore, the evaluation of seismic effects on the tunnel lining in soft saturated soils should be regarded as an important issue. In this paper the topic is assessed through the use of the FLAC software.

2. MODEL CHARACTERISTICS

The purpose of the article is to present the results of the study of the dynamic behavior of the tunnel in the soft saturated soils. For this purpose, a tunnel with the selected mesh shown in figure 1 is considered in the area. According to this figure, the tunnel is considered with 6 (m) interior diameter and the 30 (cm) thickness the center of which is located 10 (m) below the ground surface. In the analyses, first, the primary state (static analyses) is defined in drained conditions. Then the dynamic analysis is performed in undrained conditions.

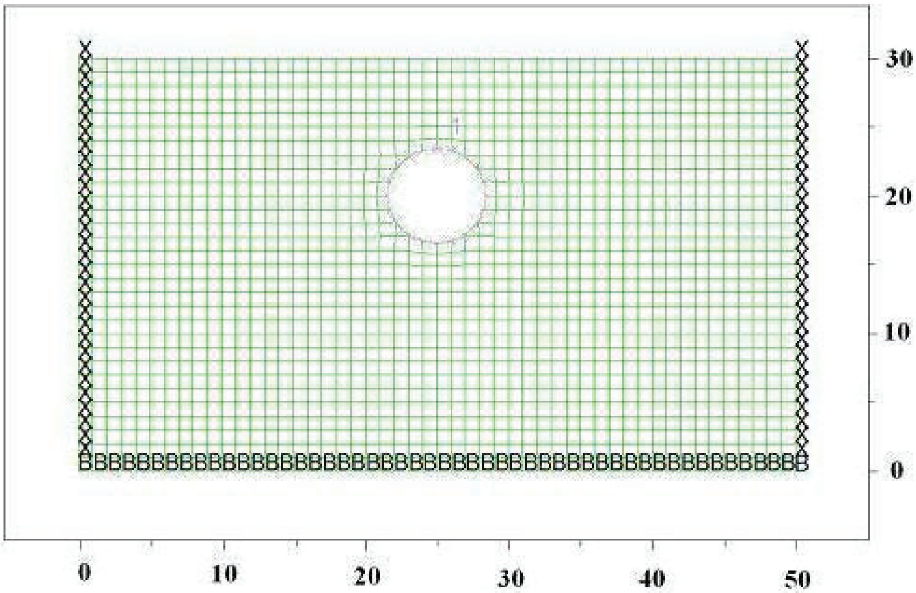

Figure 1- Display of mesh

Table 1- Soil properties

Shear Modulus (Mpa)	Bulk Modulus (Mpa)	φ (Degree)	C (Kpa)	γ_d (kN/m^3)	K (m/sec)
20	30	25	0	15	10^{-4}

The general properties of soil in the model are provided in table 1. In this model the water table is considered to be at the ground surface. Regarding the assessment of seismic effects in the soft saturated soil, the soil behavior modeling should be used to consider the excess pore pressure for undrained condition. The Finn model is capable of considering variations of the volumetric strain and shows the increase of excess pore pressure under these conditions.

The dynamic loading in the model is defined by a sinusoidal wave with the amplitude of 0.1g and frequency of 1 (Hz). The load duration is 10 (s). Meanwhile, the damping ratio is 5% and free field conditions are considered for the dynamic boundaries. In this condition, the reflection of waves in the model is prevented and the boundaries act as adsorbent boundaries.

3. ASSESSMENT OF THE RESULTS

Figures 2 and 3 show variations of the pore pressure at different points at the top and bottom of the tunnel and figure 4 illustrates a case of the effective stress variations in the area. According to these figures, an increase in the cyclic load time results in increasing the pore pressure and decreasing the effective stress in soft saturated soils. Likewise the results of the analyses show the tunnel uplift is about 42.7 (cm), which seems too much. If the tunnel lining has a segmental construction in which these segments are jointed together by bolt and hinged support, the uplift can cause devastations of the two adjacent segments. This topic has been assessed in several papers (Khoshnoudian 2002, Liu and Song 2005). It seems that the uplift of the underground structures may affect the ground surface in the tunnel location. Based on the analyses, the amount of heave due to the tunnel uplift in the ground surface is approximately 24.5 (cm), the value of which sharply decreases when shifting away from the tunnel centerline. Figure 5 shows variations of the ground surface from the tunnel centerline up to 15 meters away at each side.

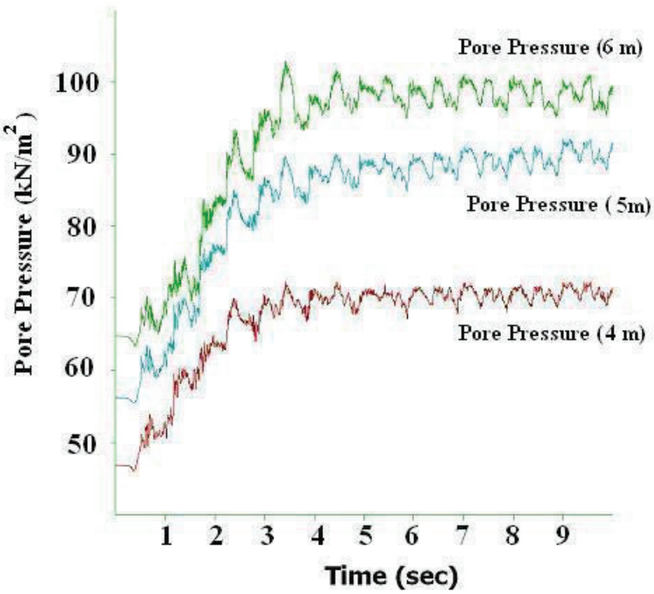

Figure 2- Variations of the pore pressure at depths of 4 to 6 (m)

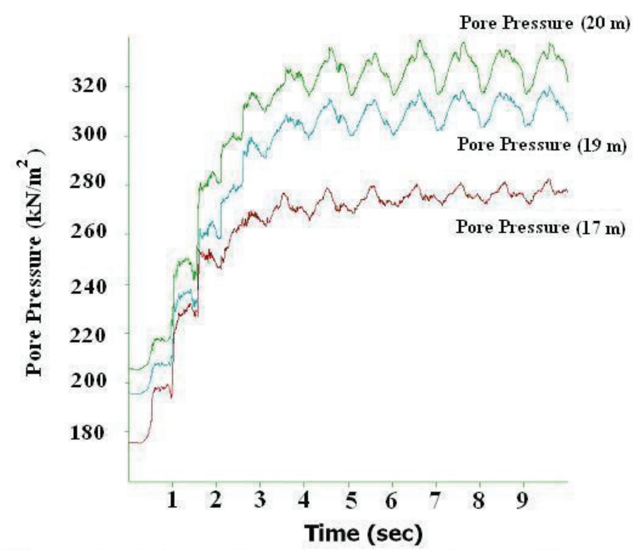

Figure 3- Variations of the pore pressure at depths of 17 to 20 (m)

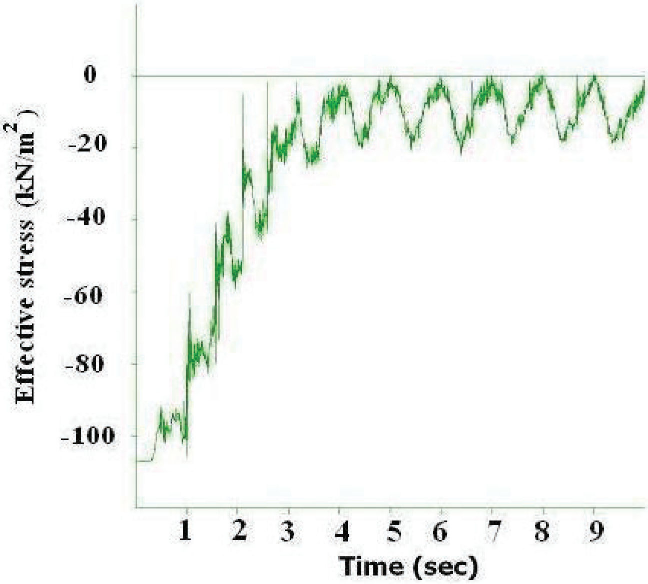

Figure 4- Variations of the effective stress at depth of 19 (m)

Based on the analyses results, the bending moment induced in the tunnel lining increases up to 16.5 (ton-m) during cyclic loading. However, applying further load cycles causes it to decrease about 33%, reaching to 11.1 (ton-m). Besides, According to the results of these analyses on the model, the maximum values of the axial and shear forces in the static analyses are 62.1 and 4.08 (ton) and in the end of the dynamic analyses, these forces reach 73.5 and 9.7 (ton) respectively.

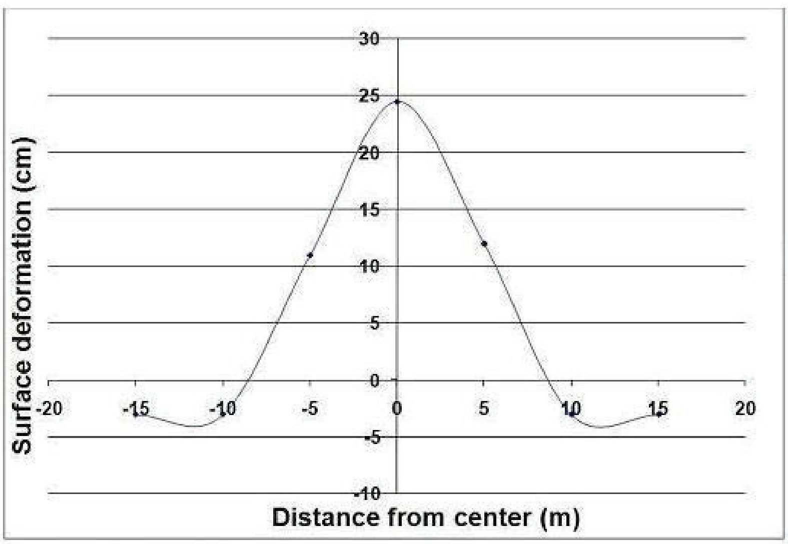

Figure 5- Variations of the surface settlement versus distance from tunnel center

4. CONCLUSIONS

In this paper, the seismic effects of the soft saturated soil on forces and bending moment of the tunnel lining have been evaluated by using FLAC software. For this purpose, the tunnel is considered with 6 (m) diameter and the center of which is located 10 (m) below the ground surface. Then the effect of dynamic loading on the variations of stresses in the soil and bending moment and forces in the tunnel lining has been assessed. In the modeling, the Finn model is used to consider the excess pore pressure for undrained condition and the dynamic loading in the model has been defined by a sinusoidal wave. According to this assessment, an increase in the cyclic load time results in increasing the pore pressure and decreasing the effective stress. The results of the analyses show the tunnel uplift is about 42.7 (cm) and the ground surface is approximately 24.5 (cm), which seems too much. Based on the analyses results, the bending moment induced in the tunnel lining increases and then decreases about 33% during cyclic loading. Besides, the maximum values of the axial and shear forces in the end of the analyses increase about 15.5% and 57.9%. It is necessary to remember these consequences are very important in the design of the tunnel lining in the soft saturated soils.

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