A Simplified Method for the Seismic Analysis of Urban Transportation Tunnels

Seyed J. Faraji, Zhang Qingping, Mahdi Shadab Far, and Hadi Kordestani, Seyed Y. Faraji

***Abstract*—**By a quick look at the states, it can be realized that many cities in the world with rapid and considerable growth suffer from three key problems including road safety, air pollution and urban traffic management [6]. Due to the reasoning ability, humans have always looked forward the best environment and comfort and therefore tried to find operational solutions to solve these problems. So, one of the fundamental steps in this direction is construction of safe and reliable buildings and structures**.** Accordingly, in this paper, attempt has been made to develop a simplified procedure in which the equivalent static method, the vertical and horizontal seismic loading as well as the effect of soil-tunnel interaction have been studied. The results of this study although can model the behavioral characteristics of the tunnel and surrounding soil, do not have any certain complexity and can easily be used for analyzing the transportation tunnels under earthquake loads.

***Keywords*—**Urban transport, interaction of soil–tunnel, tunnel response, racking stiffness, ductility, shear strain

I. Introduction

Urban transportation has been always considered as a key issue in urban and regional studies. But it can be mentioned that while transportation is the key configuration and skeleton in the efficiency and success of cities, nowadays, with the spread of urbanization phenomenon, especially in developing countries, present transportation capacity is not sufficient for people demands [2]. Thus with the development of urbanization, transportation does not meet the urban traffic needs of people. However, the rapid growth of metropolitan cities in the world with the increasing population has caused several problems including traffic problems and disruption to the transport system within the city. Hence, the problem has been one of the fundamental challenges facing urban planning in the late twentieth century that has affected the sustainable urban development. While one of the features and characteristics of the desirable urban environment are the easy, fast and reliable access of citizens to the various parts of the city [17]. So we can say that the relationship between transport planning and urban planning should be considered important from the perspective of contemporary urban management.

Urban areas are responsible to service the economic and social needs of their residents and transportation system is the most essential factor. Since about 25% of world energy consumption is in the transportation within the city, the transportation is one of the major concerns in the sustainability of cities [9]. One of the most important issues that play a role in the sustainability of cities is the systematic conduct of urban traffic. The city managers taking advantage of the new engineering capabilities have tried to contribute the human society using the concrete structures such as tunnel and provide a more sustainable urban development. Apart from the fact that the structure can be lead to a mass graveyard in a very large cost due to the incorrect monitoring in natural disasters like earthquakes. Therefore, a careful review and analysis of these structures can avoid many problems.

Hence, the aim of this study was to present a simple method for the dynamical analysis of transportation tunnels in front of earthquake and its importance for urban management system. So that it would be easier to face one of the most important structures of urban transportation in today's world.

II. Importance of Seismic Analysis

Action and communication are the foundations of the human society and this principle highlights its place more and more in today’s world. In a world where communication has an important role, undoubtedly there are ways to make these connections. Apparently, the human societies are based on the urban framework and its systematic systems while the dominant communication lines form the highways of each city. Those lines start from the highways and introduce the narrow streets to the human community.

In this century, the technology is developing so rapidly and the transportation is like a vital artery which its weaknesses will hinder the daily life and economic, political, social and cultural activities [14]. Besides transportation, working and spending the spare time is regarded as one of the four basic functions [11]. The management system in cities must be considered the healthy and sustainable transportation.

In this regard, one of the measures that have been performed in the urban management systems in order to face the transportation flow is taking advantage of the new engineering in urban areas. One of the aspects of this engineering is the

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urban transportation tunnels that are increasingly growing in the world.

In fact, transportation is one of the basic needs of the urban life and its organization is considered as one of the basic needs of each healthy city. Meanwhile considering the tunneling plays an important role in the urban traffic control and its systematical management.

The behavior of urban transportation against the dynamic soil activities and earthquake is one of its main problems. It would bring irreparable problems for the planning system of each country in the case of error estimates.

Earthquake effects on buried and semi-buried structures have been due to the interaction of soil-structure, including challenging problems in structural and earthquake engineering and have always been difficult due to the computational complexity of the problem. Therefore, understanding the analysis of existing urban tunnels can increasingly reduce the financial load related to the urban management system and also a higher safety factor can be achieved for calculations. But unfortunately most of the numerical methods to calculate the dynamic state of such tunnels have been very complex and time consuming and this has made the monitoring of tunnels states very difficult, an issue that is very important especially in earthquake-prone countries.

Despite all these interpretations, we have found the detailed dynamical analysis field of urban transportation tunnels using a very simple numerical method and have attempted to promote it in this paper. In this paper we easily analyzed this important urban structure and achieved the desired result while it can be a substantial contribution to the urban management system. Since even a manager who is not informed much about a concrete structure such as a tunnel can review and analyze it, while it can be an advantage in monitoring s these vital urban projects.

III. A REVIEW OF THE LITERATURE

The issue of earthquake and tunnels has been studied in numerous articles such as Villy A. kontogianni's paper entitled "earthquakes and seismic faulting: effects on tunnels" in 2003. This paper provided some examples to describe the vulnerability of tunnels against earthquake [15].

As study about tunnels was conducted by Y. kojima & k. yashiro entitled "Basic studies on earthquake damage to shallow mountain tunnels" that was presented at the 2008 World Tunnel Congress. This article refers to a general description about tunnels and states that they are reasonably resistant until the Earth is stable, but they can be changed after the earthquake and may bring a lot of damages. Finally this paper investigates the studied tunnel in India and examines its vulnerability to earthquakes [5].

Another study was conducted by lin Junqi et al. entitled "Evaluation of tunnels in earthquake" that was presented in the 2008 Beijing World Conference on Earthquake. This paper deals with the assessment of damages caused by earthquake and the resulted damages are divided into five sections (no damage, minor damage, moderate damage, major damage and dilapidated). Grading the tunnels in this article is based on the extent of damage suffered by the tunnel and finally the extent of damage is evaluated by replacing the obtained numbers in the formula and the preferred method is recommended for the final evaluation [7].

N. HOSSENI et al. also conducted a study entitled "Seismic analysis of horseshoe tunnels under dynamic loads to earthquake" that was presented at *Wollongong University's* online research in 2010. This paper analyzes the effect of seismic strain on horseshoe tunnels and also refers the influence of earthquakes on tunnels, so that it makes clear that if the pressure caused by the seismic loads has a devastating effect on the stability of the tunnel or not [10].

Of other studies about tunnels behavior, can mention an article entitled "Computation of Primary Tunnel Support" by Lidija Frgic et al. (2005) in which stress and strain of tunnels have been studied by using the Boundary Element Method (BEM) [4].

"Probabilistic Models for Seismic Risk Analysis" is another article by Ileana Corbi which has been presented in WSEAS conference. This paper utilized a statistical method to simulate the effect of seismic signals on structures and show the correspondence between the simulated and real models [3].

Although the methods mentioned above each have their own strengths, but have lots of computational complexities due to the use of certain numerical methods, so that they cannot be used practically by the engineering community. Hence, this paper has attempted to present a step-by-step method for the tunnel seismic analysis in an equivalent static method using the experiences gained from the previous works and new numerical methods. So that it should not have computational complexities but the accuracy is required.

IV. EQUIVALENT STATIC FORCE

To analyze the tunnel in an equivalent static method, at first the equivalent static load must be calculated to apply to the tunnel. Therefore consider a rectangular tunnel such as figure 1 that is located in the depth H of the free ground surface.

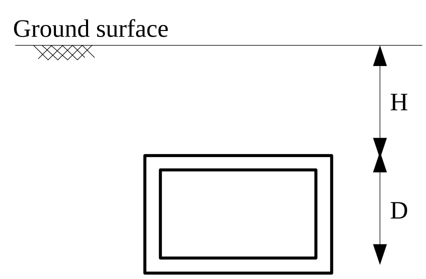

Fig. 1 a section of rectangular cross tunnel

To calculate the equivalent static force by earthquake, at first the relative displacement between the top and bottom of the tunnel must be calculated. Therefore the first step is:

Step 1: Free-field shear strain (At the level of the tunnel axis) that was created due to the vertical propagation of shear waves is calculated as follows, and then the displacement between the top and bottom of the tunnel is obtained by multiplying the shear strain by the height of the tunnel.

$$\sigma_V = \gamma (H + D) \quad (1)$$

$$\tau_{\max} = \frac{PGA}{g} \times \sigma_V \, R_d \quad (2)$$

$$\gamma_{\max} = \frac{\tau_{\max}}{G} \quad (3)$$

$$\Delta_{free-field} = H \times \gamma_{\max} \quad (4)$$

In the above equations:
γ = Weight per unit volume of soil around the tunnel
H = Tunnel depth
D = Tunnel height
R_d = Strength reduction factor

$$= \begin{cases} 1 - 0.00233z & for \quad z < 30\ ft \\ 1.174 - 0.00814z & for \quad 30\ ft < z < 75\ ft \\ 0.744 - 0.00244z & for \quad 75\ ft < z < 100\ ft \\ 0.5 & for \quad z > 100\ ft \end{cases}$$

G = The shear modulus of the soil around the tunnel

Analysis of soil response to earthquake-induced waves may bring a more accurate answer for $\Delta_{free\text{-}field}$. That is why it is recommended to perform this analysis for tunnels in soft soil.

In the next step, the tunnel stiffness must be calculated, while the necessary amount of force to move the tunnel is equal to 1 unit. Therefore, we use the step 2.

Step 2: To calculate K_S (Racking stiffness for tunnels), according to Figure 2, the tunnel walls must be modeled in a software (such as SAP) and then be placed under a load at ceiling level. When the ceiling level displacement is equal to the unit, the amount of force will show K_S. It should be noted that firstly the tunnel's wall floor bearing must be closed in line with force but it must rotate, secondly the inertia moment of the cracked section must be used in modeling the tunnel's wall.

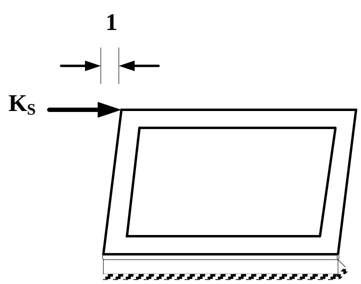

Fig. 2 How to calculate the Racking stiffness

In the next step, the ductility ratio of the tunnel should be calculated. Therefore we perform the step 3.

Step 3: the ductility ratio of the tunnel, F_r, is calculated as follows:

$$F_r = \frac{G}{K_S} \times \frac{W}{H} \quad (5)$$

In the above equation:
W = Width of the tunnel's wall
H = Tunnel's depth
G = The shear modulus of the soil around the tunnel
K_S = Racking stiffness of tunnel structures

In this step, the racking coefficient should be calculated. For this purpose, we use the step 4.

Step 4: racking coefficient, R_r, is calculated using the ductility ratio of the tunnel that was calculated in the previous step. Racking coefficient is the ductility ratio of the tunnel in soil into the deformation calculated in step 1, $R_r = \Delta_S / \Delta_{free\text{-}field}$.

According to the study of *Jaw-Nan (Joe) Wang*, the relationship between Racking deformation and ductility ratio is as follows [16].

When the structure is not entirely placed in soil:

$$R_r = \frac{4(1 - \nu_m)}{3 - 4\nu_m + F_r} \quad (6)$$

When the structure is entirely placed in soil:

$$R_r = \frac{4(1 - \nu_m) F_r}{2.5 - 3\upsilon_m + F_r} \quad (7)$$

When F_r is zero, the stiffness of the structure is infinite, or in other words, the structure is rigid, there will be no Racking deformation in the tunnel. In other words, the tunnel is completely resistant to soil and does not deform [8].

When F_r is 1, the Racking deformation in the tunnel will be the same as the soil deformation. It seems as if the tunnel had no effect on the deformation applied by the soil. When F_r is more than 1, racking deformation in the tunnel is bigger than the soil deformation [12].

It has also been proved that when the tunnel structure has no stiffness, (when $F_r \to \infty$), R_r will be equal to $4(1-\upsilon)$ [1].

Racking deformation of the tunnel should be calculated in the next step. For this purpose, we use the step 5.

Step 5: Racking deformation of the tunnel structure is calculated by multiplying R_r by $\Delta_{free\text{-}field}$.

$$\Delta_S = R_r \times \Delta_{free-field} \quad (8)$$

Step 6 is used as the final step to calculate the internal forces and stresses.

Step 6: seismic demands are obtained as the internal forces and material strain by applying Δ_s to the tunnel structure.

V. Loading the Tunnel

As also shown in Figure 4, two types of dummy loading must be used in order to apply Δ_S to the tunnel structure, Whichever had more critical response should be used as the design base. In other words, the loading must be applied incrementally like the two following figures, so that the displacement of the tunnel roof level reaches to Δ_S.

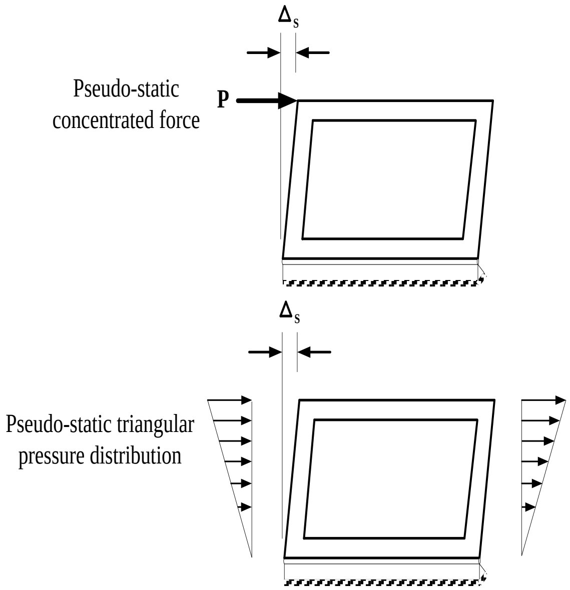

Fig. 3 How to apply displacement

VI. Vertical force of earthquake

To calculate the vertical forces of vertical propagation of shear waves, the vertical seismic coefficient that is 2/3×PGA/g must be multiplied by the combination of loads used in the static analysis. This vertical force must be applied to both the upward and downward directions. Finally the seismic demands of the tunnel structure are calculated by combining the loads of Racking deformation and vertical propagation of waves and are used for design [16].

VII. Conclusion

In this paper, the importance of tunnel behavior in urban transportation system and also the effect of earthquake on transportation tunnels were presented. In this regard, the equivalent static method was examined s for analyzing rectangular tunnels under earthquake forces. And benefiting from previous studies, including the works by Jaw-Nan (Joe) Wang and also taking into account the interaction of soil-tunnel, a simple step by step method was provided for analyzing transportations tunnels. The results of this study had no complications and can simply be used to analyze rectangular tunnels. The simplicity of this method can help the urban managers in the systematic management of underground transportation structures and provide a better understanding of these vast and complex structures.

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