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# A Review on the Dynamic Vibrations Relationship in the Metro Tunneling

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***Abstract-***In this paper, investigate on dynamic relationships and soil-tunnel interaction is discussed. Practical wave motion input method for Rayleigh wave propagation problems in time domain is proposed and applied to dynamic analysis of tunnel entrance model. Reasonable simulation result and desirable accuracy is accomplished with the proposed approach. The generation model analyzing the dynamic interaction between the rolling stock and the railway superstructure, and a propagation model describing the vibration transmission through the tunnel lining and the surrounding soils.

***Keywords-*** *dynamic vibrations, metro tunneling, deformations, earthquake*

## I. INTRODUCTION

In recent years, the environmental vibration produced by running trains has attracted much interest because high-speed railway construction is in rapid development. The vibration can vary in the range of almost 2–200 Hz on the ground surface and create a tribulation or malfunctioning to sensitive equipment. Therefore, it is indispensable for designers to predict and appraise the environmental vibration at the beginning of planning and designing a railway transportation system [1].

Dong Wu et al. (2013) were investigate on dynamic analysis of tunnel entrance under the effect of Rayleigh wave and they result that The analysis result matches well with part of field observation for damaged tunnels entrance in Wenchuan Earthquake, which indicates that the effect of Rayleigh wave should be paid sufficient attention in the research on seismic performance of tunnel entrance [2].

Taiyue et al, conducted research with numerical simulation on strata consolidation subsidence by dewatering, dynamic dewatering, and non-dewatering construction method, taking the integrated effects of fluid-solid coupling and tunneling mechanics into account. We obtained the curved surfaces of ground surface subsidence and strata consolidation subsidence. The results show that the non-dewatering construction method is the most effective method to control the strata consolidation subsidence induced by metro tunneling in saturated soft clay strata, and it has been successfully applied to the construction of the Shenzhen metro line 1 [3].

S. A. Mazek et al used a 2-D finite element analysis to understand the performance of the Cairo metro tunnel system-Line 3. The analysis takes into account the change in stress, the non-linear behavior of the soil, and the construction progress [4].

DING De-yun et al, investigated on Prediction of vibrations from underground trains on Beijing metro line 15, and the numerical results show that the influence of vibrations from underground trains on sensitive equipment depends on the track types. At frequencies above 10 Hz, the floating slab track with a natural frequency of 7 Hz can be effective to attenuate the vibrations [5].

Also Angelo Amorosi et al, investigated on Numerical prediction of tunnel performance during centrifuge dynamic tests, and a comparison between numerical analyses and centrifuge test results relative to the seismic performance of a circular tunnel is provided. The comparison between numerical simulations and measurements is presented in terms of acceleration histories and Fourier spectra as well as of profiles of maximum acceleration along free-field and near-tunnel verticals. In addition, loading histories of normal stress and bending moments acting in the tunnel lining were considered [6].

Underground metro networks can provide an effective solution to transport demand problems within a sustainable development framework although they can be characterized by high environmental impact [7-9].

Since the contact area between wheel and rail is much wider than conventional steel to steel contact, interaction forces are much lower than those experienced in conventional railways and therefore vibration are likely to be greatly reduced. However, even for these systems, there is the need to develop prediction tools in order allow transport engineers to assess potential vibration impact and to analyse suitable mitigation solutions [10].

The model can be split into due sub-models according to the usual phenomenological approach to the problem:

The generation model analyzing the dynamic interaction between the rolling stock and the railway superstructure, and a propagation model describing the vibration transmission through the tunnel lining and the surrounding soils.

The novel feature of the model is to allow the coupling between the two sub-models. The model main features and the case study where it has been calibrated are reported in the followings.

## II. DESCRIPTION OF MATHEMATICAL MODEL

The dynamic forces transmitted to the subgrade that are liable for the ground-borne vibration generations are usually calculated by means of mathematical models representing the dynamic behavior of the whole-vehicle superstructure excited by the irregularities of the track. Mathematical models employed can be grouped according to the specific component described in the followings [10]:

- vehicle models,
- rail defects models,
- rail superstructure models,

In order to evaluate vibration induced by railway traffic, a common approach is to solve the dynamic interaction between the vehicle and the superstructure and then to apply the vertical dynamic forces evaluated so far to a propagation models. However this procedure is not always correct since the dynamic response vehicle-superstructure- subgrade system should be examined as a whole.

In the proposed mathematical model, the dynamic interaction between the vehicle, the rail defects, the railway superstructures and the surroundings soils or structures are examined in a unique system. As far as the mathematical description of the model is concerned, if the connection between the railway superstructures and the surrounding soils/structures is considered as discrete (i.e. acting in a finite amount points) the following interaction forces can be identified:

$$F_{wr} = K_H.(y_w - y_p - y_r) \quad (1)$$

At the wheel-rail level, where:
$F_{wr}$ is the vertical interaction force at the wheel-rail level,
$K_H$ is the Hertzian Spring Stiffness,
$y_w$ is the vertical displacement of the wheel, $y_p$ is the vertical displacement of rail defects, $y_r$ is the vertical displacement of the rail, and:

$$F_{rs} = (K_R + j.w.C_R).(y_r - y_s) \quad (2)$$

At the rail-soil/structure level, where:
$F_{rs}$ is the vertical interaction force rail-soil/structure level,
$K_R$ is the Elastic Stiffness of the Rail pad or of the rail support,
$C_R$ is the Damping Coefficient of the Rail pad or of the rail support,
$j$ is the imaginary unit,
$w$ is the circular frequency,
$y_r$ is the vertical displacement of the rail,
$y_s$ is the vertical displacement of the soil/structure.

It is worth to be noticed that equation (1) can be written for each of the $m$ contact points between the vehicle and the rail, whereas equation (2) can be written for each of the n contact points between the rail and the underlying soil/structure [10].

## III. RESPONSE OF TUNNEL TO THE SPREAD WAVES FROM EARTHQUAKE AND SCRUTINY OF CHANGE IN PRODUCT

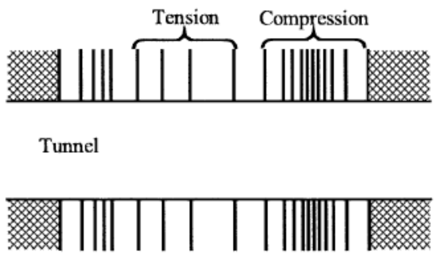
Response of tunnel to the ground vibrations caused by the movement of the waves can be classified into three main categories below:

a) Axial and Curvature Deformations
b) Oval shape deformation (circular cross section)
c) Rotation deformation or rocking (Rectangular cross section)

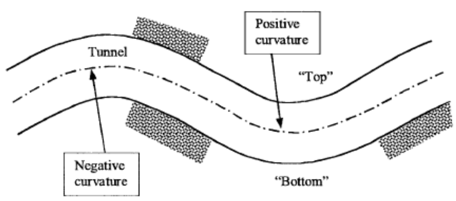
In horseshoe tunnel, distortion of cross-section as a combination of circular and rectangular sections deformations occur. In the following explanation is provided about each of these deformations.

### A. Axial and Curvature Deformations

Axial and curvature deformations develop in a horizontal or nearly horizontal linear tunnel (such as most tunnels) when seismic waves propagate either parallel or obliquely to the tunnel. The tunnel lining design considerations for these types of deformations are basically in the longitudinal direction along the tunnel axis. Figure 1 shows the idealized representations of axial and curvature deformations. The general behavior of the linear tunnel is similar to that of an elastic beam subject to deformations or strains imposed by the surrounding ground [11].




(a)




(b)

Figure 1. Idealized representations of (a) Axial Deformation, (b) Curvature Deformation

To determine the axial and Curvature deformations can be used one-dimensional models. Perhaps the simplest way to consider this tunnel as a structural beam. But for larger tunnels, it is necessary that three dimensional models used to estimate these deformations. Relations (1) and (2) can be used to estimate the free-Field stresses:

$$\sigma_{max} = \pm \rho V_p |V_{peak}| \tag{1}$$

$$\tau_{max} = \pm \rho V_s |V_{peak}| \tag{2}$$

In this relationship:
$\sigma_{max}$ :maximum axial stress
$\tau_{max}$: maximum shear stress
ρ: Density of the Materials
$V_P$ :P wave velocity
$V_s$ :S wave velocity
$V_{Peak}$: The peak particle velocity in the direction of propagation
$V_{n,Peak}$ :The peak particle velocity in the direction perpendicular to the propagation

## *B. Ovaling or Racking Deformations*

The ovaling or racking deformations of a tunnel structure may develop when waves propagate in a direction perpendicular or nearly perpendicular to the tunnel axis, resulting in a distortion of the cross-sectional shape of the tunnel lining. Design considerations for this type of deformation are in the transverse direction [11].

Figure 4 shows the ovaling distortion and racking deformation associated with circular tunnels and rectangular tunnels, respectively. The general behavior of the lining may be simulated as a buried structure subject to ground deformations under a two-dimensional, plane-strain condition.

Ovaling and racking deformations may be caused by vertically, horizontally or obliquely propagating seismic waves of any type. Many previous studies have suggested, however, that the vertically propagating shear wave is the predominant form of earthquake loading that governs the tunnel lining design against ovaling/racking. The following reasons are given:

Ground motion in the vertical direction is generally considered less severe than its horizontal component. Typically, vertical ground motion parameters are assumed to be 1/2 to 2/3 of the horizontal ones. (Note that a vertically propagating shear wave causes the ground to shake in the horizontal direction.) This relation is based on observation of California earthquakes, which are most commonly of the strike-slip variety in which horizontal motion predominates [11].

For thrust faults, in which one rock block overrides another, vertical effects may equal or exceed the horizontal ones. The effects of thrust faulting are usually more localized, however, than those of the strike-slip faulting, and they are attenuated more rapidly with distance from the focus [11].

For tunnels embedded in soils or weak media, the horizontal motion associated with vertically propagating shear waves tends to be amplified. In contrast, the ground strains due to horizontally propagating waves are found to be strongly influenced by the ground strains in the rock beneath. Generally, the resulting strains are smaller than those calculated using the properties of the soils [11].

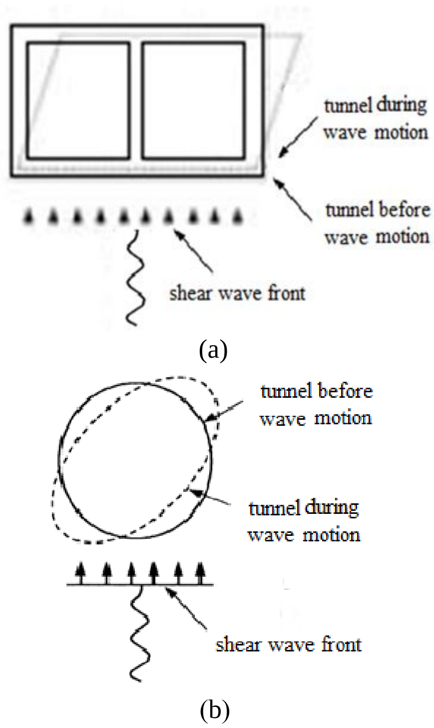



Figure 2. (a) Racking Deformation of a Rectangular Cross Section (b) Ovaling Deformation of a Circular Cross Section

concentrate on Rotational stresses can using equations (3) and (4) that free-Field of stress can be estimated as follows:

$$\sigma_{max} = \pm k_1 V_p |V_{peak}| \tag{3}$$

$$\tau_{max} = \pm k_2 V_s |V_{peak}| \tag{4}$$

In this relationship:

$K_1$: dynamic stress concentration factor for P wave, that defined as shown in Figure 3.

$K_2$: dynamic stress concentration factor for S wave, that defined as shown in Figure 4.

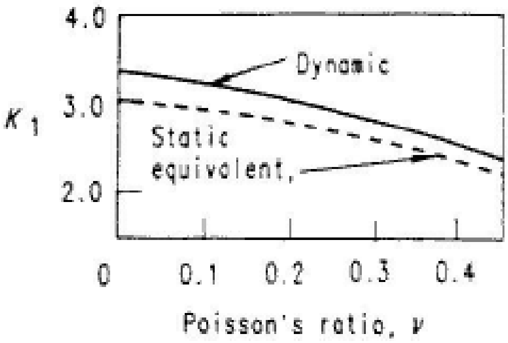



Figure 3. The relationship between the dynamic stress concentration factor ($K_1$), for P-wave and Poisson ratio

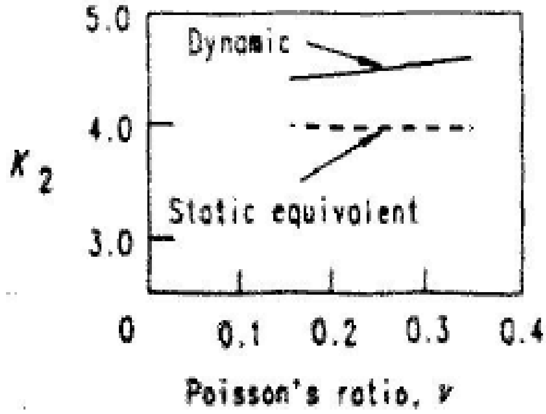



Figure 4. The relationship between the dynamic stress concentration factor ($K_2$), for S-wave and Poisson ratio

Above equations to estimate the maximum dynamic stresses around a cylindrical underground spaces without the cover, have been provided, that with little change they can also be used to cover tunnels [11].

*C. Analytical solutions of ovaling deformation of circular tunnel with soil–structure interaction*

The simplest form of estimating ovaling deformation is to assume the deformations in a circular tunnel to be identical to ‘‘free-field’’, thereby ignoring the tunnel– ground interaction [12]. This assumption is appropriate when the ovaling stiffness of the lined tunnel is equal to that of the surrounding ground [12].

The circular tunnel–ground shearing is then modeled as a continuous medium (referred to as non-perforated ground) without the presence of the tunnel (Fig. 5), in which the diametric strain for a circular section is calculated as Eq (8) in Hashash et al. (2001) [13]:

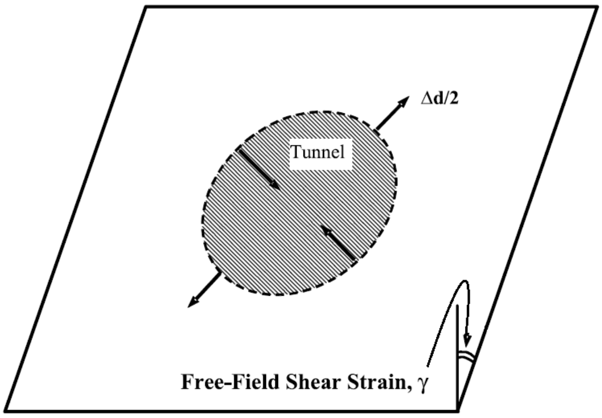



Figure 5. Free-field shear distortion of perforated (tunnel cavity is empty) and non-perforated ground (tunnel cavity is filled), circular shape

$$\frac{\Delta \mathrm{d}_{\text{free-field}}}{\mathrm{d}} = \pm \frac{\gamma_{max}}{2} \tag{5}$$

If the ovalling stiffness is very small compared to the surrounding ground, the tunnel distortion or diametric strain is calculated assuming an unlined tunnel as Eq (9) in Hashash et al. (2001) [13], (referred to as perforated ground):

$$\frac{\Delta \mathrm{d}_{\text{free-field}}}{\mathrm{d}} = \pm 2\gamma_{max} \left(1 - \nu_m\right) \tag{6}$$

This deformation is much greater in the case where the presence of the tunnel is included compared to the case where only the continuous ground deformation is assumed [12].

## IV. CONCLUSION

In this paper, a methodology to estimate the level of vibration induced by railway traffic has been proposed. In horseshoe tunnel, distortion of cross-section as a combination of circular and rectangular sections deformations occur. Also two available analytical solutions to compute induced forces and deformations due to ovaling deformation of a circular tunnel are presented. The solutions provide identical results for the condition of full-slip between the tunnel lining and the ground but differ in values of the calculated thrust for the condition of no-slip.

Also ground motion in the vertical direction is generally considered less severe than its horizontal component. Typically, vertical ground motion parameters are assumed to be 1/2 to 2/3 of the horizontal ones.

# REFERENCES

[1] H, R. Nejati. M, Ahmadi. H, Hashemolhosseini. M, Hayati. "Probabilistic Analysis of Ground Surface Vibration Due to Train Movement, a Case Study on Tehran Metro Line 4" Geotech Geol Eng 30, pp.1137–1146. 2012.

[2] D, Wu. B, Gao. "Dynamic Analysis of Tunnel Entrance Under the Effect of Rayleigh Wave" EJGE, Vol. 18, Bund. S, pp. 4231-4246. 2013.

[3] QI, Taiyue. B, GAO. "Strata consolidation subsidence induced by metro tunneling in saturated soft clay strata" Journal of Modern Transportation Volume 19, Number 1, March, pp. 35-41. 2011.

[4] S,A, Mazek. H,A, Almannaei. "Finite element model of Cairo metro tunnel-Line 3 Performance" Ain Shams Engineering Journal 4, pp.709–716.2013.

[5] D, De-yun. L, Wei-ning. S, GUPTA. G, LOMBAERT. G, DEGRANDE. "Prediction of vibrations from underground trains on Beijing metro line 15" J. Cent. South Univ. Technol. 17, pp. 1109−1118.2010.

[6] A, Amorosi. D, Boldini. G, Falcone. "Numerical prediction of tunnel performance during centrifuge dynamic tests" Acta Geotechnica, 25 November 2013, Springer, Verlag Berlin Heidelberg, DOI 10.1007/s11440-013-0295-7, 2014.

[7] M, D'Apuzzo. V, Nicolosi. "Evaluation of pavement-oriented countermeasures to mitigate traffic induced vibrations in urban areas". 5th European Conference on Noise Control: EURONOISE, May 19th-22nd 2003, Naples, Italy, pp. 1-6. 2003.

[8] M, Crispino. M, D'Apuzzo. R, Lamberti. "Development and experimental validation of a prediction model to assess railway induced vibrations". 5th European Conference on Noise Control: EURONOISE, May 19th-22nd 2003, Naples, Italy, pp.1-6. 2003.

[9] V, Aiello. D, Boiero. M, D'Apuzzo. F, Silvestri. V, Socco. "Experimental and numerical analysis of vibrations induced by underground trains in urban environment". Journal of Structural Control and Health Monitoring, Vol. 15, DOI: 10.1002/stc.247, Wiley InterScience, pp. 315-348. 2008.

[10] V, Nicolosia. M, D'Apuzzob, E, Bogazzi. "A Unified Approach for the Prediction of Vibration Induced by Underground Metro" Procedia - Social and Behavioral Sciences 53, pp. 62 – 71. 2012.

[11] Jaw-Nan (Joe) Wang." Seismic Design of Tunnels A Simple State-of-the-Art Design Approach". Parsons Brinckerhoff Quade & Douglas, Inc. June 1993.

[12] Y.M.A, Hashash. D, Park . J, I-C, Yao." Ovaling deformations of circular tunnels under seismic loading, an update on seismic design and analysis of underground structures " Tunnelling and Underground Space Technology 20 . pp. 435–441.2005.

[13] Y.M.A, Hashash. J.J, Hook. B, Schmidt. J.I.-C, Yao. "Seismic design and analysis of underground structure". Tunn. Undergr. Sp. Technol. 16, pp.247–293. 2001.