Fast frequency-domain analysis method for longitudinal seismic response of super-long immersed tunnels

Méthode d'analyse rapide dans le domaine fréquentiel pour la réponse sismique longitudinale d'un tunnel immergé à super longueur

Huang M., Liu H.
Department of Geotechnical Engineering, Tongji University, Shanghai, China

ABSTRACT: This research is prompted by the need of a practical project, which is a sea-crossing immersed tunnel between Hong Kong, Zhuhai and Macao (HZM) in China. Longitudinal seismic response of the immersed tunnel is the main focus of this paper. Based on the Fast Fourier Transformation and the theory of dynamic elastic Winkler foundation beam, a modified response displacement method in the frequency domain is proposed in this paper. Inertia of the tunnel and the dependance of dynamic stiffness coefficients on external loading frequency are considered and seismic response of the HZM tunnel is analyzed using the proposed method. Finally, some useful suggestions for aseismic design and analysis are presented.

RÉSUMÉ : Cette recherche est motivée par la nécessité d'un projet concret, qui est un tunnel immergé traversée maritime entre Hong Kong, Zhuhai et Macao (HZM) en Chine. Réponse sismique longitudinale du tunnel immergé est l'objet principal de cet article. Basé sur la transformation de Fourier rapide et la théorie de l'élasticité dynamique Winkler poutre de fondation, une méthode de déplacement modifié de la réponse dans le domaine fréquentiel est proposé. Inertie du tunnel et de la dépendance des coefficients de rigidité dynamique à la fréquence de chargement externe sont considérées comme, et réponse sismique du tunnel HZM est analysée en utilisant la méthode proposée. Enfin, quelques suggestions utiles pour la conception sismique et de l'analyse sont présentés.

1 INTRODUCTION

Recently, the Chinese government is building a large sea-crossing bridge connecting Hong Kong, Zhuhai and Macao(HZM), which is about 35.578 km long and will be the most long sea-crossing bridge after being constructed. The super-long submarine immersed tunnel(Fig. 1) over 6 km, which will be the first long immersed tunnel in the world after being built, is a very important component part of the HZM bridge. Analysis of the seismic safety of the tunnel is essential for engineering design since the HZM immersed tunnel is located at the Circum-Pacific earthquake zone. Moreover, the introduction of a simplified analysis method is also important and urgent because there is no specific code to date in China for the seismic design of immersed tunnels. Considering that the safety of the tunnel under longitudinal vibration is more important than that under lateral and vertical vibrations, this paper focuses mainly on computational methods for the seismic response of immersed tunnels under longitudinal seismic loading.

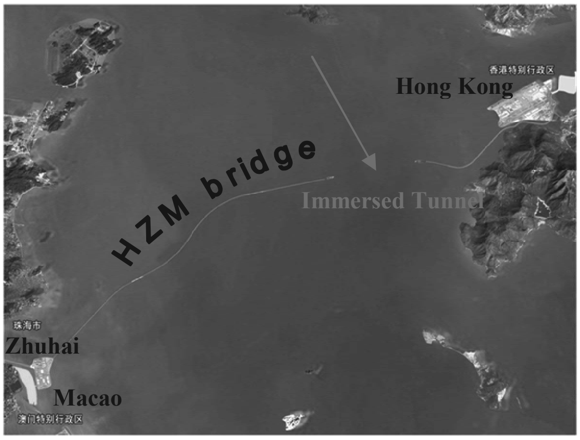

Figure 1. Location of Hong Kong-Zhuhai-Macao immersed tunnel

A number of analysis methods have been presented in the literature for computing the longitudinal seismic response of immersed tunnels. Originally, the standard for longitudinal seismic design of immersed tunnels was established during the process of constructing the Bay Area Rapid Transit (BART) system in San Francisco (Kuesel, 1969). Axial deformation due to longitudinal vibration was estimated using a simple analytical expression. BART approach was adopted in the seismic design of Kinuura Port tunnel (Aoki & Maruyama, 1972). Later, in 1988, the Japanese Society of Civil Engineers released an earthquake resistant design code for immersed tunnels, with two principal approaches of ground deformation method and dynamic response method presented (Kiyomiya, 1995). In the authors' opinion, the two methods could be all categorized as the response displacement method because the principle of them is almost identical, namely the seismic response of tunnels is estimated by applying the seismic displacement of strata around tunnels to immersed tunnel structures. However, there is still one difference between them - that is, the external loading applied to the tunnel structure corresponds the maximum response displacement of soil for the first one, whereas that is the dynamic response displacement of soil for another one. The dynamic response method is used to design the immersed tunnel across the Pearl River in China (Han & Zhou, 1999). In addition, there is another simple analytical model in which an immersed tunnel structure is discretized into a series of particles and combined with soil springs. The seismic response of tunnels is investigated by applying the ground seismic acceleration to soil springs at the base of tunnels. The model had been utilized to analyze the seismic response of several practical projects in different countries (e.g. Hamada, 1984; Kiyomiya & Tanabe, 1994; Anastasopoulos et al., 2007). With the development of computer technology, 3D dynamic finite element method has become a major way of computing seismic response of 3D tunnels. A number of studies have been reported in related literature (e.g. Stamos & Beskos, 1995 and 1996; Hatzigeorgiou & Beskos, 2010). Despite the more accuracy of 3D dynamic finite method, the cost of this method is too expensive to be used in the actual engineering design.

The presently available methods have several disadvantages including (1) computational efficiency is low when they are used to computing seismic response of super-long immersed tunnels; (2) the effects of frequencies of excitation on foundation impedances cannot be considered; (3) inertia of tunnels is often neglected in most methods. This paper presents a modified response displacement method in the frequency domain so as to overcome the defects in the present analysis methods.

2 RESPONSE DISPLACEMENT METHOD BY JSCE

The response displacement method introduced here is based on a mass-spring model presented by the JSCE in 1988. It is assumed in this model that shear motion is the main vibration mode of strata on bedrock under seismic loading. In addition, there is another assumption that self-vibration characteristics of soil layers are not influenced by the existence of the tunnel. The soil around the immersed tunnel along the longitudinal direction is modeled as a series of particles. The springs and dashpots are used to connect adjacent particles, as well as particle and bedrock. The multi-segment tunnel is modeled as a beam with longitudinal translational springs located at segment joints. The segments and its surrounding soil particles are connected through calibrated interaction springs and dashpots (Fig. 2).

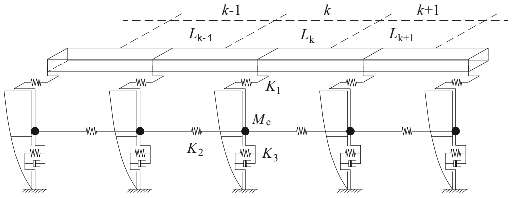

Figure 2. Mass-spring model under longitudinal seismic loading

The response displacement method is a pseudo-static analysis approach and consists of two steps: (1) determining the free-field ground seismic deformation without considering the presence of tunnel; (2) imposing the ground deformation obtained in step one on the tunnel structure as a static load. The computational process in detail is described as follows.

3 SEISMIC DEFORMATION OF FREE FIELD

Seismic deformation of free field can be derived by solving dynamic equilibrium equation of the mass-spring model. According to D'Alembert principle, the dynamic equilibrium equation can be expressed as

$$[M_s]\{\ddot{u}_s\}+[C]\{\dot{u}_s\}+[K]\{u_s\}=-[M_s]\{\ddot{u}_g\} \quad (1)$$

where M_s, C and K = lumped mass coefficient, damping coefficient and stiffness coefficient, respectively; u_s = response displacement of soil particles; and u_g = seismic acceleration at the base of bedrock. The elements of tridiagonal symmetric stiffness matrix are expressed as

$$k_{11}=k_3(1)+k_2(1) \quad (2)$$

$$k_{i,i}=k_3(i)+k_2(i)+k_2(i-1) \quad (i=2,3,\cdots,n\text{-}1) \quad (3)$$

$$k_{n,n}=k_3(n)+k_2(n-1) \quad (4)$$

$$k_{i,i\text{-}1}=-k_2(i-1)(i=2,3,\cdots,n) \quad (5)$$

where k_3 = spring between soil particle and bedrock; k_2 = spring between adjacent soil particles; i = the number of the soil particle; and n = number of soil particles.

Seismic displacement of the free-field soil at the base of the immersed tunnel can be obtained by

$$\{u_b\}=[\alpha]\{u_s\} \quad (6)$$

where u_b = displacement of tunnels; and α = ratio of soil displacement at the base of the tunnel to that of soil particles. The calculation method for α is not given in this paper due to limitation of the space and the specific computational process have been presented in detail in the related reference (Zhou, 1989).

4 INTERNAL FORCE OF THE TUNNEL STRUCTURE

The tunnel structure is modeled as a Winkler elastic foundation beam with joints, which is simplified into translational springs to simulate the behavior of compressing and tension of GINA gaskets under seismic loading (Fig. 3). The seismic response of the tunnel is obtained by applying the seismic displacement of free field to interaction springs between the tunnel and strata without considering the inertia of the tunnel. The seismic displacement of the tunnel can be obtained by

$$[K_t]\{u_t\}=[K_1]\{u_b-u_t\} \quad (7)$$

where K_t and K_1 = stiffness matrix of the tunnel and interaction spring, in which K_1 is frequency-independent static stiffness; u_t = seismic response displacement of the tunnel.

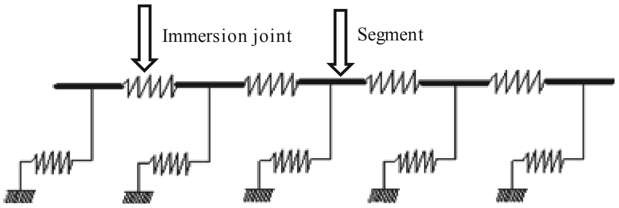

Figure 3. Simplified model of the immersed tunnel structure for response displacement method

5 MODIFIED RESPONSE DISPLACEMENT METHOD

Based on the Fast Fourier Transformation (FFT) technique and the theory of dynamic elastic Winkler foundation beam, a modified response displacement method is presented in this paper. Inertia of the immersed tunnel can be considered in this method as well as the dependency of soil-tunnel interaction parameters on the frequency of external seismic loading.

5.1 *Seismic deformation of free field*

According to FFT, Eq. (1) given in Session 2.1 is changed into

$$-\omega^2[M_s]\{U_s(\omega)\}+(1+2i\xi)[K_s]\{U_s(\omega)\}=-\omega^2[M_s]\{U_g(\omega)\} \quad (8)$$

where $U_s(\omega)$ and $U_g(\omega)$ = Fourier amplitude of particle and input seismic displacements, respectively; i = the imaginary unit; ξ = frequency-independent hysteretic damping ratio of the soil; and ω = external frequency of seismic loading. The response displacement of soil particle u_s in the time domain can be obtained by the inverse Fast Fourier Transformation (IFFT) of $U_s(\omega)$.

Likewise, eq. (6) can be changed into

$$\{U_b(\omega)\}=[\alpha]\{U_s(\omega)\} \quad (9)$$

where $U_b(\omega)$ = Fourier amplitude of the displacement of the soil at the base of the tunnel. Accordingly, the seismic displacement of the free-field soil at the base of the tunnel u_b in the time domain can be obtained by IFFT of $U_b(\omega)$.

5.2 *Internal force of the tunnel structure*

Inertia of the tunnel and dependence of soil-tunnel interaction parameters on external frequencies are taken into account in the modified response displacement method. The tunnel structure is discretized into a series of particles, which is combined with the soil through interaction springs and dashpots (Fig. 4). In addition, the form of external loading is the seismic acceleration of soil at the base of tunnel, which is different from the original response displacement method. Finally, the seismic response of the immersed tunnel is obtained by exerting the seismic acceleration on the tunnel through interaction springs and dashpots. The specific mathematical expression of the physical model in the time domain is

$$[M_t]\{\ddot{u}_t\}+[C_{ts}]\{\dot{u}_t\}+[K_{ts}]\{u_t\}=-[M_t]\{\ddot{u}_b\} \tag{10}$$

where M_t = lumped mass of the tunnel particle; C_{ts} = damping coefficient of the system shown in Fig. 4; and K_{ts} = stiffness coefficient which is constituted of K_t and K_1.

In the frequency domain, Eq. (10) will become

$$-\omega^2[M_t]\{U_t(\omega)\}+[K_{ts}]\{U_t(\omega)\}+2i\xi[K_1]+i\omega[C_s]\{U_t(\omega)\} = -\omega^2[M_t]\{U_b(\omega)\} \tag{11}$$

where $U_t(\omega)$ = Fourier amplitude of displacement of the tunnel structure; K_1 = frequency-dependent dynamic stiffness; and C_s = frequency-dependent radiation damping coefficient of the soil.

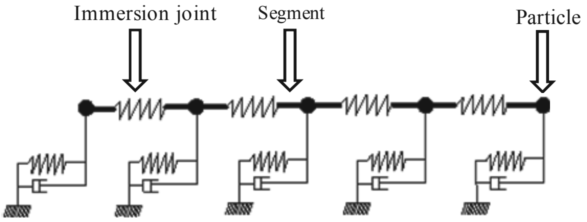

Figure 4. Simplified model of the immersed tunnel structure for modified response displacement method

6 DYNAMIC SPRING STIFFNESS AND RADIATION DAMPING COEFFICIENT

The stiffness of interaction springs is regarded as a static stiffness independant of the external excitation frequency in the response displacement method. Actually, the spring stiffness is related to the seismic excitation frequency, which have been considered in the modified response displacement method. The dynamic stiffness of interaction springs can be defined as

$$k_1 = k_{stat}k_0(\omega) \tag{12}$$

where k_1 = dynamic spring stiffness shown in Fig. 2; k_{stat} = static spring stiffness; and $k_0(\omega)$ = dyanmic stiffness coefficient. Similar to the dynamic impendance of embedded foundations proposed by Gerolymos & Gazetas (2006), the dynamic stiffness coefficient $k_0(\omega)$ and radiation damping can be approximately expressed as

$$k_0(\omega)=1+a_0\frac{D}{B}\left[\left(0.08-0.0074\frac{D}{B}\right)a_0^2 -\left(0.31-0.0416\frac{D}{B}\right)a_0-0.0442\frac{D}{B}+0.14\right] \tag{13}$$

$$C_s=\rho v_s A_b c_{sur}(\omega)+\rho v_s A_{ws} \tag{14}$$

where D and B = the height and width of the tunnel cross section, respectively; $a_0=wB/2v_s$ = dimensionless frequency; and v_s = shear wave velocity of the soil; ρ = soil density; A_b = base area of the tunnel; A_{ws} = the sum of sidewall areas parallel to loading; and $c_{sur}(\omega)$ = radiation damping of surface foundations.

7 SEISMIC RESPONSE ANALYSIS OF HZM TUNNEL

The modified response displacement method is used to analyze the seismic response of the HZM immersed tunnel. Moreover, the calculation results by the modified response displacement method are compared with that by the response displacement method.

The soil along the longitudinal direction of the HZM immersed tunnel is simplified into one particle every 22.5m, which means that there are 253 soil particles altogether. The computational model containing the whole immersed tunnel is set up in this paper in terms of the multi mass-spring model shown in Fig. 2. Analysis results in seven different positions along the longitudinal direction of the tunnel location are given in this paper (Fig. 5), and the other results are not presented considering the limited space. Time history and frequency spectrum of the input seismic acceleration are shown in Fig. 6.

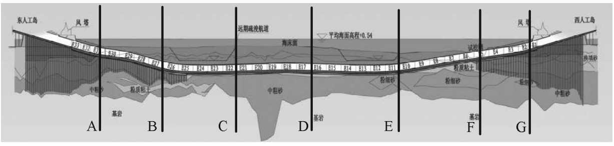

Figure 5. Profile of the HZM immersed tunnel

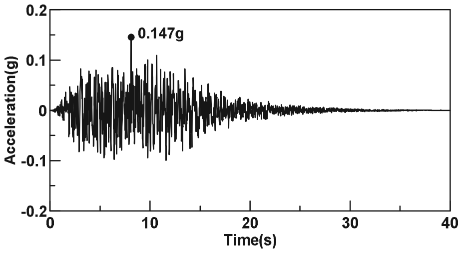

Figure 6. Time history of input seismic acceleration

8 DYNAMIC ANALYSIS RESULTS - SOIL AMPLIFICATION

Due to space limitation, only the time history of seismic acceleration at location A is given in this paper, which is shown in Fig. 7. Peak accelerations of seven different positions are illustrated in Table 1. It can be readily seen that seismic acceleration of the soil is apparently amplified compared with the peak acceleration 0.147g of input seismic motion. The reason of this is that natural vibration frequency of the site soil is relatively low, and the input seismic acceleration is also characterized by the low frequency contents.

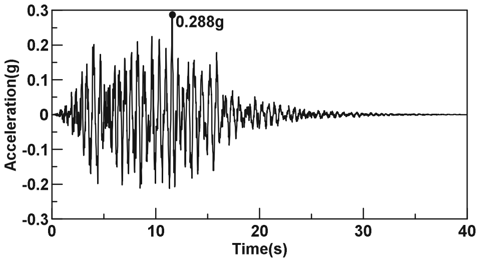

Figure 7. Time history of seismic acceleration at location A

Table 1: Peak acceleration in different positions

Location	Peak acceleration/g
A	0.288
B	0.28
C	0.241
D	0.275
E	0.322
F	0.283
G	0.255

9 DYNAMIC ANALYSIS RESULTS - AXIAL FORCE AND JOINT DEFORMATHON OF THE TUNNEL STRUCTURE

In this paper, the initial values of internal force and deformation of the tunnel under static loads have been removed from the final analysis results. The time history of axial force at location A is shown in Fig. 8 using the response displacement method (RDM) and modified response displacement method (MRDM), respectively. Moreover, peak values of the axial forces in seven different positions are given in Table 2. It can be seen that the values of axial force at both sides of the tunnel are much larger than those in the middle of the tunnel despite anyone of the two approaches, therefore the soil foundation at both sides of the tunnel should be reinforced for resisting the earthquake loading. It is also readily seen that the computed results using MRDM are larger than that using RDM, which means that inertia of the tunnel plays such an important role in the seismic response of the tunnel that it cannot be neglected. Therefore, it is suggested that the purely dynamic analysis method, i.e., MRDM, should be employed for seismic design of immersed tunnels.

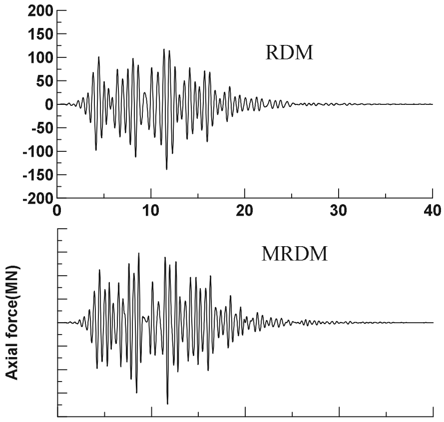

Figure 8. Time history of axial force at location A

Table 2: Axial force of segments in different positions (MN)

Location	RDM	MRDM
A	138.80	173.30
B	28.55	111.70
C	37.73	74.70
D	9.32	20.88
E	41.34	79.91
F	35.66	72.05
G	98.97	96.34

Table 3 and Table 4 show the net maximum tension and compression of GINA joints under seismic loading. It can be seen that the values of deformations of joints at both sides of the tunnel are much larger than those in the middle of the tunnel in the two approaches, which is analogous to that of the axial force. Moreover, it is concluded that excessive tension and compression will not occur under proper design of segment joints, which is not discussed here in detail in view of the space limitation.

Table 3: Maximum tension of joints in different positions (mm)

Location	RDM	MRDM
E31\E30	-8.2	-13.0
E27\E26	-3.3	-6.6
E22\E21	-2.0	-4.4
E17\E16	-1.0	-2.9
E11\E10	-3.4	-7.3
E6\E5	-0.5	-1.3
E2\E1	-10.8	-12.7

Table 4: Maximum compression of joints in different positions (mm)

Location	RDM	MRDM
E31\E30	8.4	14.1
E27\E26	2.8	5.3
E22\E21	2.1	3.7
E17\E16	1.1	2.9
E11\E10	3.4	7.0
E6\E5	0.5	1.3
E2\E1	10.4	12.9

10 CONCLUSIONS

At the basis of the present response displacement method, this paper presents a new modified response displacement method, which can consider the inertia of the tunnel as well as the dependance of soil-tunnel interaction parameters on external seismic frequencies. Inertia of immersed tunnels play a vital role in the seismic response of immersed tunnels, and hence the modified response displacement method with the dynamic soil-tunnel interaction parameters should be adopted in the practical engineering design. Although this research is prompted by need of a specific project, the proposed method is universal and can be applied to analysis and design of other immersed tunnel projects.

11 ACKNOWLEDGEMENTS

The writers acknowledge the financial support provided by the National Key Technology Research and Development Program of China through Grant No. 2011BAG07B01.

12 REFERENCES

Anastasopoulos, I., Gerolymos, N., Drosos, V., Kourkoulis, R., Georgarakos, T. and Gazetas, G. 2007. Nonlinear Response of Deep Immersed Tunnel to Strong Seismic Shaking. Journal of Geotechnical and Geoenvironmental Engineering, 9:1067-1090.

Aoki, Y. And Maruyama, H. 1972. Spectra for earthquake-resistive design of trench type tunnel. Report of the PHRI 11:4 , 292-314.

Gerolymos, N. and Gazetas, G. 2006. Winkler model for lateral response of rigid caisson foundations in linear soil. Soil Dynamics and Earthquake Engineering, 26: 347-361.

Hamada, M. 1984. Earthquake observation on two submerged tunnels and numerical analysis. Proceedings of 8th World Conference on Earthquake Engineering, 3: 673-680.

Han, D.J. and Zhou, A.X. 1999. HUANG Yan-sheng. Aseismic analysis and design of the pearl river tunnel(I)¬-time domain response method. Journal of South China University of Technology, 27(11):115-121.

Hatzigeorgiou, G.D. and Beskos, D.E. 2010. Soil–structure interaction effects on seismic inelastic analysis of 3-D tunnels. Soil Dynamics and Earthquake Engineering ,30:851-861.

Kiyomiya, O. 1995. Earthquake-resistant design features of immersed tunnels in Japan. Tunnelling and Underground Space Technology, 10: 463-475.

Kiyomiya, O. and Tanabe, G. 1994. Dynamic response analysis of immersed tunnel considering of non-linearity of flexible joint. Paper presented at the Twenty-eighth Meeting of the Japan Soil Mechanics and Foundation.

Kuesel, T.R. 1969. Earthquake design criteria for subways. Journal of the Structural Divisions, ASCE, 95(ST6): 1213-1231.

Stamos, A.A. and Beskos, D.E. 1995. Dynamic analysis of large 3-D underground structures by the BEM. Earthquake Engineering and Structural Dynamics, 24(6): 917–34.

Stamos, A.A. and Beskos, D.E. 1996. 3-D seismic response of long lined tunnels in half- space. Soil Dynamics and Earthquake Engineering, 15:111–8.

Zhou, A.X. 1989. Analysis of seismic response of immersed tunnels. South China University of Technology, Master dissertation.