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Seismic Analysis of Shallow Tunnels in Soil Medium

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Abstract. In both urban and national frameworks, tunnels form vital components of the transport and utility systems. They are being constructed in densely populated urban zones and metro cities at an expanding rate to promote rising space and passage requirements. Occurrence of any sort of seismic activity in that particular region may cause damage of these infrastructure. Hence, a careful consideration of the impacts of seismic loadings on the analysis and design of tunnels is required as a part of hazard evaluation. Different closed form analytical approaches exist, such as methods given by Wang and Penzien for seismic analysis of shallow tunnels. Ovaling deformations occur when seismic waves propagate perpendicular to the axis of tunnel and are therefore, designed for the transverse direction. In this paper, these two analytical solutions are used for the analysis of tunnel lining forces, constructed in soft to hard soil with various mechanical properties and constant shear strain. Seismic analysis carried out by means of selecting eight unique types of soil, very soft clay to highly dense sand. The study indicates a relative error in both analytical methods. It was found that the variations in thrust and bending moment are dependent on the flexibility ratio, thus, it is proposed that the stress distribution to be considered for analysis and design of tunnels lining. It is also seen that the induced circular stress in the tunnel liner is decreased with increasing soil stiffness.

Keywords: Shallow tunnel, seismic analysis, analytical solution, flexibility ratio

1 Introduction

Exponential growth in the population and infrastructure development in the last decade created the space problem on the Earth surface and pushed the human society to go underground. Most commonly constructed underground structures are tunnels, shafts and caverns. Tunnels are being constructed at an increasing rate in densely populated urban areas and metro cities to fulfill the expanding needs of space and passage. Tunnels may subjected to different types of dynamic loading conditions like impact load, blast load and seismic load. Tunnels constructed in earthquake prone areas must withstand both static load and seismic load. Sometimes it becomes impossible to avoid construction of tunnels in the areas which have already suffered historical earthquakes in past due to infrastructural demand. There are strong probability of damage of these infrastructures, if not designed properly considering the seismic effects. Hence, a careful consideration of the seismic loading effect on the analysis, design, construction, operation and damage evaluation is of great importance. There are chances of damage of these infrastructure because of any kind of seismic activities in that area.

In last decade, we have experienced several devastating earthquakes causing significant damages of tunnels in developed countries including China, Taiwan and Japan. The 1995 Hyogoken-Nambu earthquake in Kobe, Japan caused failure of underground Daikai station of railway tunnel of Kobe which shows that tunnels are vulnerable to seismic wave propagation if not designed properly. The combined effects of ground shaking and ground permanent deformation during the 1999 Kocaeli earthquake in Turkey caused collapse of the twin Bolu tunnel. Tunnel portals of Mizusawa tunnel and Longxi tunnel failed due to strong shaking during Chuetsu Earthquake (2004), Japan, and Wenchuan Earthquake (2008), China respectively. From these historical events it is clear that lack of understanding about the earthquake hazards in seismically vulnerable areas has increased the probability of failure of tunnel structures resulting into economical loss of the nation. Hence, the necessity has grown to study and evaluate the seismic hazard in earthquake prone areas and stability of tunnels to mitigate the damages of these infrastructure postured by such catastrophism.

To understand the seismic response of the tunnels, different approaches are adapted including closed form analytical solution, numerical modelling and physical modelling. To estimate the seismic internal forces of tunnels' linings, many researchers proposed the analytical solutions under certain assumptions and conditions, e.g. elastic response of the soil and the tunnel lining and simulation of seismic loading in quasi-static fashion. The analytical solutions are useful, relatively fast and easy to use for preliminary seismic design of tunnels. In the present study, analytical solutions suggested by Wang and Penzien used to investigate the circular shaped shallow tunnel located in earthquake prone area having soil media. For this purpose, classified soils including clay, silt, sand and gravel with different Poisson ratio and elastic modulus considered. Effect of various soil parameters and maximum shear strain was evaluated using sensitivity analysis.

2 Tunnel Deformation under Seismic Loading

It is assumed that tunnels can undergo three basic modes of deformation during seismic shaking: (1) longitudinal compression or extension; (2) longitudinal bending and (3) ovaling or racking. Type of deformation is decided depending on the mode in which seismic waves propagate either longitudinal or transverse direction of the tunnel axis. Earthquake induced ground shaking along the longitudinal axis of a tunnel causes axial deformations and longitudinal bending whereas for shaking in the transverse direction, the tunnel undergoes ovaling (for circular sections) or a combined racking-rocking distortion (for box-shaped sections), with racking prevailing [4].

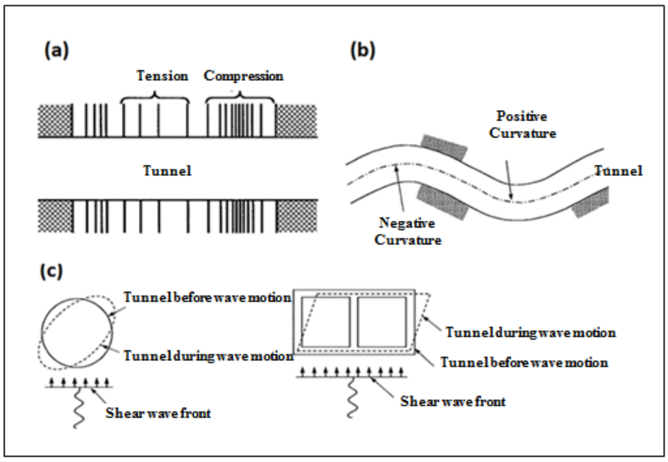

Fig. 1. Tunnel deformation: (a) axial compression and extension, (b) longitudinal bending, (c) Ovaling and racking [4]

The first seismic design basis for underground structures was proposed based on Newmark's pioneering work [3, 7]. The closed form solutions are based on slip between soil medium and tunnel. At the time, these solutions provided a very useful tool for practicing engineers to estimate the seismic behaviour of tunnels under ground shaking in both longitudinal and transversal directions. Free field deformation approach used to estimate the strains and curvature of the tunnel for ground motions propagating at an angle to the tunnel axis and furthermore proposed some modifications to account for soil-tunnel interaction effects. The soil tunnel interaction effects examined and provided two solutions, one for full slip and another for no slip contact interface conditions [8]. Similar analytical solutions developed for thrust, shear force, and bending moment in the tunnel lining due to racking deformation [6]. Later, a complementary analytical procedure provided for racking deformation evaluation of rectangular and circular tunnels [6]. For no slip condition, maximum thrust is much lower for Penzien's solution in case of no slip condition [2]. The response of tunnel lining depends on the factors like flexibility ratio and compressibility of the structure, and the in situ overburden pressure and coefficient of earth pressure (K_0) of soil at rest.

2.1 Wang's Analytical solution

The closed form analytical solutions for the maximum thrust and bending moment in tunnel lining due to ovaling deformations due to earthquake loading proposed for both full slip as well as no slip condition [8].To calculate the maximum thrust (T_{max}) and moment (M_{max}) at the soil lining interface under seismic loading, following set of equations can be used, where $\frac{\Delta d}{d}$ represents the diametric strain.

$$\frac{\Delta d}{d} = \frac{\mp K_1 F}{3} \Upsilon_{max} \tag{1}$$

$$T_{max} = \mp \frac{K_1 E_m}{6\,(1+\nu_m)} r \Upsilon_{max} \tag{2}$$

$$M_{max} = \mp \frac{K_1 E_m}{6\,(1+\nu_m)} r^2 \Upsilon_{max} \tag{3}$$

$$K_1 = \frac{12\,(1-\nu_m)}{2F+5-6\nu_m)} \tag{4}$$

$$F = \frac{E_m(1-{\nu_l}^2)R^3}{6E_l I(1+\nu_m)} \tag{5}$$

$$C = \frac{E_m(1-{\nu_l}^2)r}{E_l t(1+\nu_m)(1-2\nu_m)} \tag{6}$$

Where, E_m = modulus of elasticity of the soil medium; E_l = modulus of elasticity of the tunnel lining; I = moment of inertia of the tunnel lining (per unit width) for circular lining R; F = flexibility ratio; C = compressibility ratio; K_1 = full slip lining response coefficient; ν_m = Poisson's ratio of the soil medium and ν_l = Poisson's ratio of the tunnel lining.

Full slip assumptions under simple shear may cause significant underestimation of the maximum thrust. Equation for maximum thrust for no slip assumption is given below:

$$T_{max} = \mp \frac{K_2 E_m}{2\,(1+\nu_m)} r \Upsilon_{max} \tag{7}$$

In the above equation, K_2 is no slip lining response coefficient, which can be estimated as follows.

$$K_2 = 1 + \frac{F\,[(1-2\nu_m) - (1-2\nu_m)C] - \frac{1}{2}(1-2\nu_m)^2 + 2}{F\,[(3-2\nu_m) + (1-2\nu_m)C] + C\left[\frac{5}{2} - 8\nu_m + 6{\nu_m}^2\right] + 6 - 8\nu_m} \tag{8}$$

2.2 Penzien's Analytical solution

The closed form analytical solution developed for racking deformation of rectangular shaped tunnels [6]. An analytical solution to study deformation caused in circular as well as rectangular shaped tunnel suggested for both no slip and full slip condition under seismic loading [5]. The lining soil racking ratio can be calculated using below equation.

$$R^n = \frac{\mp 4(1-\nu_m)}{(\alpha_n+1)} \tag{9}$$

$$\alpha_n = \frac{12E_l I(5-6\nu_m)}{d^3 G_m (1-\nu_l{}^2)} \tag{10}$$

The analytical equations for thrust, bending moment, and shear force in circular tunnel linings considering full slip condition under seismic activities given below:

$$\mp \Delta d_{\text{lining}}^{n} = \mp R^n \Delta d_{\text{free-field}} \tag{11}$$

$$T(\theta) = -\frac{12E_l I \Delta d_{\text{lining}}^{n}}{d^3(1-v_l^2)} \cos 2\left(\theta+\frac{\pi}{4}\right) \tag{12}$$

$$M(\theta) = -\frac{6E_l I \Delta d_{\text{lining}}^{n}}{d^2(1-v_l^2)} \cos 2\left(\theta+\frac{\pi}{4}\right) \tag{13}$$

$$V(\theta) = -\frac{24E_l I \Delta d_{\text{lining}}^{n}}{d^3(1-v_l^2)} \sin 2\left(\theta+\frac{\pi}{4}\right) \tag{14}$$

For the case of no slip condition, the equations are presented as:

$$\mp \Delta d_{\text{lining}} = \mp R \Delta d_{\text{free-field}} \tag{15}$$

$$T(\theta) = -\frac{24E_l I \Delta d_{\text{lining}}}{d^3(1-v_l^2)} \cos 2\left(\theta+\frac{\pi}{4}\right) \tag{16}$$

$$M(\theta) = -\frac{6E_l I \Delta d_{\text{lining}}}{d^2(1-v_l^2)} \cos 2\left(\theta+\frac{\pi}{4}\right) \tag{17}$$

$$V(\theta) = -\frac{24E_l I \Delta d_{\text{lining}}}{d^3(1-v_l^2)} \sin 2\left(\theta+\frac{\pi}{4}\right) \tag{18}$$

Mathematical expression to calculate R and α is mentioned here.

$$R = \frac{\mp 4(1-v_m)}{(\alpha+1)} \tag{19}$$

$$\alpha = \frac{24E_l I(3-4\nu_m)}{d^3 G_m (1-\nu_l{}^2)} \tag{20}$$

3 Result of Analytical Solutions

Jammu and Kashmir region in northern part of India shows active seismic activities in that region falling in Zone IV and V [1]. A reference tunnel in Jammu region is considered having 20 m depth from ground surface and 8 m diameter. Earthquake parameter are $M_w = 7.5$ and $a_{max} = 0.4g$. Source to site distance is 120 km. To study the effect of soil strength parameters on shear force, thrust and bending moment, different soil models considered having different values of modulus of elasticity and Poisson ratio. Different types of soils like clay, sand and gravel considered, where Poisson ratio ranges between 0.2 to 0.45 and modulus of elasticity varies between 16000 kPa to 700000 kPa. Maximum value of shear strain was 0.0023 which is an average value of all types of soil model considered for investigation. Table 1 summarizes the earthquake and soil data considered for different model ranging from very soft clay to highly dense sand.

The calculated values of thrust, bending moment and shear force using Wang and Penzien method shown in the following Table 2 for both upper and lower limit. It can be observed that, the magnitude of error increases with increasing soil stiffness for both the methods having flexibility ratio less than 20. The error would be less than 6% for soft clay to hard sand and can be called acceptable. The conservative results are given for hard soils or soil with a flexibility ratio (F) greater than 4. The ΔT and ΔM are the magnitude of error between Wang and Penzien solution for thrust and bending moment, where subscript W-P refers to Wang and Penzien method. To compare the errors for different methods and flexibility ratio (F), the results are demonstrated in following Fig. 2.

Table 1. Earthquake and soil parameters for classified soil models

Soil Type	Model		a_{max} (g)	C_m (m/s)	V_S (m/s)	γ_m (kN /m^3)	ν_m	E_m (kPa)
Very Soft Clay	S1		0.25	180	0.45	17	0.45	159732
Soft Clay	S2		0.3	200	0.54	17.5	0.425	199500
Medium Clay	S3		0.325	230	0.58	18	0.4	266616
Hard Clay	S4	Upper Limit	0.35	250	0.63	18.5	0.375	317968.8
Dense Sand	S5		0.35	290	0.64	19.2	0.325	427900.8
Sand and Gravel	S6		0.375	310	0.67	19.8	0.3	494722.8
Dense Sand and Gravel	S7		0.4	330	0.73	20	0.275	555390
Highly Dense Sand	S8		0.45	350	0.81	20.5	0.25	627812.5
Very Soft Clay	S1		0.2	170	0.36	16	0.45	134096
Soft Clay	S2		0.25	190	0.43	16.5	0.425	169760.3
Medium Clay	S3		0.275	210	0.49	17	0.4	209916
Hard Clay	S4	Lower Limit	0.3	230	0.54	17.5	0.35	249952.5
Dense Sand	S5		0.325	250	0.58	18	0.3	292500
Sand and Gravel	S6		0.35	270	0.63	18.5	0.275	343905.8
Dense Sand and	S7		0.375	290	0.67	19	0.25	399475

Gravel							
Highly Dense Sand	S8	0.4	300	0.72	19.5	0.2	421200

Table 2. Results of analytical Solution based on Wang and Penzien method

Method		Wang 1993			Penzien 2000				
Model		T_W (kN)	M_W (kN.m)	σ_W (kPa)	T_P (kN)	M_P (kN.m)	V_P (kN)	σ_P (kPa)	F
S1		29.98	119.94	7921.68	29.98	119.93	59.96	7921.69	19.16
S2		34.17	136.64	9012.11	34.17	136.63	68.23	9027.03	24.35
S3		33.95	135.11	8967.23	33.95	135.77	67.14	8967.89	33.12
S4	Upper	36.55	146.14	9655.31	35.03	140.81	70.21	9300.62	40.22
S5	Limit	34.18	136.71	9029.68	33.00	131.98	65.94	8718.53	56.17
S6		35.95	140.21	9402.78	34.40	137.62	68.33	9088.61	66.19
S7		36.11	147.32	9767.72	35.77	143.10	71.52	9451.27	75.75
S8		41.84	167.54	11066.07	39.33	157.74	78.67	10391.92	87.35
S1		25.13	100.50	6638.27	25.13	100.55	50.22	6638.63	16.08
S2		29.72	118.89	7852.54	29.72	118.89	59.45	7852.54	30.71
S3		31.15	124.56	8226.73	31.15	124.55	62.28	8226.98	26.07
S4	Lower	33.76	135.02	8918.27	33.75	135.03	67.52	8918.29	32.2
S5	Limit	36.38	145.52	9610.33	36.38	145.50	72.76	9610.39	39.14
S6		37.76	151.02	9974.92	37.75	151.02	75.51	9974.92	46.91
S7		39.12	156.48	10335.51	39.12	156.48	78.23	10335.59	55.58
S8		40.04	172.17	11371.58	43.04	172.17	86.09	112371.6	61.04

Table 3. Error between Wang and Penzien method

Soil Type	Model	ΔT_{W-P} (%)	ΔM_{W-P} (%)	F_{avg}
Very Soft Clay	S1	1.47	5.61	17.51
Soft Clay	S2	2.16	5.13	27.34
Medium Clay	S3	1.87	4.14	29.31
Hard Clay	S4	0.91	3.64	36.46
Dense Sand	S5	1.84	4.36	47.5
Sand and Gravel	S6	1.93	4.53	56.11
Dense Sand and Gravel	S7	2.91	4.38	65.14
Highly Dense Sand	S8	1.87	4.45	71.19

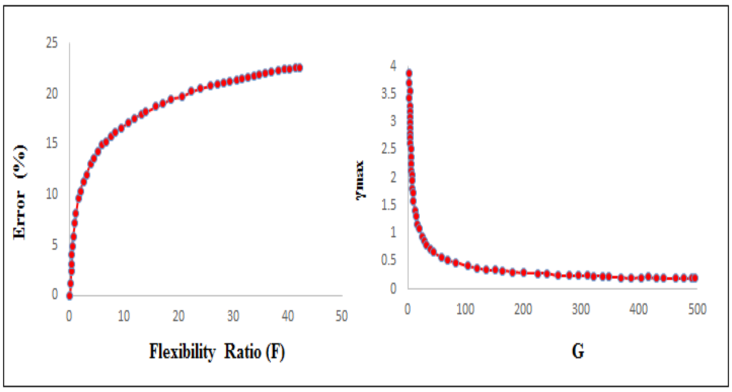

Fig. 2. (a) Variation of error between Wang and Penzien method versus flexibility ratio; (b) Variation of maximum shear strain with shear modulus

The maximum shear strain depends on shear wave velocity, which in turn dependent on two strength parameters; modulus of elasticity (E) and Poisson ratio (ν). Due to the value change of modulus of elasticity (E) and Poisson ratio (ν), shear modulus (G), maximum shear strain (γ_{max}) and C_m will also change. Maximum acceleration during earthquake activities at the ground level assumed 0.4g which can be estimated based on soil layer strata. As shown in the Fig. 2, maximum shear strain (γ_{max}) increases with increasing modulus of elasticity (E) during starting phases. Later it becomes constant for higher values of modulus of elasticity. Variation of thrust force using Wang's method and shear fore and bending moment using Penzien's method presented in the following Fig. 3.

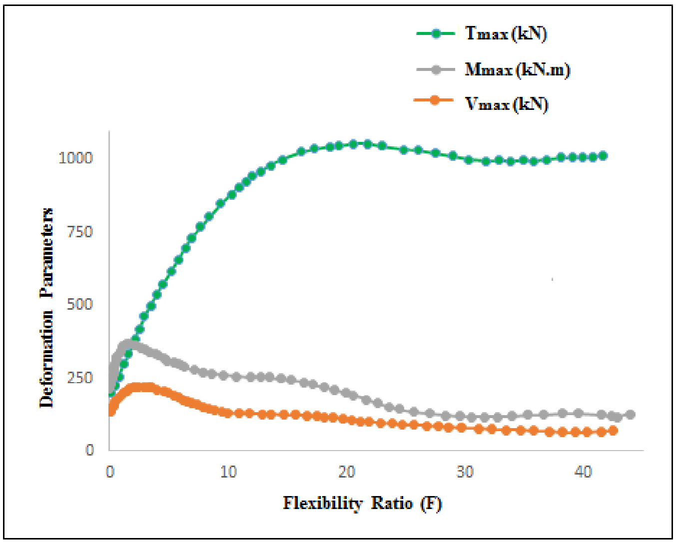

Fig. 3. Variation of deformation parameters with flexibility ratio

4 Conclusions

Tunnels constructed in a seismically active area subjected to dynamic loading in terms of seismic forces. Tunnels can undergo different form of deformation depending on the nature in which seismic waves propagate in soil medium. Basically, two modes of oval deformation defined viz. full slippage and no slippage depending on the surficial behaviour. In this study, analytical solutions given by Wang and Penzien compared to understand the seismic response of tunnel lining considering different soil media. Sensitivity analysis suggested that soil stiffness has direct effect on the magnitude of error between these two methods. For hard soils, conservative results are achieved in both methods. Analytical solutions are not useful to estimate shear strain distribution, due to which maximum shear strain can be evaluated based on real time seismic history. Deformation parameters including thrust and bending moment are dependent on flexibility ratio. For the safe design of tunnel lining when tunnels are subjected to earthquake loading, stress distribution must be considered for analysis and design.

References

1. BIS:1893.: Indian standard criteria for earthquake resistant design of structures, Part 1 - General provisions and buildings, Bureau of Indian Standards, New Delhi, India (2002).
2. Hashash, Y.M.A., Hook, J.J., Schmidt, B. and Yao, J.I.C.: Seismic design and analysis of underground structures. Tunn. Underground Space Technology, 16 (2), 247-293 (2001).
3. Newmark, N.M.: Problems in wave propagation in soil and rock. In: Proceedings of International Symposium on Wave Propagation and Dynamic Properties of Earth Materials, New Mexico, University of New Mexico Press (1968).
4. Owen, G.N. and Scholl, R.E.: Earthquake engineering of large underground structures. Report No. FHWA/RD-80/195, Federal Highway Administration and NationalScience Foundation, 279 (1981).
5. Penzien, J.: Seismically induced racking of tunnel linings. Earthquake Eng. Struct. Dyn., 29, 683-691 (2000).
6. Penzien, J. and Wu, C.: Stresses in linings of bored tunnels. Earthquake Eng. Struct. Dyn., 27, 283-300 (1998).
7. St. John, C.M. and Zahrah, T.F.: A seismic design of underground structures. Tunn. Undergr. Space Technol., 2(2), 165-197 (1987).
8. Wang, J.N.: Seismic Design of Tunnels, A State-of-the-Art Approach. Monograph 7, Parsons Brickerhoff Quade and Douglas, Inc., New York (1993).