SEISMIC DESIGN OF BORED TUNNEL SEGMENT ACCORDING TO EUROPEAN AND JAPANESE APPROACHES

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This paper compares European and Japanese approaches used for seismic design of bored tunnel segment.

1. INTRODUCTION

Foreign contractors involving in international projects in developing countries may employ different design approaches due to shortage of the local codes and standards. This paper discusses the seismic design of the bored tunnel segment where the mixed use of international codes has been observed. Our main purpose is to compare the famous Japanese beam-spring model and the equivalent stiffness of the tunnel lining method which is commonly used in Europe. As for the latter, both analytical and FEM approaches will be employed.

2. EUROPEAN APPROACH

The Eurocodes are a set of European Standards which provide common rules for the design of buildings and other construction works. However, the scope of the first generation of the Eurocodes mainly covers buildings and some other civil engineering works; and there are no parts devoted to the design of tunnels despite its unique characteristics (Athanasopoulou et al. 2019). The use of numerical methods in geotechnical design is also not covered by the current Eurocodes. Currently, all assumptions and simplifications for numerical modelling of tunnels are introduced at the discretion of designers, based on their personal previous experiences and the diverse guidance given in literature. This paper presents our little effort to decode Eurocode for the seismic design for bored tunnel.

a. Analytical

Following steps are used to estimate sectional forces of the lining. First, calculate the sectional forces of tunnel lining based on static condition by using the method developed by Muir Wood (1975). Second, estimate additional sectional forces due to earthquake by using the closed-form solutions proposed by Wang (1993) and Penzien (2000). Finally, find the sectional forces for seismic condition by sum up results of above steps

b. FEM

Plaxis 2D program is employed to simulate the soil structure interaction between tunnel lining and ground. PLAXIS plain strain analysis with stage design construction sequence is conducted to simulate the excavation of tunnel and installation of lining segment. Hardening Soil (HS) model is used to simulate the static condition and changed to Hardening Soil Small Strain (HSss) during the stage of dynamic analysis.

3. JAPANESE APPROACH

Fig. 1 shows the beam-spring model developed by Japanese Society of Civil Engineer where the segments are modelled as beams, circumferential joints of segment as rotational springs, and the axial joints as shear springs. Usually, a beam spring model consists of two or more rings.

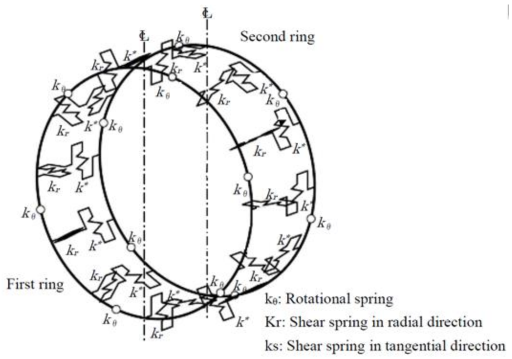

Fig. 1 Beam Spring Model

Rotational spring, radial shear spring and tangential shear spring constants can be estimated using Eq. 1 to 3.

$$k_\theta = A_b.E_s.(d-y).(d-y/3)/l_s \quad [1]$$

$$k_{sr} = 192EI/(2b)^3 \quad [2]$$

$$k_{st} = L_j.h.G/b = L_j.h.E/[b.(1+\nu)] \quad [3]$$

$$y = (n.A_b/b)\{-1+\sqrt{(1+2ab/nA_b)}\} \quad [4]$$

Where $A_b =$ cross-sectional area of bolt, $E_s =$ Young's modulus of bolt, $d =$ effective height up to bolt, $y =$ neutral axis position; $n = E_s/E_c =$ Young's modulus ratio, b = segment width, l_s = bolt length, EI = bending stiffness of the plate segment in the axial direction of the tunnel ($I = L_j \times h^3/12$), b = segment width, L_j = Axial joint spacing, h = segment thickness, $G =$ shear modulus of the segment, E = Young's modulus of the segment, and $\nu =$ Poisson's ratio of the segment.

The maximum free-field ground displacement is estimated in accordance with Eurocode 8-1, clause 3.2.2.4 while the vertical distribution of the design horizontal displacement of the ground is following conventional Japanese method.

4. CASE STUDY

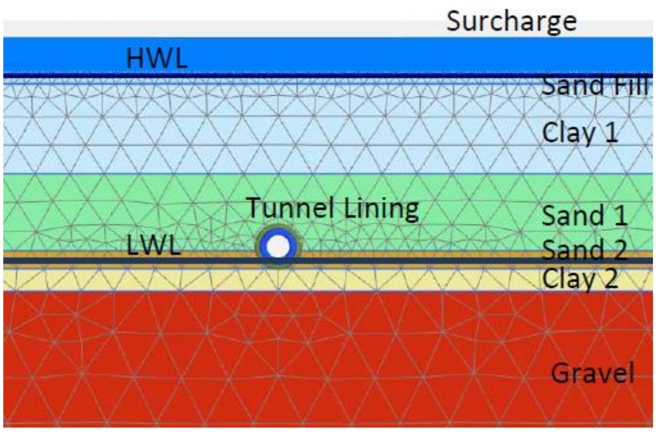

Fig. 2 Analysis Model in Plaxis

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Fig. 2 above presents the case study with the soil profile. The tunnel is about 31.5m deep, 5.9m in internal diameter and 300mm thick. The water levels considered in the analysis are below the tunnel invert (LWL) and at the ground level (HWL). The surcharge loading of 10kPa and 6kPa was used for static and seismic analysis respectively. The construction sequence is (1) initial phase, (2) activation of surcharge, (3) tunnel excavation, (5) lining installation for static condition, and finally (5) dynamic analysis. The tunnel lining properties are shown in Table 1.

Table 1. Tunnel Lining Properties

Young's Modulus, 0.5E	$1.9\text{x}10^7$ kPa
Equivalent Second Moment Area, I_e $I_e = I_j + I_c (4/N_s)^2$ (Muir Wood, 1975) Where I_c = full second moment area of tunnel lining, I_j = second moment area at joint location, N_s = numbers of segment excluding key.	$1.89\text{x}10^{-3}$ m⁴
Lining Joint Thickness, t_j	0.175m
Poisson's Ratio, v	0.2

In this paper only Eurocode Design Approach 1 – Combination 1 is used for comparison and illustration. Partial load and material factors are shown in Table 2. Input soil parameters are summarized in Table 3 below.

Table 2. Partial Load and Material Factors

Design Approach 1:			Combination 1		Combination 2	
Type of partial factor:			A1	M1	A2	M2
Actions	Permanent	Unfavorable	1	-	1	-
		Favorable	1	-	1	-
	Variable	Unfavorable	1	-	1.3	-
		Favorable	1	-	1	-
Soil Parameters	tan Ø		-	1	-	1.25
	Effective Cohesion		-	1	-	1.25
	Undrained Strength		-	1	-	1.4
	Unit Weight		-	1	-	1

Table 3. Input Soil Properties – Set M1

Soils	Density	SPT-N	Friction Angle	Cohesion	K0	Young's Modulus	Shear Modulus G_0	$\gamma_{0.7}$
	(kN/m³)		(degrees)	(kPa)		(MPa)	(MPa)	(%)
Sand Fill	19	5	30	-	0.5	12.5	46.5	0.0024
Clay 1	19	11	-	68.75	1.0	14.4	79.5	0.0385
Sand 1	18	19	29.4	-	0.5	47.5	115.2	0.0300
Sand 2	18	41	35.4	-	0.4	102.5	194.4	0.0245
Clay 2	19	6	0	37.5	1.0	7.9	52.6	0.0317
Gravel	20	160	39	-	0.4	400.0	490.7	0.0169

Design ground acceleration is a = 0.125g. Based on average shear wave velocity, the ground is classified as Type C according to Eurocode 8. The target spectrum is thus identified based on the soil type and design ground acceleration in accordance with Eurocodes. Real records are searched on the renowned PEER ground motion databases (https://peer.berkeley.edu/). The selected accelerograms are then modified by using RspMatchEDT software and finally used as inputs for dynamic analysis in Plaxis.

5. ANALYSIS RESULT AND COMPARISON

Result of analytical analysis is summarized and shown in Table 4. For fair comparison with Japanese approach where the transfer of bending moment of segment to adjacent ring in longitudinal direction is considered, a ratio of I_c/I_e is then multiplied to the bending moment result of both the analytical and numerical analyses in European method, following the recommendation by Osgoui and Pescara (2014). First, it is observed that lower water table (LWT) is critical condition regardless of the approach. It is consistent with the finding by Hashash et al. (2001). Second, the increment of bending moment due to seismic is about 2 times of the static condition in all cases. Third, the bending moment by the Japanese method is slightly smaller than by the European one. However, the latter both analytically and numerically provides much higher (~200-300%) axial force compared to the result by the former.

Table 4. Analytical Analysis Result and Comparison

Situation	GWL	HWL			LWL		
	Code	Bending Moment	Axial Force	Shear Force	Bending Moment	Axial Force	Shear Force
		kNm/ring	kN/ring	kN/ring	kNm/ring	kN/ring	kN/ring
Static	EU-ANA	71	2781	-	151	2654	-
	EU-ANA*	84	2781	-	180	2654	-
	EU-FEM	79	2114	47	132	2080	101
	EU-FEM*	93	2114	47	157	2080	101
	JP	87	1510	59	194	991	182
Addition by Seismic	EU-ANA	117	482	75	117	482	74
	EU-ANA*	139	482	75	139	482	74
Seismic	EU-ANA	188	3263	-	268	3136	-
	EU-ANA*	224	3263	-	319	3136	-
	EU-FEM	178	2554	131	258	2435	221
	EU-FEM*	212	2554	131	307	2435	221
	JP	179	1470	164	292	1005	268
Note:	*: considering a bending moment transfer ratio to adjacent rings I_c/I_e = 1.19						

6. CONCLUSIONS

Under seismic condition, the Japanese beam-spring model tends to underestimate the bending moment slightly and the axial force in segment significantly compared to the results from the analytical and numerical methods following European practice. However, when it comes to the rebar quantity, there is possibly not much difference between two approaches due to the combined effect of the bending moment and axial force.

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