STUDY ON SEISMIC CALCULATION METHOD FOR SHIELD TUNNELS UNDER STRONG GROUND MOTION

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SUMMARY

Hyogo-ken Nanbu Earthquake of January 17th 1995 caused severe damage to underground structures, due to which the seismic problems on them were once again taken seriously. The anti-earthquake code of shield tunnels and bridges was revised, in which two design levels representing low-to-moderate and strong earthquakes are considered. However, under both design levels, the elastic properties of the tunnel-ground system are assumed. This assumption is not realistic under Level-2(strong) earthquakes, because the seismic forces are so strong that the system will behave inelastically. In several relevant design guides, the seismic deformation method is recommended as a design guide for shield tunnel anti- earthquake designing. However, on the modeling of the shield tunnel itself, the method of replacing the lining structure with equivalent stiffness beam is frequently adopted, which means the actually discontinuous lining structure is considered as a continuous and uniform stiffness beam in the same axial direction. But in case of strong earthquakes such a replacement method might ignore the effect of the interaction between the shield tunnel and soil, and that of non-linear features of the ring joints and linings on the seismic response of the shield tunnel. As a result, the internal forces which occur in the shield tunnels will be evaluated excessively.

In this paper, the transfer matrix method is employed to derive a calculating method for anti-earthquake designing of shield tunnels. The method is proved to be satisfactory and the above problems are solved.

INTRODUCTION

With the development of science and technology, shield tunneling, method is now frequently applied to such urban tunnel structures as underground railways, water supply and sewerage. With the advantages of little vibration, few noises and no influence on the ground traffic, it is most suited to adapt to build tunnels on the ground of retardation and poor subsoil. Therefore, shield tunnels are becoming one of the important urban constructions.

The seismic calculating method of shield tunnels has been developed a lot through researchers' unceasing efforts. A great deal of experimental studies have been made by Miwa on the axial rigidity features of shield tunnels, which succeeds in clarifying the rigidity features of ring joints and segment rings[Miwa,1987]. Sakuma proposes to simulate ring joint and segment ring with spring and bar[Sakuma, 1990]. But by this method calculation will be rather limited, for a shield tunnel is composed of numerous ring joints and segment rings. Besides, only modeled by concentrated springs, the interaction between shield tunnel and foundation can not be accurately reflected. In order to solve this problem, Takada and Li establish transfer beam element to analyze two-dimensional seismic response along the shield tunnel axis[Takada and Li,1992]. Shiba and Kawajima employ equivalent stiffness beam to set up a seismic calculating formula of shield tunnel along the axial direction, which

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is adopted by Guidelines for Seismic Design Method of Large Underground structures[Shiba and Kawasima,1989,1992]

Hyogo-ken Nanbu Earthquake, which took place in the south of Hyogo Prefecture, Japan on January 17th, 1995 , caused severe damages to civil constructions, including underground structures. For example, the platforrn of subway Daikai Station was almost completely destroyed. Although the shield tunnels didn't suffer great damages, those applied to sewerage systems in the areas of Karumojima, Rokko island and Naruomikage cracked a lot, which means that shield tunnel did not function well in reality. At this juncture, research committees were established by such organizations and associations as the Japan Society of Civil Engineers and so on to analyze the reasons of the damages and the suggestions' book was published on concerning anti-earthquake problems.

Due to warnings taken from the Great Earthquake, the earthquake code of water supply, sewerage and bridges was revised, dividing ground motions into Level-1 and Level-2.. Level-1 ground motion is equal to external seismic force as termed in the previous designing code, happening once or twice during the lifetime of the structure, while Level-2 ground motion is that of rare occurrence, including continental type like Hyogo-ken Nanbu Earthquake and large-scale oceanic type whose location is close to the continent. Up to now seismic deformation method is normally applied for seismic design of shield tunnel which is taken as equivalent elastic foundation beam. By this method the non-linear feature of shield tunnel and that of the interaction between ground and shield tunnel will not be considered. Therefore, it does not fit the seismic calculation of Level-2 ground motion.

Upon the above problems, transfer matrix method is employed in this paper to solve the above problems, and discussion is made on how the calculation result is affected by non-linear feature of shield tunnel. Finally, comparison is made with the concurrent seismic code.

CALCULATION METHOD

In this paper, seismic deformation method is used to analyze seismic response of shield tunnels. As the modeling method for a shield tunnel, springs and elastic foundation beams are employed respectively to simulate ring joints and segment rings, as shown in Figure 1. To solve the problem of infiniteness of ring joints and segment rings that a shield tunnel has, transfer matrix method is introduced.

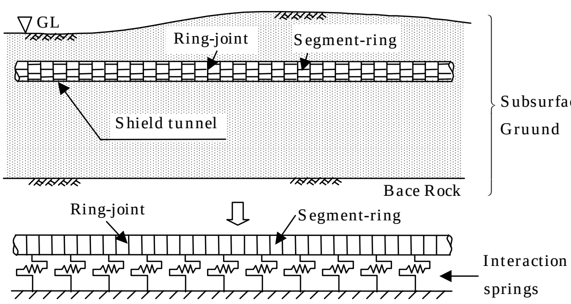


Figure 1: Modeling method for a shield tunnel

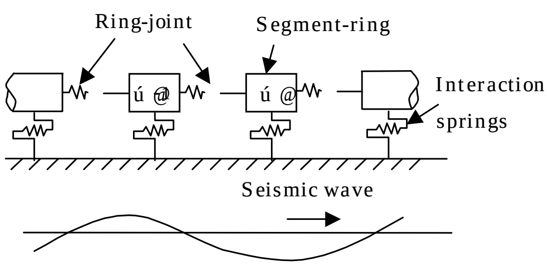


Figure 2: Model of Segment ring

According to Figure 2, the following equations of equilibrium can be set up for segment ring No.i.

$$-EA\frac{d^2U}{dX^2}+K_{sx}U=K_{sx}U_{sx0}\sin\omega\left(t-\frac{X\cos\theta}{C}\right) \quad (1)$$

$$EI\frac{d^4V}{dX^4}+K_{sy}V=K_{sy}V_{sy0}\sin\omega\left(t-\frac{X\cos\theta}{C}\right) \quad (2)$$

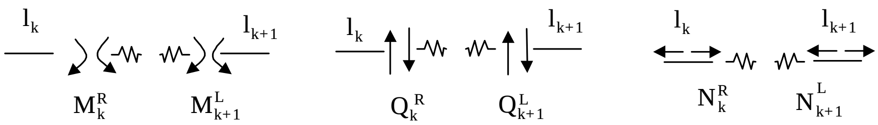
in which U is longitudinal displacement of shield tunnel, V is transversal displacement, I is inertia moment and A is acreage. K_{sx} is a longitudinal ground spring coefficient while K_{sy} is a transversal one. U_{sx0} is longitudinal amplitude of seismic wave and U_{sy0} is transversal one. C is propagation velocity of seismic wave. By solving

Equation (1) and (2), the following relation of state vector on the two shoulders of Segment ring No.i can be obtained,

$$V_i^{\ R} = F_i V_i^{\ L} \tag{3}$$

in which F is called field transfer matrix, determined by geometry and external force conditions of segment rings, while V_i^R and V_i^L indicate the state vector on the right and left shoulders of Segment No.i, composed of displacement and internal force of the segment ring.

On the other hand, as shown in Figure 3, according to the equilibrium condition of displacement and force on the two shoulders of the ring joint, where the following relation of state vector can be obtained,



$$M_{k+1}^{\ L} = M_k^{\ R} = -k_R(\phi_{k+1}^{\ L} - \phi_k^{\ R}) \qquad \begin{matrix} Q_{k+1}^{\ L} = Q_k^{\ R} \\ V_{k+1}^{\ L} = V_k^{\ R} \end{matrix} \qquad N_{k+1}^{\ L} = N_k^{\ R} = -k_T(U_{k+1}^{\ L} - U_k^{\ R})$$

Figure 3: Model of ring joint

$$V_{i+1}^{\ L} = P_i V_i^{\ R} \tag{4}$$

Here P_k is called Point Transfer Matrix. According to Equation (3) and Equation (4), the state vector of the left shoulder of the shield tunnel as shown in the analytical model Figure 1 can be transferred to its right shoulder through the following equation,

$$V_N^{\ R} = F_N P_{N-1} \cdots\cdots P_2 F_2 P_1 F_1 V_1^{\ L} \tag{5}$$

With the boundary condition of the analytical model substituted into Equation (5), the displacement and internal force occurred in the shield tunnel can be obtained.

MODEL AND RESULT OF CALCULATION

Model of Calculation

The ground condition of calculation model is as shown in Table 1. The shield tunnel is buried in the layer of alluvial clay, at a distance of 16.1 m from the ground surface, Its characteristics are shown in Table 2. In line with the design code for sewerage systems, ground displacement and seismic wave length can be respectively obtained by the following equations,

$$U_{sx0}(z) = \frac{2}{\pi^2} S_v T_s \cos\frac{\pi z}{2H} \tag{6}$$

$$L = \frac{V_{DS} V_{BS}}{V_{DS} + V_{BS}} T_s \tag{7}$$

Here S_v means the design velocity response spectrum. S_v in this paper is supposed to be 24 m/s for Level-1 ground motion, and for Level-2 seismic motion S_v to be 80 m/s. T_s is the fundamental period of vibration of the subsurface ground. H is the thickness of the subsurface ground. V_{ds} is the shear wave velocity of the subsurface ground, while V_{bs} is that of the base rock. $U_{sx0}(z)$ is the horizontal displacement at a distance of z meters from the ground surface. The spring coefficient, which indicates the interaction between the shield tunnel and the ground, is supposed to be equivalent to the shear modulus of the ground, and the yield shear stress of the ground equivalent to the standard penetration coefficient of the ground. Figure 4 shows non-linear features of the ring joints and the ground. The non-linear features of the ring joints are defined by the result of the experiment.

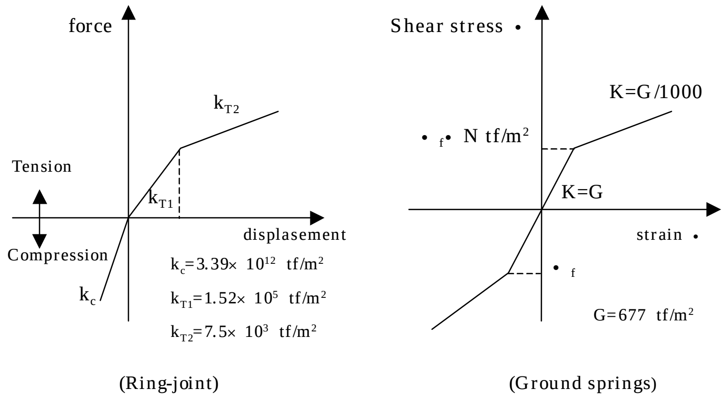


Figure 4: Non-linear features of the ring joints and the ground

Table 1: Ground condition

	Depth (m)	Thickness of layer(m)	N-valve	Density (tf/m^3)	Velocity (m/s)
Bankfill	-2.3	2.3		1.8	150
Bankfill	-9	6.7	15	1.9	200
Alluvial sandy soil	-13.6	4.6	15	1.8	200
Alluvial clay	-18.3	4.7	3	1.6	150
Diluvial sandy soil	-22.8	4.5	15	1.9	200
Diluvial clay	-30.0	7.2	20	1.7	280
Diluvial gravel	-43.0	13.0	50	2.1	350

Table2: Characteristics of tunnel

Item	Value
Tunnel diameter(m)	2.15
Tunnel thickness(m)	0.9
Tunnel elastic modulus(kgf/cm^2)	360000
Bolt type	M22
Bolt acreage(m^2)	3.03
Bolt elastic modulus(kgf/cm^2)	2100000
Bolt yield stress(kgf/cm^2)	2450

Result of calculation

The seismic response of shield tunnels is analyzed in this paper in the light of Level-1 ground motion and Level-2 ground motion. Seismic deformation method is applied for seismic calculation. Seismic wave is supposed by P wave in sine distribution. Discussions are made separately on the 5 cases as shown in Table 3 in order to find

Table 3 : Calculation cases

	Linear			Non-linear	
	Segment stiffness (uniform beam)	Equivalent stiffness (uniform beam)	Beam-spring	Ring joint	Ground spring
Case1	#	-	-	-	-
Case2	-	#	-	-	-
Case3	-	-	#	-	-
Case4	-	-	#	#	-
Case5	-	-	#	#	#

#:means being considered.

out how seismic response of shield tunnels is affected by various modeling methods.

Level-1 ground motion

Table 4 shows the stress and the displacement of the ring joints that occurs in the shield tunnel under Level-1 ground motion in different cases. It can be known from their displacement that the ring joints are not in the plastic region in any of the cases. The reason is that the external seismic force of Level-1 is comparatively weak. Although for tension stress the errors that might occur in various cases is under the rate of 2%, for compression stress the error rate in Case 1 and Case 3 is 12% and that in Case 3 and Case 5 is 41%. Therefore, equivalent stiffness beam values at a low rate the compression stress occurring in the shield tunnel, on which the non-linear features of the ground have a great effect. Shown in Figure 5 is the displacement of ring joints, and in Figure 6 the stress distribution. As the ring joints are within the linear region, the result of Case 3 is almost the same as that of Case 4. The result of Case 5 is rather small than that of any other case due to the influence of the non-linear features of the ground.

Table 4: Result of Calculation

	Compression stress(tf/m^2)	Tension stress (tf/m^2)	Displacement of ring joint(m)
Case1	1617	1617	
Case2	125	125	
Case3	1820	123	0.00076
Case4	1820	123	0.00076
Case5	1282	120	0.00074

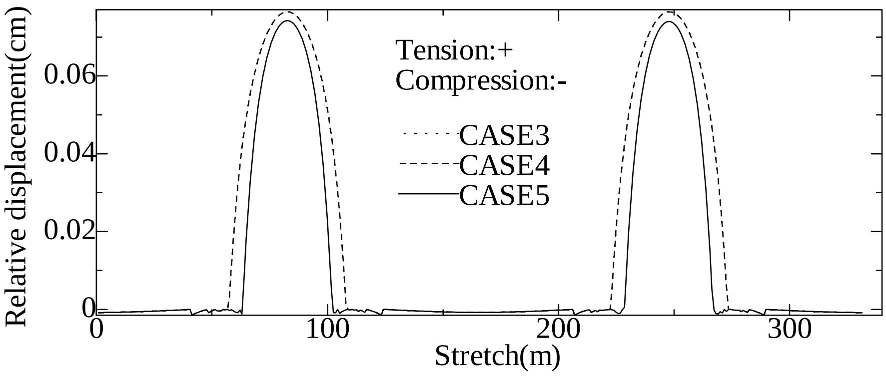


Figure 5: Relative displacement of ring joint

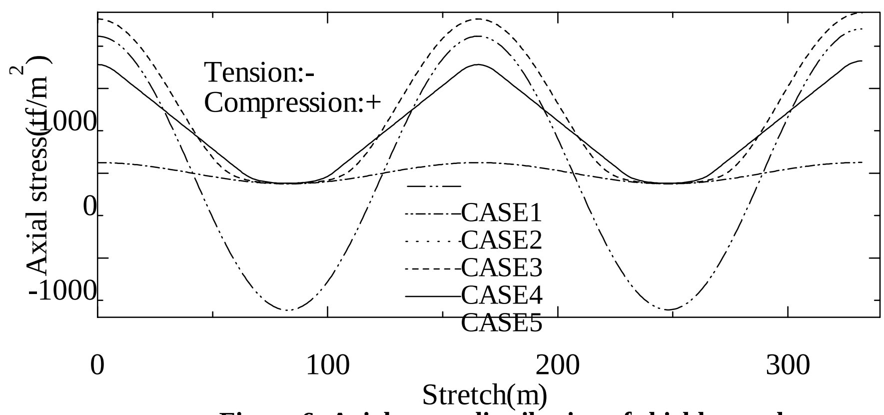


Figure 6: Axial stress distribution of shield tunnel

Level-2 ground motion

Table 5 shows in various cases the stress and the displacement of the ring joints that occurs the shield tunnel

Table 5: Result of Calculation

	compression stress(tf/m^2)	tension stress (tf/m^2)	Displacement of ring joint(m)
Case1	5389	5389	
Case2	417	417	
Case3	6067	412	0.00254
Case4	6077	178	0.00275
Case5	1552	175	0.0026

under Level-2 ground motion, which is different from those under Level-1 seismic motion. In the cases of Level-2 seismic motion, the joints are all in the plastic region. Thus the tension stress in Case 2 is 2.4 times stronger than that in Case 4. The non-linear features of the ground have few effect on tension stress but great effect on compression stress. The compression stress in Case 4 is about 4 times of that in Case 5. Therefore, the non-linear features of the shield tunnel and the ground should be considered when seismic response of the shield tunnel is evaluated in case of Level-2 ground motion. Shown in Figure 7, Figure 8 and Figure 9 are the displacements of the shield tunnel and the ring joints, and the stress occurring in the shield tunnel. Due to the effect of the non-linear features of the ground, the range of the maximum relative displacement occurring in the joints in Case 5 is smaller than in any other case, and the stress distribution is also far less than in any other case. In addition, for the sake of the discontinuous properties of the shield tunnel, the ranges of displacements which cause tension stress occurring in the shield tunnel in Case 3, Case 4 and Case 5 are smaller than those which cause compression stress. This is also because compression stress is stronger than tension stress.

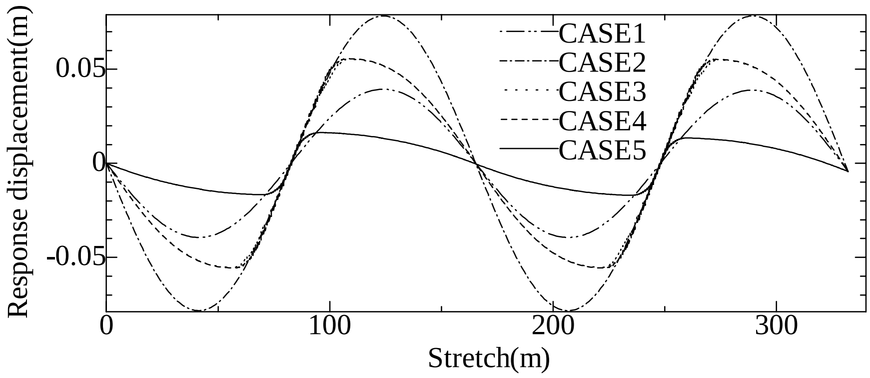


Figure 7: Relative displacement of ring joint

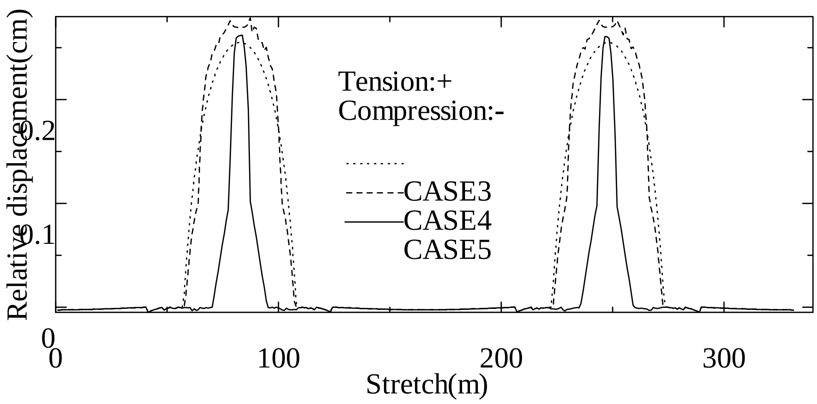


Figure 8 : Relative displacement of ring joints

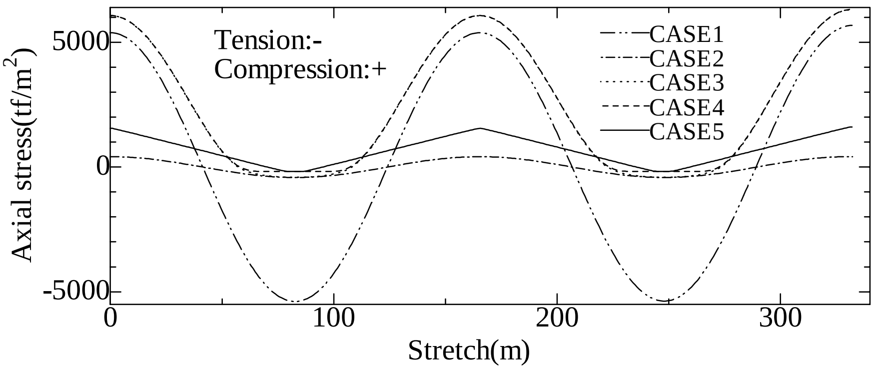


Figure 9 : Axial stress distribution of shield tunnel

CONCLUSION

In this paper, transfer matrix method is employed to analyze seismic response of shield tunnels and is compared with equivalent stiffness beam method. For Level-1 ground motion, the seismic force is comparatively weak. As a result the discontinuity of shield tunnels and the inelastic properties of the ground has a small effect on the seismic response of the shield tunnel. By the above-mentioned two methods, the error rate of tension stress occurs in the shield tunnel is under 2%, and that of compression stress is only 12%. Therefore, equivalent stiffness beam method is feasible to calculate seismic response of shield tunnels in case of Level-1 ground motion.

But in case of Level-2 ground motion, the discontinuity of shield tunnel and the inelastic properties of the ground has a great effect on the seismic response of shield tunnel. The stress obtained by equivalent stiffness beam method is 2.4 times stronger than that obtained by the method in which the effect of the inelastic properties are well considered. Therefore the effect of the inelastic properties can not be neglected when Level-2 ground motion is applied for seismic design of shield tunnels, and equivalent stiffness beam is not fit for seismic calculation in case of Level-2 ground motion.
In this paper, the problem of the discontinuity of shield tunnels is solved by transfer matrix method, which well reflects the inelastic properties of the ring joints and the ground. It can be concluded that transfer matrix method is a good method for seismic calculation in case of Level-2 ground motion. But in this paper the analysis is only made on seismic response of shield tunnels in the axial direction. Further study should be made on that in the transversal direction.

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