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L2 seismic design method for shield tunnels in soft ground

Toshishige Kishio  
*Dr. Eng, Osaka Transportation Promotion Corporation, OSAKA, JAPAN*

Youji Sumino  
*Osaka Municipal Transportation Bureau, OSAKA, JAPAN*

Hiromu Oota  
*Osaka Transportation Promotion Corporation, OSAKA, JAPAN*

Naoki Yamaguchi, Yoshinori Kurotori  
*CFK Consultants Co., Ltd., OSAKA, JAPAN*

**ABSTRACTS:** In Japan, the seismic design method against large earthquakes has been verified after the 1995 Kobe earthquake. Especially, strong ground motion, which has few probabilities to generate during the design lifetime of structure, is called "Level-2 (L2) earthquake ground motion". The L2 ground motion and the design method based on it have been discussed and studied actively. However, we could not establish the suitable seismic design method for the shield tunnels yet, because it had not damaged severely during past earthquakes. This paper proposes the seismic performance for the L2 ground motion and the seismic design method for the shield tunnels in the soft ground. We apply the seismic deformation method and require that the result should be equivalent to that of the dynamic analysis. In order to satisfy it, the interaction between the ground and structure should be considered accurately. Therefore, "FEM seismic deformation method" is adopted, in which the ground surrounding the tunnel is represented as finite elements. By comparison with the dynamic analysis, the validity of the proposed method is proved.

1 **INTRODUCTION**

1.1 **Damage of underground structure in 1995 Kobe earthquake**

The 1995 Kobe earthquake was one of the near field earthquakes, which JMA magnitude was 7.2 (moment magnitude is 6.9) and focal depth was 16km. Number of the casualty by the earthquake was over 6,300, and over 200,000 houses collapsed completely or partially in Kobe city and the northern part of Awaji island. Infrastructures were devastated as well, falling of the elevated bridge girders and collapse of the highway roads were caused, too.

On the subway structure, RC column of the station in Kobe city were damaged severely. Especially the Daikai station, which belongs to the Kobe Rapid Transit Line, suffered collapses, and the national road No. 28 settled with a maximum displacement of 3m (Figure 1).

On the other hand, the damage of the shield tunnel was slight, with some cracks of the secondary lining, and the water leakage in the shaft connection, but there were no severe damages.

Since these phenomena could not be explained by the seismic design method as before, a new seismic design method for the underground structures against the near field earthquake was required.

1.2 **Current situation of seismic design method for underground structures**

After the Kobe earthquake, the seismic design method for the underground structures has been examined. In this paragraph, the design earthquake ground motion and the current situation of the seismic design method in Japan are described.

1.2.1 **Design earthquake ground motions**

The following two levels of design earthquake ground motion are considered.

(1) Level-1 earthquake ground motion (L1)
(2) Level-2 earthquake ground motion (L2)

L1 earthquake ground motion has about several times of occurrence in design lifetime of structures.
Meanwhile, L2 earthquake ground motion has few times in design lifetime, but it is very strong.

1.2.2 Current situation of seismic design method

Table 1 shows an outline of the design method in Japan. The limit state design method, which is one of the performance design methods, is introduced for the cut and cover tunnels. On the other hand, in the design method for the shield tunnels, the allowable stress design method is adopted. However, it is not established for L2 earthquake ground motion yet.

Table 1. Outline of design method for tunnels in Japan

<table>
<thead>
<tr>
<th></th>
<th>For L1 earthquake ground motion</th>
<th>For L2 earthquake ground motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut and cover tunnels</td>
<td>Limit state design methods</td>
<td>Limit state design methods</td>
</tr>
<tr>
<td>Shield tunnels</td>
<td>Allowable stress design methods</td>
<td>Not established</td>
</tr>
</tbody>
</table>

2 BASIC CONCEPT OF SEISMIC DESIGN

2.1 Design method

We adopt the limit state design method for the shield tunnels, like the design method of the cut and cover tunnels. The limit state design method is one of the performance design methods. In this method, we need to determine the seismic performance of structure required during and after earthquakes, and design in order to put the damage state and the residual displacement of the structure within the set limit.

2.2 Seismic performance of shield tunnels

Table 2 shows the seismic performance of shield tunnels, according to the both levels of ground motion.

Table 2. Seismic performance of shield tunnels

<table>
<thead>
<tr>
<th>Design earthquake motion</th>
<th>Seismic performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 ground motion</td>
<td>Maintain a function without a repair, and no excessive displacement after earthquake</td>
</tr>
<tr>
<td>L2 ground motion</td>
<td>Need to repair after earthquake, but can restore a function early</td>
</tr>
</tbody>
</table>

2.3 Calculation method

Generally speaking, the seismic design method can be classified broadly into the dynamic and the static analysis. The typical seismic design methods are shown in Table 3.

Table 3. Major seismic design method

<table>
<thead>
<tr>
<th>Dynamic analysis</th>
<th>Direct integration method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static analysis</td>
<td>Seismic deformation method</td>
</tr>
<tr>
<td>Static analysis</td>
<td>Seismic coefficient method</td>
</tr>
</tbody>
</table>

Taking the versatility, cost performance of calculation, suitability for business and rationality into account, the seismic deformation method that is one of the static analyses is adopted.

3 STRUCTURAL MODEL

3.1 General structural model of shield tunnels

Structural model of the shield tunnel is divided into two types.

a) Conventional design model

In this model, the flexural rigidity of segment ring is regarded as a uniform one. Based on the assumption that the decrease of flexural rigidity at joints between segments can be considered as that of the whole ring, the flexural rigidity of segment ring is estimated as \(\eta EI (\eta<1)\) by using the flexural rigidity \(Ei\) of the segment itself.

b) Beam-spring model

In this model, the segment is regarded as beams, the joint between segments as a rotational spring, and the joint between rings as a shear spring. Compared with the conventional design model, evaluation of the joints is possible.

3.2 Structural model applied to seismic design

3.2.1 Structure model

We adopt the beam spring model as structural model for seismic design of FEM seismic deformation method. Figure 2 shows the model.

3.2.2 Segment

A non-linear model of RC segment is shown in Figure 3. The vertical axis is the bending moment of a member, and the horizontal one is the curvature.

Figure 2. Structural model of shield tunnel

Figure 3. A non-linear model of segment
3.2.3 Joint
The spring constant of segment joint is based on loading tests. We leave the details out because of space limitations.

3.3 Axial force for shield tunnel during earthquakes
The non-linear model described in previous paragraph depends on the occurrence of axial force. Dynamic analysis by SUPER-FLUSH gives a distribution of the axial force to the shield tunnel.

3.3.1 Dynamic analysis
Code SUPER-FLUSH is applied to the dynamic analysis. Decrease of the shear modulus of the soil during earthquakes is presented by the equivalent linear method. The conventional design model is introduced as the structural model of the shield tunnel here. Considering the damage for the L2 ground motion, the ultimate flexural rigidity, that is the secant modulus associated with the ultimate bending moment, is used. The studied tunnel has the outer diameter of 5300 mm. The thickness of the segment is 280 mm, which is RC flat type segment.

3.3.1.1 Input earthquake ground motion
One of the L2 ground motion in the fault area is input to the bedrock of the ground model. Figure 4 shows the input motion which has a maximum acceleration of 683.40gal. The earthquake ground motion is synthesized for an active fault of Osaka area, assumed the similar fault activity to the 1995 Kobe earthquake magnitude.

Moreover, the axial force distribution by normal load is included in the figure.

Generally speaking, it is considered that a change of the axial force gives a small effect to the underground structure during earthquakes. However, Figure 6 expresses that the distribution of the axial force during earthquakes is different from the one of normal loads.

3.3.1.2 Ground model
Type A ground model is used here as shown in Figure 5. The shield tunnel passes in the soil layer of soft clay (Ac layer).

3.3.2 Axial force distribution to shield tunnel
Figure 6 shows the correlation of the bending moment and the axial force obtained from the dynamic analysis, when the horizontal relative displacement between the crown and the invert of the tunnel is max. The cross axle of the figure represents the central angle of a tunnel. The ordinate axis shows the clockwise distribution of the bending moment and the axial force from the tunnel crown as initial.

Where, N: SPT test result (N value)
γ: unit weight, kN/m²

Table 1: Ground model used for comparison

<table>
<thead>
<tr>
<th>Layer</th>
<th>N</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ac</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>As</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>As</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>As</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>As</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 5. Ground model used for comparison

Figure 6. Distribution of bending moment and axial force by dynamic analysis result

4 EVALUATION OF SEISMIC LOAD ACTING ON SHIELD TUNNELS

4.1 Problems of seismic deformation method with earth spring

In general seismic deformation method, the surrounding ground of the tunnel is modeled by the earth spring, and the seismic displacements act on the ring through the earth spring.
Here, the response values obtained from both the seismic deformation method with the earth spring and the dynamic analysis. The studied tunnel is same with that of paragraph 3.3.1. In the examination, the following four ground models are introduced as follows (Figure 5).

Type A: Soft clay ground, overburden 12 m
Type B: Virtual sand ground, overburden 12 m
Type C: Virtual soft clay ground, overburden 12 m
Type D: Hard clay ground, overburden 20 m

4.1.1 Analytical condition

4.1.1.1 Input earthquake ground motion
The input ground motion is same with the one shown in Figure 4.

4.1.1.2 Dynamic analysis
As the dynamic analysis, the equivalent linear method, which is the analysis code SUPER-FLUSH, is applied. The ground motion is input to the bedrock of the analytical model shown in Figure 7. For comparison with the seismic deformation method, the response values when the max relative horizontal displacement between the crown and the invert is given are used.

4.1.1.3 Seismic deformation method with earth spring
Figure 8 shows the analytical model of the seismic deformation method with the earth spring. The load is calculated separately by the dynamic analysis (analysis code SUPER-FLUSH).

For the calculation of the earth spring, the experimental equations on the basis of the plate loading test results are used, which are the functions of the loading width and the modulus of ground deformation. Therefore, considering the loading width for the circular shield tunnel as shown in Figure 9, the coefficients of subgrade reaction is calculated by the equations (1) to (3).

\[ \text{area I: } kv = 1.3 \alpha \varepsilon_0 Bv^{-1}; \text{ kN/m}^3, \text{ clay} \]  
\[ \text{area I: } kv = 2.3 \alpha \varepsilon_0 Bv^{-3/4}; \text{ kN/m}^3, \text{ sand} \]  
\[ \text{area II: } kh = 1.3 \alpha \varepsilon_0 Bv^{-3/4}; \text{ kN/m}^3 \]  

where, \( \alpha = \alpha_s = 1 \)
\( \varepsilon_0 \): modulus of ground deformation in an earthquake
\( Bv, Bh \): loading width shown in Figure 9

4.1.2 Comparison results
Table 4 shows the comparison results. Bending moments from the seismic deformation method with the earth spring are almost equal to or bigger than results obtained by the dynamic analysis (as a safety design). On the other hand, the shear forces and the axial forces are smaller (as a dangerous design).

Therefore, the seismic design by this method lacks reasonableness, because a non-linear model of a segment depends on the axial force. It is considered that the seismic design based on the seismic deformation method with the earth spring may result in dangerous design.

4.2 FEM seismic deformation method
In the FEM seismic deformation method, the grounds surrounding a tunnel are modeled by the finite elements. The seismic displacements are converted to the equivalent nodal forces through the stiffness matrix and loaded to the nodes of the analytical model as the concentrated loads.
Table 4. Comparison of the results between the dynamic analysis, the seismic deformation method with the earth spring, and the FEM seismic deformation method

<table>
<thead>
<tr>
<th>Type</th>
<th>Dynamic analysis</th>
<th>Seismic deformation method with earth spring</th>
<th>FEM seismic deformation method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bending moment (kN*m)</td>
<td>531 (1.00)</td>
<td>565 (1.06)</td>
</tr>
<tr>
<td></td>
<td>Shear force (kN)</td>
<td>610 (1.00)</td>
<td>542 (0.89)</td>
</tr>
<tr>
<td></td>
<td>Axial force (kN)</td>
<td>647 (1.00)</td>
<td>540 (0.83)</td>
</tr>
<tr>
<td></td>
<td>Relative displacement (cm)</td>
<td>4.29 (1.00)</td>
<td>7.48 (1.74)</td>
</tr>
<tr>
<td></td>
<td>Bending moment (kN*m)</td>
<td>97.3 (1.00)</td>
<td>131.2 (1.35)</td>
</tr>
<tr>
<td>Type B</td>
<td>Shear force (kN)</td>
<td>113.8 (1.00)</td>
<td>109.1 (0.96)</td>
</tr>
<tr>
<td></td>
<td>Axial force (kN)</td>
<td>634.0 (1.00)</td>
<td>502.8 (0.79)</td>
</tr>
<tr>
<td></td>
<td>Relative displacement (cm)</td>
<td>0.77 (1.00)</td>
<td>0.84 (1.09)</td>
</tr>
<tr>
<td>Type C</td>
<td>Bending moment (kN*m)</td>
<td>355.8 (1.00)</td>
<td>441.3 (1.24)</td>
</tr>
<tr>
<td></td>
<td>Shear force (kN)</td>
<td>399.1 (1.00)</td>
<td>350.0 (0.88)</td>
</tr>
<tr>
<td></td>
<td>Axial force (kN)</td>
<td>1306.4 (1.00)</td>
<td>567.0 (0.43)</td>
</tr>
<tr>
<td></td>
<td>Relative displacement (cm)</td>
<td>2.78 (1.00)</td>
<td>3.91 (1.41)</td>
</tr>
<tr>
<td>Type D</td>
<td>Bending moment (kN*m)</td>
<td>268.8 (1.00)</td>
<td>341.3 (1.27)</td>
</tr>
<tr>
<td></td>
<td>Shear force (kN)</td>
<td>227.2 (1.00)</td>
<td>254.9 (1.12)</td>
</tr>
<tr>
<td></td>
<td>Axial force (kN)</td>
<td>594.8 (1.00)</td>
<td>764.3 (1.28)</td>
</tr>
<tr>
<td></td>
<td>Relative displacement (cm)</td>
<td>1.55 (1.00)</td>
<td>2.03 (1.31)</td>
</tr>
</tbody>
</table>

4.2.1 Analytical procedure of FEM seismic deformation method

The analytical procedure of the FEM seismic deformation method is expressed as follows (Figure 10).

Step 1: The ground around the tunnel is modeled by the finite elements. Decrease of the ground shear rigidity during earthquakes is considered here.

Step 2: The forced seismic displacements are loaded to all nodes in FEM model without the tunnel, and the nodal forces are calculated on all nodes.

Step 3: The nodal forces at Step 2 are loaded to the FEM model with the tunnel expressed by the beam elements, and also the inertia forces act. As results, the responses of the tunnel are computed.

4.2.2 Comparison with dynamic analysis

Similar to the seismic deformation method with the earth spring, the results from the FEM seismic deformation method are compared with that of the dynamic analysis. The results are shown in Table 4. The results obtained from the FEM seismic deformation method (bending moment, shear force, axial force, and relative displacement) are nearly equal to those of the dynamic analysis. This tendency is similar in all ground models. As results, it is concluded that the seismic design based on the FEM seismic deformation method is more suitable for the circular shield tunnels than the seismic deformation method with the earth spring.

4.3 Summaries of this chapter

The examination results of this chapter are summarized as follows.

a. Compared with the dynamic analysis, there is a case to underestimate by the seismic deformation method with the earth spring. As a result, it tends to be a dangerous design.

b. Using the FEM seismic deformation method, the design results correspond to those of the dynamic analysis, and the reasonable seismic design is possible.
5 SEISMIC DESIGN EXAMPLE BY FEM SEISMIC DEFORMATION METHOD

This chapter shows the seismic design example applying the proposed method.

5.1 Design condition

5.1.1 Design earthquake ground motion and the ground model
Input earthquake ground motion is L2 motion as shown in Figure 4. The ground model is Type A in Figure 5 (Soft clay ground, overburden 12m).

5.1.2 Bedrock on seismic design
It is assumed that the bedrock on the seismic design is the surface of Oc2 layer (Figure 5).

5.1.3 Segment used for seismic design
Figure 11 shows the segment used for seismic design. The joint system is connected over the bolts. The strength of the materials to use is as follows.
- Specified concrete strength; $f'_{ct} = 48N/mm^2$
- Reinforcement; $f_y = 345N/mm^2$ [yield strength]
- Joint bolts; $f_y = 940N/mm^2$ [yield strength]

The strength of the tunnel members is determined on the basis of the normal loads.

5.1.4 Setting of seismic resistant performance
The indexes of the resistant performance of members are set as shown in Table 5 for the seismic performance of Table 2.

Table 5. Indexes of resistant performance of members for a shield tunnel

<table>
<thead>
<tr>
<th>Member</th>
<th>Indexes of resistant performance</th>
<th>Ratio of responses for the index of resistant performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment body</td>
<td>Ultimate bending moment by RC theory</td>
<td>0.915</td>
</tr>
<tr>
<td></td>
<td>Ultimate shear strength by RC theory</td>
<td>0.965</td>
</tr>
<tr>
<td>Joints between segments</td>
<td>Ultimate bending moment with bolts estimated as reinforcement by RC theory</td>
<td>0.891</td>
</tr>
<tr>
<td></td>
<td>Ultimate shear strength of bolts</td>
<td>0.921</td>
</tr>
</tbody>
</table>

5.1.5 Calculation of seismic loads
The seismic loads are computed by the analysis code SUPER-FLUSH. The relative horizontal displacement between the crown and the invert of the tunnel is 92mm. Figure 12 shows the analytical model.

Figure 12. Model for computation of seismic loads by Super-Flush

5.2 Results by FEM seismic deformation method
Table 6 shows the performance check results by the response values computed from the FEM seismic deformation method. The numerical values of the table are the ratio between the response values and the indexes of the resistant performance of a member. From Table 6, it is concluded that the shield tunnel, designed by the normal loads, has the performance to resist the L2 earthquake ground motion.

Table 6. Performance check results by the response values obtained from the FEM seismic deformation method

6 CONCLUSIONS

As the reasonable seismic design method of the shield tunnels, we set the seismic resistant performance and proposed the FEM seismic deformation method as response analytical technique.

Further, in order to enhance the quality, we consider a non-linear model of the tunnel member that depends on the axial force during earthquakes, and the structural model determined by the constants of segment joint based on the results of the loading tests.

In future, we need to consider the splicing effect of the segment rings and the failure mode of the members.

REFERENCES