Prediction and Results of the Effect of Shield Tunnel Construction on Shinkansen Viaduct

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1. Introduction
A shield tunnel for electric power supply was constructed under the viaducts of Sanyo Shinkansen in Osaka City. The diameter of the slurry shield tunnel is 8m and overburden is 43.5m. The distance between the edge of the pile foundation and the shield tunnel is 16.7m. An effect of the construction on the viaduct was anticipated at first, because such a large shield tunnel had not been constructed under the Shinkansen line. However, the construction resulted in a success with only a little movement without a special protective civil engineering work, thanks to the followed procedures.

1. Construction and safety control plan based on the predictions by finite element method analysis (FEMA).
2. In-situ measurements and detailed operation of a machine.

Figure 1 shows an overview of the constructional plan. The tunnel crosses the Yodo river, Hankyu train line, Shinkansen line and other JR line. Figures 2 and 3 show the cross section profiles. The tunnel was constructed in a stable diluvial layer. Table 1 shows an outline of the construction. Photo 1 and 2 show a viaduct at a crossing part.
### Table 1. Profile of the construction

<table>
<thead>
<tr>
<th>Location</th>
<th>Osaka City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose</td>
<td>A shield tunnel for electric power supply (Inner diameter: 6800mm)</td>
</tr>
<tr>
<td>Excavation method</td>
<td>Slurry shield tunnel method (Outer diameter: 7780mm)</td>
</tr>
<tr>
<td>Construction period</td>
<td>From 1998 to 2003</td>
</tr>
<tr>
<td>Adjacent structures</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Rigid frame elevated bridge (R7,R8)</td>
</tr>
<tr>
<td></td>
<td>Reinforce concrete</td>
</tr>
<tr>
<td></td>
<td>Multi-stories</td>
</tr>
<tr>
<td></td>
<td>Various spans</td>
</tr>
<tr>
<td></td>
<td>Direction of the track: Two stories and three spans</td>
</tr>
<tr>
<td></td>
<td>Direction at a right angle to the track: Two stories and five spans</td>
</tr>
<tr>
<td></td>
<td>Pile foundation: _=600mm, L=23.0m, 20 piles</td>
</tr>
<tr>
<td></td>
<td>Underground beam: beam height=2000mm</td>
</tr>
<tr>
<td>Railway</td>
<td>5 lines, ballast track</td>
</tr>
</tbody>
</table>

### 2. Settlement prediction

#### 2.1 Outline of settlement prediction

Special protective civil engineering work for Shinkansen was not adopted from the following reasons.

1. Tunnels can be constructed with little ground deformation by closed type shield machines, because of the recent progress of shield tunneling technique.
2. Little settlement due to excavation is anticipated, because the ground is comparatively stiff diluvium.
3. The ground deformation due to grouting, which is a conventional protective measure, will generate larger ground deformation than that due to the passing of a shield machine if the ground is stiff.

To ensure safety, a construction and safety control plan was prepared and detailed estimation and measurements were performed for the protective civil engineering work.

At first, the safety of Shinkansen line was evaluated by an elastic FEMA. But, in practice, a construction control system including expertise of shield machine operation is essential for surrounding ground movements. Then, measuring points were set at more than 1000m before the viaduct for deformation of the ground due to the passing of shield machine. The measurement results were evaluated by FEMA, to confirm the fitness of coefficients. Prediction and pre-measurements were taken into the operational control plan for Shinkansen tracks and viaducts. The flow of considerations is shown in Figure 4.

#### 2.2 Initial effect evaluation

By considering the following facts, the ground stress release ratio (see Figure 5) for FEMA was set at 13%, although the value was relatively greater than the conventional value.
for a diluvial layer.

1. Details of the construction were not specified at that time.
2. 13% was calculated by analyzing the case of a shield tunnel, which was constructed in the similar ground, close to the construction site.

The analytical model and part of the results are shown in Figures 6 and 7.

Table 2 shows the ground material properties.

<table>
<thead>
<tr>
<th>No</th>
<th>Symbol</th>
<th>Layer-thickness (m)</th>
<th>N value*</th>
<th>Unit weight (kN/m³)</th>
<th>Cohesion C (kN/m²)</th>
<th>Angle of internal friction (degree)</th>
<th>Poisson ratio</th>
<th>Elastic modulus E (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B</td>
<td>2.50</td>
<td>3</td>
<td>17.0</td>
<td>-</td>
<td>29</td>
<td>0.38</td>
<td>4.50</td>
</tr>
<tr>
<td>2</td>
<td>A_s1</td>
<td>2.40</td>
<td>8</td>
<td>17.0</td>
<td>-</td>
<td>32</td>
<td>0.37</td>
<td>12.00</td>
</tr>
<tr>
<td>3</td>
<td>A_c1</td>
<td>2.80</td>
<td>8</td>
<td>17.0</td>
<td>50.0</td>
<td>-</td>
<td>0.40</td>
<td>10.50</td>
</tr>
<tr>
<td>4</td>
<td>A_c2</td>
<td>11.95</td>
<td>3</td>
<td>17.0</td>
<td>54.7</td>
<td>-</td>
<td>0.40</td>
<td>11.49</td>
</tr>
<tr>
<td>5</td>
<td>A_s2</td>
<td>2.55</td>
<td>18</td>
<td>19.0</td>
<td>-</td>
<td>32</td>
<td>0.35</td>
<td>27.00</td>
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<tr>
<td>6</td>
<td>A_c3</td>
<td>0.60</td>
<td>13</td>
<td>19.0</td>
<td>145.0</td>
<td>-</td>
<td>0.38</td>
<td>30.45</td>
</tr>
<tr>
<td>7</td>
<td>D_g1</td>
<td>6.70</td>
<td>50over</td>
<td>20.0</td>
<td>-</td>
<td>35</td>
<td>0.30</td>
<td>75.00</td>
</tr>
<tr>
<td>8</td>
<td>D_c1</td>
<td>17.50</td>
<td>15</td>
<td>18.0</td>
<td>155.0</td>
<td>-</td>
<td>0.36</td>
<td>32.55</td>
</tr>
<tr>
<td>9</td>
<td>D_s1</td>
<td>3.90</td>
<td>50</td>
<td>20.0</td>
<td>-</td>
<td>34</td>
<td>0.30</td>
<td>75.00</td>
</tr>
<tr>
<td>10</td>
<td>D_c2</td>
<td>2.85</td>
<td>29</td>
<td>19.0</td>
<td>295.0</td>
<td>-</td>
<td>0.35</td>
<td>61.95</td>
</tr>
<tr>
<td>11</td>
<td>D_s2</td>
<td>-</td>
<td>50over</td>
<td>20.0</td>
<td>-</td>
<td>33</td>
<td>0.30</td>
<td>75.00</td>
</tr>
</tbody>
</table>

* N value : resistance value to penetration, measured by a Japanese standard penetration test

The coefficients of elasticity are determined by the next equations.

Sandy ground    \( E = 15N_0.1 \)  \( N : N \) value  
Clayey ground    \( E = 210Cu \)  \( Cu : Cohesion \)

The maximum predicted settlement on the ground surface is 9.58mm and the maximum ground inclination is 29.5second. Stresses of all viaduct structural members and displacements of the railway track were checked with those results, and the safety of the line was confirmed. Table 3 shows the results of FEMA prediction.
### Table 3  Results in the initial effect evaluation with FEMA

<table>
<thead>
<tr>
<th>Item</th>
<th>Maximum settlement</th>
<th>Maximum horizontal displacement</th>
<th>Maximum settlement on the base level</th>
<th>Maximum horizontal displacement on the base level</th>
<th>Maximum deformation angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-31.43mm</td>
<td>9.90mm</td>
<td>-9.58mm</td>
<td>2.42mm</td>
<td>29.5°(R7)</td>
</tr>
</tbody>
</table>

#### 2.3  Pre-measurement and FEMA

Ground movements due to shield tunneling strongly depend on the skill of operator and the entire operational system. To confirm these effects and fitness of coefficients in FEMA, ground behaviors were measured at pre-measuring points and simulated by FEMA. Pre-measuring points were set on both banks of the Yodo river where the ground conditions are similar to the crossing section (Photo 3).

Figures 7 and 8 show the results of pre-measurements and FEMA prediction. The prediction was done with several values of release ratio. The results show that 13% is appropriate as the maximum ground settlement.

But, the maximum settlement of 3mm in the results of pre-measurement and FEMA is much smaller than that of 9.6mm in the initial effect evaluation for cross part by FEMA. The cause was considered to be the difference in the ground stiffness of two parts. The ground at pre-measurement points is only soil. But the ground at the cross part contains some stiff structures, such as piles and underground beams of the viaduct. From the viewpoint of FEMA, it was considered that those stiff structures were pulled extremely by the large ground deformation in deep parts. To confirm the phenomenon, when an imaginary stiff zone (i.e., elastic modulus in the zone is large) was set in the ground of FEM model at a pre-measurement point, the ground settlement became 1.4 times as large. Because the actual ground deformation, which takes place near the tunnel, is larger than that on surface, it is considered that the viaduct may settle largely due to the pull at its piles.

Concerning the distribution of ground settlement on the cross section, shapes of the settlement trough in pre-measurements were steeper than that in FEMA (see Figures 7 and 8). Then, it was considered that the actual ground incline angle or deformation angle of the viaduct) due to the settlement at the cross part, on which the stress of the viaduct depend, will be larger than that in the initial effect evaluation by FEMA, too. Then, the additional rate of the ground incline angle due to the results of pre-measurement and FEMA was set and stresses of all viaduct members were re-checked. When the additional rate was 150%, the maximum stress of R7 (on the No.26 column) was 239.8MN/m² and that of R8 (on the No.32 column) was 239.7MN/m². Both values were in the allowable range but close to the limit value. At the time, the deformation angle between the No.26 and No.27 columns (in R7) was 0.60°10–rad and that between the No.31 and No.32 columns (in R8) was 0.20°10–rad. Table 4 shows the results of the re-check.
Table 4. Results of the re-check

<table>
<thead>
<tr>
<th>Viaduct No.</th>
<th>R7</th>
<th>R8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column No.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limit deformation angle($\times 10^{-3}$rad)</td>
<td>0.60</td>
<td>0.55</td>
</tr>
<tr>
<td>Stress(MN/m$^2$)</td>
<td>239.8</td>
<td>-</td>
</tr>
</tbody>
</table>

3 Measurement

3.1 Location of measuring points

To collect data for confirming the safety of shinkansen line, a real-time monitoring system was prepared for the movement of the viaduct (R7, R8) and shinkansen tracks. Figures 10 and 11 show the locations of measuring points. Table 5 shows kinds and the number of measuring sensors. From the results of pre-measurement, the affected area was assumed within 45 degree lines upper the tunnel, which includes two viaduct blocks, R7 and R8. Measurement of vertical displacement for R6 and R9 was also carried out.

3.2 Period of measurement

Figure 12 shows periods of measurement. When the face of the shield machine reached 3D (the distance is three times as long as the diameter of the tunnel, about 25m) before the measuring point, pre-settlement started. When the face of the machine arrived at 2D (about 15m), the settlement rapidly increased. Deformations both in the ground and on the surface started at the same time. When the face of the shield machine reached 2D after the measuring point, the settlement comes to an end. From those results in pre-measurement, it was decided to measure the viaduct in detail, when the shield machine passes through 51m before the viaduct and a same length after that. But, to examine a coefficient of thermal compensation, the measurement started one month before the crossing. Concerning the measurement of the track, it is decided to set 2D before and after the viaduct. To check the secondary settlement, measuring settlement was continued once a week until three months after the shield machine passing.

3.3 Allowable deformation value

Allowable deformation values for the viaduct and railway tracks were set. Allowable deformation angles were set for the viaduct, because stresses in the members of a viaduct depend on the deformation angles due to the difference of settlement between columns of a viaduct. An allowable deformation angle for the viaduct, R7 was 0.60$\times 10^{-3}$rad and that for R8 was 0.20$\times 10^{-3}$rad, because stresses in the members were close to the allowable stress at re-check (see 2.3 Pre-measurement and FEMA).

Concerning Shinkansen track, the allowable displacement of 10-meter chord versine is usually 3 mm. However, because tracks can be inspected only at night, the allowable displacement between columns, which occurs after re-alignment of track, was fixed to 3mm as a measure for judgment during operation hours.
For the safety management of Shinkansen infrastructures, three stages of the control level were planned.

1. Caution level 1 (50% of the allowable value)
2. Caution level 2 (75% of the allowable value)
3. Caution level 3 (100% of the allowable value)

The contingency plan for the viaducts is as follows.

1. When the measured data reaches the caution level 1, the constructing organization has to inform JR and the measuring frequency has to be increased.
2. When the measured data reaches the caution level 2, the constructing organization has to find the cause, re-consider the constructional method and consult with JR organs on whether to stop excavation and countermeasures.
3. When the measuring data reach the allowable value, the constructing organization has to stop the construction immediately and consult with JR about countermeasures.

Contingency plan for the track is as follows.

1. When the measuring data reaches the caution level 1, the constructing organization has to inform JR and the measuring frequency has to be increased.
2. When the measuring data reaches the caution level 2, the constructing organization has to find the cause and re-consider the constructional method. JR precisely inspects tracks during night.
3. When the measuring data reach the allowable value, the constructing organization has to stop the construction immediately and consults with JR about re-start of construction. JR re-aligns the track as soon as possible.

However, it was decided that the related organs have to take each measure before measuring data reach each caution level, when the velocity of deformation is extremely high.

Table 6 shows the allowable values for safety control

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Items of control</th>
<th>Railway track</th>
<th>Viaduct</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety of railway track</td>
<td>Allowable settlement (relative settlement)</td>
<td>Column No.29-30</td>
<td>Safety of rail track</td>
<td>Safety of viaduct</td>
</tr>
<tr>
<td>Safety of viaduct</td>
<td>Allowable deformation angle between columns</td>
<td>R7</td>
<td>R7</td>
<td>R7</td>
</tr>
<tr>
<td>Safety of viaduct</td>
<td>Allowable deformation angle between columns</td>
<td>R8</td>
<td>R8</td>
<td>R8</td>
</tr>
<tr>
<td>Allowable settlement (relative settlement)</td>
<td>1.50mm</td>
<td>0.30\times10^{-3}\text{rad}</td>
<td>0.10\times10^{-3}\text{rad}</td>
<td>50%</td>
</tr>
<tr>
<td>Caution level 2</td>
<td>2.25mm</td>
<td>0.45\times10^{-3}\text{rad}</td>
<td>0.15\times10^{-3}\text{rad}</td>
<td>75%</td>
</tr>
<tr>
<td>Caution level 3</td>
<td>3.00mm (limit value)</td>
<td>0.60\times10^{-3}\text{rad}</td>
<td>0.20\times10^{-3}\text{rad}</td>
<td>100%</td>
</tr>
</tbody>
</table>

### 4 Construction plan

Because special protective civil engineering work was not adopted for the construction, the safety of Shinkansen line during tunneling under the viaduct depended on the suitable shield machine control and detailed measurement of the viaduct. Then, it was important to make a machine control plan.
Main factors, which influence ground settlement by shield tunneling, are as follows.
1. Slurry pressure at face.
2. Property of slurry.
4. Back-fill grouting method
5. Relation between volume of muck and advance-length (or advance-speed)
6. Shield machine operational control.

For safety it is necessary to set appropriate limit values against those factors and keep them with detailed operation.

Because track settlements had been smaller than those of target value (3mm), the same control plan at the pre-measured section was adopted for passing under the viaduct. In addition to that, the following factors were also considered.
1. Face stabilization when a shield machine stops in case of emergency.
2. Cycle time.
3. Non-stop excavation under the viaduct.
4. Cause of slurry pressure value.
5. Check system for keeping to those arrangements of operation.

5 Results of measurement

Figures 13 and 14 show the results of measurement tunneling under Shinkansen viaduct. When the face of the shield machine reached 4D (four times diameter of the tunnel, about 32m) before the measuring point, settlement started. When the face of the machine arrived at 2D (about 16m), settlement rapidly increased. Until the shield machine-tail reached 2D after the measuring point, settlement continued. While the tail of the shield machine was passing between 2D and 4D behind the measuring point, the increment of the settlement decreases. When the tail of the shield machine reached 4D after the measuring point, the settlement almost finished.

Concerning the safety control of the track, the maximum relative-settlement between R7 and R8 was 2.28mm. The value is almost the same as that of the caution level 2.

The maximum deformation angle on R7 was 1.80$\times 10^{-4}$rad, i.e. about 60% of the caution level 1. The same for R8 was 1.01$\times 10^{-4}$rad, which is almost the same as that of caution level 1.

By considering those results, the construction resulted in a success with only a little deformation.

Table 7 shows the results of the measurement.
Table 7. Results of the measurement

<table>
<thead>
<tr>
<th>Item</th>
<th>Block of the viaduct</th>
<th>Position</th>
<th>Value</th>
<th>Caution level</th>
<th>allowable value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum settlement</td>
<td>R7</td>
<td>D-29</td>
<td>5.00mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum relative-settlement</td>
<td>Between R7 and R8</td>
<td>A</td>
<td>2.28mm</td>
<td>1.50mm</td>
<td>3.00mm</td>
</tr>
<tr>
<td>Maximum deformation angle between columns</td>
<td>R7</td>
<td>E 26-27</td>
<td>1.80_10^{-4}rad</td>
<td>3.0_10^{-4}rad</td>
<td>6.0_10^{-4}rad</td>
</tr>
<tr>
<td>(in the direction of the track)</td>
<td>R8</td>
<td>E 30-31</td>
<td>1.36_10^{-4}rad</td>
<td>1.0_10^{-4}rad</td>
<td>2.0_10^{-4}rad</td>
</tr>
<tr>
<td>Maximum deformation angle between columns</td>
<td>R7</td>
<td>E-D 27</td>
<td>1.60_10^{-4}rad</td>
<td>3.0_10^{-4}rad</td>
<td>6.0_10^{-4}rad</td>
</tr>
<tr>
<td>(in the direction of right angles to the track)</td>
<td>R8</td>
<td>E-C 32</td>
<td>1.24_10^{-4}rad</td>
<td>1.0_10^{-4}rad</td>
<td>2.0_10^{-4}rad</td>
</tr>
</tbody>
</table>

6 Conclusion

1. A large scaled shield tunnel for electric power supply was constructed crossing under viaducts of Sanyo Shinkansen in Osaka City. The construction resulted in a success with only little influence and without a special protective civil engineering work thanks to the following measures.
   (1) Detailed evaluation by FEMA.
   (2) Measurement before the Shinkansen crossing and application of back-analysis.
   (3) Safety control plan and machine control plan when a shield machine passes under the viaduct, which is based on estimations.
   (4) Carrying out measurements and safety control in detail.

2. To confirm the fitness of coefficients in FEMA, ground behaviors were measured at pre-measuring points and simulated with FEMA. The results showed that 13% stress release ratio) was appropriate as the maximum ground settlement. But, concerning distribution of ground settlement on the cross section, shapes of the settlement trough in pre-measurements were steeper than that in FEMA. Then, an additional rate of the ground incline angle due to the results of pre-measurement and FEMA was set and stresses of all viaduct members were re-checked.

3. It was confirmed by pre-measurement that the influential area in cross section due to shield machine passing is inside the 45 degree lines. By the results, measuring sensors were arranged.

4. Results of pre-measurement and measurement of the viaduct showed the following
ground behaviors.

(1) When a face of the shield machine reached from 3D (three times diameter of the tunnel, about 24m) to 4D (about 32m) before the measuring point, the settlement started.

(2) When the face of the machine arrived at 2D (about 16m), settlement rapidly increased.

(3) Until the shield machine-tail reached 2D after the measuring point, settlement continued.

(4) When the tail of the shield machine reached 4D after the measuring point, settlement almost finished.

5. The allowable deformation of both railway tracks and viaducts were determined. Allowable deformation angles were set for viaducts, because stresses in the members of the viaduct depend on the deformation angle due to the difference of settlement between columns. When stresses in the members were close to the allowable stress at re-check, the input data were regarded as allowable angle values. Concerning the railway track, the allowable displacement between columns, which occurs after re-alignment of track, was fixed to 3mm.

6. Carrying out measurements and safety control in detail. Safety was evaluated according to the three caution levels.

   (1) Caution level 1 (50% of the limit value)
   (2) Caution level 2 (75% of the limit value)
   (3) Caution level 3 (100% of the limit value)

7. The relation between the shield machine control for excavation and results of pre-measurement was analyzed. From the results, a machine control method under the viaduct was planned.
Figure 1  Construction plan overview
Figure 2  Cross section
Figure 3  Cross section with soil profile
Photo 1  Viaduct at cross section

Photo 2  Viaduct at cross section
Primary construction plan

- Initial evaluation of safety by an elastic FEMA
- Pre-measurement and simulation by FEMA
- Re-check of stress in the viaduct
  - Safety control plan
    - Measurement plan for viaduct and track
    - Allowable deformation value
    - Contingency plan
- Shield machine control plan

Execution

Measurement and safety control

Post-evaluation of safety

FEMA: Finite element method analysis

Figure 4  Flow of considerations
Procedure for calculating ground movement due to tunneling with elastic FEM.

Step 1
Calculate initial ground stress.

Pi: Initial ground stress

Step 2
Remove elements of tunnel.
Act forth P on nodes of tunnel surface.

Forth P expresses effect of support included following things

1. support by slurry pressure
2. support by shield machine
3. support by backfill grouting
4. support by segments
5. support by three dimensional effect
6. effect of machine control
7. skill
8. etc

_: Ground stress release ratio

Figure 5  Ground stress release ratio
Figure 6 Analytical model and a part of results
Figure 7  Analytical model and a part of results

Unit: mm
Photo 3  Pre-measurement point
Right bank of the Yodo river

Figure 8  Results of pre-measurement and FEMA.

Left bank of the Yodo river

Figure 9  Results of pre-measurement and FEMA.
Figure 10  Arrangement of measuring points (cross section)

Figure 11  Arrangement of measuring point (cross section)

Table 5  Number of measuring sensors

<table>
<thead>
<tr>
<th>Measurement item</th>
<th>Measurement instrument</th>
<th>Legend</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative settlement</td>
<td>Settlement gauge</td>
<td>(reference point)</td>
<td>55</td>
</tr>
<tr>
<td>between columns</td>
<td></td>
<td></td>
<td>Include 9 reference points</td>
</tr>
<tr>
<td>Absolute settlement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>Thermometer</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Settlement</td>
<td>Detailed level survey</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 12  Periods of measurement
Figure 13 Results of measurement

Relation between distance from cutting face and settlement
Figure 14 Results of measurement