Work and design of a new tunneling method ‘SENS’ to unconsolidated ground

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ABSTRACT: The Sambongihara Tunnel is on the Tohoku Shinkansen Line. The geology of this tunneling site mainly consists of alternating layers of unconsolidated sandy soil under high hydraulic pressures and cohesive soil. This tunnel was excavated using the NATM, but the tunnel face collapsed twice, preventing the tunnel construction from advancing as scheduled. We therefore conducted an in-depth study to develop a new tunneling technique, aimed at improving efficiency and safety of the work. The new tunneling method uses a standard earth and mud pressure shield to maintain face stability and ensure good excavating capability. This paper outlines the construction and design of the linings selected for this tunneling practice.

1 INTRODUCTION

The Sambongihara Tunnel, in the east district of Aomori, is a part of the extension project of the Tohoku Shinkansen Line between Hachinohe and Shin-Aomori (Fig. 1).

Initially the NATM was planned to be used for this project. The tunnel construction started in August 2001 from Shin-Aomori side, but two significant collapses occurred in March and September 2002. It was therefore required to develop an effective means to ensure safety in the work at the face that has less impact on the structures on the surface, and countermeasures against the till then realized delay in the work schedule.

To overcome these initial difficulties, a new technique named SENS was developed, which features improved safety, economy and work efficiency. As a result, the excavation by the NATM from Shin-Aomori side was stopped, and instead tunneling by the SENS from Hachinohe side started in July 2004, and is currently being used. This paper discusses the overview of the SENS method and reports the status of tunneling.

Figure 1. Location of the Sambongihara Tunnel.

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2 OUTLINE OF THE PROJECT

2.1 Characteristics of the project

The Sambongihara Tunnel is in a double-track section on the Shinkansen Line. Its excavation outer diameter is 11,440 mm, and finished diameter 10,180 mm, and the total length 4,280 m. After 1,265.2 m had been excavated, tunneling by the NATM was stopped, and plans were made to use the SENS for construction of the remaining 3,014.8 m.

The section of this tunnel is shown in Figure 2, and the characteristics of the tunnel in Table 1.

2.2 Geological profile

Figure 3 depicts the geological longitudinal section of the tunnel. The topography of the site consists of relatively flat diluvial upland of about 60 m in altitude and alluvial valley dissected by a river. The Noheji formation traversed by the tunnel alignment consists of alternating layers of unconsolidated sand and clay. The groundwater level is above the tunnel crown in most places, and at the highest spot, about 17 m above the crown.

The ground to be excavated is in general relatively solid, allowing excavation by the NATM. However, as experienced when using the NATM, at the boundary between sand and cohesive soil layers, the fluidity of the upper Nos1 layer increased, due to water ingress to the face, causing the collapses.

3 DEVELOPMENT OF THE SENS

3.1 Definition of the SENS

The tunneling methods are largely divided into shield tunneling and the NATM. The former technique uses a TBM to ensure ‘face stability’ and perform ‘muck handling.’ It is excellent in that tunneling in urban weak soil can be performed safely. However, since prefabricated segments are used for lining, it is as a general rule more costly than the NATM tunneling.
In contrast, the NATM is excellent from the economic viewpoint, but it is difficult to apply to weak or unstable soil.

In soil such as that at the Sambongihara Tunnel site, which is generally solid although a stratum of relatively high fluidity exists, the shield tunneling is suitable from the standpoint of ‘face stability’ and ‘muck handling,’ but lining with prefabricated segments is less economical. Figure 4 is a schematic diagram showing comparison of shield and the NATM techniques in terms of economy and ground properties.

For projects classified in the boundary range between the NATM and shield, an increasing demand is recognized for techniques that offer both a safe ‘excavation mechanism’ and a reasonable ‘lining system.’ The SENS is one of these techniques. It uses a TBM to maintain ‘face stability’ and ensure efficient ‘excavation,’ with concrete structural members cast in place at the tail.

The ECL is a technique similar to the SENS. The ECL is based on the same design practice for cast-in-place concrete as that for segments of shield tunneling. However, it is not economical for relatively solid ground, that of Sambongihara site for example. In addition, records of ECL projects reveal that much labor was needed in some cases for assuring the quality of the tunnel because significant cracks and water leak occurred in the lining.

Considering the above, the authors applied the concept of ultimate state of the lining to simplify the lining structure, and to ensure satisfactory structural quality. The structure selected for achieving these goals is secondary lining inside the cast-in-place concrete.

This new method was named ‘Casting Support Tunneling System Using TBM’, and called SENS for short. SENS stands for Shield (S), ECL (E), the NATM (N) and System (S), since it is a method developed on the basis of these tunneling techniques.

### 3.2 Lining

As shown in Figure 2, the ground support is composed of a 330 mm thick primary lining and a 300 mm thick secondary lining.

The primary lining is expected to work as the shotcreting in the NATM. That is to say, it has a support function for stabilizing the excavated cavity, but it tolerates some degree of groundwater infiltration and cracking. The secondary lining that will not carry loads is placed after confirming that cast-in-place concrete deformation has well converged.

The primary lining concrete is, as illustrated in Figure 5, placed between ground and tubular form assembled at the tail. Concrete casting is simultaneous with tunnel advance. The ground is maintained by the liquid pressure of the concrete until the concrete hardens. However, while hardening, the ground continues to deform under the effect of excavation, so loads acting on the hardened concrete are expected to be smaller than those on the segment lining. The authors will measure stresses in the lining concrete to understand the mechanism of interaction between the ground and primary lining.

### 4 DESIGN OF THE PRIMARY LINING

#### 4.1 Prior design

##### 4.1.1 Validation

As a general rule, the section of the Sambongihara Tunnel was designed according to the Design and Execution Guidelines of Extruded Concrete Lining Method (draft) urban tunnel version (Japan Railway Construction Public Corporation 1992). These guidelines assume urban NATM tunneling, considering the primary lining as temporary structure and the
secondary lining as structural member that carries loads. For the Sambongihara project, however, the lining design is based on that for mountain NATM, that is to say, the primary lining carries loads, but the secondary lining doesn’t. We therefore, as shown in Table 2, studied the limit state of failure and buoyancy for the primary lining alone.

4.1.2 Conditions of validation
We set compressive strength of primary lining concrete at 15 N/mm² (at one day) and 30 N/mm² (at 28 days). Other properties are given in Table 3.

Two cases of load conditions were studied: one with a large overburden and the other with a smaller overburden. The study also considered a case where the groundwater level lowered after completion of work.

### Table 2. Comparison with the guidelines for validation.

<table>
<thead>
<tr>
<th>Kind of lining</th>
<th>Primary lining</th>
<th>Secondary lining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition for design</td>
<td>At dismantling tubular form</td>
<td>At completion of operation</td>
</tr>
<tr>
<td>Material</td>
<td>Plain concrete or steel fiber reinforced concrete</td>
<td>Reinforced concrete</td>
</tr>
<tr>
<td>Kinds of limit state for design</td>
<td>Ultimate limit state</td>
<td>Serviceability limit state</td>
</tr>
<tr>
<td></td>
<td>Limit state of destruction</td>
<td>Limit state of crack width</td>
</tr>
<tr>
<td></td>
<td>Limit state of buoyancy</td>
<td>Limit state of destruction</td>
</tr>
</tbody>
</table>

### Design method of SENS (before work)

| Condition for design | At dismantling tubular form | At completion of operation |
| Material | Plain concrete | Plain concrete |
| Kinds of limit state for design | Ultimate limit state | – |
| | Limit state of destruction | – |
| | Limit state of buoyancy | – |

4.1.3 Results
Stress resultants in the primary lining were calculated by a frame analysis using the conditions mentioned above, and were compared with the strength curve. The results verified that the primary lining is structurally safe at the limit state.

In addition, we compared buoyancy with the total of dead load and shear resistance of earth to verify structural safety.

### Table 3. Specific character of concrete.

<table>
<thead>
<tr>
<th></th>
<th>1 day</th>
<th>28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>Strength for design f'ckN/mm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension strength for design ftkN/mm²</td>
<td>0</td>
<td>Plane concrete</td>
</tr>
<tr>
<td>Modulus of elasticity E₀ kN/mm²</td>
<td>13</td>
<td>28</td>
</tr>
<tr>
<td>Unit weight γ kN/m³</td>
<td></td>
<td>23.5</td>
</tr>
</tbody>
</table>

### Table 4. Transition of ground support mechanism.

<table>
<thead>
<tr>
<th>Work step</th>
<th>Ground support mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Placing concrete</td>
<td>Concrete casting pressure support ground, inducing reaction force, and this is finally supported by tubular form</td>
</tr>
<tr>
<td>During concretion</td>
<td>Initially, ground reaction is supported by the tubular form, with concrete casting pressure. Though, a load on the primary lining increases gradually.</td>
</tr>
<tr>
<td>Dismantling tubular form</td>
<td>The primary lining bears the ground reaction which was supported by the tubular form</td>
</tr>
<tr>
<td>Completion of concretion</td>
<td>As the strength of primary lining develops, structural safety increases</td>
</tr>
</tbody>
</table>

4.2 Development of design
The ground support mechanism by the primary lining is changing in work step as shown on Table 4. The transition of the ground support mechanism occurs in practice, whereas it isn’t considered in design work. We suppose that such transition significantly influences the support mechanism. In this project, stresses in the primary lining concrete and tubular form, and displacement of surrounding ground are measured. Based on the measurement results, we will obtain information on the interaction between the ground and primary lining, which will be useful for establishing more reasonable design procedures for future projects.

5 TUNNELING OPERATIONS

5.1 TBM

Figure 6 shows the TBM and Figure 7 the entire view of the TBM and tubular form. As indicated in Figure 6, the TBM is 11,440 mm in outer diameter and 11,120 mm long. The earth and mud pressure shield was selected to prevent primary lining concrete from seeping into the
face. The machine used in this project is equipped with a tubular form removal device (demolding machine), in addition to a tubular form erector as installed on the ordinary TBM.

As shown in Figure 5, concrete is injected simultaneously with tunnel advance, through the ports provided in the stop form, at the position surrounded by ground, stop form and tubular form erected at the tail. The stop form in the shape of a ring is located between skin plate and tubular form circumference. This form is supported against the TBM body by the stop form jacks. During advance, the accumulator in the hydraulic circuit moves the stop form forward and backward in the tunnel axis direction so that the concrete pressure is kept constant, even if there is a slight variation in advance speed or concrete supply rate. Each stop form jack cylinder is separated into four chambers, and the different jacks are synchronized so that the jack strokes are nearly the same as all the others. This regulation mechanism avoids significant inclination of the stop form.

In one work cycle, as shown in Figure 8, the tubular form at the end is removed simultaneously with advance, and at the end of advance, another tubular form is assembled. The advance and tubular form assembly take about 90 minutes respectively, so one cycle is about 3 hours. Advance is continuously performed while casting concrete. However, during advance, the concrete piping tends to clog and the stop form movement becomes irregular. To cope with this difficulty, advance is interrupted at intervals of ten rings, and the pumps and piping are cleaned, and the stop form is separated from the concrete surface after ten hours when concrete has set enough to sustain itself.
Inside the shield machine
Lining concrete
Remixer
Tubular form
Concrete supply pump
Concrete pump
Shut-off valve
Two-way valve

Figure 9. Concrete lining system.

5.2 Tubular form

One ring of the tubular form is 1.2 m wide. Sixteen rings are used in total. The tubular form assembled at the tail is removed and disassembled when it comes to the end along with tunnel advance, to be conveyed to the tail and used repeatedly.

The propulsion reaction of the shield is given by adhesion of concrete to the tubular form. With concrete of 24-hour unconfined compressive strength of 15 N/mm², an adhesion of 200 kN/m² of tubular form can be obtained. On this assumption, the adhesion area of seven rings of hardened concrete is necessary to ensure sufficient propulsion reaction. Therefore, the advance per day is limited to 8 rings, so at least 8 concrete rings having 1-day compressive strength remain.

5.3 Concrete lining system

Figure 9 is a schematic diagram of the concrete lining system. Concrete is manufactured at a plant installed in the site, and transported to the supply pump by agitator trucks. The concrete pump supplies concrete through the 6 inch piping to the remixer in the trailing carriage of the TBM. Concrete is conveyed from the remixer to six concrete lining pumps. Then the concrete is sent, via the two-way valve, through 3 inch piping and poured through 12 ports.

6 DEVELOPMENT OF CONCRETE

Concrete to be used in this project is subjected to the following restrictions:

− it takes a certain time to assemble a ring of the tubular form, following the advance for a distance of the preceding ring.
− concrete is placed in water, and
− concrete shall exhibit the required strength by the time of form removal.

To satisfy these requirements, concrete having the properties given in Table 5 must be developed.

Table 5. Quality standard of concrete.

<table>
<thead>
<tr>
<th>No.</th>
<th>Quality performance</th>
<th>Quality standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flowability</td>
<td>Flowability shall be maintained for hours that are the estimated time from mixing-up to casting.</td>
</tr>
<tr>
<td>2</td>
<td>Self-compactibility</td>
<td>Concrete shall entirely fill 330 mm thick space (lining thickness).</td>
</tr>
<tr>
<td>3</td>
<td>Segregation resistance</td>
<td>Concrete shall not segregate during pumping or filling.</td>
</tr>
<tr>
<td>4</td>
<td>Antiwashout</td>
<td>Loss of cement particles from concrete placed in water shall be limited.</td>
</tr>
<tr>
<td>5</td>
<td>Pumpability</td>
<td>The required amount of concrete can be conveyed under pressure, and conveyed concrete quality shall not degrade.</td>
</tr>
<tr>
<td>6</td>
<td>Early age compressive strength</td>
<td>The strength at one day shall be 15 N/mm² or more.</td>
</tr>
</tbody>
</table>

Table 6. Control values of concrete.

<table>
<thead>
<tr>
<th>Control value</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified slump flow</td>
<td>60 cm ± 5 cm Once/day</td>
</tr>
<tr>
<td>Specified slump (After 4 hours)</td>
<td>80% of specified slump flow value Once/day</td>
</tr>
<tr>
<td>Volume ratio of air</td>
<td>4.5 ± 1.5%  Once/day</td>
</tr>
<tr>
<td>Antiwashout test</td>
<td>pH ≤ 12     Once/day</td>
</tr>
<tr>
<td>1-day compressive strength</td>
<td>More than 15 N/mm² Once/day</td>
</tr>
<tr>
<td>28-day compressive strength</td>
<td>More than 30 N/mm² Once/day</td>
</tr>
<tr>
<td>Unit water content</td>
<td>Specified water content +20 kg Once/50 m³</td>
</tr>
</tbody>
</table>

Among the properties shown in Table 5, the fluidity and exhibition of early age strength are incompatible with each other, as are antiwashout and pumpability. However, tests on fluidity and strength, and pumpability were conducted repeatedly to select the concrete mix specification.

The management items shown in Table 6 have been set up, and the tunnel construction is now under way using the concrete satisfying these items.

7 CONSEQUENCE OF TUNNELING

7.1 Displacement of lining

The displacement of lining concrete is shown in Figure 1C. The dotted lines represent settlement at the crown, right and left, whereas the solid line expresses the variation in distance between two points. Since
better in quality than the primary lining of the NATM tunneling. Concrete filling is perfect, and no un-filled sections were observed from the surface. The ultrasonic test verified that the lining thickness conformed to the requirement.

8 CONCLUSIONS
As of August 2004, about 70 meters of the primary lining have been cast. To date, tunneling construction has made good progress and no abnormal displacements of concrete or surrounding ground have been found.

We will perform in-depth measurements of stresses induced in the lining concrete and displacement of the surrounding ground. Referring to data measurements, we will determine the loads acting on the cast-in-place primary concrete lining, in the hope of proposing a reasonable lining design technique that is well suited to the process of concrete casting in place.

REFERENCE

Figure 10. Variation of crown settlement and convergence with time.

the measurements were possible only after the trailing carriage passed away, the data cover points 50 meters or more from the face. The graphs demonstrate that the settlement at each point is less than 1 mm, and the variation in distance is no more than ±1 mm. We can conclude therefore that the concrete moved very little after demolding.

7.2 Cracks and water leakage
The completed primary lining is almost free from cracking and water ingress. This ground support is