Construction of Casting Support Tunneling System using TBM in Water-Bearing Unconsolidated Ground

M. Noguchi¹, A. Ogawa¹, T. Iura¹, T. Tamai¹, T. Abe², T. Kobayashi²

¹Japan Railway Construction, Transport and Technology Agency, Yokohama, Japan
²Kajima Corporation, Tokyo, Japan

1. Introduction

The Tsugaruyomogita tunnel is part of the Hokkaido Shinkansen Line, which extends the Tohoku Shinkansen Hachinohe – Shin-Aomori Line northward (Fig.1). The tunnel is 6,190m in length and is currently under construction, with a targeted completion at the end of the fiscal year 2015. The stratum through which the Tsugaruyomogita Tunnel is built is mainly composed of unconsolidated sand below the groundwater level, with extremely high tendency to quicken. Excavation of a tunnel located at the approach portion of Seikan-Tunnel in this sandy stratum, completed in the 1980s, caused face disruption involving sediment flow numerous times and was completed with difficulty. A typical disruption in similar geologic conditions is shown in Photo 1.

Construction work of the Tsugaruyomogita Tunnel in the same geologic conditions is being performed using a Casting Support Tunneling System using a TBM (hereinafter called SENS) in order to secure digging face. This construction method was firstly developed and adopted in the 3km section in the Sambongihara Tunnel of the Tohoku Shinkansen Line from 2004 through 2006. The SENS construction method entails digging and stabilizing the face using a closed type TBM, supporting the tunnel with an Extruded Concrete Lining (ECL) as the primary lining concurrently with TBM digging and close monitoring to confirm stability, followed by a secondary lining which is not subject to loading.

Excellent result was obtained with SENS during construction of the Sambongihara Tunnel, however, issues were also encountered. In facing those issues, modifications were applied on rapid digging and long distance construction work and, at the same time, concrete casting experiment was...
conducted by using large scale experiment machine in order to improve quality and performance of primary lining concrete.

This article describes the SENS adopted at the Tsugaruyomogita Tunnel noting the various points improved from the Sambongihara tunnel, test results of the primary lining concrete where modeled experiment machine was used, as well as reports on the current construction work status. As for the natural ground supporting mechanism of SENS, the description is omitted from this article since this has already been reported elsewhere [1].

2. Geotechnical Condition of Tsugaruyomogita Tunnel

Longitudinal geologic condition of the Tsugaruyomogita Tunnel is shown in Fig. 2. Geologic condition of digging targeted is the foundation of Kanita Stratum which is anchored by unconsolidated sand. The Kanita Stratum is classified into Yomogita Stratum, Seheji Stratum and Sunagawasawa Stratum from geological characteristics. The Yomogita stratum is water-bearing stratum with low agglomeration degree totally and has wide face variation characteristics horizontally and vertically. The Seheji Stratum is featured with alternative thin stratums of pumiceous tuff and medium/fine grained sand. The Sunagawasawa Stratum is totally even quality and consisting of sandstone bed with consolidated massive non-beding.

Ground water level is almost above tunnel levee crown and the highest becomes degree of levee crown plus 40 m. In addition, tuff with low water permeability and thin layer of siltstone exist irregularly, and it is envisioned that sufficient water drainage effect is unable to be obtained for groundwater level at layer boundary.

Distinguishing geologic data of Kanita Stratum is shown in Fig. 3. It is suspected that the Kanita Stratum has the geological condition that it easily generates natural ground liquidation judging from grain size distribution, fine-grain fraction and uniformity coefficient.
3. Overview of SENS
As the result of overall reviewing on economic efficiency, construction schedule, etc, based on the above geological characteristics, Casting Support Tunneling System using TBM (SENS) which was experienced at the Sambongihara Tunnel, Tohoku Shinkansen Line (2004 ~ 2006) with similar geological condition, was adopted.
SENS is the construction system to complete tunnel in which primary lining is built up with ECL construction method (Extruded Concrete Lining) at the same time of TBM digging and after confirming stability of the primary lining through measurement and observation, then build up secondary lining as decorative winding which does not receive action load. The most characteristic design concept at SENS is that primary lining work is ranked as the one having the function of supporting member in a similar way of shotcrete at NATM. The TBM takes reaction force from friction between the inner forms and the primary lining.
For the construction work experience at Sambongihara Tunnel, drilling travel of more than two times (maximum 172.8 m/month) was accomplished while securing higher safety than NATM. In addition, economical efficiency was almost equal to that of NATM. However, considerable issues still remain at points such as occurring of facility trouble regarding cast-in-place lining and establishment of more reasonable construction work management method, and further improvement is required.

Fig. 4: Typical section of SENS

Photo 2: Inner forms Under the Backup Decks
4. Improvements of SENS in Tsugaruyomogita Tunnel

SENS machine specifications at Tsugaruyomogita Tunnel are shown in Fig. 5 and Table 1.

![Fig. 5: SENS machine](image)

### Table 1: Specification Comparison of SENS Machine

<table>
<thead>
<tr>
<th>Item</th>
<th>Tsugaruyomogita Tunnel</th>
<th>Sambongihara Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBM diameter</td>
<td>φ11,300mm</td>
<td>φ11,440mm</td>
</tr>
<tr>
<td>Type of TBM</td>
<td>Earth pressure balance type with Single Shield</td>
<td>Earth pressure balance type with Single Shield</td>
</tr>
<tr>
<td>Cutter operation</td>
<td>1,452kw (132kw x 11 units), INV 0.1 – 0.5min(^{-1})</td>
<td>1,440kw (90kw x 16 units), 0.616min(^{-1})</td>
</tr>
<tr>
<td>Thrust jack</td>
<td>105,000kN (3,500kN x 30)</td>
<td>90,000kN (3,000kN x 30)</td>
</tr>
<tr>
<td>Press ring jack</td>
<td>7,560kN (420kN x 18)</td>
<td>5,760kN (320kN x 18)</td>
</tr>
<tr>
<td>Concrete pump</td>
<td>30kw x 12</td>
<td>30kw x 6</td>
</tr>
</tbody>
</table>

Since the tunnel becomes long distant construction work extending over approximately 6 km, further rapid construction work is aimed with average of 140 m per month as target. At the adoption of SENS, following points are required to be reviewed based on the issues at the Sambongihara Tunnel:

1) Response to Rapid Construction Work
2) Response to Construction Capability, Quality Control and Safety Improvement
3) Response to Long Distant Digging

Major modification points regarding SENS machine facility are listed below;

4.1 Response to Rapid Construction Work
4.1.1 Improved concrete injecting capacity
While 6 concrete injecting pumps were used in Sambongihara Tunnel, they could not supply sufficient volumes of concrete compared to the excavation speed since the concrete used is a highly viscous type with resistance for separation in water. It therefore limited the average excavation speed to 15mm/min. In Tsugaruyomogita Tunnel, excavation speed of 30mm/min is ensured by increasing the number of concrete pumps to 12 units. (Photo 3)

![Photo 3: Concrete pumps](image)
4.1.2 Amplification of Inner Form Width
The inner form width of Sambongihara Tunnel was 1.2 m but speeding up of construction work was done by extending construction distance with inner form width widened to 1.5 m and by reducing assembly number of times by 25% at Tsugaruyomogita Tunnel. The inner form was divided to 10 pieces for 1 ring.

### Table 2: Comparison of Inner form

<table>
<thead>
<tr>
<th>Sambongihara</th>
<th>Tsugaruyomogita</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Radial insert and pullout" /></td>
<td><img src="image2.png" alt="Longitudinal insert and pullout" /></td>
</tr>
</tbody>
</table>

4.2 Improvement of Construction Capability, Quality Control and Safety
4.2.1 Adoption of Longitudinal Direction Insertion Type Inner Form
The inner form structure was radial direction insertion type at the Sambongihara Tunnel whereas inner form structure of longitudinal direction insertion type where shearing stress by casting pressure is not applied on assembly bolt of inner form was adopted and aimed improvement of safety by the reduction of inner form wearing due to repeating use of inner form for long distance digging. (Table 2)

Since longitudinal direction insertion type of inner form is unable to be pulled out if step exists between rings, backup member is equipped on rear surface of Kp (pullout) piece to let the main body piece pulled out with backup member remaining on wall surface when any step occurred.

4.2.2 Extension of the press ring jacks
The stroke length of press ring jacks was 0.9 m at Sambongihara Tunnel but maintenance capability at Tsugaruyomogita Tunnel was improved by making it to be 1.6 m which is longer than inner form width. (Fig. 6)

![Photo 4: Press ring](image3.png)
4.3 Measures to address long-distance construction

4.3.1 Longer bit life
By operating the cutter motor with inverter, the intrusion level (cutting level) is maintained properly and excessive cutter rotation is eliminated to reduce wearing by selecting the proper cutter rpm to suit the excavation speed. E3 type (JIS)* with approximately double the wear resistance compared to E5 type (JIS) which is generally used as the cutter bit material is installed.

The bit assignment was given with height difference with 30mm for shell bit and 20mm for cutter bit (Fig. 7). During the initial stages of excavation, bit life to the intermediate shaft established at a point about 3,000m from the entrance is ensured by letting the higher bit to do the cutting mainly and reducing the load on the lower bit. It is planned that the cutter bit will be replaced in intermediate shaft.

*JIS: Japan Industrial Standards

4.3.2 Adoption of Continuous Belt Converyor
Total length of the Tsugaruyomogita Tunnel is 6 km and is two times of the Sambongihara Tunnel. As the tunnel length getting longer, degradation of tunnel environment or occurring of traffic accident were concerned about since running number of dump tracks or truck mixer agitators are increased. Then continuous belt conveyer was adopted for muck evacuation to reduce the number of carrying vehicles. (Photo 5)

5. Development of primary lining concrete
Development of new concrete which meets required performance with low viscosity became required since primary lining concrete used at Sambongihara Tunnel was high in viscosity. Mortar adhesion to pipe was foreseen to increase a pressure loss at concrete pumping, and thus to suppress digging speed by causing obstruction of pipe. In addition, a new mix proportion was reviewed to take economical efficiency for usage classification depending on the amount of ground water pressure into consideration.

Initially, the development of new concrete which meets required performance (Table 3) equivalent to Sambongihara with experience was considered prime, and several sorts of mix proportion were developed after laboratory experiment. (Photo 6)

Then we prepared an experimental machine simulating a TBM to conduct an experiment to verify the relationship between the type of concrete mix and its finish. Fig. 8 shows the schematic diagram for the experimental model machine. The slide body is equipped with the press ring and concrete injecting opening, and it has a mechanism to slide along the inner formwork as the guide.

The finished primary lining concrete injected by using the experimental machine is shown in Photo 6. The appearance of the hardened body was good for any of the mixes in which resistance to separation in water was pursued in a similar fashion to Sambongihara (Photo 7 left). On the other
hand, the mixes in which economic feasibility was pursued without additives to deliver resistance to separation in water caused a phenomenon in which there were holes opened at the bottom and mortar seeped in from the joint of the inner formwork (Photo 7 right). It is surmised that it was caused by pressurized water which passed through the concrete with low resistance to separation in water. Regarding this experiment, we are currently conducting more experiments as well as data collection and analysis to develop an optimal primary lining concrete to suit the site conditions.

Table 3: Required Performance of Primary Lining Concrete Used at Sambongihara Tunnel

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Requirement Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump flow</td>
<td>600mm ± 50mm</td>
</tr>
<tr>
<td>Freshness maintenance</td>
<td>80% of the condition at kneading or higher after 4 hours</td>
</tr>
<tr>
<td>Strength properties</td>
<td>Rapid strength: 15N/mm² or higher at 24 hours</td>
</tr>
<tr>
<td></td>
<td>Strength at 28 days: 30N/mm² or higher</td>
</tr>
<tr>
<td>Pumpability</td>
<td>5m³/h injecting possible at 30m distance with a 3-inch pipe</td>
</tr>
<tr>
<td>Segregation resistance</td>
<td>No separation during force feeding and filling</td>
</tr>
<tr>
<td>Test method for anti-washout concrete cast in water</td>
<td>Concrete can be injected properly even in water-containing unconsolidated ground (controlled at pH ≤ 12).</td>
</tr>
</tbody>
</table>

Mix pursuing resistance to separation in water equivalent to concrete used in Sambongihara Tunnel

Mix pursuing economic feasibility without additives to deliver resistance to separation in water

Photo 6: Developed Primary Lining Concrete (Degree of water separation)

Fig. 8: Model Experiment Machine

Photo 7: Comparison of finished concrete from experiments
6. Current construction status
In Tsugaruyomogita Tunnel, initial excavation was implemented beginning in early November using 94m open and cover tunnel developed prior to the assembly of a TBM as the reactive force for SENS propulsion. It is planned in the initial excavation that 161m will be excavated with consideration of the facility length for the main excavation. Excavation and construction of secondary lining will be simultaneously implemented with the sheet lining stage for secondary lining and the sliding mold inserted after the completion of initial excavation.

![Fig. 9: SENS Machine Assembly status](image)

Photo 8: The portal of Tsugaruyomogita Cut and cover tunnel section

Photo 9: The entrance of SENS section