Rapid Excavation with TBM in Hard Bedrock, Utilizing Information-oriented Technique

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1. Overview of the tunneling project
The Kuriko tunnel is located between the Fukushima Junction (tentative name) and Yonezawa interchange (tentative name) on the Tohoku Chuo Expressway. It is a long tunnel spanning about 9,000 m planned near the boundary between Fukushima Prefecture and Yamagata Prefecture. When complete, it will be the fourth longest tunnel in Japan.

Before construction of the main tunnel, an evacuation tunnel was bored. The geological survey conducted in advance showed a relatively more favorable geology on the Fukushima side than that on the Yamagata side. Therefore, the length of about 5.5 km on the Fukushima side was driven with a TBM of 4.5 m diameter.

Prior to excavation, surveys of the ground ahead of the face by drill-logging and water drainage were performed, and by using auxiliary stabilizing methods including long steel tube forepiling with injection (hereinafter referred to as AGF forepiling: AGF is short for All Ground Fastening) and wood lagging with forepoling, and fiber mortar spraying, tunneling breakthrough was achieved without restricting the TBM.

The excavation started in November 2006, recording the daily maximum advance of 31.5 m (in November 2007) and the maximum monthly advance of 453 m (in May 2007), and the average monthly advance of 240 m. This is very rapid excavation with TBM, and in December 2008, reached the zone already driven by mountain tunneling on the Yamagata side, achieving breakthrough.

Photo 1 Rock drill with an increased feed length
This paper gives a description of the TBM tunneling of the project.

2. Improvement of the TBM
The TBM used for building the Kuriko Tunnel featured the following improvements in comparison with the conventional machine.

1) For improving the work performance of auxiliary stabilizing methods such as AGF forepiling, the geometry of the rock drill boom and the mounting position of the hydraulic cylinder were redesigned and improved, to increase the feed length to 3 m. The increased length reduced rod joining frequency (Photo 1).

2) If collapsing soil is on the TBM roof in a geologically weak section, the collapsing soil falls at the back of the roof as the machine advances. If the fallen soil accumulates on the invert, it takes a lot of time to remove it, impeding tunneling advance. To avoid this problem, a hopper was provided on the deck to guide the fallen soil to the first conveyor (Photo 2).
3) Use of an open TBM can reinforce the main gripper position even in unfavorable ground. Nevertheless, the main gripper may break the tunnel wall. As a solution for this inconvenience, the jack was so designed that the stretching pressure can be adjusted in three stages. The thrust can be also regulated in three magnitudes.

4) To cope with a large volume of water ingress and extensive weak sections, it is necessary in some cases to excavate and construct a by-pass tunnel or a pilot tunnel. If this work is done from the rear carriage, the work length would be very large since the total length of the TBM is about 80 m. As a solution for this problem, the rear carriage was cut off at the position of the towing beam, to perform the work from the back of the TBM main unit.

5) With the TBM of 4.5 m diameter, the width of the rear carriage is limited. Therefore, it is difficult for several staff members looking simultaneously at the tunneling management system in the operation room to evaluate the situation. To improve the situation, a JV staff management room was installed beside the operation room so that the staff members could observe the same screen simultaneously with the operator to obtain information in real time. For the same purpose, an optical cable was provided in the tunnel so the staff outside the tunnel could observe the same screen.

6) Mucking was done with many belt conveyors in series including a TBM belt conveyor, a continuous belt conveyor (Photo 3) and a stationary belt conveyor (Photo 4). At the transfer point between conveyors, problems occur very frequently in some ground conditions. Jamming of muck at the transfer point, if not found, will result in a serious accident. Therefore, a camera was installed at the transfer point so that the staff members in the operation room and at the staff station outside the tunnel could observe the situation at the transfer points.

7) With the TBM, it is impossible to visually observe the ground state at the cutter head position. Accordingly, if tunneling is continued without recognizing a collapse, collapse is accelerated. To eliminate this problem, a collapse can be recognized earlier by detecting variation in soil volume, using a belt scale and a muck scanning system for muck volume management.

Photo 4 Stationary belt conveyor
3. Tunneling situation

3.1 Geology

The geology of the TBM tunneling section is shown in Fig. 1. The first half (about 2,000 m from the portal) is mainly composed of granite of the Mesozoic age that forms the basement of this district. In the second half (beyond about 2,000 m from the portal), volcaniclastic rock mainly composed of tuff and tuff breccias covering the granite basement, with large scale intrusions of dacite penetrating the volcaniclastic rock and of rhyolite in some places. As known from this type of composition, a very complex geological structure was anticipated.

Fig. 1 Geological longitudinal section of the Kuriko Tunnel

Fig. 2 Support pattern (CII-T, DI-T)
The record of the TBM advance demonstrated predominant granite as predicted in the first half (up to 2,400 m from the portal). However, the water ingress exceeded by far the volume of 240 to 540 liters/minute predicted from the preceding boring survey, reaching at maximum 5,000 liters/minute at the portal. From the middle stage (2,400 to 4,200 m from the portal), large scale dacite intrusion had been anticipated, but actually dacite veins intruded the volcanoclastic tuff, and the tunnel wall collapsed at the stratum boundary. Water ingress decreased in the volcanoclastic rock. However, large scale dacite intrusion existed in a region spanning about 400 m from about 4,200 m apart from the portal, and water ingress through cracks increased again, recording about 8,300 liters/minute in total at the portal. The geology encountered subsequently (beyond 4,600 m from the portal) was alternating strata of conglomerate/sandstone and sandstone/mudstone, with reduced water ingress.

3.2 Support patterns used
The support patterns (Fig. 2) were determined on the basis of the comprehensive criteria according to the pattern selection flowchart prepared in advance referring to not only the results of drill-logging for the geology in front of the face but also TBM data (torque, thrust, etc.), collapse and its extent above the TBM roof during excavation, the status of cracking in the wall and water ingress. Because of unforeseen presence of weak ground zones and large amount of water ingress, the usage ratio of support pattern D that was less than 20 percent in design, actually increased to more than 50 percent, that is, nearly tripled. Fig. 3 illustrates comparison between initial design and actual record of the support patterns.

According to the initial design, the support patterns B and C accounted for 81.5 % of the total, whereas actually the pattern C 47.2% and D 52.8%. That is, about a half was excavated with the pattern DI. The breakdown of auxiliary method with the pattern DI was approximately 276 m (about 10%) with AGF forepiling injection/filling forepoling, and approximately 800 m (about 28%) with wood lagging/forepoling.
3.3 Collapse of the tunnel wall and auxiliary reinforcing methods

Almost the entire DI section exceeding 50% of the whole tunneling length, some ground collapsed, and in some cases, there was a fear of inducing large-scale collapse. Collapses of tunnel walls on the TBM roof impeding tunneling advance ranged from small scale less than 10 cm to large scale exceeding 1 m over 120 degrees of the crown.

For countering very large collapses that would restrict the TBM, AGF forepiles were driven to stabilize the ground ahead of the cutter. For dealing with large to small collapses, the auxiliary method consisting in wood lagging and forepoling on the roof and fiber mortar spraying (Fig. 4).

The following gives a description of the collapse status and stabilizing measures in the distinct geological sections.

Fig. 4 Auxiliary methods

Photo 5 Collapse
a) Granite section
The weathered section over about 700 m from the portal consisted of granite and granodiorite, where there was a large amount of decomposed rock. In the heavily fissured zone and fractured zone, the ground was noticeably weaker than ordinary massive granite. In addition, much water flowed in through cracks in the tunnel wall, accelerating crown collapse (Photo 5). Therefore, auxiliary methods were fully used, including AGF forepiling, wood lagging and forepoling with halved logs (Photo 6).

b) Dacite section
In the weathered and altered section where dacite section intruded, since significant collapses occurred due to water ingress and joints in rocks, the tunnel was excavated using the support pattern DI. In this section, tunnel wall collapse tended to expand. If similar geology was expected to continue based on the survey ahead of the face, the AGF forepiles were driven, whereas wood lagging and forepoling were conducted in the zone of medium scale collapse (less than 100 cm).

c) Section with predominant sedimentary rock
In the section where dacite veins intruded into volcanoclastic tuff, the ground was brittle at the strata boundary, and the intruding rocks themselves, heavily fissured with clay layers in between, collapsed. In the alternating strata of conglomerate/sandstone and sandstone/mudstone, water ingress induced laminar spalling and collapses due to detachment of cracks. Even in the section with less collapse, cracks opened wider with time after TBM excavation, resulting in squeezing of the tunnel wall to make it difficult to erect steel ring supports. In order to pass these sections rapidly, without stopping the TBM at the point of collapse, and by intentionally avoiding stops for forepiling, fiber mortal was sprayed over the collapsed portion, and wood lagging and forepoling were driven there to prevent the ground from loosening.

3.4 Drill-logging
Using the drilling machine mounted on the TBM, drill-logging was implemented to survey the geology ahead of the face over almost the entire tunneling zone. The drill length per logging was 50 m at maximum. Logging was made 71 times in total. The drilling machine mounted on the TBM was specially designed for improving efficiency of logging work, with a large feed length of 3 m.
Drilling energy is given by dividing the work of the hydraulic drill by the volume of broken rock, as expressed by Eq. 1.

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\text{Drilling energy} = \frac{\text{Work of the hydraulic drill}}{\text{Volume of broken rock}} = \frac{E_s \times N_s}{V_d \times A_r}
\]

where \(E_s\) = striking energy, \(N_s\) = number of striking cycles, \(V_d\) = drilling velocity and \(A_r\) = drilling sectional area.

The magnitude of energy of drilling for logging was mainly referred to as decision criterion for AGF forepiling.

Fig. 5 shows an example of decision of AGF forepiling on the basis of the magnitude fluctuation of the drilling energy for logging. With this example, the drilling energy threshold was set at 150 J/cm\(^3\), to decide whether the filling type forepoling or AGF forepiling should be used.

### 4. Conclusions

This paper outlined the TBM excavation of the east evacuation tunnel of the Kuriko Tunnel. A huge amount of data was stored during this work in the TBM advance management system. The authors are planning to analyze in detail these data, referring also to the geological observation record and drill-logging records, to make useful materials for future TBM construction projects.