SYNOPSIS: The Hida Tunnel was constructed as part of a 10.7km long highway tunnel system under the 1,000m of deep overburden. According to excavation data obtained from the excavation of a separate emergency evacuation tunnel initially built as a pilot tunnel for the main tunnel, very adverse geological conditions for a large diameter TBM excavation were identified and the most geologically challenging sections were delineated. A 12.84m diameter TBM was utilized to excavate 4.3km along the main tunnel of 10.7km. This paper focuses on possibilities for using a large diameter TBM excavation system under deep overburden conditions including criteria for the adoption of NATM excavation as an alternative.

1. INTRODUCTION

In the planning phase of the tunnel construction with a large cross-section, long distance and under deep overburden conditions, rapid construction techniques are some of the most important factors for successful completion of the project. Currently, in order to construct such a tunnel rapidly, a TBM (Tunnel Boring Machine) was considered the most appropriate excavation method. The size of the TBM has become larger in order to excavate a large section at one time. However, large diameter TBMs do not at present have sufficient adaptability for geologically adverse conditions and unstable ground. Therefore, once major difficulties arise during TBM tunneling, a total change to the excavation plan which dramatically impacts the entire construction schedule and project costs may result.

The Hida Tunnel is a very long and deep expressway tunnel with a total length of 10.7km with overburden more than 500m in over 55% of its length. The maximum overburden is 1,041m. The tunnel is located in the Shirakawa-go registered with world’s cultural heritage in Tokai Hokuriku Expressway crossing central part of Japan (see Figure 1). For the construction of the Hida tunnel, a 12.84m diameter TBM was utilized. However, in the planning phase, some squeezing ground issues were anticipated in geologically adverse zones. This made it difficult for planning the construction schedule for successful completion.

The selection of excavation methods for each different geological condition, either by TBM or NATM, was based on the analysis of the data obtained from a pilot tunnel excavated by TBM in addition to geological and measurement data obtained in the early stages of main tunnel excavated by NATM. In the following sections, an overview of main tunnel construction is described, rationale for the appropriateness of using a large diameter TBM under the extreme overburden and the excavation management methods are discussed.
2. OVERVIEW OF HIDA TUNNEL (MAIN TUNNEL) CONSTRUCTION

2.1 Overview of Main Tunnel

During the planning phase of the main tunnel, it was recognized that in some sections where a large diameter TBM would be utilized, very difficult geological conditions were anticipated from the data obtained during the previously excavated evacuation tunnel which had been built parallel to the main tunnel using a 4.5m diameter TBM. As a result, TBM application was postponed in this section and executed by NATM. Since the geological conditions of the referenced section were very complicated, the geological conditions and the drainage effect by the evacuation tunnel were insufficient to drive the main tunnel, an additional service tunnel was excavated on the opposite side of evacuation tunnel to the main tunnel as an auxiliary measure before excavating the main tunnel. At the point the evacuation (pilot) tunnel had reached approximately 2.9km from the Shirakawa side portal, the ground condition was confirmed to be improved based on the results of geological inspections and analysis for the strength of the rock mass and the effect of drainage by both the evacuation tunnel and the separate service tunnel. Therefore, it was decided to commence the main tunnel TBM driving from Sta.395+00, approximately 3km from the portal.

Excavation of the parallel separate service tunnel continued for approximately 1km due to the massive inflow of high-pressure groundwater and complex geological conditions that remained. Moreover, in order to complete the main tunnel by an early date and reduce a potential delay by an unforeseen geological condition, it was decided to excavate the main tunnel by NATM from the opposite portal. Consequently, total length of excavation by TBM reached 4.3km (see Figures 2 and 3).
Figure 3: Excavation locations of TBM and NATM tunnels
2.2 Troubles While Excavating by TBM

After starting excavation by TBM, face conditions ahead of the cutterhead were extremely unstable due to blocky, raveling rocks resulting in continuously occurring over-excavation at the center part of the face and large-scale collapses. Although the depth of the cavities due to over-excavation and collapse reached 3m to 7m at the maximum, TBM was able to drive as long as the periphery of cavities remained within the cross-section of the cutterhead. When the TBM had advanced 75m, a large scale collapse that was unforeseen by probe drilling, but without the benefit of auxiliary measures, occurred. This collapse extended beyond the cross section of the cutterhead for the first time. At this point the cutterhead was unable to rotate. Two more similar collapses occurred later and in one case caused the cutterhead to stop rotating. When the TBM had advanced 163.6m, the largest collapse (6.5m ahead of the cutterhead longitudinally and transversely 8.5m beyond the cutterhead periphery) occurred. In this zone, unstable ground existed and had caused stoppage of evacuation tunnel TBM six times. The collapsed ground loss stopped the cutterhead from rotating and also fell into and was piled-up in the cutterhead chamber, halting excavation operations for forty days.

The face collapse situations had continuously occurred over almost the entire length of the tunnel section excavated by TBM except for extremely hard rocks such as quartz porphyry and Hida metamorphic rocks (gneiss) (see Figure 4). In the extremely hard rock section, muck impacted the cutters during secondary crushing in front of the cutterhead resulting in uneven wear and breakage of cutter rings and hubs; resulting in high cutter consumption. In addition, the surface of the cutterhead, scrapers and cutter-holders became worn and damaged. Excessive wear on the cutters, hubs and the cutterhead severely impacted continuous TBM excavation. In order to carry-out extensive repair work on the cutterhead from the front side, a maintenance tunnel was excavated from the service and evacuation tunnels at three locations – TBM boring distance 250m, 766m and 3,077m (see Figure 5).

![Figure 4: Shape of the collapsed tunnel faces](image-url)
2.3 Knowledge Gained From TBM Excavation Difficulties

As the problems with TBM excavation that had occurred in the initial stage up to 500m from the portal did not occur afterwards, it seemed that these troubles could have been avoided if the TBM start location had been moved 500m farther. In this 500m section, rock strengths were extremely high but cracks were densely developed and large quantities of highly pressurized ground water-inflow had occurred in the evacuation and service tunnels. By driving these two tunnels ahead of the main tunnel, the effect of drainage seemed to improve the stability of the ground. But the effect of fissured rocks to a large diameter TBM excavation was conspicuous, and it seemed necessary to be deliberate on the commencement of TBM excavation. However, as TBM boring progressed, it was recognized that auxiliary measures such as steel pipe forepoling which was able to inject grout for filling cracks were very effective at improving the stability of fissured rocks. As for the troubles after the previously-mentioned section passage, most were related to the cutters and face of the cutterhead. These troubles were caused by driving in high strength but unstable fissured rock.

3. RATIONALE FOR USE OF A LARGE DIAMETER TBM UNDER DEEP OVERBURDEN

3.1 Analysis of Geological Conditions

Before excavating a large and long tunnel with deep overburden, it was apparent that it would be difficult to obtain accurate geological condition with limited expense. Therefore, geological information for main tunnel had to depend on the data obtained from the evacuation (pilot) tunnel excavation which had been excavated prior to the excavation of main tunnel. In case of Hida
tunnel construction, the evacuation and service tunnels were advanced ahead of the main tunnel excavation. All the data obtained from both tunnels (for example; geological inspection data, measurement data, strike and dip of rock strata, joint spacing, ingress water inflow records and TBM machine data, etc.) had been analyzed and used for deductively predicting the rock conditions of main tunnel. Regarding previously-mentioned 500m section, the rock in which the densely developed cracks with large quantities of high pressure groundwater was observed during excavation of the evacuation and service tunnels. A 4.5m diameter evacuation tunnel TBM was temporarily stuck (trapped) in this area. In order to investigate the geological condition of this section in more detail before starting of main tunnel excavation by TBM, seismic tomography tests between the evacuation and service tunnels were performed.

3.2 Rationale for Appropriateness of a Large Diameter TBM Use

The characteristics of the ground under deep overburden is evaluated by initial stress, rock mass strength and deformability. Specifically, the measurement data obtained from the main tunnel excavated by conventional methods were applied to the simulation using back-analysis that determined the modulus of elasticity of the ground. As shown in Figures 6 and 7, determinations were made in accordance with the analysis of ground deformation corresponding with excavation of main tunnel by TBM. Figure 6 shows the relation between depth of overburden and rock deformation (convergence) analyzed with estimated modulus of elasticity; 300~1,000 (MPa). The dotted line indicated in Figure 6 shows convergence of 20cm. This value means that the overcutting of TBM in squeezing ground is 10cm on the radius and its simply calculated convergence is 20cm. If an estimated convergence value larger than 20cm, it becomes very likely that TBM would become stuck (trapped) by excess ground deformation. In this analysis, an estimated convergence value is supposed to be 60% of the total elastic deformation resulting after excavation. For example, in Figure 6, at Sta.394+00, the overburden is 600m and if modulus of elasticity is estimated as 800MPa, the analyzed result shows 20cm of deformation. This figure shows that the TBM has a possibility to be stuck due to squeezing conditions if the existing ground does not have modulus of elasticity larger than 800MPa. Figure 7 shows the relation between overburden and ground pressure acting on TBM in case of rock modulus of elasticity 200~1,500MPa. From this Figure, it can be seen that if the ground pressure is less than the limited thrust of the TBM, the TBM will not become stuck. Determinations have also been made from excavation data of evacuation tunnel and the result of geo-tomography tests investigated in sections where troubles occurred during excavation. For evaluation of main tunnel excavation by TBM, certain difficulties were anticipated based on this data and whether a large diameter TBM would actually be able to excavate the main tunnel while concurrently solving the periodic problems using auxiliary measures system were analyzed.

![Figure 6: Relation between overburden and modulus of elasticity](image)
4. CONTROL TECHNIQUES OF A LARGE TBM UNDER EXTREME OVERBURDEN

4.1 Driving Control Techniques for Unstable Section

While excavating the tunnel with large diameter TBM, the phenomenon of face collapse occurred throughout the entire tunnel excavation except in hard rock sections. A root cause investigation of the face collapses were performed with 3D excavation analysis. Considering the factor of initial stress situation and cracks distribution, the result of the analysis showed that the crown and sidewalls near the tunnel face could be stabilized by being dependent on rock condition or the application of auxiliary measures even if the center area of the tunnel face was unstable. Therefore, the excavation would be strengthened with driving control management technique assuming that center over-excavation in front of the face shall be considered as a “constant condition”.

In general, while excavating tunnel by large diameter TBM, advance is controlled from correlation of penetration rate, thrust force and cutterhead revolution speed and torque, however, if the number of cutters that contact with tunnel face was not determined, usual driving control management technique did not function well. Therefore, considering of frequency of face collapse, a categorization produced a theoretical value calculated from the number of cutters penetrating into the face and an adjusted a thrust force based on this in real-time, and control management to prevent cutter overload became important. Figure 8 shows the relationship between ideal calculated TBM machine data and the data provided by actual excavation. It shows that the cutter wear appears where the penetration rate exceeds more than 2mm. However, while excavating in various geological conditions, it seems difficult to control thrust force because number of penetrating cutters can not be identified. Therefore, in practical measures, penetration rate shall be reduced and boring speed shall be adjusted in order to avoid wear of cutters. As a future problem to be solved, it may be required to provide cutter load cells and cutter revolution sensors for each cutter at all the times to improve the driving control management technique.

![Figure 7: Action of ground pressures](image-url)
4.2 Counter-Measures Against Excess Wear of Cutters

According to the site records, 80% of abnormal wear of cutters were described as partial wear of cutters and rest 20% were partial chipped and/or failed cutters. By analyzing worn cutters, it was found that many cases of abnormal wear was caused by failure of cutter body because of cutter axis shifted to the cutter face side. Reasons of abnormal wear of cutters are considered as overload of the bearing, abnormal increase in temperature of cutter body and seizing by the skidding torque resistance. However, main reason for abnormal cutter wear came from overload of each cutter. As it was mentioned in Section 4.1, the driving control management technique and avoiding cutter over-load is important for avoiding abnormal wear of cutters. In case of excavation in unstable face conditions, some cutters may be damaged because of crushing of deposited muck. Regarding cutter installation onto the cutterhead, it is important to provide protection devices (armor plating) to avoid damage by crushing from loose muck. Therefore, it is also important to change shape of scrapers, shape of buckets in order to discharge excavated muck for avoiding crushing of loose muck by cutters or avoiding wear on the face of the cutterhead.

5. CONCLUSIONS

As a result of the Hida Tunnel construction, we were successful in breaking-through the main tunnel excavation without having the large diameter TBM being stuck; by allocating appropriate application of TBM methods and conventional methods according to geological conditions. In this report, it has mentioned that the evaluation method against face collapse and unstable face conditions for the large diameter TBM used under deep overburden. We believed in the planning and design phase for the use of a large diameter TBM, that the knowledge mentioned in this report would be able to contribute to rapid construction of a long distance tunnel at great depth.

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