GIBE II TUNNEL PROJECT - ETHIOPIA - 40 BARS OF MUD ACTING ON THE TBM

“SPECIAL DESIGNS AND MEASURES IMPLEMENTED TO FACE ONE OF THE MOST DIFFICULT EVENT IN THE HISTORY OF TUNNELING“

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ABSTRACT

In October 2006, a 7 m Double Shield TBM, boring through very poor volcanic formations, was pushed back by fluid mud, which presence had not been detected during previous field investigations, due to the high covers characterizing the majority of the tunnel axis.

The present work describes the investigations made to gain better knowledge of the conditions in front and all around the TBM, the special measures implemented, the exploratory and bypass tunnels excavated, the extraordinary occurrences came true during the execution of these tunnels, the drainage campaigns, the design of the chamber excavated to free the TBM, the dismounting and restarting of the TBM.

INTRODUCTION

The Gilgel Gibe II Hydroelectric Power Plant is the second one after Gilgel Gibe I HPP. It is located approximately 240km southwest of Addis Ababa, in Ethiopia, between the Gibe and the Omo Rivers.

The Project layout mainly consists of a concrete lined headrace tunnel (Figure 1) spanning from the Gilgel Gibe River valley to the Omo River valley, a penstock and a power-house located on the right bank of the Omo River.

SALINI Spa and SELI Spa respectively are the Contractor and the Specialized Subcontractor for the excavation of the 25,8km of tunnel.

The tunnel is currently excavated by two Double Shield TBMs: the former started at the Intake Tunnel Portal on August 2005 and stopped on October 2006 at the ch.: 4+196 due to an exceptional geological event. Then the excavation started again on August 2008 along a new tunnel alignment; the latter started from the Outlet Portal on November 2005.

The excavation with both, Intake and Outlet TBMs, is almost completed.
DESIGN CONSIDERATION

The Main data of the water conveyance project are listed in the following Tabs. 1, 2 and 3.

| Tab.1 Water Conveyance project main data |
|-------------------------------|---------------------------------|
| PURPOSE                      | HPP (432MW)                     |
| TUNNEL LENGTH                | 25.8 km                         |
| INTERNAL TUNNEL DIAMETER     | 6.3 m                           |
| DESIGN DISCHARGE             | 100 m³/s                        |
| DESIGN INTERNAL PRESSURE     | min.2 bar max.7 bar             |

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The initial geological investigations mainly revealed 5 rock formations along the tunnel alignment. In particular, the rock mass mainly consists of tertiary volcanic rocks, rhyolite, trachyte, basalt and some dykes close to the surge shaft. Some fault zones were identified thanks to site analysis performed through aerial photo interpretation; they are mapped along the geological longitudinal profile (Figure 2).

According to the foreseen geological profile, the TBM tunnel, from section ch.: 0+000 to approx ch.: 11+000 (Intake drive), is in the Omo basalt formation, comprising massive, amygdaloidal and scoriaceous layers, inter-bedded with some weak layers of sedimentary tuff, and brick-red paleosol. The Intake TBM drive encountered the Omo formation since the beginning of the excavation, which was mainly composed of the weak layers of sedimentary tuff and paleosol formation.
Figure 2. Geological profile
**EVENT AT THE CHAINAGE 4+196 FROM INTAKE HEADING**

**Description of the Event**

The Omo rock formation was excavated by the Intake TBM during September and October 2006. The geological and geomechanical characteristics (at the chainage 3800 ÷ 4100) can be resumed as follows:

⇒ Tunnel overburden: about 670m
⇒ Volcanic unit = Omo Vulcanites (Basalt flows with intercalation of Miocene Trachyte layers)
⇒ Rock description:
  - Weathered brecciated basalt: greenish grey, dark to light grey and brown incolor, highly joined and fractured, moderately to highly weathered, weak to moderately strong and slickensided basalt with reddish brown, highly weathered to decomposed. Joint planes are filled with calcite and clay infillings.
  - Decomposed Basalt: reddish brown, highly weathered to decomposed, weak and slickensided basalt, grey to greish grey, smooth to slickensided highly weathered tuff-clay.
⇒ Rock Mass Rating between 17-19
⇒ Rock Mass Class V – Very poor
⇒ No ground water was encountered. The rock was only damp.
⇒ The temperature was varying from 42 to 53°C

At the end of October 2006, the TBM was stopped (chainage 4100) as consequence of the sudden extrusion and collapse of the tunnel front face against the cutterhead and the front shield.

Two times it was attempted to excavate a bypass tunnel in the tunnel crown in order to free the front shield and cutterhead. In both occurrences the bypass collapsed due to the very high pressure of the rock mass.

The extraordinary ground pressure was mainly coming from the tunnel face (semi-horizontal) and, in particular, from its left side (inclination of 30°). The rock mass moved towards the TBM 40-60 mm/hour. No support was able to stop this movement.

The TBM has been pushed back and displaced laterally more than 40 cm. All the free spaces were filled by the plastic rock mass till a new static equilibrium was reached. As consequence, severe damages occurred to the shields, the cylinders and the last 7 segment rings installed behind the TBM.

Figures 3, 4 and 5 show the results of the TBM backward displacement (bent shield and cylinders, damaged lining segments).
Figure 3. Tail TBM Shield damaged and bent

Figure 4. Lining segments moved and severely damaged
For this particular event, Lombardi Consulting Engineers was involved. Really both SELI and Lombardi Consulting Engineers never encountered before a similar behaviour of the Rock Mass in a TBM tunnel drive.

Some boreholes, drilled through the front shields after the event, were performed with extreme difficulties, sometimes blocked at 17-18m and, in some cases, the rod bars were pushed out by the high pressure of the rock (clay and mud poured out with a temperature of about 40° and the pressure raised to 40 bar – Figure 6).
Nature of the exceptional Event

The front face instability was not due to gravity failure, generally with brittle behaviour and sudden collapses. In the observed zone the rock mass had an elasto-plastic behaviour with long deformation (squeezing).

The rock behaviour can be assumed as a consequence of the poor properties of the rock mass, characterised by low strength and plastic deformation (viscosity), the effect of water drainage either on the rock conditions (passage from undrain situation at short time to a drained situation at mid-long term) and on its properties, with the decomposition of the sound rock in clay or mud.

Figure 7 shows the rock mass at the front face at the beginning of the decomposition and few hours before the TBM displacing.
EVENT STORYBOARD

On January 2007 was designed and planned the strategy to overcome the event in the shortest time:

- additional campaign of investigations (boreholes and geophysical survey) in order to characterise geometrically and geomechanically the fault zones;
- monitoring plan
- rehabilitation works to repair the damaged lining rings;
- construction of a rescue chamber (Back Chamber) surrounding the TBM Shields to repair the TBM and the Back-Up;
- excavation of an Exploratory Adit on the left side of the power tunnel;

The new investigations had to be carried out with no effect on the Back Chamber works; both had to be performed by using site materials.

Figure 9 show the Back Chamber aimed to free, repair and re-align the TBM.

Its design, including the shape, the support structures and the excavation phases, was performed by Lombardi Consulting Engineers and carried out through a back analysis of the event for estimating the geomechanical properties of the rock mass and the loads have been acting on the TBM.

The Back Chamber construction, with the excavation works and the installation of the support structures, developed in four next phases depending on the Chamber part (Figure 8 and 9):

- top heading;
- I bench;
- II bench;
• invert.

These works were executed with typical mining methods.

Continue monitoring was executed in order to prevent unexpected events and improve the Back Chamber design step by step with the new data and the relative interpretation. Daily contact between SELI’s staff on site and Lombardi in Switzerland was maintained. SELI’s daily reports were analysed and discussed in Switzerland and, when necessary, new proposal were transmitted directly to the site by e-mail. Continuous contacts with SELI’s staff in Rome were also maintained.
Figure 8. Back Chamber Layout
At the end of May 2007:

- almost 60% of the Back Chamber was built;
• the left Exploratory Adit reached the fault zone;
• about 550m of investigation boreholes were completed.

Figure 10 shows the situation at that time.

In June 2007 a collapse of the front face started at the left Exploratory Adit, producing three controlled leaching of about 3500 m$^3$ of mud, which filled the all Adit and about 80m of the power tunnel (Figure 11 to 16).
At the same time, the monitoring devices (strain gauges applied on the steel structure and distometers) showed an increasing of the loads and displacements in the Back Chamber structure and on the TBM itself (see Figures 17 and 18). In particular, Figures 17 and 18 describe the TBM and the Gripper Shields position monitoring respectively.
Figure 17. Topographic monitoring of TBM displacements

Figure 18. Distometer measurements of Gripper Shield backing
A new strategy was then defined:

- the Mud was removed from the power tunnel and partly only from the left Exploratory Adit (a plug wall was erected in the middle of the left Exploratory Adit);
- the Back-Up of the TBM was extracted from the tunnel;
- the construction of the Back Chamber was temporary suspended;
- a more powerful drilling equipment was positioned behind the TBM shields (having removed the Back-Up of the TBM);
- the construction of a new Exploratory Adit on the Right side (40m behind) then started.

The state of the works at the end of September 2007 is shown in figure 19.

Figure 19. State of the intervention at the end of September 2007

New boreholes were made behind the shields by the more powerful drilling equipment, which allowed reaching the basalt formation behind the fault zone. Then the water drainage started, lowering the pressure surrounding the TBM head and the constructing Back Chamber. Consequently, the excavation of the Back Chamber restarted (October 2007).

A new attempt to reach the TBM cutterhead was carried out from the right side Exploratory Adit but the monitoring of loads and deformations suggested renouncing (Figures 20).
The right Exploratory Adit was then continued along a bifurcation, crossing completely the fault zone and entering into the basalt formation (sound rock). The excavation of the right Exploratory Adit was always anticipated by exploratory and drain boreholes. Finally, the chainage 4+270 was reached (about 70m in front of the TBM).

On December 2007, monitoring measurements have shown a further lowering and next stabilization of the rock stresses, while the right Exploratory Adit was crossing the fault zone. The intervention at the beginning of 2008 is shown in Figure 21.

A further new strategy was considered:
- Completion of the Back Chamber through a concave shot-concrete wall, reinforced with horizontal steel ribs HEB200 (see figure 22)
- TBM Dismantling inside the Back Chamber and carrying outside
- Refurbishing and reconstruction of the TBM (in the external yard)
- Construction of a new assembly chamber and TBM launching chamber
- Segmental lining dismantling and casting of a concrete plug in the Power Tunnel
- Resuming of the Intake drive excavation along a new alignment at ch. 3+805.

Figure 22. 3D Model of the Rescue Chamber realised to recover the TBM

The recovery of the TBM was successfully completed and at the end of February 2008.

**Bypass Power Tunnel**

The new Power Tunnel alignment was chosen maintaining a minimum distance from the explorative Right Adit, satisfying the hydraulic requirements of the main tunnel and considering the minimum radius of curvature achievable with the TBM (600m) (Figure 23).

For the Assembly and Launching Chamber was reached a zone of class II (ch. 3760-3805). In this area the main tunnel section has been enlarged by drill and blast method. In the transition area (totally 160m) the segmental lining was removed.

In order to improve the TBM steering, to contain the backfilling volumes and to reinforce the pillar between the two tunnels, in the transition zone the old tunnel has been filled with concrete (Figure 24).
Figure 24. Restarting of excavation and plug in the transition zone
TBM repair, modification and assembly

The TBM has been refurbished on site and pre-assembled on the external yard between March and May 2008.

In order to reduce squeezing effects acting around the shields in the rock mass with plastic behaviour, the excavation diameter has been enlarged from 6980mm to 7074mm while the Shields diameter has been maintained according to the original TBM SELI design. For this purpose, peripheral cutter housings (from n°37 to n°44) have been moved and re-positioned as shown in figure 25.

![Figure 25 TBM cutting profile after modification](image)

The assembly chamber was completed during the month of May 2008 installing three monorails for trolley and lifting hoists anchored to the crown (Figure 26).

The TBM was re-assembled (Figure 27) and the excavation along the new alignment restarted on August 1st, 2008 as planned.

![Figure 26 Monorails in the Assembly Chamber](image) ![Figure 27. TBM cutterhead](image)
**FINAL CONSIDERATIONS**

The success of the intervention was possible only after the releasing of the pressure and the stresses acting in the area and surrounding the TBM.

Some numbers are significant for the Event n°19:
- 3500 m$^3$ of mud flowed and removed
- 39600 m$^3$ of water drained during the intervention
- 230 m of Exploratory Adit excavated with traditional method
- 1600 m of investigation boreholes

Figure 28 shows the variation of the pressure in the rock mass, measured some meters in front of the TBM. The three events represent the most important leaching of mud in the left Exploratory Adit. Each event was immediately followed by a sudden reduction of the acting pressure and convergence (Figures 29 and 30). Important pressure reductions were also obtained after August 2007, when the new boreholes crossed the fault zone, draining water (Boreholes BH- SM- 1 to BH-SM-18).

![Figure 28. Pressure variation measured in the Back Chamber](image-url)
The intensive campaign of investigation allowed shedding light the geology in the fault zone (Figure 31).

The TBM crossed the fault zone along the new alignment during the month of October 2008, performing later excellent production. Figure 32 resumes the monthly TBM excavation from August 2008.
Figure 31. Geological model of the area

Figure 32. TBM production chart after the excavation resuming