1 PROJECT

1.1 Introduction

The Croydon Tunnel Project was undertaken to upgrade and expand the National Grid Cable Network in London. The contractor for the tunnel, MORGAN EST, performed the tunneling works with the use of a LOVAT ME140SE Series 23000 Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM). The construction of underground tunnels was decided on to minimize the disturbance to both surface structures and local traffic patterns. With the building of a tunnel, future expansion is made easier as it allows for the installation of new cables within the tunnel, without the need to disrupt traffic and above ground structures for a second time. The tunnel was built to replace existing 275kV lines with new 400kV lines between two existing substations, Beddington and Rowdown. [2]

1.2 Geology

The geology encountered along the tunnel alignment consisted mainly of upper chalk, with an Unconfined Compressive Strength (UCS) between 1.5 – 9.6 MPa, and frequent occurrences of flint with an UCS of approximately 800 MPa. The alignment between Shaft #1 and Shaft #3 (6,980m) was below the groundwater table with a maximum water height above the tunnel invert of 26m. The drive between Shaft #3 and Shaft #4 (2,816m) was also through the chalk and flint but was above the water table. [3]

1.2 Alignment

The horizontal alignment of the tunnel required that the TBM bore along major highways and routes to avoid crossing residential (private) properties. The 1989 Electricity Act in the UK allows for utility lines to cross certain industrial properties which may be along the route, but does not allow for crossing residential properties [2]. The minimum radius of the tunnel was 200m with a maximum slope of 0.8%.

2 PROJECT CHALLENGES

During the course of mining, several challenges were anticipated during the initial design of the TBM. These were: high ground/water pressure, abrasive geology, and a tight project schedule.

2.1 Geology

The original alignment of the tunnel route called for the TBM to bore at a depth of 80m below the ground level. This depth required the TBM to be designed and built to withstand an anticipated pressure of 8.0 bar. Once the alignment was changed to allow boring through lower ground pressures, only the TBM main drive sealing system design was maintained at 8.0 bar while the remaining systems were designed to a new requirement of 4.0 bar.
2.2 **Flint**

During the initial geological investigation of the tunnel alignment, flints were found within the chalk. These flints could have a UCS of up to 800MPa and were a cause of concern for their effects on the wear of the Cuttinghead, cutting tools, and the screw conveyor. The flints are extremely brittle and fracture into small abrasive shards which can wear the TBM tools and muck transfer systems quickly.

2.3 **Project Schedule**

The project called for average mining rates of three rings per hour during operation. All TBM systems had to be designed for higher mining rates in order to meet this critical project requirement. The segment ring consisted of six trapezoidal pieces of a universal design with a length of 1,200mm, an outer diameter of 3,360mm and a final inner diameter of 3,000mm.

3 **TBM DESIGN**

![Figure 1: TBM](image)

3.1 **Main Drive**

The TBM main drive consisted of four variable frequency drive (VFD) motors with a total installed power of 452 kW. The main drive was designed to operate at the following values after accounting for inefficiencies:

- **Maximum Torque:** 2,230 kN•m @ 1.8 rpm
- **Minimum Torque:** 1,210 kN•m @ 3.4 rpm
- **Break Out Torque:** 2,780 kN•m

These values correspond to a TBM alpha (\(\alpha\)) design value of 5. [3]

3.2 **Propulsion**

The propulsion system of the TBM consisted of twelve cylinders that produced a combined maximum thrust of 13,560kN, with a typical operating thrust of 9,420kN. Propulsion cylinder spacing was arranged to prevent pushing on joints in any of the six ring positions. The average advance rate throughout the project was 200mm/min. [3]

3.3 **Ground Conditioning System**

The TBM was equipped with a Ground Conditioning System [GCS] to condition the excavated material at the face and within the screw conveyor before it was extracted onto the belt conveyor. The system used allowed for the injection a foam mixture (water, soap and pressurized air) or a
polymer as required. The TBM system was designed to inject up to 1,000L/min of foam measured at an expansion ratio of 10:1. Depending on the geology, the GCS injected different ‘cocktails’ to reduce friction, torque, and stabilize the EPB pressures. The system helped fluidize the muck for easier movement through the screw conveyor and muck removal system, as well as helping to prevent clogging and buildup in the cuttinghead chamber.

3.4 Earth Pressure Balance Excavation

The EPB method of excavation works under the principle that the mining pressure at the front of the TBM must be maintained equal to that of the earth pressure around the TBM. Pressure sensors allow for the monitoring of the pressures in the cuttinghead chamber. This information is transmitted to the control station where the operator is able to modify the excavation speed and material extraction via the screw conveyor to balance the two pressures. By maintaining balance between the chamber pressure and ground pressure the TBM may advance while minimizing or eliminating settlement above the tunnel alignment.

3.5 Cuttinghead

The design of the Cuttinghead (Figure 1) is based on an individual project basis in order to allow for maximum efficiency of the mining operation. The design starts with a review of the type of geology to be encountered by the TBM. Once a detailed analysis of the geology is completed, the Cuttinghead is equipped with the Cutting Tools most appropriate to that geology. The cuttinghead for this project was equipped for an aggressive soft ground layout. The use of abrasive resistant plating allowed for minimal wear of the cuttinghead when abrasive flints were encountered. The cuttinghead design also incorporated the use of grizzly bars. Grizzly bars are installed at the cuttinghead openings to prevent any encountered boulders over a pre-determined size to penetrate into the chamber and clog the screw conveyor. In order to allow for the TBM to transfer the anticipated muck more easily, the cuttinghead was equipped with GCS injection ports on the face, rim and chamber. The opening ratio of the TBM cuttinghead is also an important factor in the movement of muck. To prevent buildup in the chamber, an open centre section was utilized for maximum movement of muck during each push.

![Figure 2: TBM Cuttinghead](image)

3.6 Cutting Tools

Ripper Teeth, Scraper Teeth, and Centre Cutter were used to mine through the anticipated types of geologies. The Rippers were outfitted with a variety of Tungsten Carbide inserts for maximum abrasion resistance. The face Rippers utilized a beak style insert which would allow for maximum
penetration by the cutting tool. The outer edge Rippers were of a barrel type design. The outer rim consisted of button type Ripper tooth which is designed for maximum impact resistance. Each style of the Ripper tooth is manufactured from a hardened steel (CHT100) with abrasive resistant chromium carbide plating installed on the sides for maximum wear resistance. The resulting muck is loaded into the chamber by the scraper teeth. The TBM Cutting Tools were designed to be back-loaded from within the Cuttinghead chamber, where the risk of injury to the operators is minimized during tool changes.

![Figure 3: LOVAT Bullet Type Ripper Tooth](image)

### 3.7 Main Drive Sealing System

As the original tunnel alignment called for sections of the tunnel to be bored at 80m below the surface, a sealing system that is capable of withstanding the high pressure was required. With the use of single lip type seals from Merkel, the TBM contained both oil seal cavities and a single continuously flushing grease cavity. Readings from the EPB cells within the cuttinghead chamber would automatically send a signal to a system that sets the seal cavity pressure via the TBM Programmable Logic Controller (PLC) system. Excluding the main drive sealing system the other TBM systems were designed to operate at 4.0 bar.

### 4 UNEXPECTED PROBLEMS

During the start of the second drive, from Lloyd Park to Beddington, the tunnel experienced a high level of water inflow from the tunnel shaft behind the TBM. The water inflow flooded the tunnel and halted operations for two months while remedial actions were taken to halt the flows. Once the water inflow was stopped, the contractor undertook the task of de-watering the tunnel and drying out the TBM and all damaged systems. Once the TBM was flooded, the contractor immediately contacted the TBM supplier in order to provide components as required to replace those damaged beyond repair by the water. The TBM supplier and contractor immediately began creating a plan of action to order the components required for replacement and provided field procedures to dewater and salvage as many components as possible. This process of returning the TBM to service was undertaken with the help of supplier TBM technicians working in conjunction with the contractor TBM technicians to check and test each system for proper operation prior to continuing mining along the planned tunnel alignment.
5 RESULTS

The LOVAT TBM broke through at Beddington Shaft on April 28, 2009. The following results were achieved by the TBM crew:

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Best Shift</td>
<td>30 Rings</td>
</tr>
<tr>
<td>Best Week</td>
<td>203 Rings</td>
</tr>
<tr>
<td>Best Mining Time</td>
<td>6 Min</td>
</tr>
<tr>
<td>Best Ring Build Time</td>
<td>9 Min</td>
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These results [1] were a combination of an effective and reliable design as well as the excellent work performed by the TBM operators from the contractor. Upon the completion of the project, the TBM supplier and contractor worked together on a ‘Product Improvement Workshop’. The document was prepared in co-operation to allow both supplier and contractor to review the project and analyze the successes and recommended improvements for future co-operation. A team of TBM supplier engineers met with the contractor and the TBM operating crew to discuss issues and ways to improve existing designs for future project implementation. This document is an important step towards new projects as it allows both the manufacturer and the end user to learn from one another and provide valuable input on both the successes and failures of project.

6 CONCLUSION

As with any project, communication between the stakeholders is extremely important. The TBM had to be designed to the project requirements and with the contractor’s input. Once the unexpected flooding occurred, both the contractor and the TBM supplier worked together to get the project back on track as soon as possible. Through the co-operation of both supplier and contractor, the document created will be able to benefit both parties in future projects by documenting lessons learned and incorporating them into future design considerations. With both parties working together, a project is more likely to be completed successfully.

Figure 4: TBM Breakthrough
REFERENCES

[1] MORGAN EST. Daily Tunnel Reports


[3] LOVAT Archive Library