Design of Tunnel Boring Machines for Escalator Access
Tunnel Construction, Moscow, Russia

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Summary

From its early construction the Moscow Metro System has consisted of very deep tunnels and stations. As newer lines are added to cope with the booming population they are being built so at much shallower depths more typical of Metro Systems in other countries. In order to connect the two levels of Metro Lines, deep inclined shafts are constructed for escalators (30\(^\circ\) decline). Historically this work was done by ground freezing and then hand mining the inclined shafts. Worked progressed well until the completion of the shaft until the ground was allowed to thaw. Due to the fined grained and saturated nature of the underlying soils in the Moscow region large ground settlements were typical causing damage to the adjacent buildings and structures. In some instances this damage was catastrophic.

A new method of construction was required and Mosmetrostroy in cooperation with Lovat came to the conclusion that a TBM may be what was needed to undertake these short but challenging tunnels. Below we summarize the issues, specifications and results of the first drive with this new construction method.

Challenges of the Project

The Project held various and unique challenges not typical to Earth Pressure Balance Tunnel Boring Machine (EPBM) operation. Some of this challenges are:

- Mucking out on a steep decline
- TBM overturning with center of gravity of machine close to being forward of the front edge.
- Supply of equipment and consumables to the machine down the tunnel
- Assembly of the machine on the decline
- Gantry and Material Handling
- Screw conveyor angle once the machine was tipped into position
- Hydraulic systems operating at a steep angle
- Water Pressure multiple level aquifers, constantly increasing pressure
- Machine disassembly – parts are pulled out and have a tendency to move forward to a level / plumb position
- Machine Retrieval back up through the tunnel

All these conditions, potential problems had to be overcome with unique design features, operating methodologies and or new technologies not typical to an EPBM.

The final project challenge was the project schedule which called for the design and manufacture of the TBM in twelve months [with all the new design features and challenges noted above to be
overcome] followed by two months for delivery to site, three (3) months site assembly, three (3) months mining and then three (3) months disassembly. Total time would therefore be 23 months or just under two years from start to finish.

**TBM Design and Manufacture**

The machine would be the first of its size and kind and was specifically designed to operate on the 66% slope. Consideration needed to be given for how all the TBM systems would operate at this high angle and to how the operators would manage material handling, segment bolting and simply moving around the TBM.

Cuttinghead design was for a mixed face soil condition [Figure 01 & Figure 09]. The machine was intended to be used on multiple projects over several years so cuttinghead design had to allow for as many possible soil types as it could with one design. The head could be equipped with a full face of ripper teeth or disc cutters depending on the anticipated geology. It should be noted that the type of tools was decided for the entire tunnel before launch. As the drive was only 104m no tool changes were anticipated or needed.

The Main Drive of the TBM was not designed to achieve high production rates but was instead designed to minimize the required equipment on the trailing gantry and the size of all its components. Every extra tonne of equipment used would have to be supported on the steep angle. The final main drive specifications would allow for a maximum cuttinghead speed of one revolution per minute with a maximum continuous torque of 25,160 kN•m. \( \alpha = 1.95 \). Peak starting / break out torque was rated at 31,450 kN•m.

The propulsion system on the TBM did not need to be high as the angle of the tunnel meant the weight of the machine itself would do a large portion of the work and would in itself maintain EPB pressure at the face. In addition the back up did not need to be towed but instead held from moving forward until needed. Total installed thrust was therefore relatively low for a machine of this diameter at 10750 tonne. The layout of the propulsion was different as there were twice as many cylinders below the center line as there were above. This configuration was to assist in steering the TBM should it begin to drop from the planned alignment.

The typical design of an erector on an eleven meter TBM would be to use a vacuum pick up system. The weight of the segments is high and is better suited to a vacuum system rather than a single pick up point. However, a vacuum system was not applicable due to the angle of the tunnel. The shear loads on the vacuum seal were potentially to high to risk a vacuum type system. Instead a stinger type arrangement [Figure 02] that mechanically locked to
the segment (Segment design included a structurally reinforced pick up point for mating with the stinger) with a shear pin to prevent rotation of the 8.2 tonne elements). Segment design was short one meter long elements 600 mm thick.

Sacrificial skins and internal disassembly were incorporated into the TBM design so that the machine could be removed from the tunnel with minimal disassembly of the main structures. Each TBM element was constructed in four or five elements that could be disassembled and removed back through the finished tunnel. The sacrificial skins would stay in place to support the tunnel during this procedure and before the final lining was cast in place.

Gantry construction was sub contracted by Lovat to Rowa Tunnelling Logistics AG of Switzerland (Rowa). Rowa specializes in the construction of trailing gantries for Tunnel Boring Machines (TBM) and has had previous experience with inclined tunnels of smaller diameters. The decision to engage Rowa was based on the challenges of a back up design on such a steep incline and their experience made them the preferred choice of partners.

Auxiliary equipment position on the gantry was crucial and had to be placed at the angle required for operation during tunnelling. Each component was placed at the required 30º angle so that during operation they would be level allowing for their correct operation and ease of maintenance.

Muck removal from the machine was accomplished utilizing a two stage screw conveyor design coupled to a positive displacement (piston type) muck pump. Specifications of the screw conveyor and muck pump:

**Multi Stage Screw Conveyor**

- Screw Conveyor nominal diameter of 1100mm
- First Stage length of 15480 mm
- Second stage length of 9970 mm
- Total installed power for both screw stages of 350 kW (value taken at 100% efficiency)
- Maximum throughput of the screw of 146 m³/hr

**Muck Pump**

- Dual Piston type pump equipped with 2 No. boundary layer injection systems (1 No. at pump and 1 No. along tunnel)
- Maximum theoretical capacity of 150 m³/hr
- Maximum discharge pressure of 65 bar
- Discharge pipe diameter of 200 mm
- Total installed power of pump of 315 kW (value taken at 100% efficiency)
- Scissor type pipe extension system – 3m capacity
Total combined design and manufacturing time from Order to Delivery was twelve months. EPBM design and construction was done in Toronto at Lovat's facilities, the back-up was designed and constructed by Rowa at their facility in Switzerland and the muck pump was produced by Putzmeister in Germany. The systems meet for the first time at the job site in Moscow. After the completion of the manufacturing the two sections were shipped to site where the integration and final testing was conducted prior to the launch.

Site Assembly Challenges

Site Assembly began on April 20, 2008 and finished with the completion of testing on August 20, 2008. Total assembly time was 123 calendar days. Long term the goal is to be able to assemble the machine within 90 days from the completion of site preparation and launch cradle construction to the completion of testing.

The overriding challenge of the assembly was doing it at a 30º angle combined with the size of the individual components. Calculations to ensure lifting of components was done at exactly 30º was necessary to ensure that bolt positions lined up on the machined surfaces between the components. As much work was pre-done on level surfaces until the maximum capacity of the cranes were reached at which time the piece would be lifted at the 30º angle. This helped to ease the problems with lining up the sections for assembly and bolting. [Sequence 01]

The site was located in Moscow which presented additional problems with available space for laying out the equipment before assembly and of transporting the large components through the city. Man power during assembly consisted of up to 14 men per shift (3 to 4 from Lovat and 10 from the contractor). Space would not allow for additional manpower to be utilized.

Sequence 01 (Top left to bottom right)
(a) Cuttinghead Placed on Launch Cradle, (b) Lowering of Forward Shell, (c) Completion of stationary Shell Installation, (d) Lowering Screw Conveyor, (e) Completion of Main Body Assembly, (f) Ready to Launch
Construction: Progress Rates, Problems

During mining operations the EPBM performed as anticipated. There were several issues and problems that arose that were unique to the tunnel itself. Mucking out proved to be very difficult and required extensive modification of the ground conditioning and muck pumping parameters to “dial in” the process.

Typical operating parameters for the systems were as follows:

- Penetration Rates designed for 20 mm/min with 5mm/min achieved.
- Screw Conveyor Primary Drive required torque of 98 kN•m to 295 kN•m
- Screw Conveyor Secondary Drive required torque of 98 kN•m to 245 kN•m
- Main Drive Torque was averaging around 11,770 kN•m (47% of maximum) with peaks to 21,580 kN•m at start-up (69% of maximum break out)
- EPB pressure at the top of the cuttinghead chamber of 1-2 bar
- EPB Pressure at the invert of the cuttinghead chamber of 2-3 bar with peaks of 5 bar
- Typical propulsion thrust of 3000 tonne
- Peak propulsion thrust of 5000 tonne (50% of maximum available)

The TBM and Back-Up systems were designed to achieve a steady advance rate and not to break production records. With safety as the primary concern the material handling (segments weighed in at 8.2 tonne each) was a methodical and carefully executed process where speed was not the primary goal.

During construction the primary issues that arose was the inability to make the excavated material pumpable and from this to maintain proper pressure in the chamber. By tweaking the ground conditioning and EPBM speed and muck pump operation we were eventually able to overcome this issue. It proved difficult to achieve the desired results due to the constant changes in the excavated material as the tunnel drove.
downwards through multiple soil layers. In the end the systems worked but a large percentage of
the tunnel was already done. The tunnel was only 104m long and any experimentation took
several meters to take affect. As a result by the time the system was “dialled in” the tunnel was
nearly complete. This will likely prove to be the overriding issue for this EPBM design regardless
of the location of the future projects.

Another concern and problem was weather in Moscow. Winter comes early and quickly and
several days during the later half of the mining experienced snow and extreme cold weather.
Mining was completed on December 20, 2008 – 123 calendar days after the commencement of
mining. Mining was done seven days a week, twenty-four hours a day for the duration of the
operation.

Disassembly Problems and Challenges

The disassembly of the machine began
on January 6, 2009 and was completed
by April 24, 2009. A total of 109
calendar days was spent taking the
machine components out of the tunnel
in a controlled and safe manner.

Specialized equipment [Figure 07] was
constructed by the contractor to facilitate
the disassembly of the machine and the
transport of the components (some as
large as ninety tonne) back up along the
tunnel to the launch portal.

Prior to commencement of the
disassembly the contractor did what all tunnellers try to avoid and grouted in the machine. Grout
was pumped 360° around the machine under pressure to seal the ground and machine in place
and to prevent the movement of water towards the machine once pressure was released in the
cuttinghead chamber.

Safety was the top priority with the
disassembly of the machine. Large
components were being pulled out of
secure positions at an angle to the vertical.
As soon as there attachment was released
they would swing forwards to the front of
the machine. Securing the components
and controlling their movements was an
absolute necessity to maintain safe
operations. The contractors site staff
showed great ingenuity during this phase
of the works.

Sacrificial skins (second skin on the
outside of each of the EPBM sections)
were left in place as the machine was
disassembled. This provided temporary support to the tunnel while the disassembly took place.

Conclusions

With the first project successfully completed the EPBM is now being prepared for a second project in Moscow. There were several issues that arose during mining that are being addressed prior to the next project commencing. Lessons learned are being incorporated into the EPBM design and operation. Once in full operation the method of construction will be faster and most importantly safer (which it has already proven) than the more traditional method of ground freezing and sequential excavation.

In spite of the large number of design issues and logistics problems the tunnel was successfully constructed. This “first attempt” at mechanized tunnelling of escalator tunnels has proven the viability of the construction method and therefore future development and refinement of the method will continue.

The original schedule of twenty three months from start to finish was not achieved. Each of the site segments (Assembly, Mining, Disassembly) took four months vs the planned three months and there were delays in the delivery to site, access to the site, smaller site footprint and finally due to holiday schedules. Overall, all parties were pleased with the final results.

One particular lesson learned was to never underestimate the time required for the development and implementation of new technology with particular emphasis on site set up and operation (learning curve).

Summary of Figures and Sequences.

Figure 01  EPBM at Lovat Plant prior to delivery
Figure 02  Segment Erector “Stinger” pick up system and shear key
Figure 03  EPBM General arrangement on 30º slope indicating compact design.
Figure 04  Transport of Segments from Portal to machine on specially designed cars
Figure 05  View up along top of gantry showing walkway and auxiliary equipment placement
Figure 06  View down and tunnel portal
Figure 07  Special transport sled in position to remove crown piece of Stationary Shell in tunnel
Figure 08  EPBM removal showing remaining components in tunnel (Cuttinghead) with all other pieces removed
Sequence 01  Sequence of TBM site assembly from installation of cuttinghead on portal face to the assembly of the trailing gear on a pivoting platform.