Latest Innovations in Tunnel Boring Machines

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Innovation in TBM technology is driven by the tunnel infrastructure market demand. Long and large diameter tunnel projects for transport infrastructures and large hydropower projects have influenced the research and the development in TBM design over the last 10 to 15 years. New TBM types have been introduced to cope with mixed rock/ground conditions and adapt their operational mode depending on such conditions. Large TBMs with diameters ranging from 14 to 17 m have been manufactured and utilized all around the world. New technologies and materials to treat the ground ahead of the TBM and control the ground water inflows have been developed and successfully experimented.

However, there are still geological conditions that, especially for large diameter TBMs, can put at risk the success of their implementation. For important projects that foresee long and large diameter tunnels under critical and/or uncertain geological conditions it is still advisable and profitable to anticipate the execution of an exploratory tunnel.

Figure 1: My mother "Marisa", the first TBM in Italy 1969 to 1971

1 Last century innovations in TBM technology

Over the second half of the last century, the utilization of TBMs in the construction of infrastructure projects progressively expanded in number and type of applications. In parallel with the exponential increase in the number of utilizations several important innovations were introduced (**Figure 1**).

The innovations in these long 40 years lapse of time were focused in improving the TBMs design and efficiency for the following 2 main fields of the TBM technology:

- Rock Tunnelling – Main beam gripper type TBMs and double shield TBMs, mainly utilised for long hydropower and water tunnels
- Soft Ground Tunnelling – Pressurize face TBMs, EPB and Slurry Shields, utilized mainly in urban environment for metro and city services.

During this long period, the development in technology was mainly focused in the following 2 fields.

1.1 For hard rock applications

- Increasing power, thrust and cutterhead tools diameter in order to achieve better penetration in hard rock;
- Designing new TBM shields to increase the TBM capacity to overcome unstable rock conditions, faulty and squeezing ground;
- Implementing more efficient back-up and transport system to boost the TBM daily productions;
- Designing segmental lining systems to be installed by the TBM and avoid the necessity, saving time too, for final in situ concrete systems.

1.2 For Pressurize face TBMs

- New conditioning agents were introduced (foam, polymers, fines mixes) to enlarge the field of application of EPB TBMs to the widest possible range of soft ground types and granulometries;
- Improved slurry mixes, more efficient separation plants and cutterhead chamber crushers contributed also to widen the range of application of Slurry and Hydro-shields.

With view on this development it is important to note that

- rock TBM innovations were mostly focused in increasing the productivity of the machines, reducing the time of completion and reducing the risks related to unforeseen adverse geologies.
- soft ground TBM innovations were mainly focused on extending the capacity of the machines to stabilize the face and avoid surface settlements even in the most critical soils and conditions.

During those times the typical tunnel diameter for both hard rock and soft ground TBMs rarely exceeded the range of 3.5 to 8 m diameter. The requirement of TBM applications for railway and highway tunnels, and thus of larger diameter TBMs, was at that time minimal.

2 Trends of innovation in TBM technologies

In the last 10 to 15 years the TBM tunnelling market literally exploded also thanks to Chinese, Indian and, in general, Asian Market huge demand. Hundreds of TBMs have been manufactured every year and utilized to excavate tunnels for every kind of infrastructure and in the most different geologies.

This massive experience gave the opportunity to experiment the limits of the existing technologies and to gain and collect a great amount of significant data to help the technological developments. At the same time the infrastructure market started to demand several large diameter TBM applications for long railway and highway projects, often crossing complex geological formations under cover.

The combination of the experiences made in the tunnels already executed and of the new demand of the infrastructure market led the research and the consequent innovations to very specific targets.

The innovations introduced during these recent years have been in the type/general design of the TBMs as well as in the special features and equipment that could be mounted/fitted on the TBMs. Just to mention the main significant innovations in the type of TBMs see the following list.

EPB TBMs

The geological range of application has been extended virtually to all type of soils as well as to soft/medium rock formations thanks to the improvement in design and in the chemical agents utilized for muck conditioning (**Figure 2**).

Figure 2: Fine injection EPB TBM

EPB-Slurry dual mode TBM

This type of TBM is able to change operational mode from EPB to Slurry and is utilized when a soft ground tunnel shall be excavated through soils formation having variable nature, characteristics and ground water pressures.

Double Shield Universal TBMs

This type of TBMs was designed to cope with highly squeezing formations and in general to bore tunnels in rock under high cover and in variable ground conditions (**Figure 3**).

Single shield TBMs with ground water pressure control

There are some projects where, for different reasons, it is re-

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quired not to drain water from the rock mass even during the excavation phase. These projects require the water to be kept confined in the excavation chamber and the TBM to advance against high water pressure erecting a precast lining watertight.

Figure 3: Double Shield Universal TBM for the Himalaya

Double Shield/EPB TBMs
For very special applications, when in a single tunnel are present long sections in hard rock and other sections in soft ground, these TBMs can adapt the operational mode (**Figure 5**).

Compact TBM system
Designed for pilot tunnels and mining tunnelling, it is an extremely short and simple TBM, but also powerful and efficient for high performances (**Figures 6, 7**).

In order to these new advanced types of TBMs to be capable to cover the widest possible range of geologies and conditions, several new auxiliary technologies have been also developed.

Face consolidation treatments – executed through the shield and through the bulkhead of the TBM by multiple drilling machines (**Figure 8**).

Muck extraction systems – able to confine the water in the excavation chamber at high pressure while the TBM is excavating.

Chemical agents – for conditioning of soils in soft ground applications, consolidate rock masses, seal the ground water, filling caverns and large over-excavations.

Advanced TBM parameters monitoring systems – able to elaborate set of information in real time and provide the operators and the supervision with indications on TBM operation.

Figure 5: Double Shield/EPB TBMs

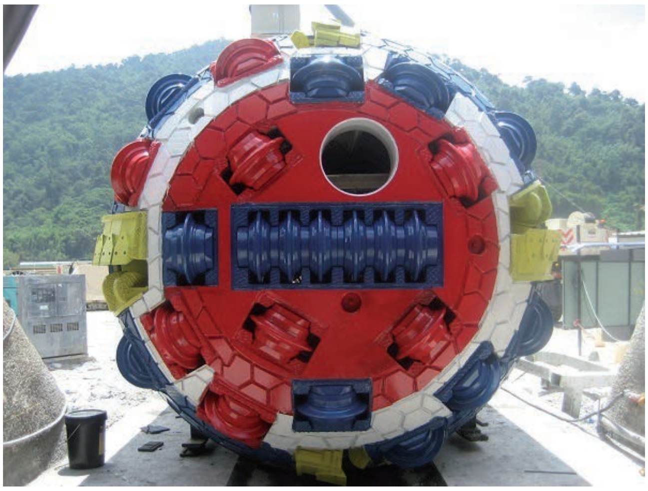

Figure 6: Compact TBM

Figure 7: Compact TBM System

Segmental lining gaskets – sealing the tunnel from high pressures (over 20 bar) of ground water.

Figure 8: Face consolidations through Compact TBM

Both the new types of TBMs and the associated technological innovations, were mainly focused in extending the range of geological formations and conditions that the TBMs could successfully face with rather than further increasing the productivity of such TBMs in terms of peak advance rates.

In other words the research and innovation has been mainly targeted technologies to reduce the risks in executing tunnel infrastructures in presence of geological criticalities.

Clients and designers have immediately tested these technology achievements to their limits for the execution of many large diameter long tunnels for ambitious projects in critical geological conditions.

3 Large diameter TBMs for railway and road infrastructure

Parallel to the development of new technologies the diameter of tunnels to be excavated by TBMs substantially increased in respect of the ones utilized 10 to 20 years ago for similar infrastructure.

In railway tunnels the increase of the train speeds and the increased safety and design standards caused the typical tunnel diameters to increase from 8 to 10 to 11 m for single line tunnels (**Figures 9, 10**).

In road tunnels multiple lanes and again the increased safety and design standards caused the typical tunnel diameters to increase from 11 to 15 to 17 m (**Figures 11, 12, 13**).

For a given rock formation the stability of the tunnel is strictly dependent from the tunnel diameter. For tunnel diameters more than 9 to 10 m there are virtually no rock formations that

Figure 9: Perthus Tunnel – High Speed railway

Figure 10: Perthus Tunnel – connecting Spain to France

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can grant the full stability at short term. Even in the best and harder rock blocks and debris fall down from the tunnel walls immediately behind the TBM cutterhead and require systematic support.

Figure 11: Brisbane Highway Tunnel

Figure 12: M30 Tunnel Madrid

Figure 13: M30 Tunnel in Operation

Figure 14: High Speed Cordoba – Malaga (Spain) – Abdalajis Double Shield Universal TBMs

In poor rock formations, in fault zones and, in general, in critical geological conditions, the negative influence of a larger TBM diameter on the stability of the tunnel and on the capacity of the TBM to advance is further enhanced (**Figure 14**).

For the above, a certain TBM type that in a small/medium diameter configuration can successfully bore a tunnel in given geological conditions, in a substantially larger diameter configuration may fail to excavate in the same geological conditions.

The choice of the type of TBM and of the support/lining system to face a given geology is largely dependent from the dimensions of the tunnel and the maximum feasible diameter of a bored tunnel is more dependent from the geology than from the technological limits of designing and manufacturing large TBMs (**Figures 15, 16**).

The variable results achieved by the recent TBM Monsters, especially under mix geological conditions, demonstrate the need to evaluate even more carefully the geological environment in case of a large diameter tunnels.

Figure 15: Sochi Railway Tunnel (Russia)

Figure 16: M30 Twin Cutterhead EPB TBM

Figure 17: Los Bronches Exploratory Tunnel (Chile)

4 Exploratory Tunnels

For large and critical infrastructure projects, despite the progresses of the TBM technology made in the last years, it can be convenient to execute an exploratory tunnel in advance. This particularly for long, large diameters tunnel projects in complex and/or unknown geological conditions under high overburden (**Figure 17**).

These types of infrastructure requires huge investments and complex financing schemes and the respect of budgeted costs and times of execution is an absolute must.

An exploratory tunnel brings several advantages to the subsequent execution of the larger main tunnel (**Figures 18, 19**) and in particular allows to

- drain the water in the area of the main tunnels to be executed;
- provide with a full scale geological investigation;
- reduce substantially the need and cost of other geological investigation campaign;
- give important indications about TBM excavation parameters to be utilized in the design of the large diameter TBMs;
- reduce the prices offered by the bidding contractors due to the full knowledge of the geology;
- treat in advance faults/adverse ground sections;
- optimize the main tunnels support and lining system dimensioning;
- reduce drastically the possible claims and litigations with the contractor and the consequent savings;
- provide an additional access that an be utilized as service tunnel during the construction of the main tunnels.

The execution in advance of an exploratory tunnel virtually reduces up to eliminate the risk factors resulting from: tunnel design, TBM selection, tunnel execution, bid price, contract management time of completion, project budget.

For large infrastructure tunnelling projects the costs of an exploratory tunnel amounts to small fraction of the overall project budget and this costs are largely recovered by its advantages (**Figure 20**).

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5 Future developments

The trend towards larger and larger TBMs will continue since there are several infrastructures that could benefit from the possibility to execute larger tunnels (**Figures 21, 22**).

Highways, railways, safety structures, power lines, aqueducts and services could be combined in a single large tunnel section (**Figures 23, 24**).

Figure 18: Brenner Base Exploratory Tunnel

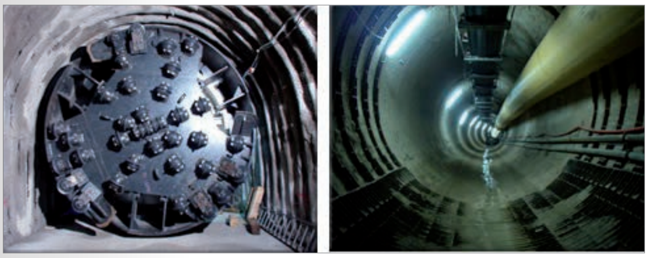

Figure 19: Faé Exploratory Tunnel

Figure 20: Sochi Exploratory and Services Tunnel (Russia)

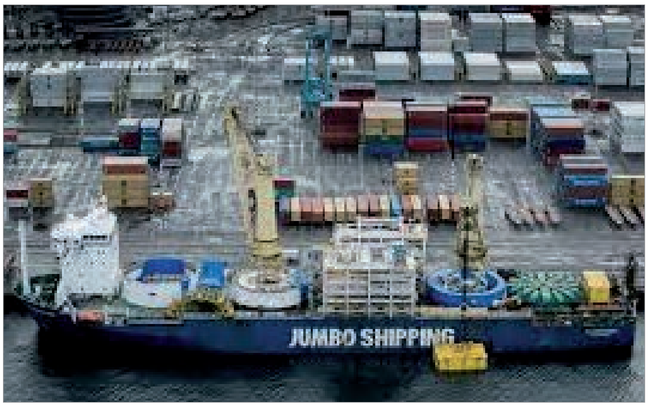

Figure 21: Seattle 17 m TBM on board

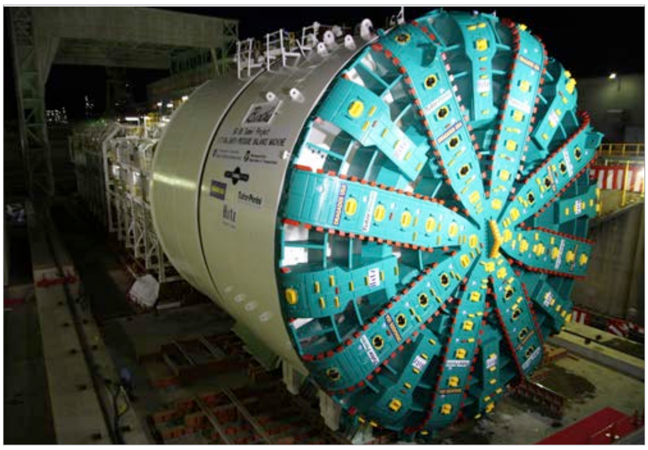

Figure 22: Seattle 17 m TBM assembled

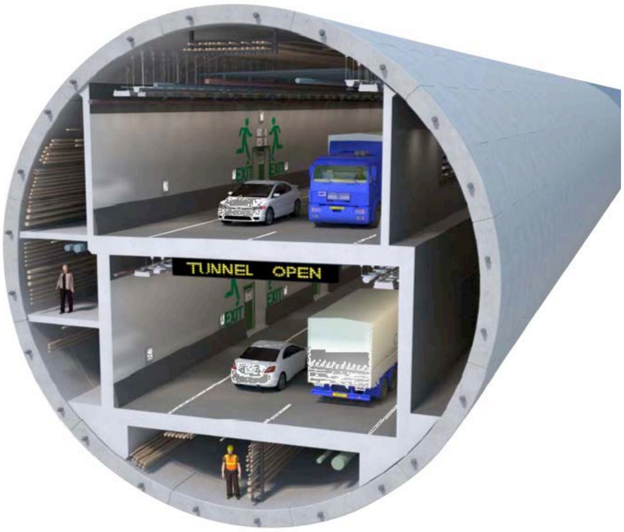

Figure 23: Multi purpose tunnel system

Figure 24: TBM with 15.5 m diameter for Italian highway project

To make these applications successful also in difficult ground conditions it will be necessary to further develop the pre-treatment facilities as well as the possibility to control, confine and/or drain the ground water (**Figures 25, 26**).

In this regard large diameter TBMs have the advantage of having more space available for drilling, grouting and water control systems.

TBM peak performances in good hard rock are already near to their physical limits, but the average advances could be significantly increased by improving the TBMs capacity to face adverse geological conditions.

6 Conclusions

TBM tunnelling today is a mature technology and the technological improvements of the recent years consolidated the efficiency and reliability of this tunnel execution method.

Productivity and capability to cope with different rock and soil conditions is well proved and self-explanatory.

However there are still risks in the applications of this technology, especially for large diameter tunnels in difficult and/or unknown geologies.

In the next few years the trend towards larger TBM diameters will continue and thus the technology innovations shall be focused in developing new and more efficient systems to treat

Figure 25: Open Gripper TBM for Gotthard

Figure 26: Main Beam TBM with 14 m diameter for Niagara

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the ground ahead of the tunnel in adverse geologies and deal with high pressure ground water (**Figure 27**).

Figure 27: Lake Mead TBM – Confining water at 14 bar

We can therefore expect

- precast lining systems that can resist to 30 to 40 bar of external pressure, eliminating the necessity of a secondary lining even in very deep tunnels;
- TBMs that can efficiently treat the ground in the face and around the face, eventually executing jet grouting/piling and other special consolidation technologies from inside the TBM shields;
- TBMs which are able to confine the water at the face even at significant pressures (up and above 20 bar).

The additional space available in large diameter TBMs will help the development of these technologies.

For major infrastructure projects however as per today, at least until these new technologies will be fully developed and tested, the execution of an exploratory tunnel can substantially eliminate the risk of construction. This together with the proper selection of the TBM type and support/tunnelling design.

References

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