Trends of Future Tunnel Projects and their Impact on the Design of TBMs

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1 INTRODUCTION

Engineering has always been an area pushing boundaries and of world record breaking, and tunneling is no exception. Periodically we assist to a new record announcement – the deepest, longest, largest tunnel to be constructed. More often than not, the project develops and succeeds, effectively pushing the limits further.

Several tunnel construction methods are opposed in a competition, each with its advantages and drawbacks. Here also, competition fosters innovation. As a result, Tunnel Boring Machines have progressively overcome their initial flaws and are currently put at work in increasingly demanding projects. Civil engineers and tunnel builders simultaneously gain confidence in the technology and the extended capacity of TBMs, and actively fuel this search for higher performance and versatility.

In this paper we examine the situation and current trends, and discuss the developments that are expected on the TBM side in order to meet the challenges future tunnel projects will set.

2 HISTORICAL BACKGROUND

2.1 Underwater tunnels

The most emblematic underwater tunnel – at least in Europe – is the Channel Tunnel, which is history in itself. It is no surprise that this almost mythical piece of work was made using TBMs, and a review of underwater TBM tunnel projects can only start with this masterpiece.

1988-1991 – Channel Tunnel

This tunnel comprises two tubes of 7.6 metres in diameter. The works started with the boring of a pilot tunnel. Altogether five EPB TBMs were used (on the French side), occasionally meeting 7 bars of ground pressure at 70 metres below sea level. The ground, mainly clayey chalks, with sections in flinty chalks (French side) and calcareous marls (British side) is very homogeneous and was considered as perfectly suited for TBMs. Today it is likely that only one or two large EPBs would be used, boring a single tube housing two levels of traffic, and that a pilot tube would not be seen as necessary.

1990-1994 – Storebaelt

This famous road bridge and railway tunnel across the “Great Belt” strait reaches 100 metres down below sea level. Two thirds of the drive was bored in the homogenous underlying marl, and the rest in very abrasive glacial till. This context made it an easy but dangerous site for TBM tunnelling. Pressures of up to 8 bars were expected by the 4 EPBs that bored the two 7.7-metre internal diameter tubes, although the maximum recorded was 6.3 bar [1].
1993 – BPNL (Ring road around Lyon)
This road tunnel under the Saone River is often considered as the first “geologically” difficult TBM-bored tunnel. It is mainly characterised by the variety of grounds – ranging from very hard gneiss (above 300 MPa uniaxial compressive strength) to glacial alluvia. A single 11-metre EPB bored the two tubes (2 x 3,250 m in length), with a pressure reaching 4 bars. Seen as a major challenge back in 1992, this project remains an unquestionable achievement, yet this type of job is now common practice in areas such as Hong-Kong, Singapore, and other cities where metro lines are bored at the bedrock/residual soil interface. These problematic mixed faces have become usual situations in TBM tunnelling.

1989-1997 – Tokyo Bay
Once the world’s largest underwater road tunnel, the Aqua Line tunnel runs 60 metres below the Tokyo Bay as two parallel tubes of 9.5 km in length. The eight slurry TBMs that were used were designed to withstand pressures of up to 9 bar. The main difficulties came from the very large machine diameter (14.1 m) and from the specifically designed earthquake-proof lining scheme, rather than from the geology which was fairly “easy” ground, mainly silty and sandy clay, and sand.

2008 and beyond – Bosphorus
The Bosphorus strait is currently the scene of several tunnel projects involving TBMs: the Melen River water tunnel; the Marmaray railway tunnel with an immersed tunnel section connected to the surface by bored tubes; and a still to be constructed highway tunnel (3.3 km long, 12.86 m diameter TBM, running 80 to 90 m below the surface).

2.2 Land tunnels

2003 - (under construction) – Barcelona Metro Line 9
Boring these two tubes (12 m diameter) in downtown Barcelona was performed by two dual mode (open/EPB) TBMs. An impressive mix of difficult geological conditions was met all along the 7-km way: granitic bedrock with important surface weathering, and shale. This resulted in unprecedented problems of tools and disc cutters wear; unexpected changes in the geology were handled with two cutter head redesigns and exchanges. Although the pressure remained below a reasonable 2.5 bar, this tunnel is among the most difficult projects in the early 2000’s.

2005 - (under construction) – Hallandsås
This train tunnel is well-known for its tortuous history. Started as a drill and blast job, the project was stopped and restarted as a bored tunnel (10.6 m in diameter). Construction is plagued by complex geology, with completely weathered rock and very high groundwater pressure.

2006 - (under construction) – Niagara Tunnel
This hydroelectric tunnel is also a geological nightmare, with huge over-breaks that have constantly slowed down the 14.4 m diameter TBM progress in its 10.1 km drive.

2.3 Mountain tunnels
The history of mountain tunnels is far beyond the scope of this paper. However, looking at recent European bored tunnel projects (Gothard base, Pajares, Brenner base, and the planned Lyon-Turin) shows that they have common features: a diameter around 10 m; increasingly long tubes, exceeding 25 or even 50 km; and increasingly high overburdens, up to 2300 m).
2.4 Overview

The main characteristics of the underwater and underground tunnels listed above are shown on the following diagram. The vertical position of the bubbles indicate the depth (underwater tunnels in blue) or maximum pressure (underground tunnels in brown) while the size of the bubbles is proportional to the geological difficulty. The trend (larger bubbles, higher depth/pressure) from left to right is clearly shown.

![Diagram showing the depth and pressure of various tunnels](image)

Figure 1. Overview of “difficult” tunnels history

3 NEW REQUIREMENTS ON TBM DESIGN

3.1 Tunnel diameter

Requirements on tunnel diameter seem to have come close to a limit, not because of technological reasons, but because the most demanding road or railway configurations can now be satisfied with single tube tunnels (diameter in the range of 14 to 17 metres). This is likely to be the standard size of the future TBMs we are discussing hereafter, although there will as always be exceptions to this, with larger sizes projects.

3.2 Tunnel depth

The main change in the new TBM-bored tunnel projects is obviously an increase in tunnel depth. For underwater tunnels in permeable soils, this means a significant increase in water pressure. Looking at some key projects (Bosphorus highway: -90 m, Gibraltar strait: between -420 m and -620 m depending on selected profile, 28 km under the sea), pressures of 20 bars should be handled – not as peaks but in a continuous mode.

Structure design

Operating at increased depths means an increased soil pressure exerted on the TBM face and shield. Assuming an unchanged penetration rate, this in turn implies that the required TBM thrust must also increase in the same proportion. Increasing the pressure inside the chamber means that mixing the extracted material will require an increased torque. Thrust and torque are also directly impacted by the increase in diameter D, respectively varying as $D^2$ and $D^3$. 
Consequences are a complete re-dimensioning of the main TBM elements: structure, to obtain the required stiffness; drive unit bearing, in order to withstand the huge force and torque on the cutter head. The result is a considerably increased weight and therefore of apparent density, which poses potential problems of steering.

Sealing
The drive unit and its bearing are the most crucial elements in the TBM, but are also the ones exposed to the highest stress. Reliability is the key subject here, and therefore this area requires highly efficient protection against contamination by external material, which would result in a catastrophic failure. From outside to inside, sealing is ensured by a labyrinth and a set of lip seals; compounds and/or lubricants are injected in the labyrinth and in the chambers in between adjacent lip seals, which reduces the differential pressure exerted on each seal. This scheme is considered to be applicable for pressures up to 10 bars. Extending it above this value, by adding one or more lip seals, leads to additional overhang on the bearing, and additional efforts on the structure. At some point, it is expected that this approach would reveal itself inapplicable. New materials are being developed that open perspectives for innovative sealing devices; advanced modelling tools allow in-depth analysis of the seals behaviour in varied configurations and over a wide range of environmental parameters, resulting in safer designs. Better approaches should therefore be looked for, possibly using a totally different concept.

The same considerations apply to tail shield sealing, which is traditionally designed as a series of brushes inside which a special compound is injected in a continuous manner while the TBM advances. Here also a possible answer to the increased pressure is the addition of brushes, with an extra consumption of compound but it is unlikely this would withstand 20 bars continuously.

Tunnel lining
Although outside the scope of TBMs in a strict sense, tunnel lining is also bound to adapt to the ground pressure increase and TBMs will have to follow suit. The design of lining will change, because it guarantees the overall tunnel water-tightness, and participates in sealing the TBM-tunnel interface. Lining will also be re-dimensioned in order to cope with the higher ground pressure, but even more because it is directly submitted to the TBM increased thrust. The need for filling the annular void, and the related process, will also possibly change radically, imposing new constraints and requirements to the TBM side.

3.3 Geological configuration of tunnel site

TBM versatility
It is nowadays commonly accepted that TBMs are not restricted to easy tunnelling through a uniform type of ground. Several attempts at “difficult” tunnels have shown the potential of TBMs, and even though problems were encountered in many of them, engineers found solutions and developed methods and procedures that have given more and more confidence in the technology. Increasing tunnel length also increases the probability of dealing with a more varied geology along a given drive.

What will be needed tomorrow is a TBM capable of boring into soft soil, cope with boulders, go through rock masses, and handle extremely abrasive ground over long distances. The variety of grounds that a TBM will face within a same tunnel can be such that theoretically different types of machine should be used. But contractors are more and more tempted by multi-mode and (re)configurable TBMs, in order to save huge investment costs and the consequences of difficult and risky operations such as dismantling a TBM inside a tunnel. Reconfiguration (i.e. changing tools from one type to another, but also from one operation mode to another, e.g. open mode to slurry, or even EPB to slurry and vice-versa) must be anticipated, and will be performed at programmed points along the tunnel.
On-board geological prediction

Boring deeper tunnels generates new problems for geologists, who have greater difficulty in accessing and probing the ground where the tunnel will be built. Preliminary studies will cost more, and it is likely that in the end insufficient data – or less accurate data – will be made available to support the actual TBM operation.

Boring more demanding tunnels incorporates an inherently increased level of risks, which are partly related to geology and its local changes. The need for accurate local geological data is therefore bound to increase, and consequently the production of such data will be shifted to the TBM side, with requirements for real-time and reliable information, even at a microscopic scale.

Geological analysis systems that can be used in tunnelling are available commercially, with known ranges of application and obvious limitations. Most require highly skilled expertise for the on-line analysis of the produced data. Further developments are under way, using various approaches and detection technologies (electrical, seismic, radar). These techniques need to be turned into actual instruments that can be effectively implemented on-board TBMs, and operate reliably in segment-lined tunnels. As opposed to medical research (imaging technology) and oil/gas extraction, the stakes are obviously insufficient to raise adequate funding. A more global effort is required if this part of the system is to be ready in due time.

Ground improvement and stabilisation

Maintaining a stable face and surrounding ground above and around the tunnel is one of the basic requirements in tunnelling. When faced with complex geology, ground stabilisation is likely to be required and the TBM must incorporate adequate drilling and grout injection equipment. Ground improvement will be necessary in a continuous mode, in order to reduce water inrush and/or reduce the nominal operating ground pressure.

3.4 Tunnel length

TBMs can only operate over a limited span of approximately 10 km (closed mode) or 15 km (open mode), and this poses a problem when tackling some of the very long tunnels which are envisaged. Consequently, boring tubes of over 20 km with pressurized machines means that at some point very heavy maintenance work will be required, possibly under water courses. This requirement must be incorporated in the machine concept from the start if tunnels such as the Bering Strait crossing (over 100 km) are to be bored.

However, it is likely that paying passengers have a psychological barrier to using extremely long tunnels, even when traveling by train, which may very well imply that the most extreme projects could never get past the drawing board.

3.5 TBM operation mode

Apart from pure rock sections of the tunnels, where boring can be made in open mode, the previous discussion demonstrates that the required TBMs are obviously of a closed type. The issue therefore takes us one step back to the question: EPB or slurry? This debate used to be focused on soil characteristics, and the choice was basically made based on an expected grain size distribution, as follows: EBP when the percentage of fines was high, slurry when this percentage was low. In addition, a high percentage of coarse gravel precluded the use of EPBs [2], see figure 2A. However, thanks to improved products and techniques for ground treatment and conditioning, this limit has become blurred when considering standard depths and pressure levels [3], see figure 2B. The choice is now made more on investment cost and operational costs, together with considerations for the environmental impact that usually favours the EPB solution.
Operating a TBM in a continuous high-pressure condition produces excavated material that has to be transported across a 20-bar pressure difference. With regards to this, the fully hydraulic design of Slurry TBMs offers many advantages over the EPB concept. Although very long screws can be designed and have indeed been implemented, there is currently no experience at so high pressures. Screws are prone to intense wear, and this will be exacerbated at high pressures. Screws also present a risk of going into a flow-through situation that cannot occur on slurry delays and huge costs.

Figure 2. Choice of EPB or slurry TBM based on grain size distribution
Improvements achieved through soil conditioning

3.6 Designing for risks
Risks are present in many aspects of tunnelling, and high ground pressure makes most of them even more critical. Risks concern the people working inside the tunnel, buildings at the surface, and tunnelling equipment. Unmanaged risks potentially turn into casualties but also into project delays and huge costs.

We will focus here on the tunnel area and more specifically on the TBM. A first level of risk is due to geology, generating accidents such as sudden ground or water ingress, collapse of face, TBM jamming, to name a few. Most of the remaining risks are related to human interventions in exposed areas such as the TBM cutter head and chamber, and in the segment handling zone. Following are the concepts that need to be further developed in order to address future tunnel projects.
Lifetime of tools and exposed parts
Most of the TBM maintenance activities are due to wear and failure of mechanical parts, among which the cutter head and its tools are the most exposed. Increasing the lifetime of these parts will reduce the requirements for human intervention.

Predictive maintenance tools
Maintenance interventions can be either planned or initiated upon the detection of a problem such as a worn out or damaged part (e.g. tool, disc cutters). Implementing wear measurement or wear prediction systems will allow for a better planning of human interventions and reduce the total number of operations inside the risky areas.

Geological prediction
As described in paragraph 3.3, implementing local geological prediction instruments contributes to risk mitigation. Detecting and locating obstacles (faults, boulders, former construction remains) ahead and to the sides of the tunnel face will avoid potential material damage that could entail risky maintenance operations.

Safety in maintenance
Implementing wear resistant parts and wear prediction features will reduce – but not fully eliminate – the need for maintenance. Special care must therefore be given to the design of the cutter head in order to offer protection to maintenance operators. Tools and disc cutters should be made easily replaceable.
Hyperbaric operations must be expected and planned for, and the related saturation diving equipment must be incorporated, both inside the TBM and at the surface.

3.7 Validation of concepts
Concept validation is a critical phase in any innovation process, but the specificities of tunnelling add up with the levels of required innovation and of risk to make this even more critical. Testing a TBM in actual operational conditions is virtually impossible in the factory, therefore alternatives are needed to test subsystems independently.
Simulation tools are vital in this process. Geomechanical modelling should be integrated into structural mechanics modelling, which will allow virtual testing of the TBM behaviour within its surrounding ground, using real life cases based on available geotechnical data and previous tunnelling experience.
Special attention needs to be given to endurance testing of key components.

4 CONCLUSION – LOOKING INTO THE FUTURE
Tunnelling is a risky operation, but is not unique in this respect. In other sectors, we have witnessed that man was constantly searching for solutions that would make his life easier and safer, and we can anticipate that this will also be the case in tunnelling. Risks also have a cost, and increasing the cost effectiveness – or business profitability – is another driver towards risk mitigation.
Calling upon the services of deep sea divers used to be the only possible way of handling underwater offshore work. At depths above 50 metres this type of work is now widely done by robots and through teleoperation. This approach does reduce human risks related to the pressure level (e.g. decompression accidents), but also abolishes the limitation on the working time that humans can sustain in such conditions. Similar examples can be found in the space exploration sector and in the nuclear industry [4].
Based on such successful experiences, we can anticipate that the tunnelling industry will in turn introduce and progressively rely on increased automation and robotics.

We believe that TBMs will face the coming challenges and keep up with their promise of being the most efficient method for tunnelling. This can only be achieved through a common effort and cooperative work between the TBM manufacturers and contractors, and support from the scientific community. We have no doubt that on this condition we will all succeed and come up with innovative solutions: deep and difficult tunnels are a necessity and will become reality.

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REFERENCES

