Large to very large Tunnel Boring Machine Diameters for today’s Infrastructure Systems

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ABSTRACT
Numerous very large diameter tunnelling projects with TBM diameters exceeding the 14 meter mark were completed successfully in the past with acceptable and also outstanding progress in challenging conditions. This has had the effect of encouraging the design of more and more large or very large diameter tunnel projects that are accepted and trusted by the public not only based on outstanding progress but also on the fact that these large scale projects were realized reliably in time, within budget and also fulfilling the demand for high quality standards. This paper provides an overview on the state of the art mechanized tunnelling technology that is demanded and perspectives on tunnelling projects with large to very large diameters. Highlighted are some projects that provided significant improvement in delivering underground structures which contribute to resilient and sustainable urban solutions.

1 INTRODUCTION
The ongoing trend of designing larger diameter infrastructure tunnels is supported by the successful completion of large and very large diameter tunnelling projects. In the 1990s a 12 meter diameter TBM was considered to be the size limit for tunnelling machines whereas today TBMs with diameters in the range of 15 to 17 meters are based on previous experience acquired in proving the functionality of very large diameter TBMs. Examples of very large bores are the 15.6 meter diameter EPB Shield that was used between August 2011 and July 2013 in line with the project schedule for the Galleria Sparvo highway tunnel in Italy and the 17.6 meter diameter Mixshield that finished a 650m long section of a large-scale subsea road tunnel project in Hong Kong in November 2015. Since the 1990s numerous very large diameter bores were successfully completed for underground infrastructure systems. Mainly these applications have been for road tunnel constructions but also quite a number of very large diameter multi-purpose tunnels and metro tunnels were built since then. All projects have needed to deal with the complexity of geology, site constraints and tight time schedules. The paper highlights three large to very large diameter projects that differ not only in diameter, machine type, geology but also on the specific project conditions. These projects are a large diameter metro tunnel project that was executed in Spain with a 12.06 meter diameter EPB Shield and two of today’s largest soft ground TBMs, the 15.6 meter diameter EPB Shield that excavated a 4.8km long tunnel section in Italy and the 17.6 meter diameter Mixshield that was used in Hong Kong.

2 EXAMPLES OF LARGE TO VERY LARGE DIAMETER TBMS FOR METRO AND ROAD TUNNELS
Mechanized tunnelling is continually opening up new dimensions in tunnel profile, tunnelling length and complexity of subsurface conditions. Larger diameters are accompanied by large face areas that have to be dealt with in respect of geotechnical aspects but also in respect of technical aspects of large diameter TBM design developments such as for example cutterhead design, cutterhead intervention, excavation process and supply logistics. [1] The cited large to very large diameter TBM projects address the machine design that was adapted to the specific project demands.

2.1 12.06 meter diameter EBH shield for Barcelona Metro Line 9, Spain

With a population of about 1.6 Million, Barcelona is after Madrid the second largest city in Spain. The purpose of the Metro Line 9 in Barcelona is the construction of a peripheral line that surrounds the city of Barcelona. This line includes 52 stations of which 32 are deep shafts and 19 are transfer stations. Of the total of 52km of the Metro Line 9 a section of 28km was bored using TBMs. Part of this underground section was excavated and lined with a 12.06 meter diameter Herrenknecht EPB Shield that started tunnelling at the end of August 2013. At that time it was the largest EPB Shield ever applied. The machine was operated by the UTE GORG Joint Venture (Dragados, Nesco, ACS, Comsa and Sorigué) along a...
10km section between the stations Gorg and Sagrada and between Zona Franca to Zona Universitaria. A special feature of Line 9 is the single tube metro system where the two tracks run side by side in one large diameter tunnel tube along the metro corridor. In the station area the tracks run one upon the other and a specific feature is the double deck configuration in the station area that was first implemented for the Metro Line 9 in Barcelona.

With most of the metro projects that are built with mechanized tunnelling technology, the stations are built first using open cut construction or cut and cover method. After the tunnelling machines reach the future stations they are pushed or pulled through the stations to continue their next tunnelling sections.

For the Metro Line 9 the procedure was different. The large diameter of the EPB Shield was chosen due to the high urban density along the metro corridor. This required the construction of the stations underground with the integration of the passenger platforms within the tunnel profile in the station area. That’s why first the EPB Shield excavated and lined the tunnel and then later, the underground stations were constructed.

The subsurface conditions along that metro corridor are characterized by variable geological conditions with gravel and sand in a clayey matrix, clay, boulders and a 200m long section with the presence of granite banks. Based on the predicted geological conditions the cutting wheel was of closed design with an opening ratio of 35%. It was equipped with soft ground tools and also disc cutters to handle the rocky parts and boulders.

Figure 1. Stations of Metro Line 9, layout of the platforms and the vertical shafts

Figure 2. Metro Line 9 Barcelona: 12.06 meter diameter EPB Shield for variable geological conditions

Reliable information on the condition of the soft ground tools and buckets, especially those working hardest on the periphery of the cutting wheel, is vital for an efficient excavation and for avoiding possible damage to the tools and steel structure of the cutting wheel, and this information was obtained by equipping the cutting tools with a wear detection system. Herrenknecht engineers developed an electronic tool monitoring system capable of providing data on the soft ground tools and buckets lips online and thus alerting the TBM operators in real time. This system was integrated in two buckets and four soft ground tools of the large diameter EPB Shield that was used in 2003. The heart of the system was a new tool support with an integrated sender electronic that was permanently connected to the soft ground tool through induction loops. Thus it can be detected whether the wear limit is reached. The sensor/sending unit was electrically connected to a power supply. If the probe is intact a certain current is maintained, but if the probe is damaged due to the wear of the cutter this is sensed by the sending unit which is inductively connected to the receiver and the cutter probe through a small gap. This leads to a significantly higher fault current that illuminates a LED to inform the machine driver about the possible wear.

A further requirement that resulted from the specific routing of the metro line was that the machine had to deal with tight curve radii of 300 meters. So therefore the EPB Shield was designed with a shield articulation. Design related solutions such as shield articulation, overcut and articulated attached back-ups enabled the excavation of the required tight curve radius of 300 meters.

Due to the large diameter and the predicted geological conditions along the tunnelling section, the EPB Shield was installed with a torque of 45 million Newton meters. It comprised the greatest torque ever used in a TBM until this time. With the large diameter EPB-Shield used for the construction of the Metro tunnel in Barcelona, the maximum limit regarding machine diameter and torque for soft ground shields was still not reached.

The increasing dimensions the projects is shown for example with the successful completion of projects such
as the M30 highway tunnel in Madrid (EPB Shield ∅15.2m) Shanghai Changjiang Under River Tunnel Project in China (Mixshield ∅15.43m), and the Galleria Sparvo Tunnel in Italy (EPB Shield ∅15.6m).

2.2 15.62 meter diameter EBP Shield for the Galleria Sparvo Highway Tunnel in Italy

In 2011 the largest EPB Shield that was designed and built by Herrenknecht started tunnelling for a twin tube road tunnel in Italy. The tunnel profile carries three lanes of traffic. The very large diameter EPB Shield had a diameter of 15.62m and was designed to suit the predicted specific project conditions along the planned alignment of the Galleria Sparvo road tunnel that is located between Bologna and Florence.

The demand on the design of the EPB Shield was based in general on the predicted geotechnical issues and was related to topics such as the control of tunnel face support, mixed face conditions, cohesive soils, methane gas all along the alignment and possible squeezing conditions.

With focus on such a large diameter it has to be mentioned that the larger the tunnel diameter, the higher the probability of a heterogeneous tunnel face and possible variation of soil or rock constituents that can even vary from ring to ring thus that the geological distribution along the alignment remains an uncertainty. Compared to shields with liquid supported tunnel face, large diameter EPB Shields require a higher torque. The cutting wheel torque is affected by machine and process technical factors such as drive and bearing unit, the design of the cutting wheel and the rotational speed of the cutting wheel. Part of the torque is consumed between the tunnel face and the cutting wheel. The 15.62 meter diameter EPB Shield had a maximum torque of 125 million Newton meters. In cohesive soils the EPB Shields can face clogging affects that must be counteracted by an appropriate soil conditioning. Special focus here in the center area of the cutting wheel because of a more limited muck flow and lower cutting speeds in the center area than in the outer part of the cutting wheel. A special focus in respect of appropriate conditioning is also in the working chamber. Injection points and foam lances were thus also installed in the outer cutting wheel area on the front face as well as additional foam and water injection openings in the center plate of the main drive to ensure an adequate conditioning of the muck in the working chamber.

A special hazard potential was the presence of methane gas so the machine was therefore specially designed to cope with this hazard potential. Gas detectors were coupled to switches that shut down the power to the machine if gas concentrations are measured above the threshold levels and portable measuring/alarm devices were used to measure the concentration of combustible gases. Furthermore a continuous feed of large volumes of fresh air was provided to dilute any gas. During TBM advance the excavation chamber was always completely filled with muck to prevent an inflow of material into the working chamber in case of instable tunnel face conditions were encountered. But for this project the main reason for an overall closed mode EPB operation was to prevent the possible hazard of formation of a combustion chamber due to potential gas presence in the rock mass. In the back-up area technical measures were taken which exclude any concentration of methane. To eliminate the risk of explosion and to counteract the prevailing risk of gases in the shield and back-up area where people are working, the machine design included a double-walled enclosure for the back-up conveyor belt from the screw discharge gate to the transverse conveyor belt on back-up number three with permanent ventilation inside and outside of this system. In between this encapsulated double shell, overpressure was present so that any gas would be pushed back in the channel. The area from the transfer belt conveyor and loading chute to the tunnel belt was not covered thus that from this point on the completely built tunnel was equipped with fully explosion proof equipment. The air quality and the tightness of the system were permanently monitored. This together with the constant level monitoring of the working chamber to guarantee that the chamber is always completely filled to avoid the danger of gas pocket formation, allowed a controlled excavation process through the sections with a potential for gas presence.

Figure 3. Galleria Sparvo road tunnel – 15.62m diameter EBP Shield

Figure 4. Illustration of the interface of material handling from screw conveyor to encapsulated conveyor belt [2]
A further demand from geology that was considered in the TBM design was the possibility of facing converging (squeezing) ground. This was dealt with the TBM design that considered technical measures to reduce this risk by installing sufficient high thrust force, the conical shield design, lubrication of the shield shell and a reliable overcutting.

Projects in general, especially large to very large diameter tunnel projects, demand specific solutions for tailor-made tunnelling equipment where a standardization of TBMs is not feasible. This is in respect of the loads that have to be considered resulting from the subsurface conditions and also in respect of material handling systems and logistics of large-scale machines.

2.3 Largest TBM with a diameter of 17.6 meter in use for part of the bored tunnels of Tuen Mun-Check Lap Kok Link in Hong Kong

An efficient road link is being created between mainland China and the International Airport. The centerpiece of this road tunnel is a huge traffic feeder that the Dragages-Bouygues Joint Venture approached with a unique design concept. This has led to a previously unseen TBM configuration with a supersize diameter of 17.6m. The Mixshield manufactured by Herrenknecht started tunnelling in May 2015 and excavated a 650 long tunnel section with prevailing hydrostatic pressures of up to 4bar. The section is part of the Tuen Mun–Chek Lap Kok Link (TM-CLKL) in Hong Kong that comprises twin bored tunnel sections of 4.2km. The overall demand along the bored tunnels sections for the TBMs is to deal with high hydrostatic pressures exceeding 5bar and the associated highly unstable ground conditions that are mainly characterized by alluvium (mainly sand with alternations of clay and silt), completely to highly decomposed granite, slightly decomposed to fresh granite and marine deposits (sand and clay). In total 3 TBMs were supplied for these twin tube bored tunnels. Tunnelling operation will face about 50% mixed face conditions of rocks and soil and about 50% full face in alluvium. Rock strength of the granite was predicted to be in the range of 70 to 170MPa. Apart from high support pressures and expected high wear in the granite, clogging potential in the clayey soils and pockets of biogenic gas within the marine and/or alluvial deposits were considered when designing the TBMs. Based on the geological and hydrogeological conditions, three Mixshields were specified; one of supersize diameter of 17.6m and two with diameters of 13.6m.

The mega TBM started its operation for the 650m long section of the feeder tube in May 2015. After the 17.6m Mixshield has reached its target in an intermediate shaft in November 2015, the planned transformation of the machine in the size began. The main drive and back-up system of the supersize TBM was kept and implemented in the 13.6 meter diameter Mixshield that continued tunnelling operation for the remaining bored sub-sea tunnel section. The parallel bored section of the road tunnel towards the airport is excavated and lined using the 13.6 meter diameter sister machine.

Due to the demands from geology and specific project conditions, the TBMs were specified and designed to minimize routine maintenance. Thus maximum reliability and good access to all components can be provided. With focus on required cutterhead interventions for regular inspection and maintenance of cutting tools and the cutterhead, redundant systems are needed for inspection.
and replacement procedures especially with focus on hyperbaric intervention. The machines were prepared for worst case conditions and designed to inspect the cutterhead with prevailing high water pressure and unstable face. Thus the machine is equipped with all the necessary basic installation for chamber access in saturation mode. In addition to the piping and connections that are required for saturation access this included a permanent pre-chamber in the shield to which a transport shuttle can be connected when needed. A clear passage to transport the shuttle through the back-up to the pre-chamber was also foreseen in the design and the transfer under pressure shuttle was available on site.

Figure 7. Supersize TBM for TM-CLKL, concept of hyperbaric interventions with permanent pre-chamber

3 CONCLUSION

The selected reference projects for today’s infrastructure systems described in this article highlight the demand of the design of large to very large diameter tunnel boring machines with innovative solutions such as the double deck configuration of the underground stations in confined urban area, the construction of a three lane road tunnel or the TM-CLKL in Hong Kong for a huge traffic feeder tunnel section.

Looking back in the history it is shown that numerous very large diameter tunnelling projects with TBM diameters even exceeding the diameter range of 14 meters have been completed successfully generally with acceptable or outstanding performances in variable and challenging conditions. This shows that these supersize diameters are accepted and trusted by the public. Feasibility studies are already underway for future large-scale infrastructure projects that will even exceed the already proven diameter ranges of up to 17.6m. Supersizing underground infrastructure is a fundamental trend. Beside bold visions, moving from record to record requires proven expertise and trustworthy partnership between all involved experts from the conception of the project start until breakthrough.

4 REFERENCES
