TBMs for extremely tight radius curves

TBMs that are designed to execute extremely tight radius curves provide a number of benefits for projects located in dense urban environments with a lack of shaft site availability/ access or where standard tunnel alignments are not possible. William Brundan, Terratec Ltd, and Hitoshi Danno, JIM Technology Corporation, explain the development of articulation systems used on these specialist machines and cover the operational range of curves that can be constructed with this technology. Other features of these Tight Radius Curve TBM's, including spoil discharge systems and backup deck designs, are also discussed along with several case histories from recent projects in Bangkok, Thailand.

The first TBM designed to navigate a sharp curve was developed in Japan, in 1976, for the Inokashira drainage tunnel in Tokyo. This was a time when Japan was promoting its economic growth and prosperity and responding to social demands through improved infrastructure. Numerous tunnel construction projects were undertaken throughout the country and water supply, sewerage, electricity and communication networks were all vastly expanded. As the majority of these tunnel projects were constructed by TBM, many intermediate shafts were also required, in order to change direction and rotate the machines on curved alignments.

As Japan's cities became increasingly densely developed, it became more and more difficult to find shaft locations, due to existing structures both above and below ground and also the traffic jams that would be caused during shaft construction. To eliminate these restrictions TBMs that could negotiate tight radius curves were required. The development of this technology simultaneously led to a reduction of costs and construction lead times. Tunnel construction using tight radius curve TBMs remains very popular in Japan to this day.

In recent years Terratec has supplied a number of tight radius curve TBMs for challenging project alignments, particularly in Bangkok, Thailand, where owners/contractors are witnessing the use of these machines and realising that they can solve tunnel alignment issues in dense urban environments where limited shaft access is available.

Design considerations

During the design of a TBM a number of factors need to be considered, i.e. geology, tunnel alignment, lining design, overburden, water levels, etc. The same is true for tight radius curve TBMs.

Geological Conditions
Geology is the one of most important factors in TBM design. For tight radius curve TBMs it particularly affects the type of overcutting equipment. In soft ground a copy cutter is normally used, but in rock or mixed ground - depending on the type and UCS value - overcutting by disc gauge cutter or over cutter with disc cutters is required.

Tunnel Alignment Conditions
Tunnel Alignment Conditions refer to the tunnel's size, length, minimum radius curve (mR) conditions (horizontal and vertical), gradient and other unique conditions e.g. a curve that is a combination of horizontal and vertical curves.

Pre-cast Tunnel Lining
It is also important to define the type of segmental tunnel lining to be used (Reinforced Concrete, Steel, etc.), outer and inner lining diameters, segment thickness and width, number of pieces in the ring and their weight, during TBM design. In particular, the clearance between the inside of the TBM's tail shield and the extrados of the segment should be adequate for the curved section.

Construction Conditions
Overburden and groundwater pressure should also be confirmed in order to select the type of articulation (V-type or X-type) to be adopted (described in the following section) and number of articulation seals.

Development of articulation systems

The conditions necessary to adequately execute a tight radius curve by TBM are determined by the following points:

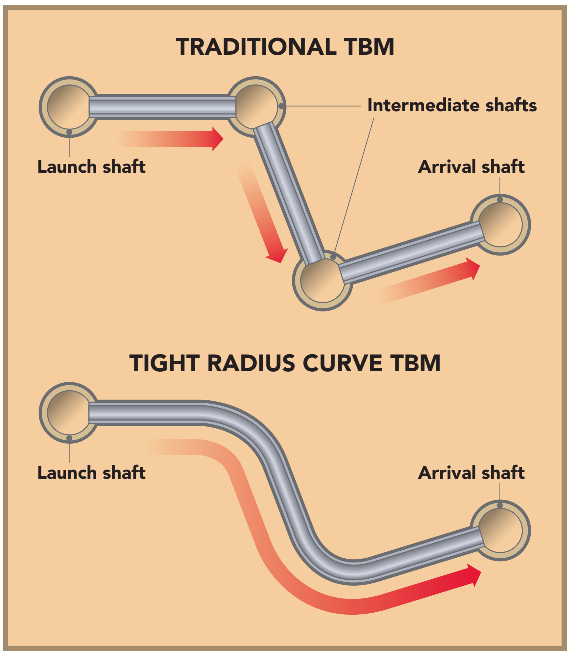


Figure 1. Traditional TBM tunnel and shaft staging vs. tight radius curve TBM.

- The segmental lining can be assembled within the tail shield with adequate clearance between the shield wall and the extrados of the segment.
- The segments do not deform or move and can take the TBM reaction force sufficiently.
- Space for manoeuvring the TBM can be achieved by overcutting, in order to facilitate steering.

To fulfil the above conditions and keep the TBM on its planned alignment while negotiating extremely tight curves, the following TBM technologies are especially important:

- Articulation system
- Sealing system (articulation structure, articulation seal, tail seal)
- Overcutting system (e.g. copy cutter)
- Others (screw conveyor, back-up systems, etc.)

Articulation System

In Japan, a large number of curved tunnels have been constructed by TBM. Improvements to TBM designs now mean that manufacturers can supply machines that can execute curves under 10mR.

Active Type and Passive Type

With the increasing popularity of curved tunnels in Japan in the early 1980s, problems soon arose with the use of 'passive' TBM articulation systems, which were the norm at that time.

With a passive articulation system, the TBM is manoeuvred via shield jacks that are fixed to the forward shield. When steering through a tight curve the shield jacks rotate eccentrically. This means that the jack shoes push against the edge of the segment at an angle, introducing an offset/ point load, which can cause segment damage and lead to deformation and displacement of the lining.

In 1982, IHI (now JIMT) developed the 'active' articulation system to solve these problems. The shield jacks on an active articulation system are instead fixed to the TBM's tail shield. This means that the shield jacks do not rotate when the forward shield is steered into a curve and therefore remain aligned with the flat edge of the segment, greatly reducing the risk of damage.

During the execution of a tight curve the shield jacks are also able to push the segments rearwards using their full stroke. This has the advantage of securing the required clearance between the inside of the tail shield and the extrados of the segment. That is why active articulation has become popular around the world and especially in Japan.

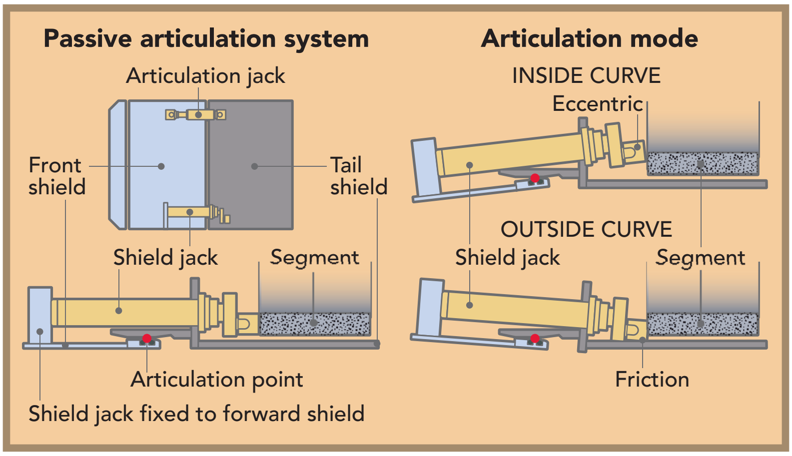


Figure 2. Passive TBM articulation system

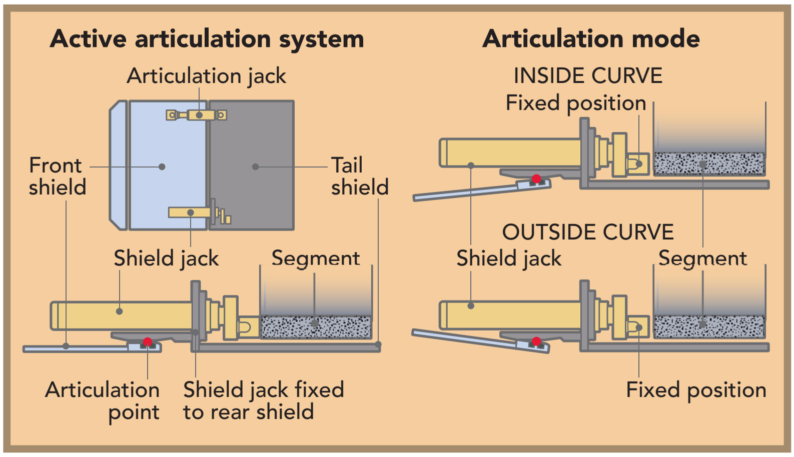


Figure 3. Active TBM articulation system

V-type and X-type

There are two types of articulation systems, the 'V-type' and 'X-type'. Both were developed in the early 1980s. The main difference between them is the point of articulation. The V-type system works by extending the articulation jacks opposite the curve direction so that the point of articulation is opposite the extended jack. The X-type uses jack extension and retraction to articulate, so the point of articulation is located centrally

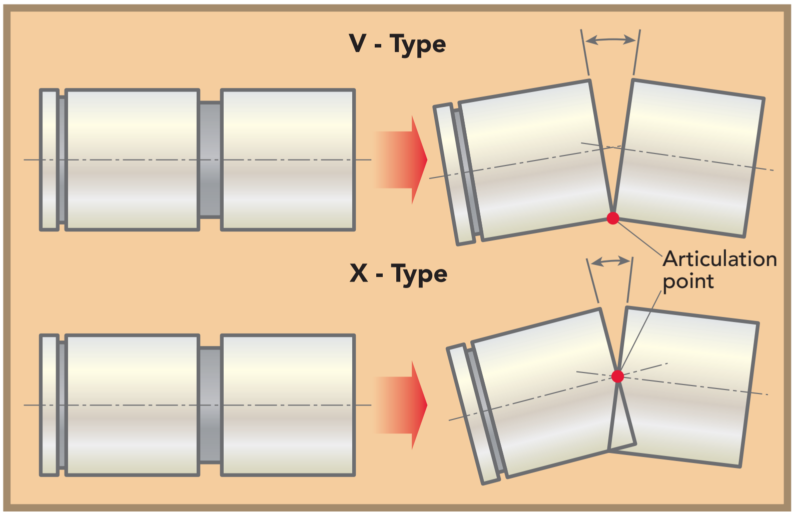


Figure 4. The 'V' and 'X' types of articulation systems.

(see Figure 4). It is difficult to say which system is superior, but the V-type is regularly applied under 5 bar water pressure, although it can often depend on the number of articulation seals.

The V-type system can also be used to retract the forward shield for cutterhead interventions without drawing back the whole TBM and consequently damaging the tail seals. On the other hand, the X-type system is more suitable for extremely tight curves at depth and with high groundwater pressure. This is due to the X-type articulation system's spherical structure and also that using a balance of extending and retracting the articulation jacks provides constant clearance of the articulation seals.

Articulation Structure
There are several types of articulation structure to suit different design conditions. These can generally be categorised as 'flat' or 'spherical'. The tighter the articulation angle the more spherical the articulation structure needs to be. The type of articulation structure is designed considering TBM diameter, articulation angle, water pressure and so on.

Overcutting System
In order to steer the TBM correctly, manoeuvring the forward shield with the articulation jacks and following the curved alignment, enough space around the TBM is secured using an overcutting system (e.g. copy cutter).

The copy cutter is operated by a hydraulic jack. By changing the jack stroke the overcutting volume and position can be adjusted.

Details of articulation
Within the articulation study that is done for each tight radius curve TBM a 'Curve Simulation' is carried out to evaluate whether the TBM can adequately negotiate the designed curve. At the same time, an equipment study is done, to consider the position and angle of each piece of equipment inside the machine. If there is any concern about friction, the position and/or angle of the equipment is adjusted, or the equipment is relocated or moved outside of TBM for the duration of the tight radius curve. In the case of screw conveyor interference, it is possible to swing the screw and fend off the interference by installing a spherical joint on the end of screw conveyor casing.

Articulation is executed via the combination of the articulation system and the overcut: At first creating adequate room by overcutting; then extending the articulation jacks to steer the forward shield; and, finally, extending the shield jacks.

Figure 5. A fully-articulated tight radius curve TBM.

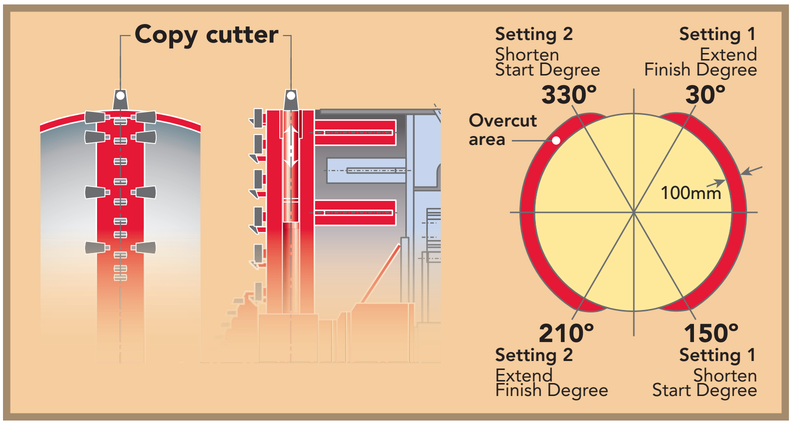


Figure 6. Copy cutter system on a tight radius curve TBM.

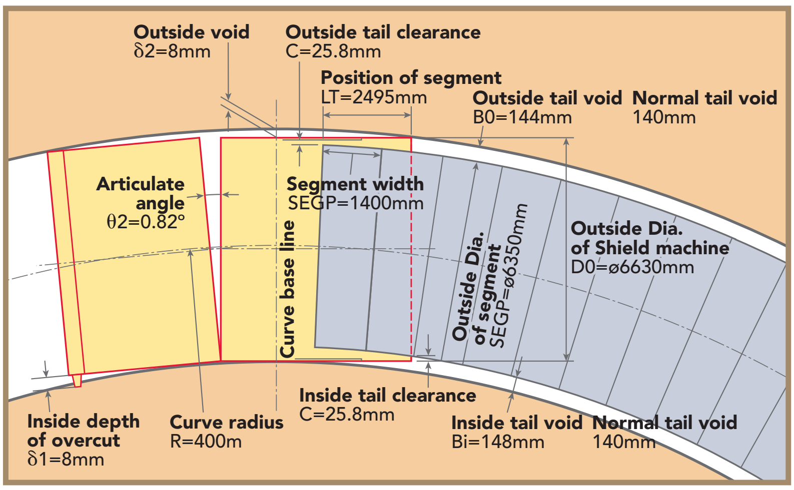


Figure 7. A typical Curve Simulation study.

Design range

When tight radius curve TBMs were first developed they were mainly intended for the excavation of utility tunnels, including water and wastewater tunnels, electricity and communications tunnels. However, the technology has been since been employed for large diameter highway ramp sections (>10m diameter) with radius curves of 45mR and there is potential for further applications.

Based on experience gathered from more than 1,400 tight radius curve TBM projects, the design range under 50mR is as follows:

- Lining outer diameter: 1,800mm - 10,000mm
- Minimum curve radius: 10mR

Other special features

Muck discharge

There are various options for muck discharge, especially for EPBMs, e.g. belt conveyor + muck cars, piston pump system, hose system, etc. Muck discharge methods are selected taking geology, water pressure, tunnel length, and curve conditions in to consideration. The means of discharge will be considerably restricted in small diameter EPBMs and tight curve conditions. Useful counter measures can include the 'Hose System' and 'Curved Belt Conveyor System'.

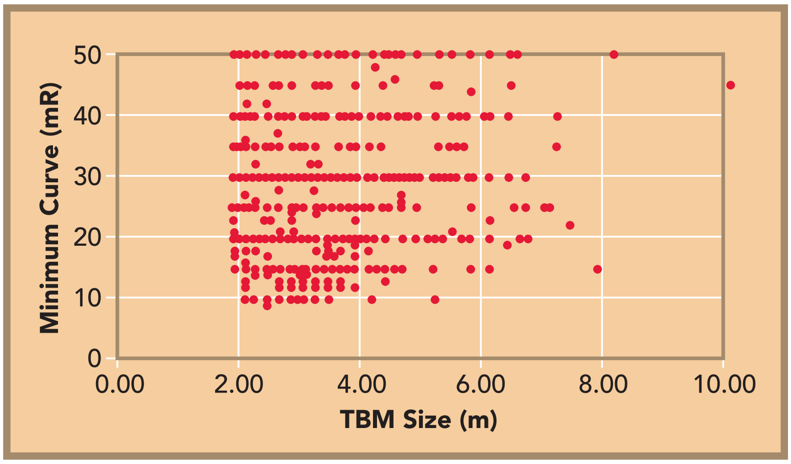


Figure 8. Design range for tight radius curve TBMs.

Hose System

A hose system can be installed on the screw conveyor gate with a special attachment.

The hose system has the following advantages:

- Easy to install on the screw conveyor
- Flexibility of the hose line frees up space in the segment handling area
- Can easily be accommodated through the backup gantries, facilitating a curved alignment; and
- Easy to handle within small diameter tunnel

Basically, in this system the excavated spoil is discharged to muck cars via the force of the screw conveyor. However, in the case that the excavated spoil is clogging or is not being smoothly discharged from the hose, the material can be improved by ground conditioning or be pushed out by air pressure from an installed port on the hose attachment.

Curve Belt Conveyor System

When a belt conveyor is applied on a tightly curved tunnel it is designed to follow the curve's alignment. To be more specific, each belt unit on the backup is shorter and the steering of each unit little by little allows the belt to run along the curve alignment.

Back-up Design

Back-up gantries are towed by the TBM via a towing beam (wirer) or towing jack. In order to avoid the back-up gantries de-railing, the following needs to be considered:

- Selecting bogie wheels for No.1 back-up gantry
- Whether the wheels of each back-up gantry need to be flanged or not, and
- The length of backup-cars and wheelbase differential at the curve section to prevent any collision with locomotives.

Segment Transportation

Segment transportation is difficult in tight curve conditions as the hoist beam is inflexible and not as adaptable as other equipment inside the TBM. Therefore, the space and route of segment transport, and its relative position to the hose system, belt conveyor and towing beam should be considered in detail. A swing hoist is one of several hoist systems that can mitigate space constraints.

Recent Case Histories

In recent years Terratec has supplied a number of tight radius curve TBMs for challenging project alignments in Bangkok, Thailand, where owners/contractors are witnessing the use of these machines and realising that they can solve tunnel alignment issues in dense urban environments where limited shaft access is available. Five Terratec tight radius curve TBM's are currently in use in the city on approximately 15km of tunnels.

TBM S48: Klong Phra Khanong Cable Tunnel

In 2016, Terratec supplied a new 3.2m diameter EPBM for

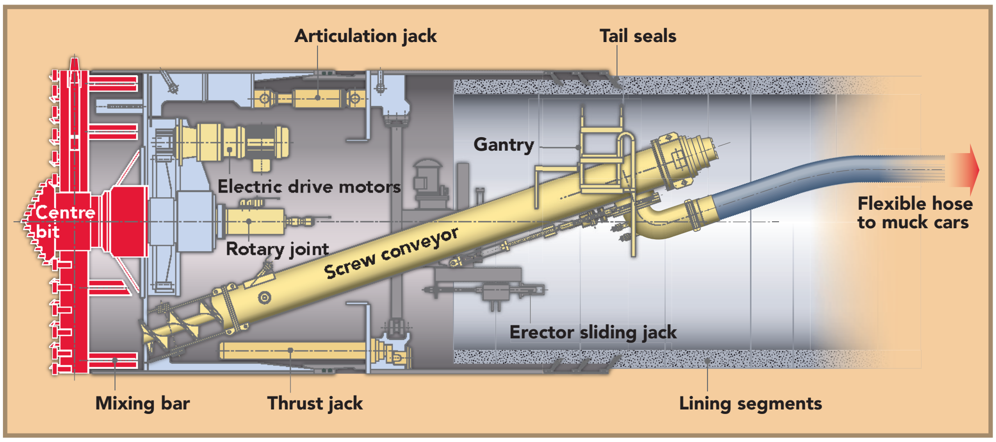


Figure 9. Hose System installed on the EPBM's screw.

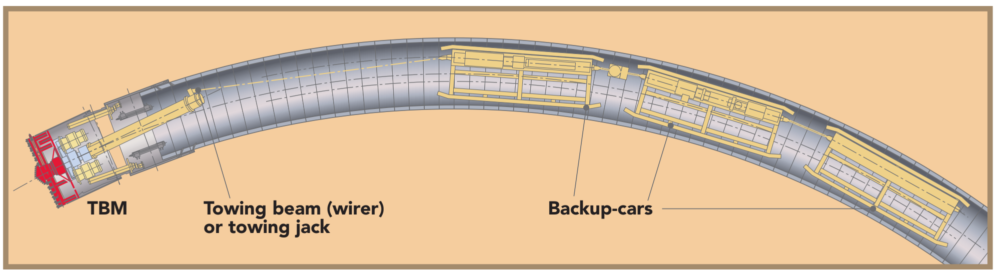


Figure 10. TBM towing back-up gantries through curve.

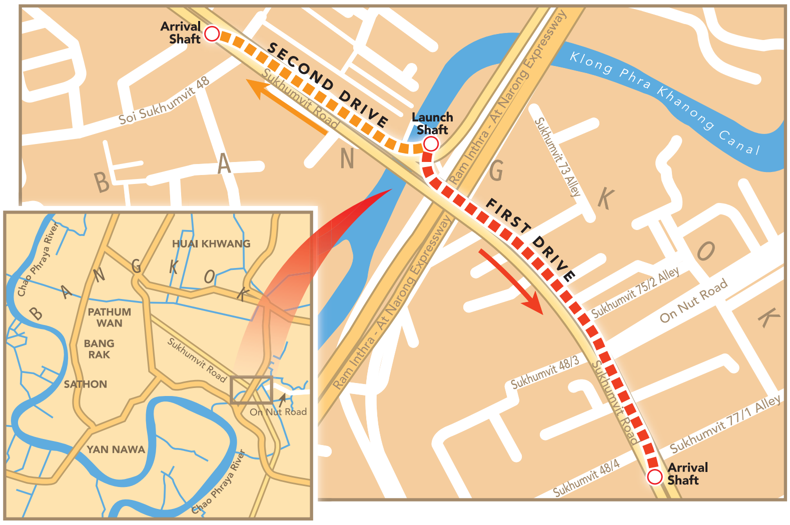


Figure 11. Map showing the two S48 drives.

the Klong Phra Khanong Cable Tunnel Project, in Bangkok. The owner of the project, Bangkok's Metropolitan Electricity Authority (MEA), and its contractor Nawarat Patanakarn PCL were in attendance.

The TBM was designed to excavate tunnels for a new high-voltage cable system – the first of a series of tunnel projects planned for electrical supply upgrades in Bangkok.

Located at the intersection of the Phra Khanong canal and Sukhumvit Road, the project is situated in one of the busiest areas of downtown Bangkok and is subject to tight alignment constraints requiring a number of tight radius curves.

The TBM was launched on its first, 495m long, drive from a 7.0m diameter shaft – located between an elevated expressway ramp and the Klong Phra Khanong canal – with limited working head room. Due to the presence of the expressway piles, the TBM was required to embark on a sharp 32m-radius curve immediately upon exiting the shaft.

Tunnelling operations were closely observed throughout the manoeuvre via a settlement monitoring programme that demonstrated minimal impact on the existing above ground structures.

As the machine progressed through the curve it installed a tunnel lining of short 300mm wide x 125mm thick bolted steel sets, before transitioning to 1.1m wide x 225mm thick traditional tapered precast concrete segments (left/right/straight). From the reception shaft the EPBM returned to the launch shaft under the expressway ramp.

On the 293m-long second drive the EPBM again had to negotiate a 43.7m radius curve, this time in order to pass under the canal. The sharp alignment was also necessary due to obstructions caused by the foundation piles of the elevated roads and nearby buildings. At its closest, the TBM cleared piles by a distance of just 0.5m.

The EPBM, equipped with the X-type articulation that provides a maximum articulation angle of 6.6 degrees, is capable of executing 30m radius curves. In order for these tight radius curves to be managed the backup was also specially designed, including a spoil removal system using a screw conveyor that was connected to a compressed air transfer hose and lastly the TBM backup conveyor.

The geological conditions of tunnel consisted of fine sand and very stiff clay, with an average overburden of 26m and groundwater pressure up to 3 bar. The EPBM's cutterhead was designed for the soft ground conditions and featured an open-spoke design with knife bits to assist in break out of the SFR concrete shaft eyes.

Figure 12. Short steel segment sets in a 35mR curve.

TBM S48B: Chidlom Terminal Station Outgoing Cable Tunnel
After a full refurbishment the S48 EPB machine was re-designated 'S48B' and set to work on a second project for MEA, this time with contractor Italian-Thai Development PCL (ITD). The Chidlom Terminal Station Outgoing Cable Tunnel located in one of the most exclusive and built up areas of downtown Bangkok. It runs from the 'ultra-luxury' Central Embassy mega mall, located on Phloen Chit Road – within the former gardens of the British Embassy – southwards to Lumphini Park.

In order to remain within public road easements, as well as negotiate building foundations and the deep piles of the BTS Sukhumvit Skytrain that run along Phloen Chit Road, the tunnel alignments are subject to strict constraints that require several tight radius curves to bring them into MEA's Chidlom Terminal station.

Tunnelling commenced at the end of 2018 with the S48B EPBM beginning excavation on the 395m long Tunnel C (see Figure 11) with an immediate 35mR curve under a busy five-lane road, negotiating a curved alignment through a major road intersection, and between the pile foundation structures of an exclusive department store and the BTS Skytrain viaduct (Foley 2019).

TBM S69: Chidlom Terminal Station Outgoing Cable Tunnel
ITD is also using a second Terratec TBM on the Chidlom Cable Tunnel described above. The new S69 machine is a 4.27m diameter EPBM that was launched in January 2019 and is currently excavating a 1,349m-long tunnel (Tunnel A) from Lumphini Park to the MEA's Chidlom Terminal Station. Both machines will then execute a further short tight radius curve drive to complete tunnelling on the project.

TBM S54 and S55: Bueng Nong Bon Drainage Tunnel
Two 5.70m diameter EPBM's were supplied for the 9,187m long Bueng Nong Bon to Chao Phraya River Diversion Tunnel Project. The project owner is the Bangkok Metropolitan Administration (BMA) and its contractor is STECON. Located in the south-east of Bangkok, the 9,187m-long Bueng Nong Bon to Chao Phraya River Diversion Project is the third of four major flood prevention tunnels to be built under the BMA's long-term plan to manage the severe flash floods that currently plague the Thai capital during the rainy season. When complete, the tunnel will have a drainage capacity of 60 cubic metres per second, providing much needed flood relief to an area of approximately 85 square kilometres.

The first machine, S54, started excavating its first of two drives in November 2018 and to date has excavated nearly 2000m of the 3000m drive. Once this drive is completed a second drive of 850m will complete the section. The second machine, S55, is yet to be launched on its 5500m drive.

The EPBMs were built with X-type articulation systems to manage a number of very tight radius curves including several of 65mR and one of 40mR.

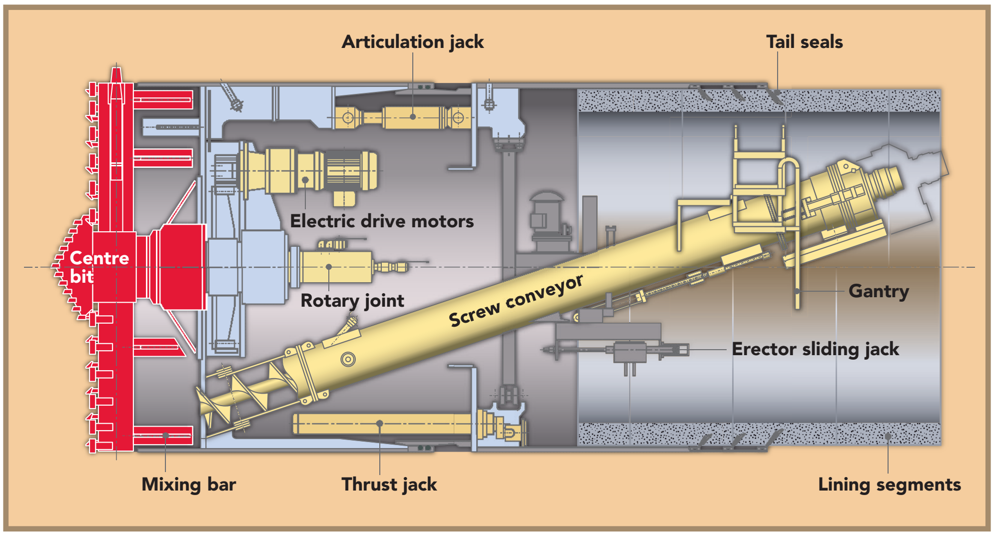
The TBMs' soft ground cutterheads feature an open spoke design with the addition of knife bits to assist break-in and break-out of the shafts. Traditionally reinforced 1.2m thick, 5m internal diameter, precast concrete segments will typically be installed as the machines progress, with shorter steel segments utilised during the course of the sharp 40m radius curves.

Conclusions
There is a long history of tight radius curve TBM projects in Japan. First developed in the early 1980s, the technology remains popular to this day, due to the densely developed nature of Japan's cities and the lack of shaft site availability/access.

In Bangkok, Thailand, owners and contractors are now also witnessing the use of these machines and realising that they can solve numerous tunnel alignment issues in dense urban environments. Successful results have led to further projects that would not have been otherwise possible.

The continued successful application of these tight radius curve TBMs could open up new possibilities for many utility providers and water agencies around the world that face similar alignment challenges.

Figure 13. Configuration of the Chidlom EPBMs.



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