ABSTRACT: A tunnel is a linear work site which may involve for the tunnel boring machines (TBM) to cross previously excavated structures like station boxes, launching/retrieval shafts, etc. TBM transits in such structures can be divided into three main phases: reception, transit and relaunch. Among these phases, TBM break in and break out are delicate work operations. During the breakings, face pressure may be lost if appropriate measures have not been taken. A lack of control of the confining pressure can cause instabilities of the front resulting in settlements on the surface or even major problems. Nevertheless, there are different solutions to perform an adequate break in/break out.

This paper discusses both the break-in and break out requirements, explains the main techniques used for such operations and draws examples from different solutions used for enter and exiting structures built well in advance to the arrival of the boring machine.

KEYWORDS: TBM; EPB; Slurry; Shield; Break in; Break out

1. INTRODUCTION

There are two major shielded methods for soft soils: earth pressure balanced (EPB) and slurry type shield machine. Selection of the shield method depends on different items: ground conditions, surface conditions, tunnel diameter, distance to be bored, tunnel alignment, etc. Both, EPB and slurry, are closed-face type shielded machines, that is, the head of the machine is closed and separated from the rear part of the machine. A working chamber, located at the head, between the cutting face and the bulkhead, is filled with soil or slurry to stabilize the cutting face under soil pressure.

The EPB type shield machine turns the excavated soil into mud pressure and holds it under soil pressure to stabilize the cutting face. Basically, the EPB has an excavation head to cut the soil, a mixing system to mix the excavated soil into mud pressure, a soil discharge system to discharge the soil and a control system to keep the soil pressure uniform. The EPB is used in different type of soils but mainly at ground predominated by clayey soil.

On the other hand, the slurry type machine uses the external pressurized slurry to stabilize the cutting face. The slurry is circulated to transport the excavated soil by fluid conveyance. Besides having an excavation system, the slurry type shield machine has a slurry feed and a discharge equipment to circulate and pressurize the slurry and slurry processing equipment on the ground to adjust the slurry properties to the needs of the excavation process.

Therefore, Earth Pressure Balance and Slurry TBM work on the principle that pressures at the face of the machine and around the cut annulus is maintained at a pressure equal to the pressure from the surrounding ground plus the ground water. During tunnelling, TBM face pressure is provided by ensuring the chamber between the cutter head and the bulkhead is full of excavated material. By balancing the rate of advance against the muck extraction rate, the goal is achieved in both types of shielded machines.

This face confinement pressure ensures the stability of the ground and thus to limit the potential settlements on the surface. The level of pressure required mainly depends on the nature of the ground, the depth of the tunnel and the presence of a ground water table. A lack of control of the confining pressure can cause
instabilities of the front, resulting in settlements on the surface, or at the extreme in chimneys or surface collapses if the grounds are of poor quality.

The construction phasing of the running tunnels for a lineal underground infrastructure may require the tunnel boring machines to traverse previously excavated structures; the entry into the structure or in the ground are delicate work phases.

At this point, it would be worthwhile to give a brief clarification on these concepts: “break in” and “break out”. The “break in” is the entrance of the tunnel boring machine in the ground, or what is the same, the start of the tunnel construction. On the other hand, the “break out” is the entrance of the tunnel boring machine into the chamber, into the station or into a cavern or a shaft… or better to say the exit of the machine from the ground; it is the end of the tunnel construction (section or whole tunnel) and the TBM daylights.

2. CROSSING OF STRUCTURES BY SHIELD TYPE TUNNELING MACHINES

Hence, when the TBM starts its breakthrough (in or out) a station box, shaft, etc., special control of the face pressure is needed. When a break is performed, the contention structure of the ground (diaphragm wall, piles wall, etc.) is demolished to allow passage of the TBM and ground will behave almost according to its nature. The risk of instability of the front varies according to the nature of the terrain crossed (clay, sand, intact rock, fractured rock …), and according to the position of the water table and soil permeability values. A highly fractured rock will have a kind of soil behaviour and the presence of water always enhances instability phenomenon. In non-cohesive soils under water table in particular, the flow forces generated towards the front are particularly destabilizing.

The phenomena of instability can then cause a significant increase in the extrusion of the front, or even the breaking of the ground in the excavation chamber of the TBM. This can damage or even block the machine, by imposing a temporary stop of work.

In addition, there is the risk of water inflow into the tunnel depending on the hydrogeological context and the permeability of the ground. The normal development of the works and its schedule may also be affected by these phenomena.

As aforementioned, a Shielded TBM works on the principle that pressures at the face of the machine and around the cut annulus are maintained equal to the pressure from the surrounding ground and ground water. While tunnelling, pressure at the front is provided by filling the chamber of muck and balancing its extraction versus the rate of advance through the screw conveyor or the extraction system used (for example pumps in the case of slurry machine). Simultaneously, the annulus created around the shield, as a consequence of the overcut by the rotary head, is filled with bentonite (or a similar mud) to be supported by hydraulic pressure. A little later, this gap is filled with mortar, cement grout, bi-component or similar mix once the precast concrete segmental lining are erected.
At the break-in/out, the TBM first and the segmental lining after, have to pass through the demolished contention structure. Both have a diameter which is smaller than the openings or eyes left for the purpose and the resulting gap must be sealed. Likewise, when the break-in/out is in progress it is necessary to provide a temporary substitute of the contention structure to control ground and manage water.

2.1 Highlights for the Break in

In the case of a TBM break-in below ground water table, to ensure the stability of the front when opening the retaining wall becomes particularly delicate. No face pressure or at least all the face pressure that the TBM is capable of can be applied. Also the excavation chamber can only be partially filled. Therefore, when boring begins it is often impossible to start with enough pressure during the first meters of excavated ground behind the wall of the retaining structure.

The second main item is to limit or prevent water circulation. Water inflow generates entrainment of fine materials, and could generate, in addition to the flooding of the structure, settlements, decompressions, instabilities... Usually, the grouting of filling mortar at the extrados of the concrete segments is used to ensure watertightness, however this can only be put in place after the first ring is out of the shield of the TBM. Due to this reason the seal between the diaphragm wall and the shield is not secured on the first metres of tunnel. Therefore, the excavation presents a risk of water coming through the annular gap.

Once the shield is fully into the ground, the gap between the segmental ring and wall is sealed, the excavation chamber can be full filled of muck, the working face pressure applied and the tailskin injection to minimize and control volume loss started.

2.2 Highlights for the Break out

In case of entering the tunnel boring machine in the structure (break-out) the objectives are quite similar. The difficulty of ensuring the stability of the ground because of reduced pressure at the face is always present. During the approaching of the TBM to the station, face pressures have to be scaled down in order to avoid overloading the diaphragm wall. Soft-eye (fiber-glass reinforcement) is normally used to provide an easy D-Wall crossing operation. When reaching the head-wall, the plenum (excavation chamber between the cutter head and the bulkhead) is partially filled. If no provision is made for alternative support, face pressure is lost when the boring machine starts its breakthrough into the structure. During the cutting head entrance and after the breakthrough no grout injection can be done and the annular gap around the shield is not sealed.

Hence, there will be a portion of ground temporarily unsupported until the length of the TBM, that will allow installing the necessary rings to make the sealing against the wall, has crossed the shaft. Part of these rings will be permanent and the rest dismantled. As a result, during break out, groundwater and soil can flood into the structure and local settlements can be produced.

All the risks here mentioned associated to break-in/out operations may have quite serious consequences on the neighbouring ones. The reason is that they imply an increase in surface settlements and this can cause damage to existing structures. The level of damage, sometimes architectural, functional or structural, will depend on the type and condition of the structure in question.
Figure 3. Highlights for the “break-in” or beginning of the tunnel

- During the Shield entrance, no face pressure can be applied.
- Excavation chamber only can be partially filled.
- Groundwater and soil can flood into the station.
- Local settlements can be produced.
- Face instability issues can appear.

- Once the shield is fully into the ground, the gap between ring segment and slurry wall is sealed.
- Excavation chamber can be fully filled.
- Working face pressure can be applied.
- Tailskin injection can start to minimize and control volume loss.

Figure 4. Highlights for the “break out” or exiting the tunnel

- During the approaching of the TBM to the station, EPB pressures have to be decreased in order to overload the slurry wall.

- The slurry wall cutting process during the breakthrough has to be without EPB pressure, with the excavation chamber partially filled.

- After the breakthrough and during the Shield entrance, no pressurized grout injection can be done.
- Local settlements can be produced where no proper grout filling can be done.
- Groundwater and soil can flood into the station through the gap between shield and station walls.

- Until the full TBM shield is inside the station, sealing the existing gap between last ring and station wall can’t be done.
- When the gap is sealed, a secondary injection through the last installed rings has to be done in order to assure a proper backfilling.
Therefore the leading criteria for designing a break-in/out structure are to stabilize the ground, to manage the groundwater and to minimize and seal the resulting gap of crossing the structure. Additionally for break-in process there is the need to give to the TBM a thrusting means.

There are several ways to mitigate the associated risks while at the same time protecting on-site workers and the structures involved. Hereafter will be described the most common.

### 3. METHODS OF ENTERING AND LEAVING

Several techniques and methods are used to ensure the safe retrieval and launching of a tunnel boring machine. The aim of all these methods is to ensure the stability at the face of the machine and to prevent the inflow of water and fines in the reception/launching structure. Thus, the two main objectives of these methods are ground improvement and waterproofing. As a result, some of the methods share elements with other well-known special geotechnical works. In general, in order to providing a temporary substitute of the contention structure to control ground and manage water both, ground treatment and mechanical barriers, can be used. The target is to have at the works a kind of element allowing the TBM entering or exiting with certain working pressure. Table 1 below summarizes the most common techniques used.

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#### 3.1 The Sealing Ring

The sealing ring is nowadays one of the most preferred solutions for break-in and many times there are attempts to use it also for break-out.

The technique makes it possible to limit the inflow of water through the annular void during the entry or exit of the tunnel boring machine. It consists of installing a rubber device that will be pressed against the shield to seal the annular gap between the wall and the shield and later between the wall and the segmental ring erected inside the shaft during the launching.

The sealing ring usually shows a form of a waterproof shell (typically made of steel or reinforced concrete) of 1,5m to 2,0 m length (depending on the TBM head size) fitted with a rubber membrane (usually double but sometimes even triple) which acts as non-return device. When using this method, care must be taken not to break the device when entering or leaving the shaft.

For the break-in it is the only one system that, at the same time, can stabilize the ground using the TBM itself, manage the ground water by closing the gap, minimize this gap by allowing the TBM to bore through the retaining wall and seal the gap by immediately filling of the annular void against the retaining structure. Nevertheless, engineers sometimes do not consider this technique reliable for the break-out and argue different reasons as incertitude on the exact position of the tunnel boring machine with regards the ring and the consequent possible damage to the seal by the cutter head when crossing the wall or a possible lock and damage of the joint. As a result, the sealing ring is, general speaking, less used for the TBM entering into the reception chambers. Figure 5 below shows however that its use as break-out is perfectly valid.

The sealing rings are usually combined with other technique to guarantee that everything works properly and to limit the risks related to the failure of the device. For example jet grouting blocks at the breakin/out or grouting of the soil for its improvement, enclosures with groundwater table drawn, etc.
Figure 5. Construction of and sealing ring installed in the D-wall before TBM launching. Tel Aviv Red Line Metro Project launching shaft (own source)

Figure 6. Sealing rings installed in the D-wall for break-out (picture on the left) and TBM break-out at Station (own source)
3.2 The Fake Tunnel

Another possible solution for the break-in/out is the use of fake tunnels, but especially for the break out. It consists in installing a retaining structure to hold the shield while ensuring its whole length sealing. This structure can be done with reinforced concrete or steel, however, the steel solution is the most used due not only to its reliability, but especially to its versatility. The steel fake tunnel (also called steel sleeve method) can be used to cross several diaphragm walls or even in different projects; conversely, the reinforced concrete fake tunnel has a certain cost to have to be later demolished and, in general, imposes other schedule requirements.

The steel sleeve method is quite used for launching and retrieval in some countries. In China, for example, more than 20 projects can be reported at different cities during the last years, were this technique has been used in order to solve different problems related to chamber or/and site dimensions, hydrological conditions, geotechnics, etc…, but it is also used in Europe. Steel sleeve types use to be patented solutions.

The steel sleeve can be of “long” or “short” type; this last one quite similar to a sealing ring. Its use requires embedding a connection steel ring plate on the diaphragm wall surface; connection ring to which the sleeve will be welded and water-tight of the contact between embedded steel ring plate and surface of the wall guarantee (usually with the use of hydro-swelling rubber sealing strips). For launching operations the bottom section of the sleeve is placed, welded to the connection ring, the TBM assembled inside and the top armoured section installed and welded. Finally the pushing ring and frame are placed and the TBM is ready for launching.

Figure 7. Steel sleeve installation for break-in. Nanning subway Line 1 (pictures courtesy of CRTG).
For the break-out, the use of the steel fake tunnel is quite similar to the launching. However, the main difference is that for break-out case, the assembly of the sleeve shall be completed adding an end-cap at the end of the sleeve and filling with soil and water the sleeve to balance forces, before TBM arrival.

Figure 8. Steel sleeve installation for break-in. Nanning subway Line 1 (own source).

Figure 9. Steel sleeve installation for break-out (end-cap and filling process). TBM retrieval finished. Nanning subway Line 1 (pictures courtesy of CRTG).
3.3 Other Mechanical Barriers

Another common mechanical barrier used is the one obtained from the construction of a plain cement concrete block. This technique is mainly intended to break out operations and a concrete block is built inside the reception chamber to allow keeping the face pressure up to the last ring has been erected and sealed against the diaphragm wall (Figure 9). Concrete block may have different dimensions depending on the arrival conditions, but sometimes requires of considerable dimensions. Once the TBM crosses the cement block it is demolished. However, cement concrete blocks may also be used for break-in, as described in the following example.

In 2009 the extension project of the Railway FGC to Terrassa (Barcelona-Spain) required the entry and exit at three stations under different circumstances. The cement concrete block was used as technique both, for break in and break out. The project consisted in a 3.5 km enlargement of an existing railway line through the excavation of twin tube TBM tunnels (single track) with a clear inner diameter of 6.75 metres and cross passages with a 250 metres spacing. The depot, three new stations and a section under passing a public park were built by the cut and cover technique.

At the exit of UPC-Vallparadis Station, concrete caissons executed by cut and cover were used in a section of the alignment that would pass under a future public space (Vallparadis Park). At the end of this cut and cover section the bored tunnel should start under a compromised slope with a rock retaining wall protecting a building. In order to improve the ground and enhance the slope stability before the pass of the two EPB used at the project, some treatments were performed: a forepoling based in steel pipes of Ø114/96 mm and 20 meters length, ground anchors of 20 meters length and a diaphragm wall with an anchored capping beam.

Figure 10. Cut and cover section where breakin at UPC-Vallparadis Station took place. Extension project of the FGC Railways to Terrassa (own source).

On the other hand, to allow the EPB to work with face pressure before break-in the ground under such compromise section, a mortar block was placed inside the cut and cover caissons. The construction sequence used is described in Figure 9.
Stage 1. Once the TBM cutter head rests against the mortar block inside the concrete caisson, the excavation of the block is done without face pressure until enough distance has been crossed to allow performing the tailskin sealing (ring A1369 approx.). The pushing frame was assembled at chainage 2+857.6.

Stage 2. After this running through the block, the muck chamber is emptied and bentonite poured into the chamber for the crossing. Once the ninth ring erected (A1369), that is, with the rotary head at the diaphragm wall for break-in, a closure is done using a perimetral formwork and pouring mortar to fill gap between segmental rings and concrete caisson. If necessary mortar is also injected through the segments; works are restarted 6 hours latter once mortar set.

Stage 3. Once the closure set, the crossing progress with the muck chamber completely filled adding bentonite for a correct muck homogenization. After having crossed the mortar area, the bentonite is substituted by the muck resulting from the head advance. The working pressures for next rings will be:

- A1370: P0=0.60 bar
- A1371: P0=0.90 bar
The tailskin mortar injection pressure once achieved $P_0 = 1.1$ bar is $P_0 + 0.5$ bar.

Stage 4. The zone for crossing has low overburden and the material is an anthropic filling, therefore the excavation had to be done with chamber filled and the highest attention to the monitoring devices until have mounted the ring A1377.

The working pressure to be

- A1372: $P_0 = 1.10$ bar
- A1377: $P_0 = 1.10$ bar

Figure 11. Break-in construction sequence at UPC-Vallparadis Station. Extension project of the FGC Railways to Terrassa (own source).

At the same station, the break-out method with mortar block was used to enter into the station by the second TBM. Completing the excavation stretch and before entering the Vallparadis station, the tunnel had to be executed under the slab of a car park building (of recently completion) close to the station. At this point the cover decreased up to 6.30 meters (between crown and bottom side of the parking slab). The existing groundwater table, in this area was approximately 14.50 meters above the tunnel invert (at the extrados of the parking diaphragm walls). Due to the existence of this structure, a micropiles protection, as a ground improvement to allow the passage of the TBM, was done. The micropiles Ø200mm diameter and 15 m length with steel pipe reinforcement and arranged as “protection tent” were 1.50 meters away from the tunnel section in the most committed cases. Additional measures included maximizing precautions to the supervision of the monitoring, especially the EPB pressure, were required when crossing. The methodology followed for breaking-out into the station using a mortar block are described at figures 12 & 13 below.
Figure 12. Crossing under a parking building at UPC-Vallparadis Station. Extension project of the FGC Railways to Terrassa (own source).

Figure 13. Cement concrete block at UPC-Vallparadis station break-out (left) and TBM break trough. Extension project of the FGC Railways to Terrassa (own source).
Stage 1.- TBM approaches the station box under passing the car park structure.

- Earth pressure:

- Mortar pressure:

Stage 2.- TBM approaches the diaphragm wall and the mortar block (C20/25). The face pressure is progressively reduced:

A1358: $P_0=1.1$ bar
A1359: $P_0=0.9$ bar
A1360: $P_0=0.7$ bar
A1361: $P_0=0.5$ bar

Stage 3.- Once the chainage 2+616.9 reached (approx. ring no. A1363 erected), once the mortar block touched, the face pressure is reduced until $P_0 = 0$ bar.

Stage 4.- Once without pressure, the excavation of the block begins until breaking-out into the station box.

Figure 14. Break-in construction sequence at UPC-Vallparadis Station. Extension project of the FGC Railways to Terrassa (own source).
3.4 Ground Improvement Methods

There are different methods for improving the ground at the launching and arrival areas. All of them intended to achieve a tight solid and consolidated mass of soil. The most typical one is the jet grouting. The jet grout technique is well-known and is not deemed object of description. Another quite similar way of getting the block is by the technique of replacement by secant columns (plastic – by addition of bentonite- or mortar piles).

Or combined techniques, as the used in Sofia Metro Project L3 (Bulgaria), where fiber glass nailing with permeation grouting treatments, carried out from inside, were used in the break-in and break-out of the so-called MC8 Station. Soil nailing uses grouted resisting elements (nails) installed in the excavation face to reinforce the soil creating a retaining element for temporary excavation support. Soil nails are installed into a pre-drilled hole that penetrates through the initial loose soil layers and grouted. The finished soil nails produce a zone of reinforced ground.

The strength, the mesh and the sequence of the bolts installation are determined according to the type of terrain crossed in order to maintain the stability of the front and to control the ground displacements. In Sofia, the face soil nailing was based on fiberglass pipes of 15 metres long and Ø60/40mm (outer/inner) diameter, inserted into drilled holes of 133 mm diameter and grouted in place. The used drilling mesh was of 1.20x1.20 metres and the nailing was performed in three stages from the perimeter towards the centre of the tunnel. The geology of these zones mainly corresponds to interbedded Pliocene levels of clay, silt and sands of different granulometries.
Figure 17. Plan view of the ground treatments for break-in/out at MC8 Station of Sofia Metro project L3 (own source).

Figure 18. Ground treatment for break-in at MC8 Station of Sofia Metro project L3 (own source).

Same ground treatments but carried out from surface were also used for the so-called MC14 Station. The drilling meshes were closed to 1.0x1.0m at this station.

Figure 19. Ground treatment for break-in at MC14 Station of Sofia Metro project L3 (own source). Break-out treatment at the left hand side and break-in at the right hand side.
Other few common techniques of soil improvement have also been used for the break-in/out in some projects, as for example the AGF (Artificial Ground Freezing). Freezing is a technique used for the consolidation and temporary waterproofing in terrains with considerable water presence. The main principle is freezing the in-situ pore water by thermal transference to convert it into ice to strengthen the soil and to form an impermeable barrier. It is an old technique but not with the same level of use everywhere (and not just talking about tunnels). For example, while in Europe there are very few experiences as ground improvement method for breakthrough of TBM, some more for the cross-passage openings, in China it is a popular construction technique in railway projects. Shanghai is one place where it has been widely adopted for launching and receiving the machines into shafts.

Basically, the ground treatment is carried out by a series of freezing plants and freezing pipes installed interconnected into the block object of the treatment through which a coolant fluid at very low temperature is driven. By thermal exchange, columns of frozen soil begin to form around pipes as the fluid flows through the network. Two are the main fluids used nowadays for freezing: brine (high-concentration salt solutions) and liquefied nitrogen (LIN). Circulating temperatures are -25 °C for brines and -196 °C for LIN. During the last two decades soil freezing with LIN has developed from an application with lots of uncertainties into a more standard procedure for treating unstable soil and leakages.

Actually the uses of LIN and efficient refrigeration compressors results in greater frozen ground strengths, almost totally watertight and less time for freezing processes. The low temperature of LIN allows freezing in about one week which is faster than the brine freezing process which easily can take a month. Even, under certain conditions, ground freezing with LIN is better solution compared to other conventional soil treatment methods.

The frozen block can reduce the water ingress during the TBM launching. However, like other techniques, the freezing may have to be used combined with other elements like sealing rings. In any case, the crossing of the TBM through the block (it does not matter its nature), as it happens when crossing the ground, generates a gap due to the rotary head and the conicity of the shield. This annular gap at the excavation section may be a path for the groundwater with leakage result into the chamber. The sealing ring helps to prevent this phenomenon until the segmental ring is sealed against the diaphragm wall.

It should also be noted that this technique could induce swelling of the soil because of the freezing and then settling after thawing. To avoid additional settlements is one of the reasons of its scarce use in urban areas, especially if sensitive structures with sensitive structures on the surface unless treatment done at great depth.

3.5 Flood of the Reception Chamber

This solution is only used for breakout into the chamber. Based in filling the reception chamber with water up to the ground water level is commonly used where insufficient space or difficulties to build other common
solutions for breakout. The ground water balance method avoids a hydraulic gradient through the soil and reduces risks at the break. The method was used for example at Cairo Metro Line 2 Project in 2000 at St Theresa Station. However, flooding of the stations did cause delay to other woks in the station and the methodology and the treatments foreseen were changed (1). This solution has been recently used (October 2017) at Metro Nice Line T2 for the arrival of the EPB to the reception shaft and also at same date in Metro Paris Line 14 (extension towards the North, to Mairie de Saint-Ouen).

Figure 21. Picture above, Paris Line 14 (October 2017), TBM “Solenne”, 8.91m diameter, arrival by flooding to the reception shaft “Pierre”; partially flooded shaft view. Source: prolongerligne14-mairie-saint-ouen.fr

Picture below, Nice Metro Project Ligne T2 Ouest-Est (October 2017). TBM “Catherine”, 9.68m diameter, at reception shaft already empty of water but with the muck resulting from the excavation. Source: tramway.nice.fr.

4. CONCLUSION

Based on the site conditions, the TBM breakthrough (in or out) in reception/launching chamber could be a delicate operation requiring special measures. Different geotechnical or structural techniques can be used inside and outside the structure to be crossed. The most common used methods as the sealing ring or ground treatments, among others not so common like the fake tunnels, have been briefly described through some already executed examples demonstrating that different solutions are viable in function of the project and its circumstances.

REFERENCES