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Case study

Common engineering methods and control of TBM break-in and break-out operations

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Abstract: Break-in and break-out operations represent critical construction phases in shield tunnelling, particularly in water-bearing and heterogeneous ground conditions. During these transitions, temporary modifications in confinement and hydraulic boundary conditions disturb the equilibrium between face support pressure and in-situ stresses, increasing the risk of ground instability and groundwater inflow. The paper discusses the mechanical behaviour of the ground during TBM breakthrough through diaphragm walls and station boxes, with emphasis on operational pressure control, annular gap sealing and monitoring requirements. Selected engineering solutions applied to mitigate breakthrough risks are presented, including sealing rings, cement concrete blocks and ground improvement techniques. Their structural configuration, operational role and limitations are analysed in relation to groundwater pressure and soil permeability. Practical implementation is illustrated through case studies from metro projects, including the FGC Terrassa extension and Sofia Metro Line 3, where combined mechanical and geotechnical measures were adopted to ensure safe TBM transition under low cover and high groundwater conditions. The presented examples confirm that successful breakthrough operations require integrated design combining structural solutions, ground treatment and strict operational control. Break-in and break-out should therefore be treated as governing design stages in tunnel portal engineering rather than routine construction steps.

Keywords: break-in, break-out, ground improvement, sealing ring, TBM, tunnel portal

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1. Introduction

Shield tunnelling in soft ground conditions is commonly performed using closed-face tunnel boring machines – either in Earth Pressure Balance (EPB) or slurry ones. The selection of the tunnelling method is determined by geological and hydrogeological conditions, tunnel depth, diameter, alignment constraints and surface sensitivity. Both systems are designed to ensure face stability by maintaining controlled support pressure within a pressurized chamber located between the cutterhead and the bulkhead.

In EPB machines, excavated soil is conditioned and retained in the excavation chamber to act as a pressure-transmitting medium. Face support is achieved by regulating the balance between the rate of advance and the rate of soil extraction through the screw conveyor. This method is particularly suitable for cohesive or low-permeability soils, where the conditioned material can maintain plastic behavior and effectively transmit pressure.

Slurry shields stabilize the excavation face using externally pressurized slurry. Hydraulic pressure is transferred to the ground through the slurry, while excavated material is transported to the surface separation plant. Slurry properties are continuously adjusted to maintain the required pressure and filtration characteristics. This method is generally preferred in granular, permeable formations, where hydraulic confinement is critical.

In both systems, face stability depends on maintaining equilibrium between applied support pressure and the combined earth and groundwater pressures acting at the excavation face. The required support pressure is governed by soil strength parameters, tunnel depth and groundwater level. Deviations from the required pressure conditions may lead to volume loss, surface settlements or progressive instability.

When the TBM approaches or crosses previously constructed structures such as shafts or station boxes, boundary conditions are modified. These transitions involve temporary changes in confinement, pressure control and annular gap sealing. The term break-in denotes the initial advance of the TBM from a launching structure into the ground. Conversely, break-out refers to the exit of the TBM from the ground into a receiving structure. In contrast to steady-state tunnelling, these breakthrough phases are characterized by altered stress distribution and hydraulic conditions, resulting in increased operational complexity and risk.

2. Mechanical and hydraulic conditions during breakthrough operations

2.1. Altered confinement conditions during breakthrough

In shield-driven tunnelling, the operations of break-in and break-out represent some of the most critical stages of the entire construction process. Although both operations are relatively short in duration compared to the overall excavation length, they involve complex mechanical and hydraulic interactions that significantly increase construction risk.

During standard shield tunnelling in soft ground, stability is achieved by maintaining a balance between the in-situ earth and groundwater pressures and the support pressure applied at the tunnel face. In Earth Pressure Balance (EPB) and slurry machines, this equilibrium is ensured through controlled chamber pressure and regulated excavation rates. However, at break-in and break-out, this natural pressure balance is inherently disturbed. The transition between ground and structural elements, such as diaphragm walls or retaining systems, creates a temporary discontinuity in confinement conditions.

The tunnel portal therefore becomes a location where the natural equilibrium of face pressure is interrupted. When the TBM approaches or crosses a retaining structure, full face pressure cannot always be maintained [1]. The excavation chamber may be only partially filled, tailskin grouting may be delayed, and the annular gap cannot be immediately sealed. As a consequence, the confinement normally provided by the surrounding ground is reduced or temporarily lost. This condition makes the breakthrough phase fundamentally different from steady-state tunnelling.

These operations are more risky than standard advance because several stabilizing mechanisms are simultaneously weakened. The ground may experience temporary unsupported conditions, especially in water-bearing or permeable formations. In addition, the mechanical interaction between the cutterhead, the retaining wall, and the surrounding soil introduces additional uncertainties. If face pressure is not adequately controlled, local instabilities may develop, potentially leading to excessive settlements, water inflow, or even sudden ground collapse phenomena.

For these reasons, break-in and break-out should not be treated as routine construction transitions but rather as governing design phases that strongly influence portal geometry, structural detailing, groundwater control measures and monitoring strategy. The design of tunnel portals must therefore explicitly account for the temporary loss of equilibrium conditions that characterize these critical breakthrough stages.

2.2. Influence of ground conditions on breakthrough operations

The response of the ground during breakthrough operations is governed by its mechanical strength and hydraulic characteristics. In contrast to steady- state tunnelling, break-in and break-out phases involve transient modifications in confinement, which increase the sensitivity of the soil mass to variations in strength parameters and groundwater conditions.

Limit equilibrium and numerical analyses indicate that the minimum required face support pressure is primarily controlled by cohesion, friction angle, unit weight and tunnel depth [2], [3]. In cohesive soils, short-term stability may be maintained under reduced confinement due to undrained shear strength. Conversely, cohesionless soils exhibit significantly lower tolerance to pressure fluctuations. In stratified or heterogeneous formations, contrasts in stiffness and strength may induce localized deformation and stress concentration near the excavation front.

Groundwater conditions further influence breakthrough stability. Elevated groundwater levels increase total stress acting at the face while reducing effective stress within the soil mass. When support pressure is reduced, hydraulic gradients may develop toward the excavation chamber, generating seepage forces that contribute to instability [3]. In permeable soils, rapid transmission of pore pressure changes may trigger sudden ground response.

Inadequate control of face pressure results in volume loss around the shield and associated surface settlements [4, 5]. Under unfavorable conditions, progressive failure mechanisms may develop above the tunnel crown, forming chimney-type zones of loosening. In shallow tunnels, such mechanisms may extend to the surface, leading to localized sinkholes [6].

Breakthrough behaviour therefore depends on the interaction between mechanical unloading and hydraulic response of the ground. Accurate assessment of soil strength, permeability and groundwater regime is essential for defining safe operational pressure ranges during TBM transition.

3. Mechanical behaviour during break-in and break-out

3.1. Break-in

Break-in operations performed below the groundwater table represent one of the most critical phases of shield tunnelling [7]. When the retaining structure is opened and the TBM begins its advance into the ground, face stability becomes particularly sensitive to both operational and hydraulic conditions.

During the initial stage of advance, full face support pressure cannot be immediately applied. The excavation chamber is only partially filled, and steady-state tunnelling conditions have not yet been established. Consequently, the support pressure generated at the face may be insufficient to fully balance the in-situ earth and groundwater pressures. In the first metres of excavation behind the retaining wall, it is often not possible to reach the target pressure required for equilibrium. This temporary reduction in confinement increases the susceptibility of the face to instability.

Groundwater control constitutes a second major concern during break-in. Once the retaining wall is cut, hydraulic continuity between the excavation chamber and the surrounding ground may develop. If groundwater inflow occurs, it may induce erosion and transport of fine particles, progressive loss of ground, and potential flooding of the launching structure. The combined effects of reduced face support and seepage forces may lead to settlements, stress redistribution within the soil mass and localized instability [8].

Under normal tunnelling conditions, watertightness is achieved through grouting of the annular gap at the extrados of the segmental lining. However, this sealing process cannot be activated immediately during break- in. Tailskin grouting can only commence after the first segmental ring has exited the shield. During the initial advance, the interface between the diaphragm wall and the shield remains temporarily unsealed, creating a potential pathway for groundwater inflow through the annular gap.

Once the shield is fully embedded in the ground, operational conditions progressively stabilize. The annular gap between the segmental lining and the retaining structure can be sealed, the excavation chamber can be fully filled, the required working face pressure can be applied, and tailskin grouting can be initiated to control volume loss. At this stage, tunnelling approaches steady-state conditions and the risk of instability is significantly reduced.

The main operational constraints during break-in, including the absence of face support pressure, delayed annular sealing and the gradual establishment of stable tunnelling conditions, are summarized in Fig. 1.

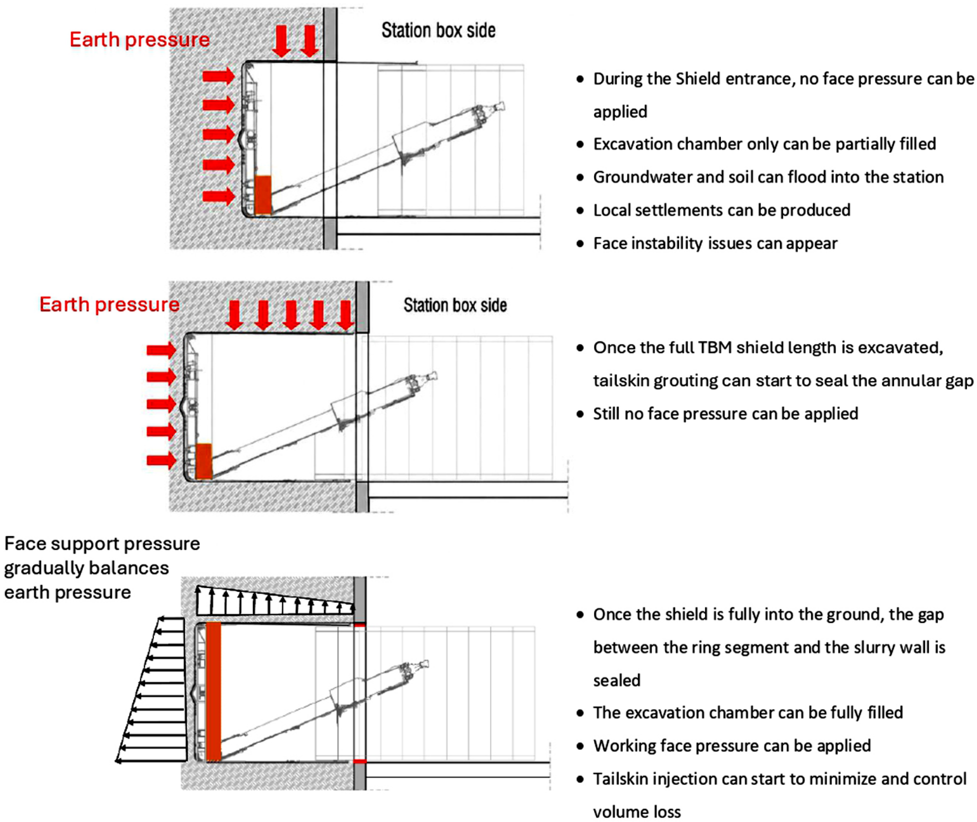


Fig. 1. Key conditions during break-in

3.2. Break-out

Break-out refers to the exit of the TBM from the ground into a receiving structure. As the machine approaches the diaphragm wall, face pressure must be gradually reduced to avoid excessive loading of the retaining structure. A soft-eye zone is typically provided to facilitate controlled cutting of the wall.

When the cutterhead enters the structure, full face support cannot be maintained. The excavation chamber is partially filled and tailskin grouting cannot be performed. Consequently, the annular gap remains temporarily unsealed. Until a sufficient length of the TBM has advanced into the structure and segmental rings can be installed and sealed against the wall, a portion of the surrounding ground remains unsupported.

During this phase, groundwater inflow and soil migration into the receiving structure may occur. Reduced confinement and temporary lack of sealing may result in local settlements and volume loss. The associated ground movements may affect adjacent infrastructure, particularly in shallow or permeable ground conditions [9].

Therefore, break-out design must focus on controlled pressure reduction, stabilization of the surrounding ground and effective sealing of the annular gap to limit groundwater inflow and surface deformations. The main operational constraints during break-out, including pressure reduction, temporary lack of tailskin grouting and annular gap sealing, are summarized in Fig. 2.

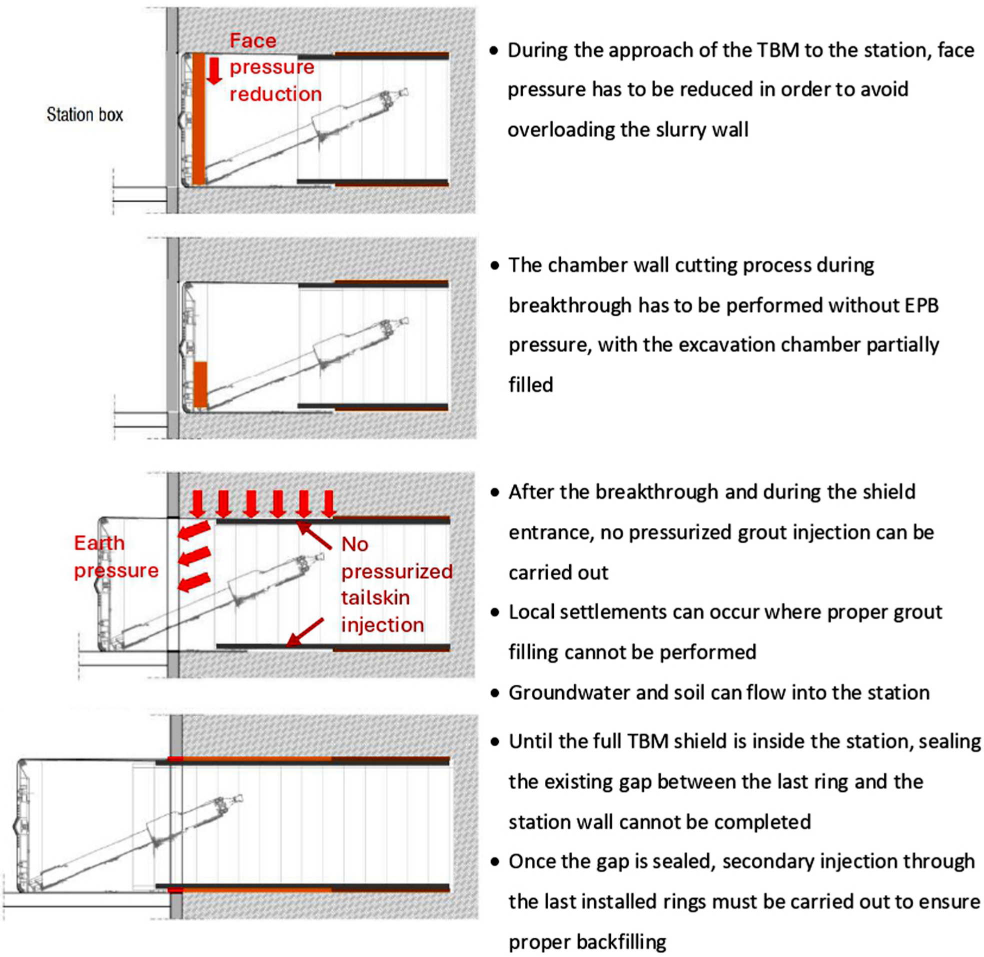


Fig. 2. Key conditions during break-out

4. Engineering solutions for breakthrough operations

Various engineering techniques are applied to ensure safe TBM launching and retrieval. These solutions are intended to maintain face stability and prevent uncontrolled inflow of groundwater and soil into the launching or reception structure. The fundamental objectives of break-in and break-out design are therefore ground stabilization and watertightness.

In breakthrough conditions, the original retaining structure is partially removed to allow passage of the TBM. This creates a temporary discontinuity in confinement and hydraulic conditions. To compensate for this loss of support, additional measures must be introduced. These measures act either by improving the mechanical properties of the surrounding ground or by providing a temporary structural substitute capable of maintaining controlled pressure conditions during crossing.

Two principal categories of solutions can be distinguished: ground improvement techniques and mechanical barriers. Ground improvement methods aim to increase soil strength, reduce permeability and enhance overall stability in the vicinity of the opening. Mechanical systems, on the other hand, provide a physical interface between the TBM and the structure, limiting groundwater inflow and enabling controlled pressure application during the transition phase.

In practice, combined approaches are frequently adopted. The objective is to create temporary boundary conditions that allow the TBM to enter or exit the structure while maintaining adequate face support and minimizing volume loss. The most commonly applied techniques are summarized in Table 1.

Table 1. Common engineering methods for TBM break-in and break-out

<table>
<tr><th>Ground Improvement</th><th>Mechanical Barriers</th><th>Other</th></tr>
<tr><td>Jet groutingPermeation groutingFreezingFiberglass soil nailing</td><td>Sealing ringFake tunnelsCement concrete blocks</td><td rowspan="2">Flooding of the chamber</td></tr>
<tr><td colspan="2">Secant pilesWatertight enclosures with groundwater table drawn</td></tr>
</table>

4.1. Mechanical barriers

The sealing ring is one of the most commonly applied mechanical solutions for TBM break-in operations and, in selected cases, for break-out. Its primary function is to limit groundwater and soil inflow through the annular gap created when the TBM crosses a diaphragm wall or other retaining structure.

Structurally, the sealing ring consists of a watertight shell, typically fabricated from steel or reinforced concrete, anchored to the retaining wall. The length of the structure generally ranges from approximately 1.5 to 2.0 m, depending on the TBM diameter. The shell is equipped with one or more layers of elastic sealing elements, commonly rubber membranes or brush-type seals, which are pressed against the outer surface of the shield. The system is designed to reduce hydraulic communication between the ground and the launching or reception chamber during breakthrough.

During break-in, the sealing ring performs multiple functions. It allows controlled penetration of the retaining wall, reduces the effective annular gap between the shield and the structure, and enables application of face pressure while limiting water ingress. Once the first lining rings are installed, the annular space can be grouted, and the sealing system transitions from temporary to permanent confinement control. For this reason, the sealing ring is considered one of the most efficient integrated solutions for break-in under groundwater conditions.

However, its application in break-out operations is more limited. During TBM exit into a receiving chamber, uncertainties related to machine alignment and positional tolerances may lead to uneven contact between the shield and the sealing element. Cutterhead interaction with the sealing components may damage the membrane, reducing its effectiveness. For this reason, sealing rings are often supplemented with additional ground improvement measures, such as jet grouting blocks, permeation grouting or local groundwater control.

Modifications of the standard sealing ring design have been proposed for highly permeable or high-pressure conditions. These include extended shell lengths, additional restraining plates, multi-layer waterproof membranes and systems allowing controlled pressurization of flexible sealing elements. Such solutions aim to increase hydraulic resistance, improve pressure distribution along the annular interface and reduce the risk of uncontrolled inflow during breakthrough.

In practice, sealing rings are rarely used as standalone systems. They are typically combined with pre-treatment of the ground in the vicinity of the opening to provide redundancy and improve reliability. The selection of the sealing ring configuration should therefore consider groundwater pressure, soil permeability, expected alignment tolerances and the operational sequence of the TBM during breakthrough.

The examples of the use of sealing ring are presented in Fig. 3.

Fig. 3. Sealing ring in launching chamber – Tel Aviv Red Line Metro Project (own source)

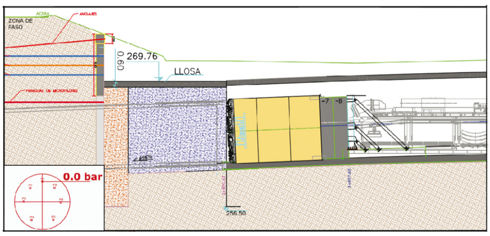
A frequently applied mechanical solution for TBM break-out is the construction of a plain cement concrete block inside the reception chamber [7]. The primary objective of this method is to maintain face support pressure until the last segmental ring has been installed and sealed against the diaphragm wall. The concrete block temporarily replaces the ground confinement and enables controlled pressure conditions during the final stage of approach.

The dimensions of the block depend on tunnel diameter, groundwater conditions and expected hydrostatic pressure. In projects with high external water pressure or limited overburden, the block may require substantial thickness to provide sufficient resistance. After the TBM has passed through, the concrete mass is demolished to allow completion of permanent structural works.

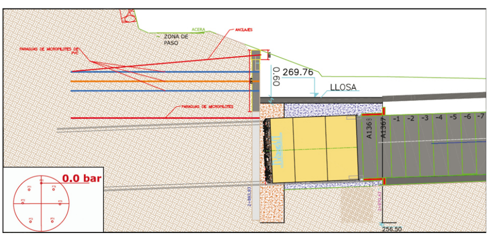
Although primarily intended for break-out, cement concrete blocks may also be used during break-in operations. An example is provided by the extension of the FGC railway to Terrassa (Barcelona, Spain), where the method was applied for both TBM entry and exit under varying geological and geometric constraints [7]. The project involved twin single-track TBM tunnels with an internal diameter of 6.75 m and cross passages spaced at 250 m intervals. Several stations and surface sections were constructed using the cut-and-cover method.

At UPC-Vallparadís Station, the TBM transition occurred beneath a future public park and adjacent to a slope stabilized by a rock retaining wall. Due to unfavourable ground conditions and stability concerns, additional measures were implemented prior to TBM passage, including forepoling with steel pipes (Ø114/96 mm, 20 m length), ground anchors of similar length and a diaphragm wall with an anchored capping beam. In this configuration, the concrete block provided temporary confinement while complementary ground improvement techniques enhanced global stability.

The concrete block method is therefore considered a robust mechanical solution, particularly in situations where groundwater pressure is high and precise control of face support is required during breakthrough. However, its use may increase construction time due to installation and subsequent demolition, and it is often combined with ground improvement measures to provide redundancy and reduce breakthrough risk. A detailed construction sequence of the break-in operation is presented in Fig. 4.



When the TBM cutterhead reached the mortar block inside the concrete caisson, excavation of the block was carried out without applying face support pressure. Advance continued under these conditions until a sufficient tunnel length had been completed to enable tailskin sealing. A pushing frame was installed to ensure controlled thrust and stability during this initial stage.



After completion of the excavation through the mortar block, the excavation chamber was emptied and subsequently filled with bentonite slurry to provide controlled conditions for the crossing phase. When the cutterhead approached the diaphragm wall, a closure was executed using peripheral formwork, and mortar was placed to fill the gap between the segmental lining and the concrete caisson. Where required, additional grout was injected through the segments to ensure proper sealing. Tunnelling operations were resumed after sufficient setting of the mortar to guarantee stability and watertightness of the interface.

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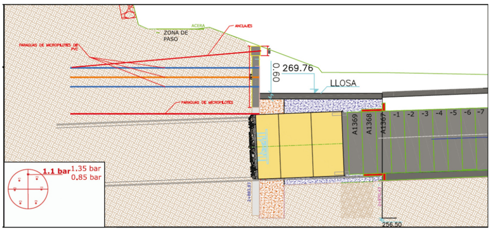
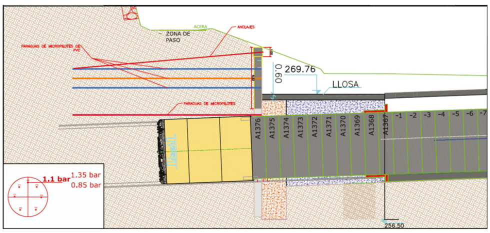


After the closure had achieved sufficient strength, the crossing operation was continued with the excavation chamber fully filled. Bentonite was added to ensure proper conditioning and homogenization of the excavated material during the transition phase. Once the TBM had passed beyond the mortar-treated zone, bentonite conditioning was progressively replaced by the natural muck generated during normal advance.Face support pressure was increased stepwise during this stage in order to re-establish equilibrium conditions. The working pressure was gradually raised from an initial reduced level to the target value required for steady-state tunnelling. After reaching the nominal face pressure, tailskin grouting pressure was adjusted accordingly, typically maintained at a value exceeding face pressure to ensure adequate backfilling and control of volume loss.



The crossing zone was characterized by limited overburden and the presence of anthropogenic fill material. Due to these conditions, excavation was carried out with the chamber fully filled in order to maintain continuous face support. Particular attention was paid to real-time monitoring of operational and geotechnical parameters during this stage.The working face pressure was maintained at the target level required to ensure stability under low cover conditions. Continuous control of pressure and deformation indicators was implemented to minimize the risk of excessive settlements and ground disturbance.

Fig. 4. Cut-and-cover structure at UPC-Vallparadís Station used for TBM break-in during the FGC Terrassa extension

At the same station, the break-out procedure using a mortar block was applied for the second TBM. Prior to entering Vallparadís Station, the tunnel alignment passed beneath the slab of a recently completed parking structure located adjacent to the station. In this section, the cover was reduced to approximately 6.30 m, measured between the tunnel crown and the underside of the parking slab.

Groundwater conditions were particularly demanding. The groundwater table was located approximately 14.50 m above the tunnel invert, corresponding to the extrados level of the parking diaphragm walls. Due to the proximity of the existing structure and the limited overburden, additional ground improvement measures were required to ensure safe passage of the TBM.

A system of micropiles was installed as a protective measure. The micropiles, with a diameter of 200 mm and a length of 15 m, were reinforced with steel pipes and arranged in a protective “umbrella” configuration above the tunnel alignment. In the most critical sections, the micropiles were positioned approximately 1.50 m from the tunnel profile, as shown in Fig. 5. This arrangement provided additional confinement and limited deformation of the overlying structure during breakthrough.

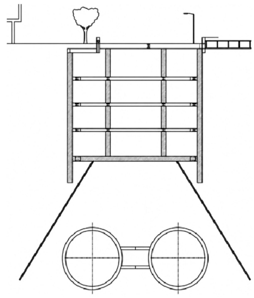
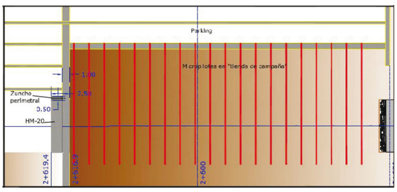
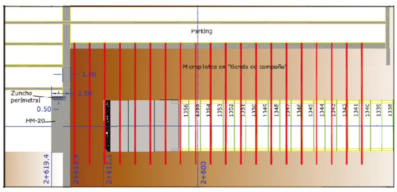


Fig. 5. TBM passage beneath the parking structure at UPC-Vallparadís Station during the FGC Terrassa extension – micropile layout

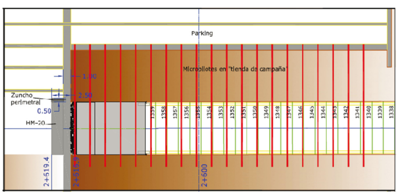
In addition to structural reinforcement, strict monitoring procedures were implemented during crossing, with particular emphasis on control of EPB face pressure. The break-out sequence using the mortar block was carried out in accordance with the staged methodology illustrated in Fig. 6.



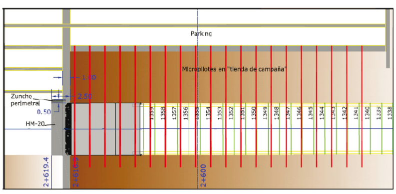
The TBM advanced towards the station box, passing beneath the existing parking structure



The TBM approached the diaphragm wall and the C20/25 mortar block. During this stage, the face support pressure was progressively reduced.



Once the TBM reached the mortar block, the face support pressure was gradually reduced to zero. This reduction was implemented in a controlled manner immediately prior to breakthrough into the reception chamber.



Once face pressure had been fully released, excavation of the mortar block was initiated and continued until breakthrough into the station box was achieved.

Fig. 6. Break-out construction sequence at UPC-Vallparadis Station

4.2. Ground improvement

Ground improvement techniques are commonly applied in TBM break-in and break-out zones to enhance soil strength, reduce permeability and provide temporary confinement during the crossing of diaphragm walls [10]. The objective of such treatments is to create a locally stabilized soil block capable of maintaining face stability and limiting groundwater inflow until the segmental lining and annular grouting establish permanent support conditions.

One of the most frequently adopted approaches involves the use of face reinforcement combined with grouting. Soil nailing systems introduce grouted reinforcing elements into the excavation face to increase shear resistance and control deformation. When properly designed, this method improves the short-term stability of heterogeneous or low-cohesion soils and reduces the risk of progressive ground loss during breakthrough.

At Sofia Metro Line 3, ground improvement was implemented at selected stations to ensure safe TBM transition through diaphragm walls under variable geological conditions, as shown in Fig. 7. The adopted solution consisted of fiberglass face nails installed in a predefined drilling grid and combined with permeation grouting. The reinforcement was executed in stages, progressing from the perimeter toward the tunnel axis, in order to maintain controlled stress redistribution and minimize deformation. The technique proved effective in interbedded clay, silt and sand formations, where variability in strength and permeability required localized stabilization.

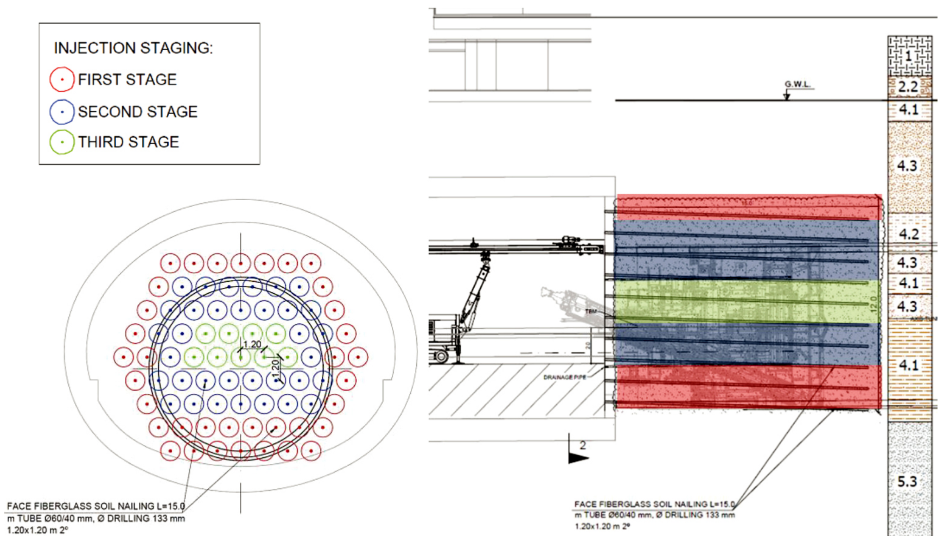


Fig. 7. Ground treatment for break-in at Sofia Metro project L3 (own source)

The experience from Sofia Metro Line 3 demonstrates that properly designed ground improvement measures can provide sufficient temporary stability during break-in and break-out operations. Such techniques are typically combined with mechanical systems, such as sealing rings or other interface solutions, to ensure continuity of confinement and hydraulic control throughout the transition phase.

5. Conclusions

Break-in and break-out operations constitute critical stages of shield tunnelling, during which the equilibrium between face support pressure and in-situ ground and groundwater conditions is temporarily disturbed. These phases are characterized by reduced confinement, delayed annular sealing and increased sensitivity to soil strength and permeability.

Insufficient control of face pressure during breakthrough may result in volume loss, settlements and, in unfavorable ground conditions, progressive failure mechanisms. The risk is particularly significant in permeable, heterogeneous or shallow formations.

To mitigate these effects, a range of engineering measures can be applied. Mechanical solutions include sealing rings, steel sleeves and cement concrete blocks, while ground improvement techniques involve jet grouting, permeation grouting, soil nailing and, in specific conditions, artificial ground freezing. In practice, these methods are frequently combined to ensure sufficient confinement and hydraulic control during TBM transition.

The presented case studies demonstrate the application of some of those measures under varying geological and operational conditions, highlighting the importance of integrated design and staged execution. Successful breakthrough operations require coordinated use of structural solutions, ground treatment and continuous monitoring.

Breakthrough phases should therefore be treated as governing design stages in tunnel portal engineering, and not as routine construction operations.

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