EPB Shield Tunnelling Through a Volcanic Chain In Mexico

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ABSTRACT

The contribution gives insight to the challenges and respective engineering measures in the Mexico-Toluca Interurban Train tunnel project.

Each of the twin tunnels has a length of 4.7 km and is excavated with two EBP shield machines of 8.57 m diameter. The tunnel overburden varies from 1 diameter up to 130 meters and hydrostatic pressures up to approximately 6.0 bar are expected.

The geology of the region is composed of rock of andesitic spills, interspersed with brecciated horizons that are, in turn, interspersed with tuffs and lytic tuffs of variable thickness.

The tunnel face is highly heterogeneous and varies both along the alignment and within the tunnel horizon. It is composed of volcanic rock, fractured rock, presence of blocks, open discontinuities and geological faults, rock with different degrees of weathering, breccia, and tuffs.

The biggest challenge of the project is the heterogeneity of the tunnel face. It is partly unpredictable and impedes TBM operation. The characteristics of this type of tunnel face and its unpredictability lead to a high risk of tool wear, excessive consumption of tools and long durations of interventions. In addition, if tool wear is not properly controlled, both cutter head and screw conveyor can be easily damaged.

The key to success of the project is the permanent adjustment of the operation mode and the main excavation parameters of the TBM by real-time analysis. This allows to minimize the reaction time, to optimize and control the excavation parameters, and to improve the control of water inflows as well as the TBM steering.

Key Words: EPB Shield, Heterogeneous Ground, Volcanic Rock, Mixed Face, High Groundwater Pressures.

1. PROJECT DESCRIPTION

The Mexico Toluca Interurban Railway Project is located at approximately 3000 m above sea level, has an extension of 57.7 km and 6 stations. It will connect the metropolitan zone of the Valley of Toluca with the west zone of Mexico City. This modern and fast means of transportation will promote the use of non-motorized transportation and sustainable mobility providing a mass public transport to serve 230 thousand of passengers per day. It will connect to the metro lines L1 and the future lines L9 and L12, as shown in Figure 1. The twin tunnel with an excavation diameter of 8.57 m, an excavation length of 4.7 km and an almost permanent slope of 4.0 % are excavated with 2 TBMs, as shown in Figure 2.

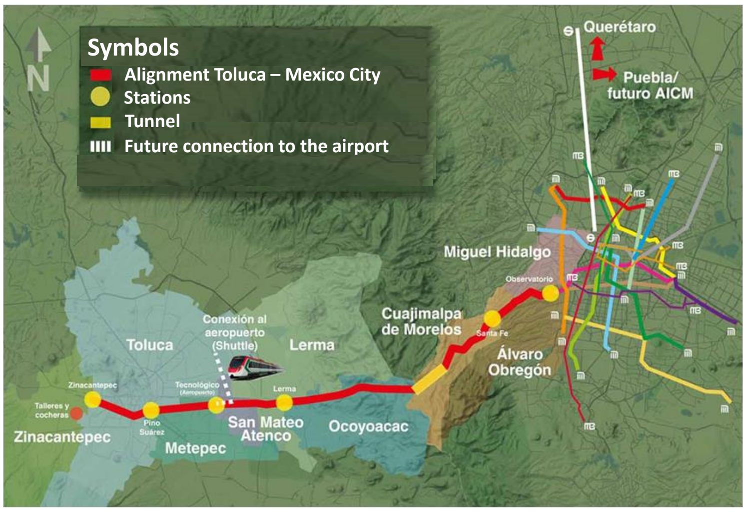

Figure 1. Alignment of the Interurban Mexico-Toluca Railway Project and metro lines connection.

Figure 2. Alignment of the tunnel, start and end portal.

2. GEOLOGY, GEOTECHNICS AND HIDROGEOLOGY

2.1. Geological settings

The geology of the region is composed of rock of andesitic spills, interspersed with brecciated horizons that are, in turn, interspersed with tuffs and lithic tuffs of variable thickness.

The tunnel face is highly heterogeneous and varies both along the alignment and within the tunnel horizon. It is composed of sound volcanic rock, fractured rock, presence of blocks, open discontinuities and geological faults, rock with different degrees of weathering, breccia, and tuffs.

Based on the geological profile the TBMs excavate mostly in andesitic rock and breccia in homogeneous, heterogeneous and mixed tunnel faces with or without water, as shown in Figure 3. In general, the typical tunnel face geological characterisations along the alignment are:

- Traquiandesite (Ug-4)
- Andesitic Breccia of poor quality (Ug-3c)
- Poor fractured Andesite (Ug-3a)
- Hard Andesite and fractured (Ug-3a)
- Argitilized Andesite (Ug-3d)
- Fractured Andesite (Ug-3a)

- Oxidized Andesite (Ug-3b)
- Andesitic Breccia poor to very poor (Ug-3c)

By sections the degree of fracturing varies from low to very high. The tunnel face is often in transition zones with mixed face in hard weathered rock and breccia or soft weathered rock with soil behaviour.

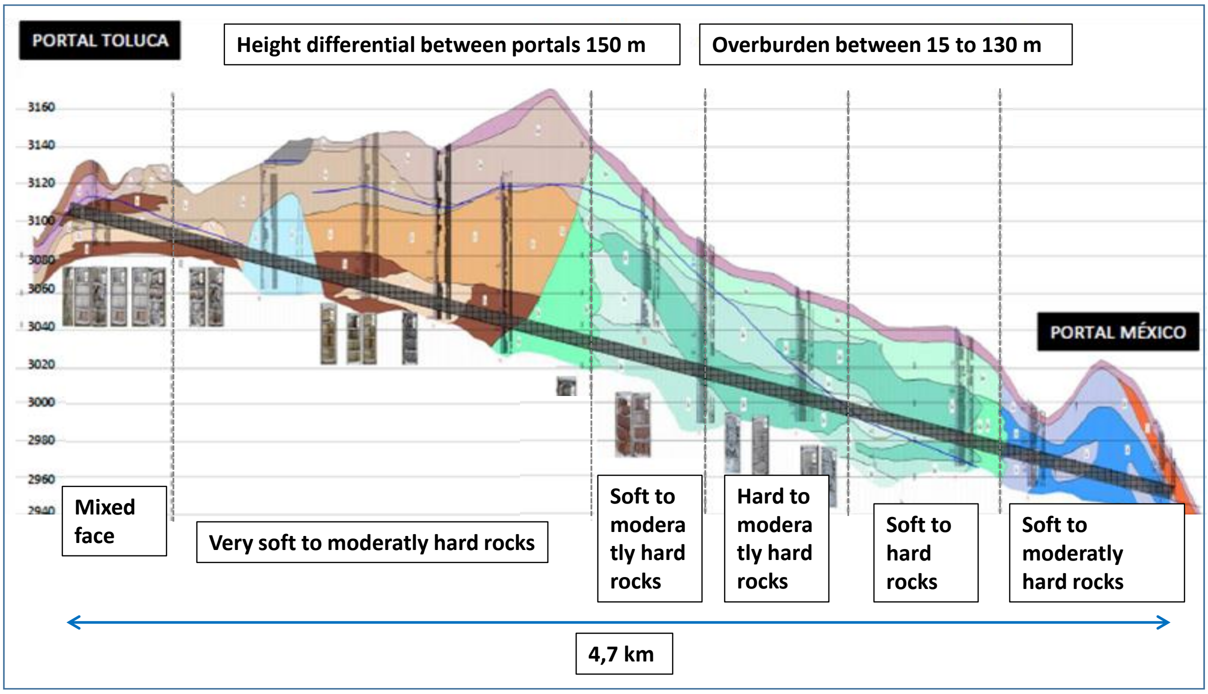

Figure 3. Geotechnical profile of the project.

The geotechnical parameters are shown in Table1.

Table 1. Geotechnical parameters of the project (in parenthesis the average value)

Geology		γ [kN/m³]	C [kPa]	ϕ [º]
Andesite	Ug-3a	20.4 – 26.7 (24.6)	330 – 4500 (1720)	53 – 62 (59)
Altered Andesite	Ug-3b Ug-3d	18.2 – 26.5 (22.4)	95 – 1100 (450)	35 – 58 (50)
Andesitic Breccia	Qan-br Ug-3c	17.8 – 25.1 (21.7)	132 – 1300 (460)	30 – 55 (47)
Tuffaceous Breccia	Qtb-br – brt Ug-2d	16.4 – 24.6 (20.7)	47 – 700 (170)	27 – 37 (32)
Consolidated Breccia	Qtb-br – brc Ug-2e	15.5 – 24.6 (20.3)	26 – 1300 (280)	31 – 38 (34)
Lithic Tufa	Qan-br Ug-3c	15.1 – 22.6 (17.9)	14 – 110 (60)	30 – 35 (32)

2.2. Hydrogeology

The presence of water is expected in along most of the project, but there is a certain unpredictability regarding the water pressure and permeability along the project. Furthermore the conditions can change from excavation in dry face to face with high water flows at any time, partly associated to the sudden change of material in the tunnel face. Water pressures of up to 6.2 bar are expected in specific areas and pressures above 5,0 bar in long stretches of excavation. In a large part of the project pressures between 4.0 and 5.0 bar are handled. Permeabilities vary depending on the type of geology at the tunnel face as can be seen in Table 2.

Table 2. Water pressure, permeability and water flow for each geology

Geology		Quality of the rock	Water Pressure	Permeability	Water flow
Andesite	Ug-3a	Good to regular quality (RQD > 50%) Failure Zones	0 – 6.2 bar	Permeable to very permeable Failure zone - Permeable	< 0.1 a 7.7 l/sec/m (< 72 a 5550 l/min)
Altered Andesite	Ug-3b Ug-3d				
Andesitic Breccia	Qan-br Ug-3c	Poor quality - soil	0 – 5.7 bar	Little permeable to very permeable	< 0.1 a 3.3 l/sec/m (< 72 a 2380 l/min)
Tuffaceous Breccia	Qtb-br – brt Ug-2d				
Consolidated Breccia	Qtb-br – brc Ug-2e				
Lithic Tufa	Qan-br Ug-3c	-	0 – 1.1 bar	Little permeable	< 0.1 l/sec/m (< 72 l/min)

In total there are 37 drill holes with permeability tests and a total of 158 tests in average range from k_f= 1.35x10^{-6} m/s to k_f= 9.95 x10^{-8} m/s. The main values are shown in Table 3.

Table 3. Permeability according to the geology

Geology	Data Quantity	Permeability (m/s)		
		Maximum	Minimum	Average
Lithic Tufa	8	3.10E-06	1.22E-08	7.62E-07
Altered Breccia	3	1.64E-07	2.46E-09	9.95E-08
Tuffaceous Breccia	15	1.74E-06	4.30E-10	5.18E-07
Consolidated Breccia	19	7.29E-06	4.65E-10	2.10E-06
Andesite	43	1.53E-05	1.00E-09	1.35E-06
Altered Andesite	16	9.44E-06	3.07E-08	2.15E-06
Andesitic Breccia	10	9.59E-07	2.57E-09	1.40E-07

3. OPERATION MODES

As described in the next chapter, one of the key aspects to overcome the unpredictably changing ground conditions is the definition and adjustment of the shield advance to different operation modes according to the encountered geotechnical and hydrological conditions. The main features of the operation modes defined and used at the Mexico-Toluca project are listed next:

- Open Mode (OM)
- Transition Mode with Compressed Air (TMA)
- Semi-closed Mode (SCM)
- Closed Mode (CM)

The operation modes and their selection criteria are schematically represented in Figure 4 and Figure 5. The experience gained in the excavation to date, has allowed to adjust the definition of operation modes for the particular project conditions. How the operation modes are being applied to overcome some of the main risks encountered in the project will be described in section X of this paper.

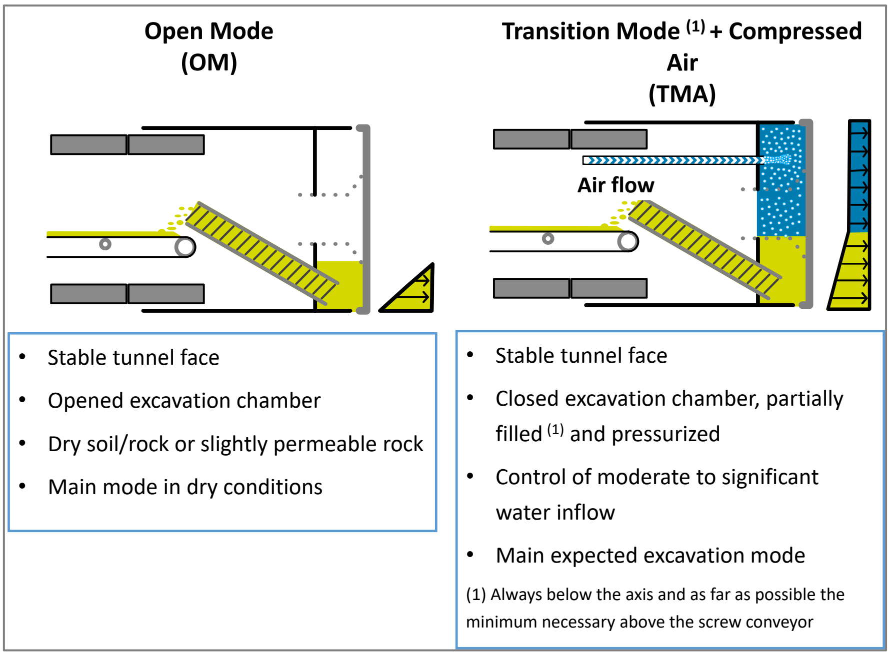

Figure 4. Operation modes of EPB applied on the project.

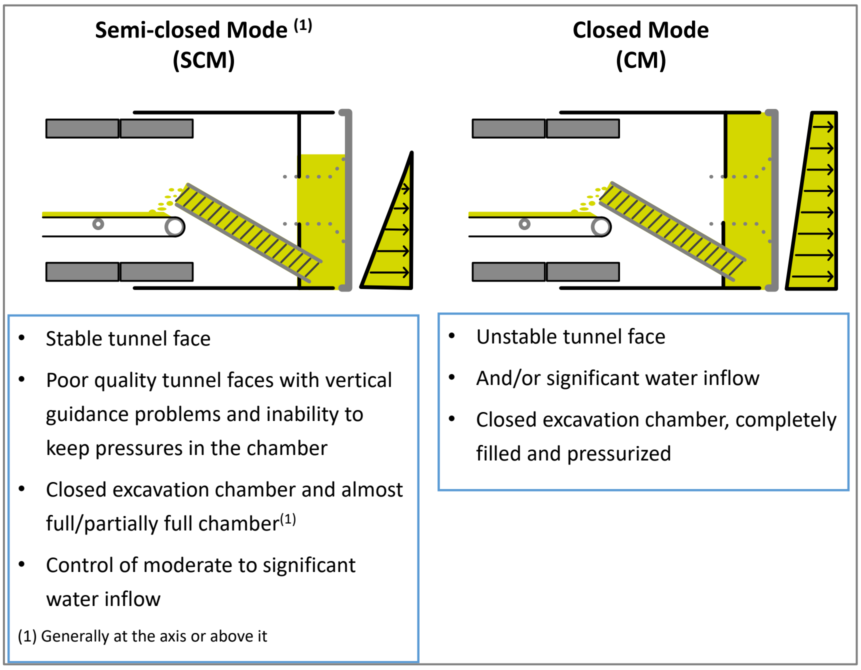

Figure 5. Operation modes of EPB applied on the project.

4. MAIN RISKS FOR TBM EXCAVATION AND COUNTERACTING MEASURES

During the excavation in this project, several risks are expected in relation to the interaction between TBM and geology and the uncertainty on the geotechnical and hydrogeological conditions. The risks and the applied countermeasures are described next.

4.1. Cutting tool overloads and damages in mixed face and blocky ground conditions

The overload of tools takes place mainly due to the transfer of excessive cutterhead contact force on the tunnel face. The risk of overload is higher in mixed face conditions (Figure 7) and in blocky ground conditions (Figure 8). In such conditions impact loads also occur damaging the tools. Typical damages at the Mexico-Toluca tunnel project are shown in Figure 6.

Figure 6. Damage on discs due to overloading and impact loads.

Figure 7. Mixed face conditions.

The formation of block in front of the cutterhead poses a severe risks to the integrity of cutting tools and cutterhead structure if not monitored adequately. When large blocks are loosened at the face (Figure 8), the blocks tend to get trapped between the cutterhead and the tunnel face (Figures 9 and 10). This is especially critical in areas where there are no openings in the cutting wheel. The accumulation of blocks generates secondary wear on the tools and increases the probability of damage due to impact loads or blockage and not only of the discs but also on the scrapers and buckets.

Figure 8. Block formation at the tunnel face.

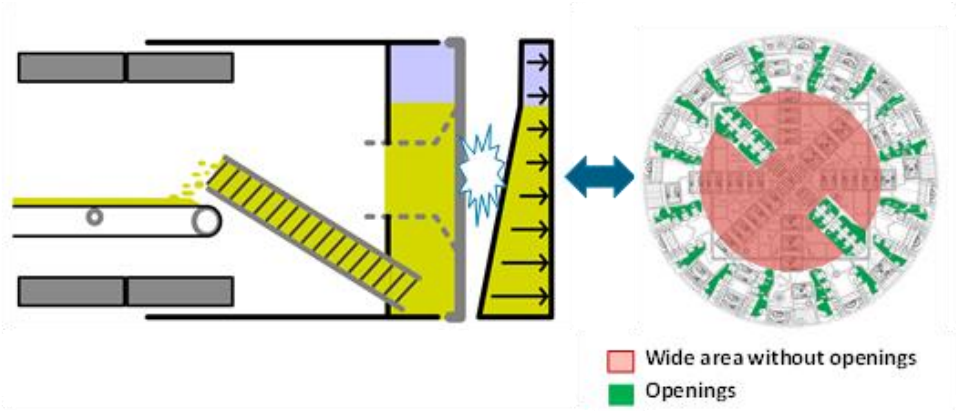

Figure 9. Risk zone on cutter head due to material accumulation with blocks.

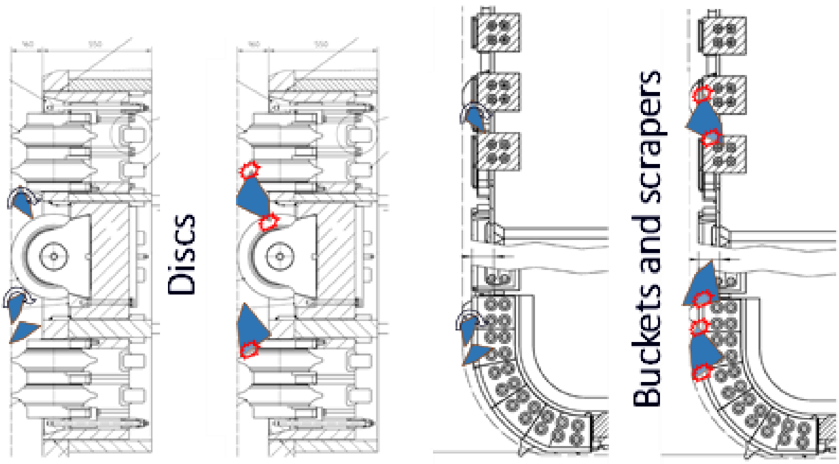

Figure 10. Representation of the effect of block sizes on damages to tools due to accumulation of material in front of the cutterhead.

The measures to counteract these risks are:

- Installation of a metal detector in order to reduce the reaction time
- Visually control of the excavated material directly at the conveyor belt in order to:
    - evaluate the type of geology
    - the size of the rock chips
    - size of blocks (small < 15 cm, medium 15 to 25 cm, big 25 to 40 cm)
- Real time adjustment of the excavation parameters, based on the visual control at the conveyor belt according to the criteria defined in Table 4.

Table 4. Shield operation criteria to avoid cutting tools overload

	Weathered rock and sound Andesite	**Fractured Andesite with small blocks**	**Fractured Andesite with large blocks**
Contact force cutterhead	< 12.000 kN	< 10.000 kN	< 10.000 kN
Penetration	No particular limitation	< 10 mm/rot	< 8 mm/rot
Cutterhead rotation speed	No particular limitation	< 2.5 rpm	< 2.2 rpm
Muck level in the chamber	The lower the better	The lower the better	It is critical to maintain well below axis
Specific energy	Optimum < 60 MJ/m^3	< 120 MJ/m^3	< 120 MJ/m^3

4.2. Geological faults

Geological faults consisting of open discontinuities are also encountered unexpectedly on the tunnel face and with several meters extension (Figure 11). In such conditions operation in pressurized mode is not feasible and proper conditioning of the muck is not too effective since the conditioning medium escapes through the discontinuities. Also additional grout must be injected in the annular gap to compensate for the grout loss that takes place through the discontinuities.

Figure 11. Encountered discontinuity in the rock mass (Left: view against drive direction above the shield; Right: view in drive direction at the face).

4.3. High water inflow and muck fluidification

During the excavation process it is very important that the material does not come out very fluid to avoid spills of material by the conveyor belt and so it can be transported to the tunnel portal and to the final disposal. When the muck is very fluid it is difficult to control the extraction of material through the screw conveyor and it spills on the segment feeder which implies losses of time for cleaning and notorious losses in the daily production. Additionally, fluid muck impedes to generate a plug in the screw conveyor required to control confinement pressure in the excavation chamber.

A large part of the project has high pressures and high water flows which increases the risk of fluidification of the material (Figure 12).

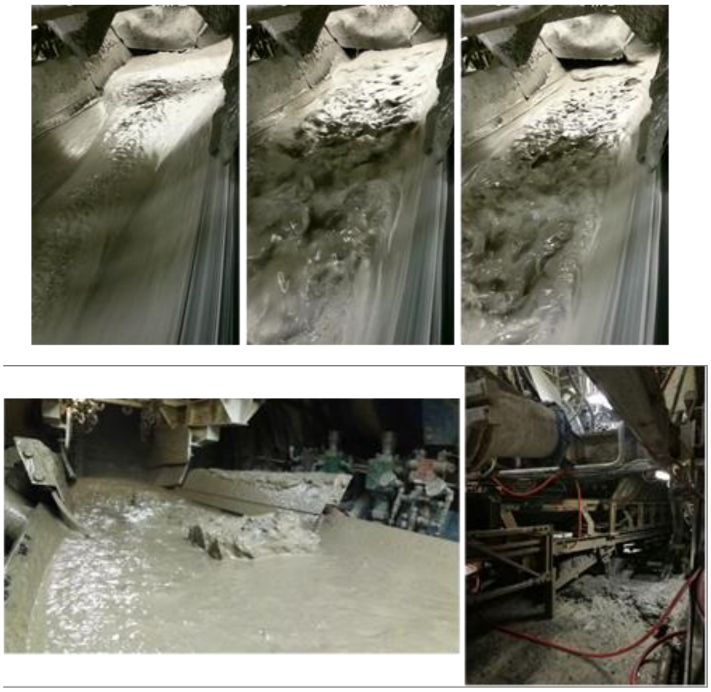

Figure 12. Fluidification of the excavated material due to excessive water inflow.

The measures to counteract these problems are:

- Increase the support pressure and keep it above the hydrostatic pressure of the ground both in advance and during stop. This is feasible in TMA as shown in Figure 14 that illustrates an advance with confinement pressure of 5.0 bar in the excavation chamber (upper coloured curves) and with a plug in the screw, i.e. the pressure sensor at the rear of the screw measures 0 bar (red line) and the screw turns at approximately 10 rpm (purple line). We note that the average advance speed in this advance was 45 mm/min.
- Adjustment of the conditioning scheme according to Figure 13. Additionally to the conditioning with dry foam (high FER) at the cutterhead, polymer is injected into the excavation chamber through lines at the bulkhead. Figure 14 shows the condition of the muck at the screw discharge with the above mentioned conditioned scheme working with a confinement pressure of 4 bar in the excavation chamber.
- The periodical injection of polyurethane foam has shown its effectiveness to stop the collection and water flow generated from the tunnel along the TBM until the excavation chamber and it is a measure that is being implemented in the project.

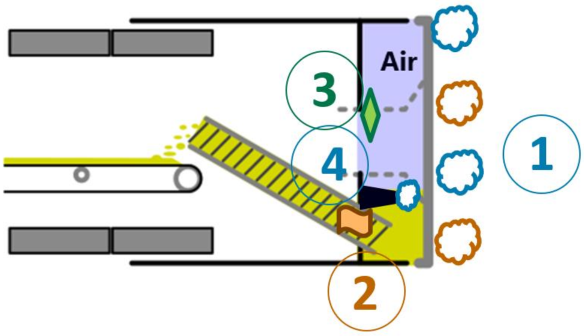

Figure 13. Conditioning scheme for operation in TMA with high groundwater pressures.

(1. Foam and bentonite conditioning at the cutterhead; 2. Bentonite injection at the screw conveyor; 3. Polymer injection through the bulkhead; 4. Foam injection through the stators at the bottom of the chamber).

Figure 14. Muck discharge at the screw conveyor with conditioned material forming a plug in the screw with 4 bar of confinement pressure in the excavation chamber (no fluidification).

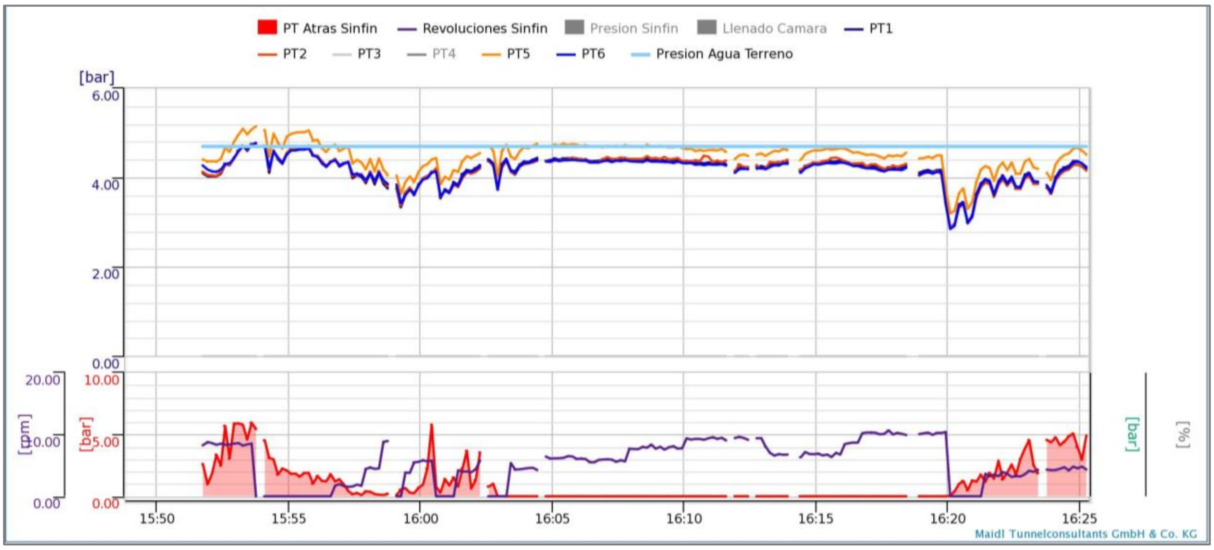

Figure 15. TMB operational data with confinement pressure 5 bar and a plug in the screw.

4.4. TBM vertical steering at constant alignment slope

The tunnel alignment has an almost continuous slope of 4.0 %. Therefore maintaining the vertical steering is crucial for the project. The problems with the vertical steering arise when the material at the tunnel face is soft (Soil, soft Breccia) or when the rock mass is highly fractured and mainly when excavating in open mode or with a very low level of material in the excavation chamber.

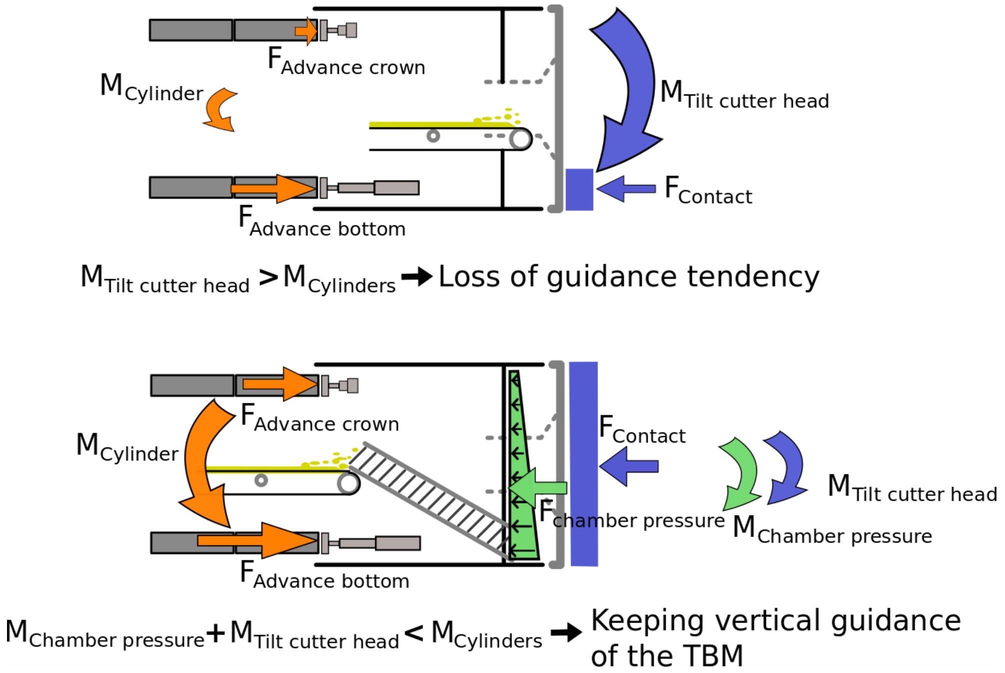

Figure 16. Effects achieved with the pressurization of the chamber.

The cause for difficulties in the TBM vertical steering are schematically illustrated in Figure 16. The tilt moments $M_{tilt\ cutterhead}$ and $M_{chamber\ pressure}$ produce the downward tilting effect on the shield that must be counteracted by the control of steering forces. The difference between the top and bottom thrust cylinder forces generates the counteracting tilt moment $M_{cylinder}$. Problems arise in soft grounds where it is not possible to apply high thrust forces, so $M_{cylinder}$ is relatively low compared to the acting TBM tilting moments. Additionally, in soft grounds due to the intended steering correction, the resultant of the cutterhead contact force is located in the lower third of the cutterhead (Figure 16 top). Also when operating with an unpressurised chamber, the resultant force of earth force is located in the very bottom of the excavation chamber. Thus, despite the forces $F_{chamber\ pressure}$ and $F_{contact}$ being also relatively low, they generate a relatively high lever effect that generates tilting moments $M_{tilt\ cutterhead}$ and $M_{chamber\ pressure}$ higher than the achievable $M_{cylinder}$. Measures that help elevating the position of resultant forces $F_{chamber\ pressure}$ and $F_{contact}$ will help to reduce the resulting tilt moments and to achieve and adequate vertical steering of the shield (Figure 16 bottom). Therefore, pressurizing the excavation chamber either with muck (SCM or CM) or with an air bubble (TMA) allows to counteract the steering difficulties.

Approximately the first 150 meters of tunnels were excavated with a rock type TBM configuration with muck discharge onto the conveyor through a hopper. With this configuration it is not possible to pressurize the excavation chamber since the bulkhead is open at the centre. In this first section of the tunnels, severe deviation of the TBM from the alignment occurred since the encountered brecciated andesite was considerably softer than expected. It was then decided to change the shield configuration to screw conveyor mode which allowed to pressurise the chamber. However, vertical steering difficulties still occur in highly fractured rock mass where it is not feasible to pressurize the chamber with an air bubble (TMA) since pressure is lost through the rock discontinuities.

4.5. Cutter head inspections in high water flow stretch in fractured rock

In stretches consisting of weathered or highly fractured rock, with high water pressures and high water flows it is too risky or practically impossible to carry out an hyperbaric intervention in order to check the cutter head. The filter cake will not be stable and the compressed air will escape putting into risk the divers. In this project there are long stretches with these characteristics. However, whilst all interventions to date have been carried in atmospheric conditions, this has proven also very difficult when large flows of groundwater occur. The large flows of water cannot be evacuated fast enough from the chamber, so the chamber rapidly fill up with water.

Limiting groundwater flows from the rear part of the tunnel has been achieved with the measures shown in Figure 17 and explained next:

- Perform a grout reinjection campaign in several rings behind the TBM
- Next injection of a hardening mud (mud + cement)
- Polyurethane foam injections which have proven their effectiveness to stop/reduce the water flow from the tunnel along the TBM until the excavation chamber (Figure 18)

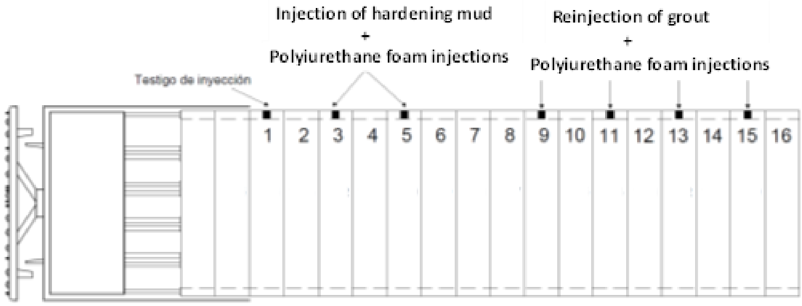

Figure 17. Reinjection campaign to reduce water inflows in the chamber.

Figure 18. Intervention after stop of water inflow.

Other measures foreseen to reduce the groundwater flow coming from the overburden include drilling an umbrella of drains over the shield and over the face from the shield (Figure 19).

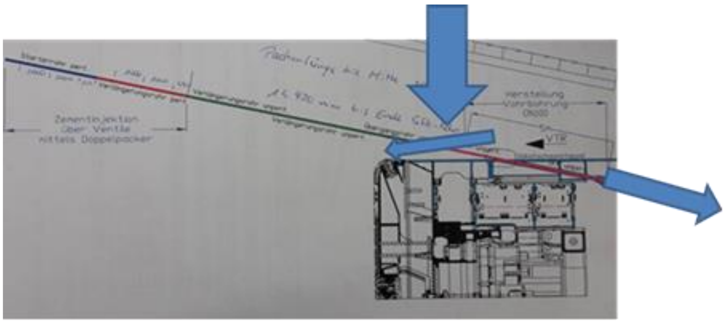

Figure 19. Drilling of drains through the TBM skin.

5. CONCLUSIONS

The Mexico-Toluca project poses a wide range of risks that challenge the applicability of EPB shield tunnelling in unpredictable heterogeneous ground conditions under high groundwater pressures.

Experience gained to date has compelled the Contractor team to implement TBM process controlling systems that allow to monitor the TBM operation and the ground conditions in real time. The threshold for key advance parameters is adjusted continuously depending on the encountered ground conditions.

Shield operation modes and ground conditioning scheme are also adjusted to the ground conditions. To date this has enabled to achieve regular EPB shield excavation with 5 bar confinement pressure in permeable rock mass conditions.