Earth Pressure Balance Tunnel Boring Machines, Experience in Mixed Face Conditions

E. Chiriotti\textsuperscript{1}, P. Jackson\textsuperscript{2}, S. Taylor\textsuperscript{2}
\textsuperscript{1} SYSTRA SA, Paris, France, \textsuperscript{2} COWI A/S, Copenhagen, Denmark

1. Introduction

Constructing tunnels in urban areas for metros and other infrastructure inevitably has some effect on overlying or adjacent buildings and utilities. It is now normal practice as part of the design of such works to predict the settlement that arises from the tunnel construction and to assess the resulting effect on the buildings and utilities. The magnitude of the settlement and the lateral extent are normally predicted and the associated vertical and horizontal displacements can be derived. From the predicted displacements, the tensile strains in the affected structures can be assessed and a damage category derived.

The starting point for these predictions and assessments is usually the total settlement at the surface or the equivalent volume loss and this is associated with the following mechanisms, after Guglielmetti et. al. \[1\]:

- short term settlement caused by the tunnel excavation that is a function of the stability of the face (i.e., face losses) and the rate of advance, the time necessary to install the segmental lining and fill the tail void which is a result of the void (overcut) formed between the cut size of the tunnel and the shield and the closure of the tail void between the shield and the segmental lining;
- settlement caused by deformation of the tunnel lining;
- long term settlement, caused by the residual primary consolidation (stabilisation of the deformations around the cavity) and by the secondary consolidation (creep).

The short term settlement occurs as the tunnel is driven and it can be converted into an equivalent volume loss which may be considered as a combination of face loss and radial loss from the overcut and tail void closure. A significant part of the volume loss can be caused by the radial loss particularly in soils where the overcut is likely to close before the permanent lining and grouting is completed and if the tail void grouting is poorly controlled.

The modern solution to meeting the requirements for small settlements and to manage the risk to adjacent buildings during the construction of urban tunnels is the “City Machine” as described by Guglielmetti et. al. \[1\]. The “City Machine” is a machine capable of providing the necessary face-support pressure (and hence the necessary total thrust and torque), which has to be used in “close mode”. It requires automatic face-support-pressure control facilities, a cross-control system for the key parameters of the machine, probe-drilling ahead of the face, ground treatment facilities, an adequate guidance system, etc. This is often an earth pressure balance (EPB) tunnel boring machine (TBM), as the range of ground conditions that EPB TBMs can be used in has widened thanks to the use of soil conditioning products, as a more extended experience has been gained in their use, and as the management of the tunnel construction process has improved.
However, the successful application of these “City Machines”, particularly the EPB TBMs in soft soils and mixed face conditions, is a combination of the correct machine choice, skilled operators and having the correct management systems in place to ensure that they are operated in the required manner. Despite such machines having been operated for almost 20 years, it is clear that EPB TBMs are not always the correct choice, or that they have not been correctly operated and there have been cases of “unacceptable” settlements or sink holes being formed on a number of urban tunnel projects.

The experience in mixed face conditions from a number of projects is examined to assess the likely range of settlements and volume losses that can be expected and the lessons learned for how the management of the tunnel construction can be used to control the risks of unacceptable settlement is discussed.

2. Operation of Earth Pressure Balance TBMs

The EPB TBM has a bulkhead separating the head from the rest of the machine to form a closed excavation chamber from which the spoil is removed in a controlled manner using a screw conveyor. The design and operation of EPB TBMs and their key features are described by Guglielmetti et. al. [1] and illustrated in Figure 1 below.

![Figure 1 - Key features of EPB TBMs, (from Guglielmetti et. al. [1])](image)

The three parameters that have to be controlled (along with other parameters such as the grouting, steering etc.) are the following:

- **Pressure at the tunnel face**: a number of pressure sensors are installed on the bulkhead at the back of the excavation chamber. If the pressure drops below the predefined value, the operator reduces the rate of extraction of the spoil to bring the pressure back to the defined operational value.

- **Spoil Density**: the difference in pressure between the different sensors enables the density of the spoil in the excavation chamber to be monitored and measures taken to control it, particularly to avoid that bubbles of air are formed in the upper part of the chamber, which could not transfer the required active supporting pressure at the tunnel face.

- **Volume**: the estimation of the volume of the material extracted from the excavation chamber is critical, but it has an uncertainty associated with it. It has been traditionally controlled
through the measurement of the extracted weight (by installing a scale on the EPB belt, which transfers the muck from the screw conveyor to the tunnel mucking system) and through the assessment of the in-situ density of the soil/rock (which requires executing a sufficient number of geological face mapping or probing ahead to confirm/update the design forecast based on available investigation data). Then the extracted volume can be derived and compared with the theoretical excavation volume per ring. Its precision is a function of the precision on the weight measurement and on the density assessment. In spite of its degree of uncertainty, this control avoids excavating beyond the theoretical volume (over-mucking) if it is properly associated with the real-time control of other TBM’s key parameters.

Limitations exist to how and to what precision these parameters can be controlled and thus to how EPB machines can be operated with the consequent reliably that the volume loss or settlement can be controlled. Significant advances have been made in the technology and operation of EPBs in recent years in order to improve on the control, particularly of the face support pressure. These key developments are: (a) the integrated and automatic control of the earth pressure in the excavation chamber, of the volume of the excavated material and of the apparent density of the spoil; (b) a system to inject a bentonite slurry into the excavation chamber to actively control the face support pressure when it drops below the operational range defined for the project; (c) improvements in application of additives in the spoil to control its properties and grading.

These developments are accompanied by a broadly recognised need to put in place effective risk management plans as a general requirement for most of the Owners of underground infrastructures in urban environment. Finally, the availability of geographic information systems (GIS) which permit a real-time follow-up of the TBM advance, of the monitoring instrumentation, of the visual inspections at the surface, of the injections if any, and an integration of the last geological and hydrogeological information, allows a proper cross-check of information (provided that an adequate organisation is present on site) and a timely detection of anomalies in tunnelling. However, in spite of the availability of these recent improvements, there is still a residual risk of unacceptable settlement, which in some cases can lead to sink holes formed by significant over excavation due to face instability. The experience from a number of different projects is discussed below with EPB TBMs operating in mix face conditions.

3. Copenhagen Metro

On the first phase of the Copenhagen Metro (in the period 1998 to 2001) the tunnels were largely constructed in the Copenhagen Limestone, a weak bedded rock that proved to be very suitable for EPB tunnelling machines. However, some sections of the alignment, at the launch and recovery locations and at one location in the centre of the city, required the tunnels to be constructed in the glacial soils or in mixed face conditions. At these locations some difficulties were experienced in controlling the support pressures in the cutter head and at several locations significant over excavation occurred. The difficulties experienced in these sections of tunnel illustrate the technical risks associated with tunnelling in mixed face conditions and the difficulties in managing the work to ensure that the appropriate protocols are followed.

Prior to the first phase of the Copenhagen Metro there was very little local tunnelling experience and the only deep tunnels being constructed in the Copenhagen area were: three utility tunnels beneath the harbour constructed in the early 1900’s; the southern harbour tunnel from 1921 (Sydhavntunnelen); the Svanemøllen sewer tunnel constructed 1939-1945; a heating tunnel beneath the harbour in the 1970’s. These tunnels are described by K. Hansen [2] with the tunnels being constructed as mined excavations. No TBM tunnels were constructed in the area until the first phase of the Metro. Since then, two further local TBM projects have been undertaken, the Distrcit Heating Tunnel (Fjernvarmetunnelen) in the period 2006 to 2007 and most recently the Malmö Citytunnel, which has quite similar geological conditions to those in Copenhagen.
The existing Metro running tunnels were constructed with two NFM EPB machines predominantly in the Copenhagen limestone. A long section of the alignment is shown in Figure 2 and the construction of the tunnels is described by S. Polycarpe & J. Maucorps [3]. The TBMs were generally operated in a semi closed mode (maintaining the plenum either totally, or partially empty, without applying a confinement pressure and controlling the pressure at the tunnel crown) in the limestone with a foam injection system to help condition the material in the cutter head. The cutter head was not kept full in this operational mode, but the foam injection and the partial filling of the cutter head provided together with the screw conveyor, a method to balance the hydrostatic pressure and prevent too much water entering the head. This enabled the moisture content of the spoil to be kept sufficiently low for handling on the belt conveyor for conveyance to the muck wagons. If the machines were operated in fully open mode, too much water entered the head.

There were several sections of tunnel in mixed face conditions, (Limestone/Quaternary deposits) these were short sections at the launch and reception locations together with a significant section in mixed face conditions beneath the Inner Lakes. The final section of the tunnels to the reception shaft at Falkoner Allé was in mixed face conditions for quite a long length. These two sections of mixed face tunnelling are discussed below.

### 3.1 Inner Lakes

Beneath the Inner Lakes the first phase of the Metro passed through a major fault zone (Rådhuspladsen fault) where there is a depression in the limestone surface which is filled by relatively coarse Quaternary deposits.

The location of the interface between the limestone and the Quaternary deposits had been extensively investigated and the location where the TBMs were to be operated in fully closed mode was defined together with the TBM operational parameters in detailed method statements. The Quaternary deposits were encountered within the expected zone, but in spite of this, a major over-excavation event occurred when the Quaternary deposits were encountered which led to the formation of a sink hole and a loss of compressed air to the lake surface. This over-excavation continued for some length of tunnel until it could be brought under control.

In contrast, when the second TBM reached this location, there was significant focus on this issue and it was ensured that the cutter head was full, the TBM operating protocols being adhered to and no over mucking occurred when the mixed face conditions were encountered. The second TBM drive through this area was able to be carried out without the same problems being experienced.
3.2 Hostrupsvej to Falkoner Allé Section

Mixed face conditions were encountered during the final section of the tunnel drive between the Hostrupsvej shaft and the Falkoner Allé reception shaft. This was a section of approximately 300 m in length located at the left most section of Figure 2. The Quaternary soils that overlay the limestone in this section were quite heterogeneous with meltwater sand, and clay till directly overlaying the limestone.

Significant over-excavation was experienced when the first TBM encountered the Quaternary deposits but once this initial zone was passed the TBM was able to perform as expected with no further over-excavation. The event where the over-excavation occurred did not result in significant surface settlement as the stiff clay till arched over the voids and these voids were later filled by grouting from both the surface and the tunnel. Again the second TBM passed through this area without any significant problems and performed as expected. Surface settlements were observed to be approximately 10 mm. This was well within the predictions and would approximate to a volume loss of approximately 0.5 %.

4. Porto Metro

The Porto Metro is a light rail system consisting of 70km of line, among which almost 7km consist of double-track, single-tube tunnels (internal diameters of about 8.0m) in the city centre. Tunnels were excavated using Herrenknecht EPB-TBM, in the period 2000 - 2004.

The average overburden thickness ranges from 15-30m, with the minimum value of 3-4m in the centre of the city and under pre-existing buildings). The geologic horizon is composed of heterogeneous materials (Porto's granite) with rapidly changing properties within short distances. The weathering profile of the “Granito do Porto” ranges from residual soil to weathering granite, maintaining the original structure, to sound, fairly fractured granite. It is characterized by the irregular presence of corestones, faults, pegmatitic dykes, and loosened horizons. The weathered granite exhibits a local, metastable structure that may generate a high potential for instabilities, depending on the high porosity and reduced cohesion of the residual soil (Grasso et al, [4]). The ground may follow an elastic-brittle-plastic behaviour, leading to sudden, unforeseeable failures at the surface, if the ground is not adequately supported or if over-excavation is allowed. The hydrogeological setting is characterized by the presence of preferential flow channels (both natural and artificial), which locally facilitates sudden recharges of the water table. The water table is located at a level of 10-25m above the tunnel.

The first tunnel stretch began in June 2000 but was soon interrupted due to three major sink holes in October (affecting the ground floor of a building, through a presence of a buried water well, which had been identified already at the design stage), December (affecting the basement of a building under construction) and January 2001 (causing the sudden collapse of a small house and a fatality), after the excavation of 500m of tunnel, that is almost in the learning curve of the TBM. The last sink hole occurred 50m behind the tunnel face and the time elapsed between the passage of the TBM and the collapse was in the range of 25 to 28 days. Settlement registered at this building before the accident were limited, being less than 10mm and showing a trend of stabilization, which implies that the ground exhibited a brittle behaviour.

All the accidents occurred in mixed face conditions (sudden changes at the tunnel face, from sound granite to weathered granite and cohesionless residual soil), with the EPB TBM advancing in semi-closed mode (practically in open mode, since the excavation chamber was filled for only 2/3 of the height) due to problems in setting a proper conditioning system of the excavated material in the working chamber. The sudden changes of the geology were not followed by a quick operator response adapting the advance mode, emphasizing the need of setting automatic and redundant controls on the TBM. Settlements before all the collapses remained in the range of
few millimetres. A follow-up team on site involving the designer was not present, or limited to observe the values of surface and building settlement, which were obviously not relevant, if not correlated with the TBM data and in-ground monitoring.

The collapses obliged to deeply and critically review all the tunnelling process, from the construction design to the excavation procedures and equipments, to the overall organisation of the project. This process was started with a deep review of the project’s risk analysis which lead to the implementation of a comprehensive real risk management plan (RMP). The revision of the risk analysis identified two key parameters: (1) adoption of the correct method of excavation as a primary countermeasure for limiting instability and collapse; in particular, in an extremely heterogeneous environment the risk of accidents due to human errors in reacting to a sudden face condition change still remained and this kind of risk was considered unbearable for the project; the design requirement of working always in closed-mode was established and the impact of adopting always the closed-mode on both advance rate and completion date was corrected by a different distribution of the excavation length between the two EPB-TBMs. (2) a strict control of the secondary countermeasures for controlling the residual risk and for limiting the eventual instability.

Several actions were required for applying the RMP requirements to the construction phase (Guglielmetti et al [5]): (a) select additional the key parameters of the TBM to be strictly controlled by defining their allowed intervals of operation; (b) installation of an Emergency Double Piston Pump (EDDP) after the screw conveyor in order to deal with liquid muck and uncontrollable support pressure oscillations; (c) installation of a second belt scale in order to cross-check the results of the first one; (d) installation of a Secondary Face Support System (SFSS), an automatic system which injects bentonite in the excavation chamber if the face support pressures decrease beneath the pre-defined values; (e) installation of an alarm system in the TBM-driver cabin that is activated when threshold values of extracted material, face pressure, etc. are exceeded or not met (alarm for trespassing the extracted weight upper limit, which automatically stopped the advance; alarm for trespassing the face support pressure lower limit, which automatically switches on the SFSS; alarm for trespassing the muck apparent density lower limit); (f) elaborate the TBM operating procedure to ensure the correct use of the construction methodology, which also include actions and information flows to face anomalous events; (g) create a follow-up team composed of the Designer and representatives of the Contractor to systematically interpret and cross-check the key parameters and to manage the interface among the process of design, construction, monitoring, and design modifications; (h) use a GIS-based system for supporting the project interfaces at the level of design, construction, monitoring, interpretation and back-analysis, with real-time access to the system given to all the involved Parties.

Thanks to the implemented RMP it has been possible to achieve the following results which do not require comments: handle the ground heterogeneity (from loose soil to hard rock) with increased confidence, no more collapses and maximum settlements of the order of 3-8mm (volume loss < 0,5%); enhance the TBM production always maintaining the highest safety standard; excavate underneath very sensitive buildings, in the centre of the town, with a cover reduced down to 3,7m in residual soils without causing any significant settlement.

5. Published Case Histories

Experience and the observed settlement from only a limited number of projects has been reported in the literature. Shirlaw et al [6] reports the experience from the construction of the Singapore North East Line and compares this with published information from other projects where EPB TBMs have been used. The Singapore ground conditions are variable with Holocene and late Pleistocene clays and old alluvium overlying weathered sedimentary rocks or weather granite. The tunnels were largely constructed in the weather sedimentary rocks and granite with the weathering being highly variable. Shirlaw et al [7] presents a summary of the measured
volume losses from EPB during the North East Line tunnel construction. The data reported shows the following: most of the observed settlement (approx 55% of the measurement points) was very small, equivalent to a volume loss of 0.5% or less; a small number of settlement measurement points indicated volume losses in the range 2 to 3%; there were 20 incidents of very high local ground losses (sinkholes) that were not reflected in the settlement measurements.

Shirlaw et al [6] states that as measures were taken to limit the settlement due to poor grouting or excessive overcutting, the face pressure used was a major factor in magnitude of the measured settlements. Shirlaw et al [6] recognised, and this is discussed also by Guglielmetti et al [1] & [5], the variation in the face support pressure during an excavation/ring build cycle and its influence on the stability of the face and the consequent volume loss. Shirlaw proposes that the volume loss in soils increases exponentially with reducing face pressure and that the effect of transitory pressures lower than the typical face pressure is significant. In mixed face conditions, sinkholes were reported to have occurred and the reasons stated for them was that the necessary change in face pressure at the transition between the different formations was not correctly implemented although the transitions had been identified from the site investigations. Shirlaw et. al. also notes that several instances of excessive ground losses or sink holes occurred on one contract where only water was used for soil conditioning and that plugging of the cutter head was occurring and high wear was experienced. The cutter head was not kept completely filled and face pressures were low, thus the risks of sinkhole formation and of significant over excavation would be high.

Published experience of the operation of EPB machines on a number of projects has been reviewed by Shirlaw, where similar problems with mixed face conditions were encountered. Among them the case of Storebaelt tunnels, Denmark has also been discussed. The construction of the Storebaelt twin 7.7 m railway tunnels is described by Doran & Athenoux [8] where the tunnels were constructed in heterogeneous glacial soils with a high hydrostatic head. Doran reports that the glacial tills had a sufficiently high clay content to maintain a stable face. Then, the TBMs were operated in open mode with the cutter head approximately 70% full of spoil. However, in the soil with lower clay contents and in the glacial sands the spoil in the cutter head did not have suitable properties to allow the face pressure to properly balance the earth and ground water pressures. When sand bodies were encountered significant over excavation occurred and chimneys were formed to the sea bed. A series of attempts were made to break the connections by operating the TBMs in closed mode at pressures in the range 2.3 to 2.5 bars. This was however not possible with the torque limit of the TBMs being exceeded, with the blocking of the central part of the cutter head occurring, and with the screw conveyor to control the pressure in the cutter head. A major dewatering exercise was carried out to reduce the ground water pressures and the tunnels were able to be completed within the limitations of the TBMs. Doran describes difficulties of operating the Storebaelt TBMs in the challenging mix face conditions with high water pressures with the TBM technology of the 1980’s. Many of these difficulties have been resolved with modern EPB however the maintenance of the face pressure particular in mix face conditions and at high ground water pressures remains a challenge.

6. Discussion

The case histories from the Copenhagen Metro, Singapore North East line, Porto Metro and other projects illustrate the difficulties of reliably maintaining acceptable low volume losses and settlements particularly when operating EPBs in mixed face conditions, leading to a certain number of events where over excavation occurs (unacceptable settlements or formation of sink holes). The reasons for these over “excavation events” are either that: (a) the face pressure has not been correctly controlled, (b) the density of the spoil in the cutter head is insufficient, (c) the conditioning of the spoil is not adequate, or that (d) the cutter head has not been maintained full (non application of the excavation procedures or limitations imposed by the limited torque of the TBM which was not properly dimensioned for the considered project). It apparent that, despite the advances in TBM design, without particular attention being paid to managing the TBM operations
the risk that the volume loss is not correctly controlled is significant and much higher than is acceptable to the industry, clients and stakeholders.

The ways to improve the management of the TBM operations are now well known (Guglielmetti et. al. [1]) and consist of: (a) proper dimensioning of the EPB TBM, selection of its equipment and preliminary characterisation of the conditioning agents to be used in the working chamber based on an accurate preliminary assessment of the project risks; (b) implementation of working procedures covering all the tunnelling phases to ensure that the TBM operations are carried out in a consistent and controlled manner; (c) set up of an integrated follow-up team between the Contractor and the Designer to manage the design, construction, monitoring and review process; (d) detailed TBM advance plans (Protocol for Advancing the Tunnel: PAT) prepared for each section of tunnel by the review team, so that all parameters and design issues are effectively addressed prior to tunnelling work commencing; (e) implementation of secondary mitigation measures to ensure that the correct face support pressure is applied. This includes a Secondary Face Support System (SFSS) that can automatically pump bentonite slurry into the cutter head to maintain face support pressure; (f) installation of adequate instrumentation to monitor the pressure in the cutter head, the apparent density of the spoil in the cutter head and the weight of spoil on the conveyor belt, with automatic alarms set on pre-determined operational ranges of the key parameters along the tunnel alignment, and which are subject to the review process; (g) installation of an emergency double piston pump (EDPP) at the secondary discharge gate of the screw conveyor in order to deal with unforeseen support pressure fluctuations.

7. References