"Process control in mechanized urban tunnelling"

By Vittorio Guglielmetti

1. Introduction.

Tunnelling is a complex process, and tunnelling in urban areas is even more complex and needs special care for disturbing as little as possible the integrity of the ground surface and the built-up environment above.

Nowadays we have a powerful method for excavating tunnels in urban environment: the use of Tunnel Boring Machines (TBMs) or "mechanized tunnelling", due to the low disturb of the daily activities of the cities, assuring at the same time quality, safety, and the project's target in term of time & cost.

Furthermore, tunnelling by using Closed-face Machines (which is necessary in urban environment) is "factory" like, not the "mining" type. This means a safer work environment for the workers, but also a more industrialized process, which is based on standard operations during working cycle, being thus possible or even let say "easy" to control.

A robust control system for the excavation process is necessary for being ready to react *in time* to anomalies situations, based on the analysis of various parameters, but of course not on the direct analysis of the ground conditions, because excavation face is not visible, when tunnelling with Closed-face Machines, except during maintenance interventions into the working chamber.

The operating control system is so important, that the British Tunnelling Society in its book "Closed-face Tunnelling Machines and Ground Stability – a Guideline for Best Practice" (Thomas Telford Publishing, 2005), has written:

"The correct choice of machine
operated without
the correct management and operating controls
is as bad as choosing the wrong type of machine for the project"

(BTS/ICE, 2005)

2. Why to control?

All existing guidelines for underground works require:

- *A Solid Design* based on site investigations, geotechnical interpretation, design calculations and necessary studies
- The *choice* of the most appropriate *excavation method*
- A *Monitoring Plan* with definition of threshold values for the key parameters to be checked during construction
- Detailed *Technical Specifications* & *Method Statements* for construction

In addition to all this, for assuring the necessary performance to the project it is needed:

- An *Experienced Contractor*
- *A Designer Representative* on site to follow the implementation of his design
- A *Resident Engineer* responsible for construction supervision

Clearly, all of the above elements are necessary, but they are not enough.
Too much incidents have been experienced, when excavating in urban environment, and collapses can heavily injure third parties and/or cause serious damages to people and private properties.
We shall wonder ourselves why do accidents occur, despite we are following correct rules and guidelines, and we are using the right methods?
The causes can be many and various like, among others:

- *Variability & uncertainty in geological, geotechnical and hydrological conditions,*
- *Deviation of ground behavior from predicted*
- *Lack of excavation process control, due to:*
    - *Lack of timely interpretation of monitoring data;*
    - *Lack of (adequate) counter-measures;*
- *Human factors*.

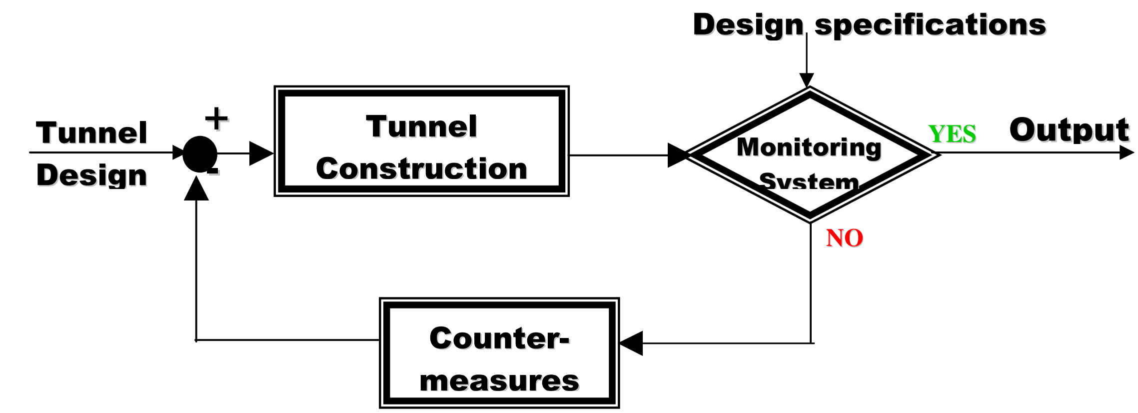
Due to the first two points, a probabilistic approach is necessary, based on a rigorous *risk analysis,* which, starting from a *Robust Design* not based on deterministic parameters values*,* lead to identify and evaluate all the possible hazards and their relevant probabilities and consequences.
After that, for facing the other points, a complete and effective **process *control system*** shall be implemented, which include:

- Design *a Monitoring Plan,* with definition of *Thresholds* for the key parameters to be measured and controlled;
- Predefine the *counter-measures,* necessary in case of anomalies should occur or thresholds should be trespassed; and prepare an appropriate mechanism for their *activation*;
- Collect in *real time* the monitoring data and share them among all people involved, in order to:
- Take the *Right Decision* at the *Right Time*.

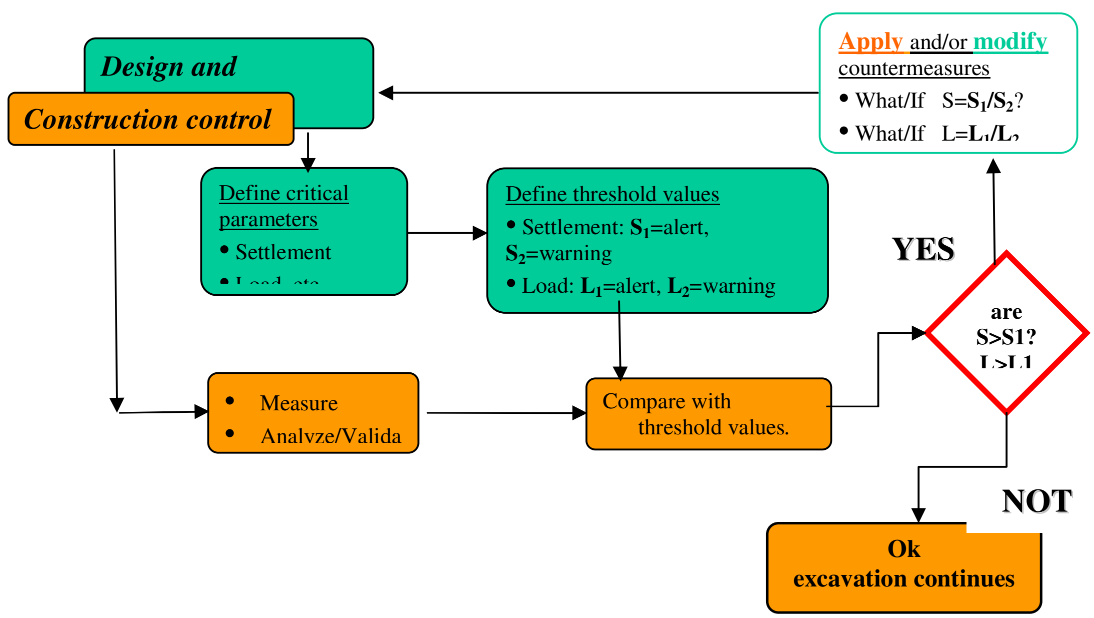
The theory states that in a control system, the output of a process is fed back through the measurement of the output parameters which have to be compared with reference values; the result of comparison shall be to verify that the output parameter values are included into the operational ranges (between the minimum – maximum thresholds).
The *controller* then takes the *error* (i.e. the difference between the output and the reference) for changing, if and when necessary, the inputs to the system under control, with the aim to get back the output values into the correct range.
Of course, when the process is complex like Tunnel Construction, things get harder, but let say, even more necessary.
So, for measuring the output data, we need a monitoring system, which is generally made by two parts: one for surface monitoring, and one for underground monitoring.

It is absolutely necessary to integrate all the data in one data-base, which collect and record

1. Monitoring data of surface and utilities;
2. Monitoring data of buildings;
3. Environmental monitoring (air, noise and vibrations);
4. Hydrological data (piezometers reading)
5. extenso-inclinometers measurements
6. Underground data, i.e. TBM parameters



There are usually a huge quantity of data to be examined in real time, plus a quantity of recorded data to review and compare for understand what has happened and what to do for obtaining the desired results.
What is important is to have in mind that the data logger with all its recorded data is working like a flight recorder (the black-box of the airplanes), but we shall have the presumption to use these data not only to understand the causes of an incident, but for avoiding it.
The purpose of our control system is to prevent accidents, not to explain them "a posteriori", looking for a possible guilty (too often identified in the "unforeseen and unforeseeable" behaviour of the ground).

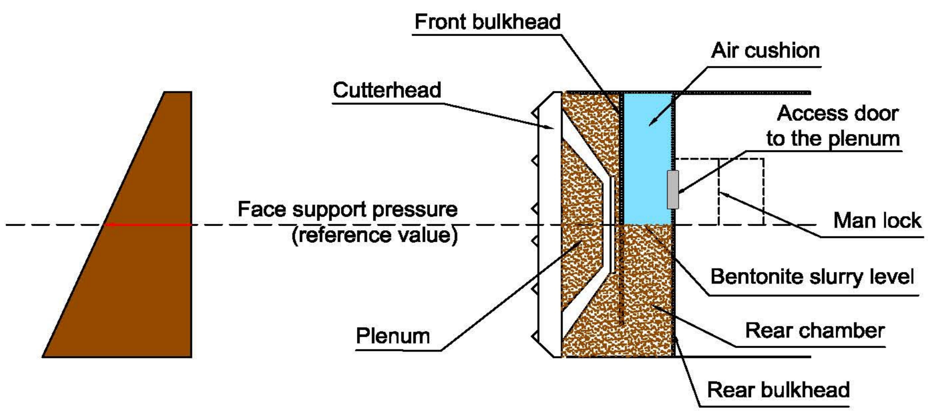


The control system activation gives real-time warnings to the process controllers, even before the threshold values are being exceeded, when their *trend* is showing a tendency to the limits, thus allowing the prompt adoption of counter measures.

3. What and How to control?

Urban Tunnelling means to use Closed-face-Machines, i.e. Slurry or EPB TBM.
Let us look at which parameters and in which way we can control the excavation process in the two types of machine.

SLURRY SHIELD CONTROL



The following are the key excavation-parameter values to be measured on the Hydroshield (or Slurry Shield, like it is called generally today)

Parameters	Control system
Pressure at the face:	
Compressed air pressure and slurry pressure	TBM automatic system plus slurry level control
Slurry level in the chamber	Automatic (or manual) control system for feeding and extraction pumps
Quality of the slurry:	
Viscosity, Yield value, density, cake thickness	On site laboratory
Quantity and quality of mucked material	Calculations derived from double measurement system (density and flow) as well observations at the treatment plant
Segment mortar grouting	Injection pumps, manometers and automatic control system

It would be interesting to examine some activities to be done when "anomalies" occur during excavation.

- **i - The pressure in the chamber decreases.**

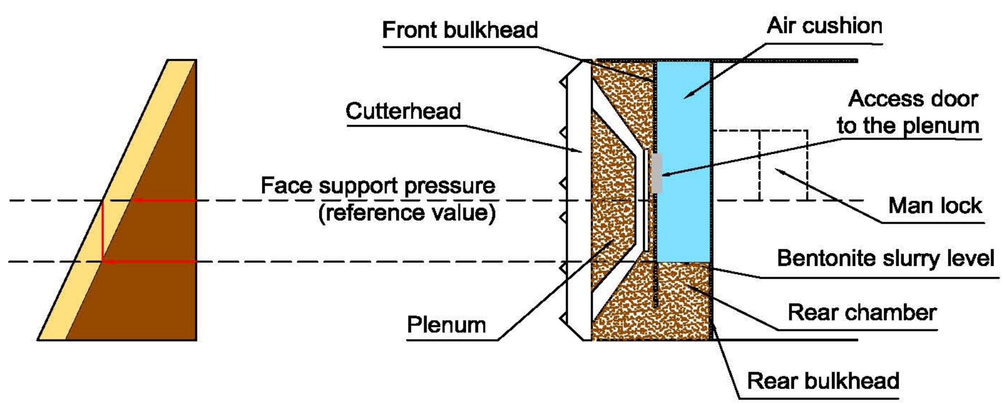
This implies a loss of bentonite slurry. The regulating system increase inflows of compressed air. The level of bentonite has to be corrected to the previous value, operating by means of the feeding pump and/or the discharge pump.

- **The pressure in the chamber suddenly increases**.

This means that there is a possible inflow of excavated ground into the plenum. The system reacts by discharging compressed air. The bentonite level must be immediately recovered and kept under control. The volume of mucked material shall be checked: it must be the same or less than the theoretical value.

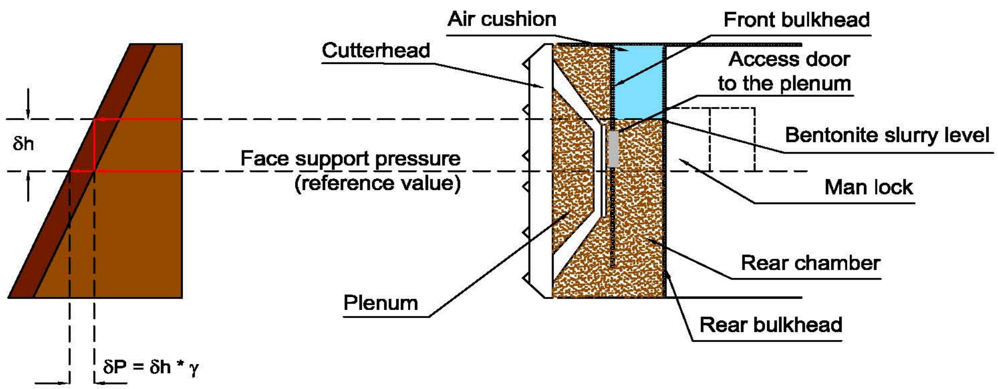
- **iii - The slurry level in the chamber decreases. (1)**

Loss of slurry – and consequently loss of the relevant pressure – could be caused by ground fissures, ancient wells, open piezometers, and unsealed boreholes. In this case, the slurry level could drop below the bottom of the "front bulkhead", and the air flow into the upper front section, just against the excavation face and the support of slurry cake could be eliminated. This condition could be manageable in case the compressed air pressure is kept constant (no escapes) due to the low permeability of the encountered soils. Excavation can go ahead by taking special precautions: reducing muck flows and feeding the chamber with bentonite slurry with higher Yield value and density. On the other hand, when sandy soils or soils with higher permeability are encountered, air could escape through the ground and the front becomes unstable
Additional air is pushed into the chamber by the automatic compressed-air regulating system. The slurry level must be increased to the correct figure; otherwise, the confinement pressure will give an insufficient value (see Figure). Therefore, the corrective measures shall be implemented: increasing the inflow through the feeding pump and, if necessary, decreasing the flow of the return pump).



- iv - **The slurry level in the chamber increases.**

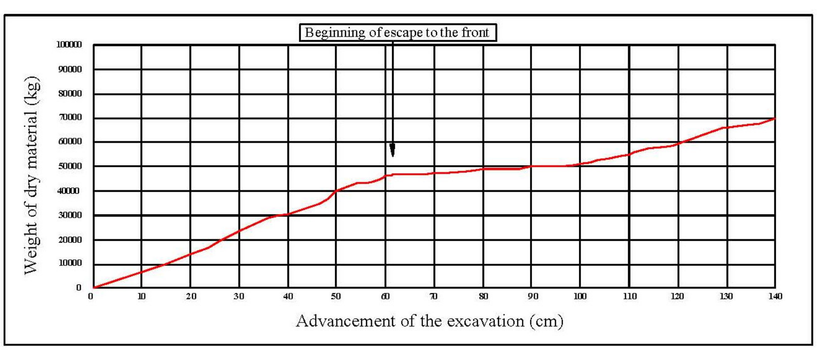
The automatic regulating system discharges air. The slurry level must return to the correct value, otherwise the pressure will increase.



This could be a very dangerous situation as consequence of material entering into the chamber due to a face collapse. Another possible cause could be some difficulty into the discharge line (see next point).

- **v - The extracted soil quantity is smaller than the theoretical.**

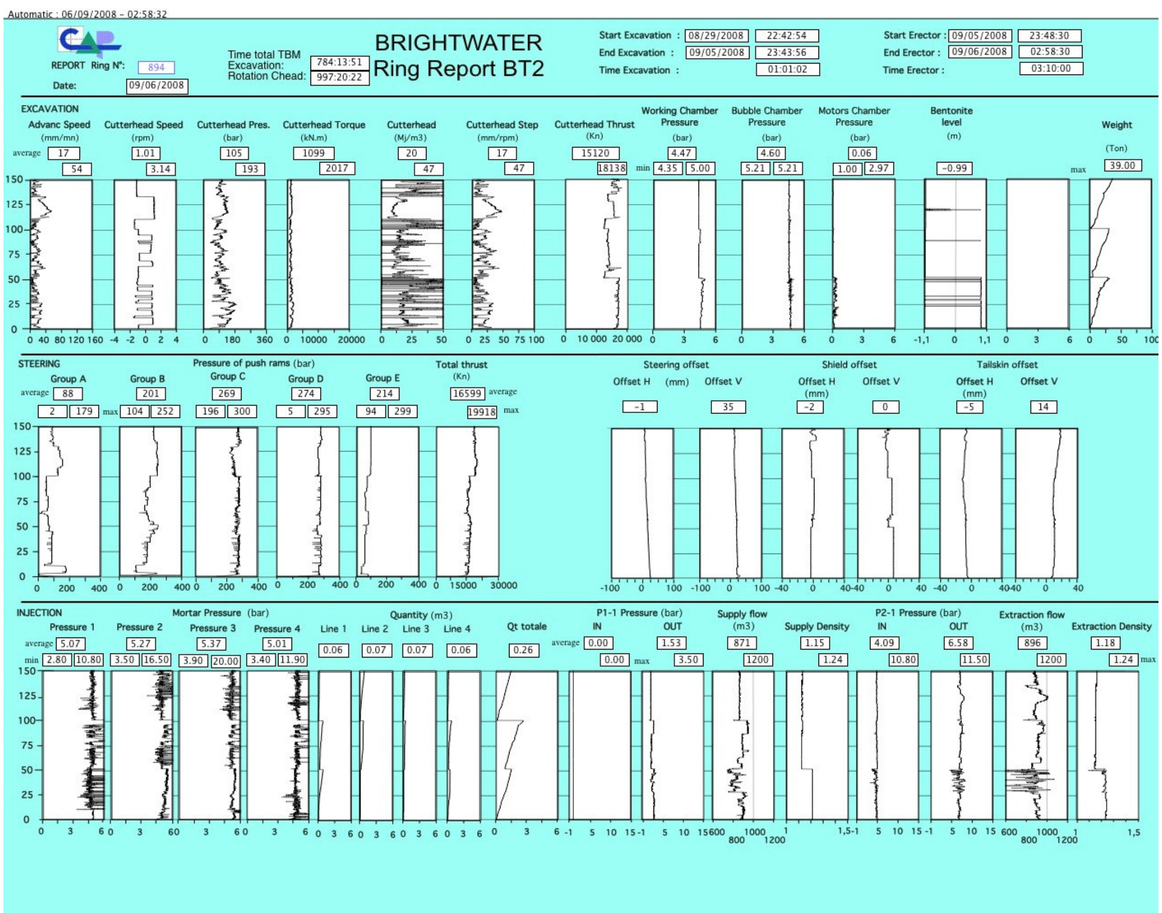
It is necessary to check whether less dense in-situ soil is encountered or obstructions (like boulders or plugging) appear in the chamber suction zone or along the return circuit. In the latter case, the obstruction must be localised and the relevant pipeline section cleaned (and the TBM temporarily stopped). Otherwise, high-pressure water jets, installed close to the chamber suction point, could be used for cleaning the obstruction. In some cases, the slurry flow could be inverted as well, using the circuit by-pass. But the crusher (potentially present inside the chamber) could be an obstacle to this jetting operation and, furthermore, specific combination of the size of boulders and the soil consistency could make this measure inefficient. Therefore, access to the chamber could be required.



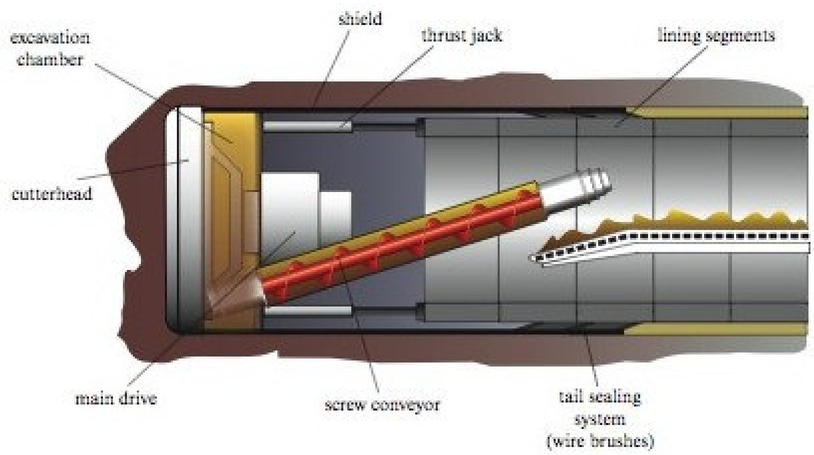
The extracted soil quantities are higher than the theoretical values.

A cross-check between the pressure and the slurry levels in the chamber is mandatory to verify the face stability. In fact, such an event could provide a warning about the potential

existence of a chimney. It could even create or increase the effect of chimney. Advance speed must be immediately reduced and the return pump-flow reduced, eventually increasing the feeding flow as well.
A significant change of inclination of the graph showing the dry quantity of extracted material, can signify two equally dangerous things: (a) the beginning of a *loss* of slurry out of the face into the surrounding ground, with consequent loss of extracted material, or (b) the start of a blockage on the out-pumping system due, for instance, to boulders at the aspiration point, or the formation of blockages along the first stretch of the pipeline.
Conversely, a sudden increase of slope of the curve, which is less frequent but even more worrying, would signify a sudden unexpected "ingress" of solid material in the chamber, i.e. the possible beginning of face instability with the danger of collapse, or at least the beginning of an over-excavation.
The most adequate control consists in verifying the successive mortar grouting parameters
in the affected area.

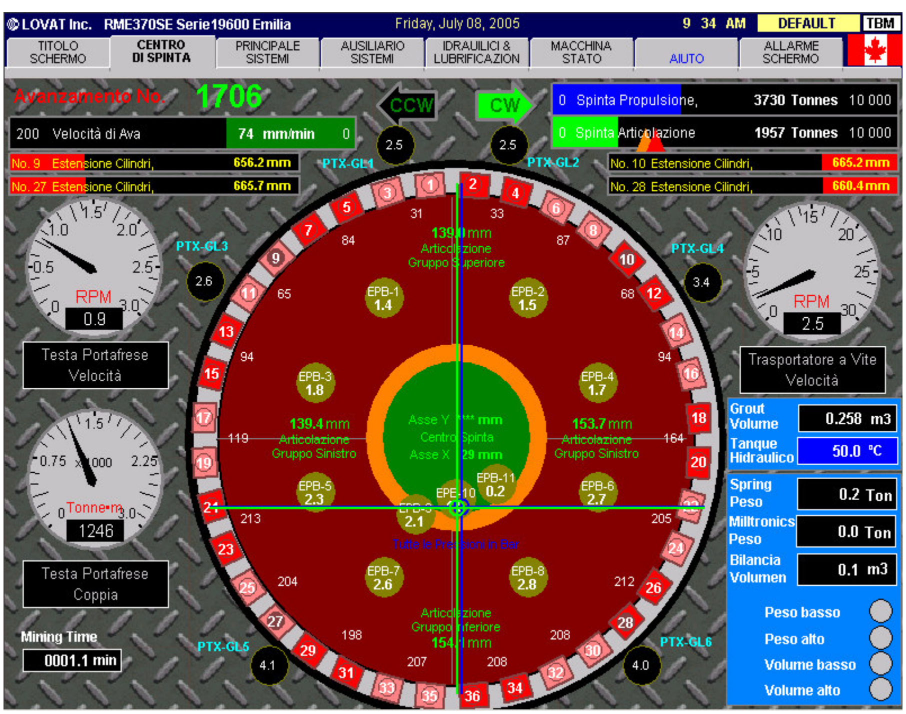


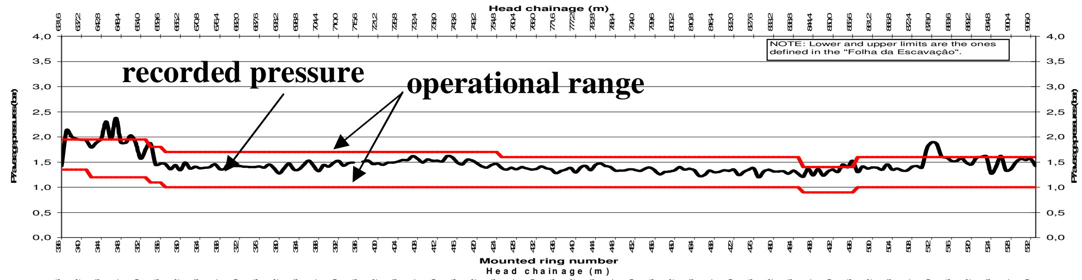
EPB Machine CONTROL

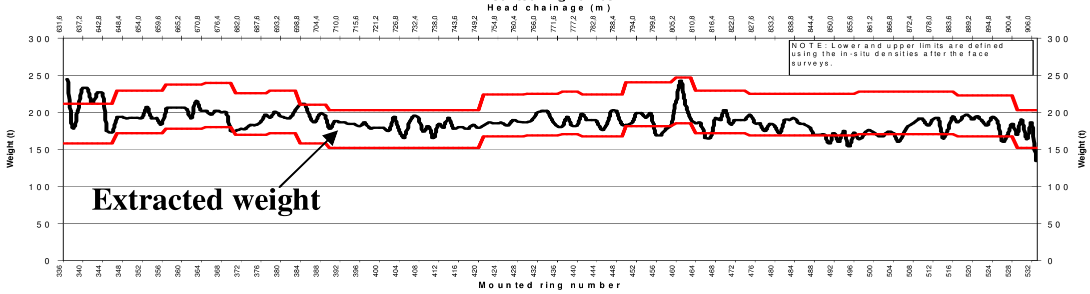


The following are the fundamental parameters that are necessary for monitoring the process and controlling the excavation (in the form of graphs and tables).

- **Pressure in the excavation chamber and along the screw conveyor.**
- **Extracted quantity of material (in volume and/or in weight).**
- **Apparent density of the material into the chamber**
- **Volume and pressure of injected grout in the annular gap.**
- **Torque, stroke, rotating speed of the cutterhead, and TBM advancement speed.**







The control of "face support pressure" is necessary to ensure that the face stability is maintained during the EPBS advance but also during the stoppages. The support pressure is applied, within the excavation chamber (plenum), via the excavated and appropriately conditioned muck, by the pushing of the thrust jacks.

During the design stage, the reference value, at the crown level or at tunnel centreline (to be measured through the relevant sensors in the excavation chamber), and the relevant operational range (high and low threshold limits) are defined.

First of all, the chamber shall be maintained full of muck mixed with conditioning additives (typically foam and polymers). If the chamber is not full of "stiff" material, all the actions here described are not effective, and even the face support cannot be assured. Maybe "stiff" is not the correct word; the muck shall have a "paste" consistency, like a tooth-paste.

During excavation, if the pressure decreases below the threshold value, the operator reduces the screw conveyor rotation speed (i.e. reduces the outgoing volume), thus favouring the material accumulation into the chamber, and, therefore, the increase of the pressure until the safe value is re-established. The opposite action would be necessary in case of increasing of the pressure value.

The final purpose is to maintain the "earth pressure" value within a 'safe operating' range.

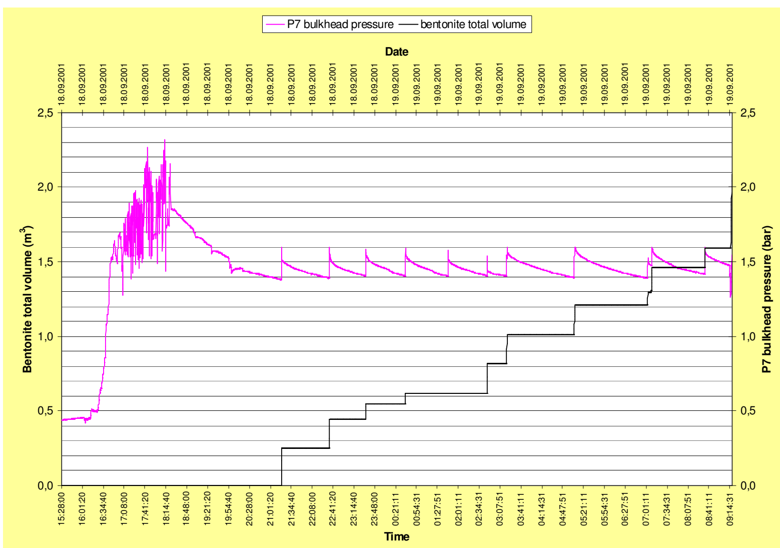
The following is what has to be done for controlling face support pressure:

During excavation:

- Verification of pressure variations in relation to the varying operating conditions:
  - rotation speed of the screw conveyor at the corresponding rate of advance and vice-versa;
  - pressure variation as a function of the total thrust, under a steady rotation speed of the screw conveyor;
  - and verification of the torque values as a function of the thrust and plenum pressure.
- Control that the pressure in the excavation chamber (e.g. average value measured at the crown sensors) is always within the range established at the design stage.

During standstill:

The thrust is now reduced to the minimum and the muck in the chamber will tend to consolidate due to the effect of gravity, thus separating the solids from the aerial and lighter components (e.g. the air contained in the foams). In this case, the pressure should be controlled so that it does not fall excessively and, if needed, bentonite injections should be used to re-establish the design levels.
For this purpose, the **Secondary Face Support System (SFSS)** has been demonstrated to be useful. If possible, the air present in the chamber should also be eliminated via an exhaust valve, located close to the crown of the front shield.
One pressurized tank filled with bentonite slurry is installed on the TBM back-up and one pump can inject it into the chamber through a pipe and a valve.
When the pressure into the chamber should decrease below the lower threshold, the pressure sensor opens the valve and the slurry is pushed into the chamber. Under condition that the chamber be full of “stiff” material, injecting a small quantity of bentonite slurry is enough to restore the pressure (see the following figure, where the red line represents the pressure and the black one the slurry quantity).



For controlling the “extracted weight”, the most efficient method so far tested is to install a scale on the EPBS belt, which transfers the muck from the screw conveyor to the tunnel mucking system, be it a continuous belt or muck wagons. In this manner, it is possible to measure the ***extracted material weight*** and to have a continuous measurement. By time-integrating the instantaneous extracted weight, the cumulative value of the extracted weight is obtained. Through an evaluation of the in-situ density of the material, its volume can be derived and compared with the theoretical value, which represents the quantity of material that can be effectively excavated.
This type of control avoids excavating beyond the theoretical volume (over-excavation), which can be the most dangerous condition, leading to increase ground-loss and consequently to induce surface settlements or even face collapse.

The controls to be implemented are:

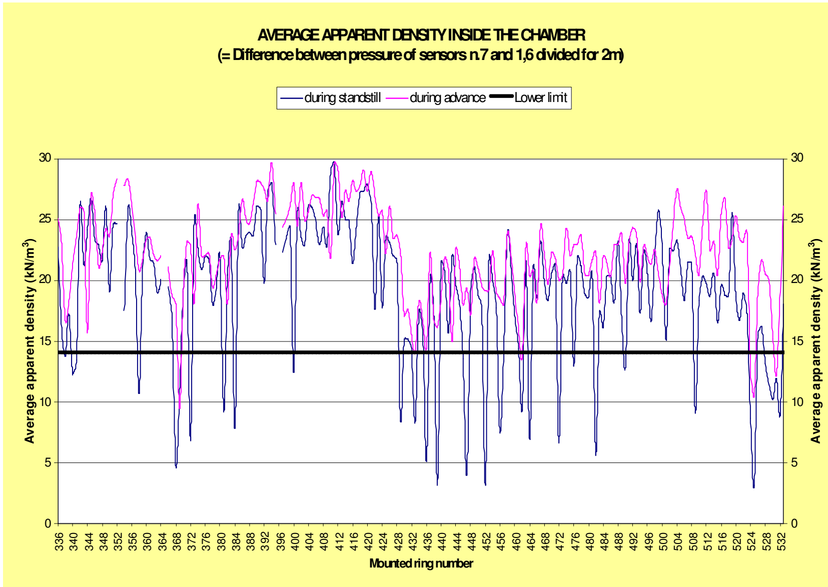
- Calibration of the scales, both statically and dynamically using a known weight.
- Verification of the relationship between the weight of the extracted material and rotation speed of the screw conveyor for the same penetration rate (during excavation), and vice versa.
- In situ material density evaluation with regular observation and controls of the face condition and controlling the muck.
- Water flow-meter calibration for the quantity of water loaded with the conditioning additives; instrument calibration of the cumulative water pumped at the face during the whole excavation cycle.

The "apparent density" provides an indication of the consistency of the material in the excavation chamber (in relation to the conditioning effect characterised by liquid and aerial components), as well as its capacity to supply adequate face support pressure. It also gives an effective indication of the ***filling rate*** of the plenum.

The apparent density (γ_{app}) can be easily calculated as the ratio between the differences of the pressure values (ΔP) measured by two sensors at two adjacent levels and their vertical distance (Δh).

$$\gamma_{app} = \Delta P / \Delta h$$

Remember this is not a real "physical parameter", it is only a good "marker" of what happens into the excavation chamber.



The control of grouting behind the lining segment is made by controlling pressure and volume of injection, which shall be implemented during the excavation

The following controls are necessary:

- - Control that the grouting operation is carried out concurrently with the excavation and accordingly to the foreseen procedures;
- - Control that the final injected-grout volumes correspond to the design range.
- - Execute systematically boring-sample tests to check the effectiveness of the filling.
- - Make laboratory tests on site on the backfill grout to evaluate its consistency and deformability.
- - Verify the adequate greasing of the shield's tail brushes (and of the gaps between the brush rings) to avoid grout inflow during the backfill operations.

4. Lessons learned:

All urban underground projects shall be based on a rigorous Risk Analysis, which leads to identify, evaluate, and minimize all the potential hazards.

- **'No construction project is risk free. Risk can be managed, minimized, shared, transferred, or simply accepted, but it cannot be ignored'. (Sir Michael Latham, 1994).**

The correct choice of the machine should be considered as one of the "primary risk-mitigation measures" for controlling the effects of tunnelling in urban areas.

The design of a rigorous system for controlling the excavation represents a true and proper "secondary counter measure" aimed at further containing the residual risks.

- **Be wise 'a priori': nowadays the "unexpected" is no longer acceptable from a risk management point of view.**