"Process control in mechanized urban tunnelling“

Zurich, 10 May 2012

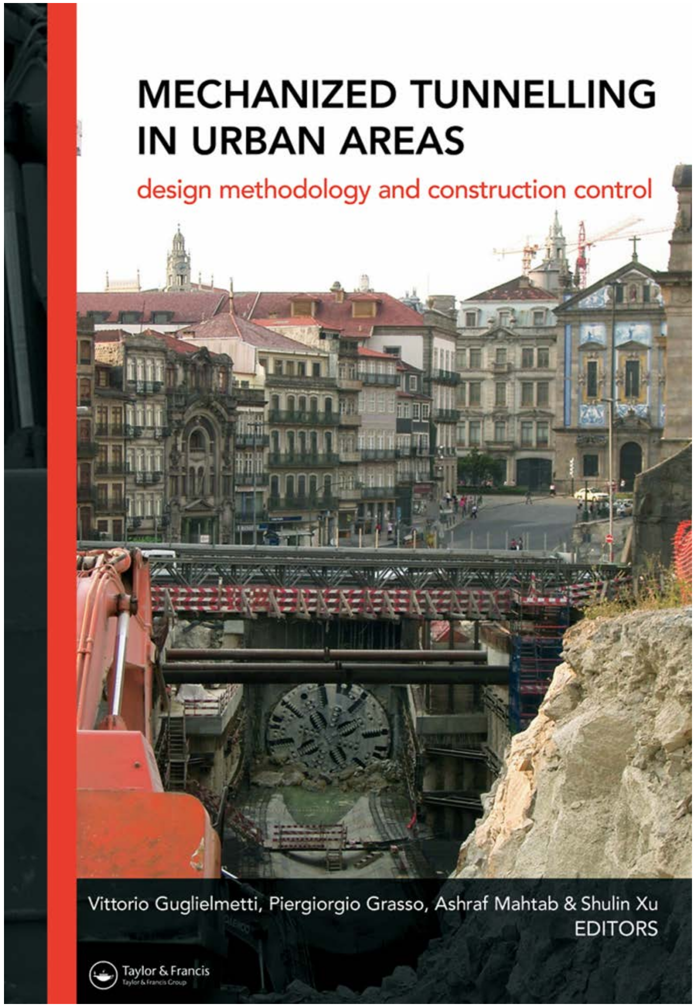
All the concepts contained in this presentation are taken from the book

“Mechanized Tunnelling in Urban Areas”

Edited by Vittorio Guglielmetti, Piergiorgio Grasso, Ashraf Mahtab, Shulin Xu

Balkema - CRC Press – 2007

(Taylor&Francjs Group)



- 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.

Tunnelling by using Closed-face Machines (which is a "must" 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.

It should be highlighted that methods of excavation or TBMs endowed with "magic" powers do not exist, thus

any excavation method requires a strict system to control its use,

respecting relevant procedures and work instructions.

If the correct choice of the machine can be considered as **"primary mitigation measure"** for the excavation risks, the application of the control system can be seen as a **"secondary mitigation measure".**

In fact, it shall enable an actual "minimisation" of the construction risks to the point of making them acceptable, or to the so called **"residual risk".**

Of course, if the residual risk-level is still too high (i.e. non acceptable), additional mitigation measures must be implemented, like for example, ground treatments.

"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

All existing guidelines for underground or geo-engineering works require:

- ***A*** ***Solid Design*** **based on site investigations, design calculations and necessary studies**
- **A** ***Monitoring Plan*** **with definition of threshold values of 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!**

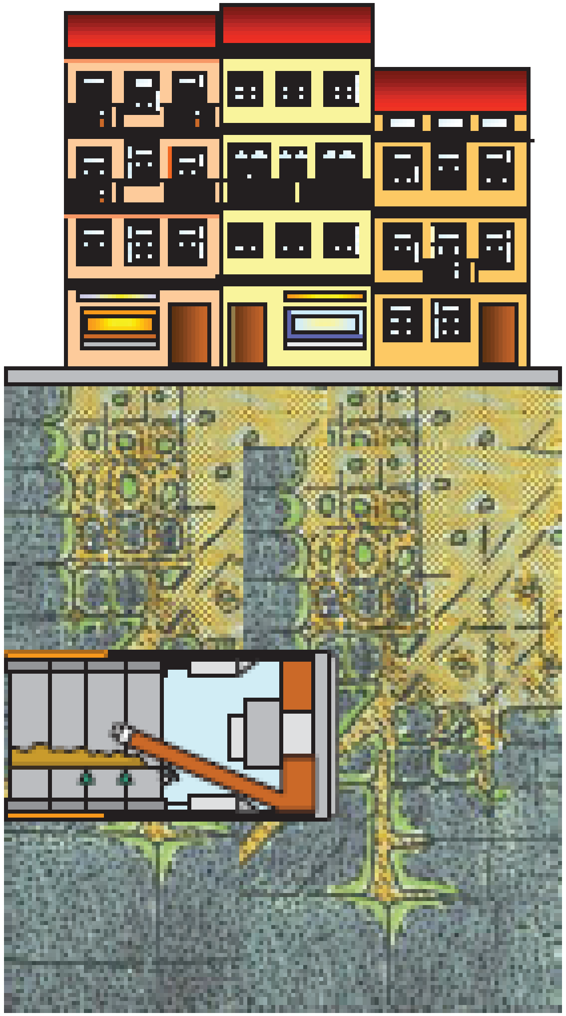
  but

  - **Are they enough?**

Collapses can heavily injure third parties and/or cause serious damages to people and private properties.

Even if a solid design is done, checked and approved, and a consistent monitoring system is implemented for the construction, accidents could still occur!

WHY ???



Why do accidents occur ?

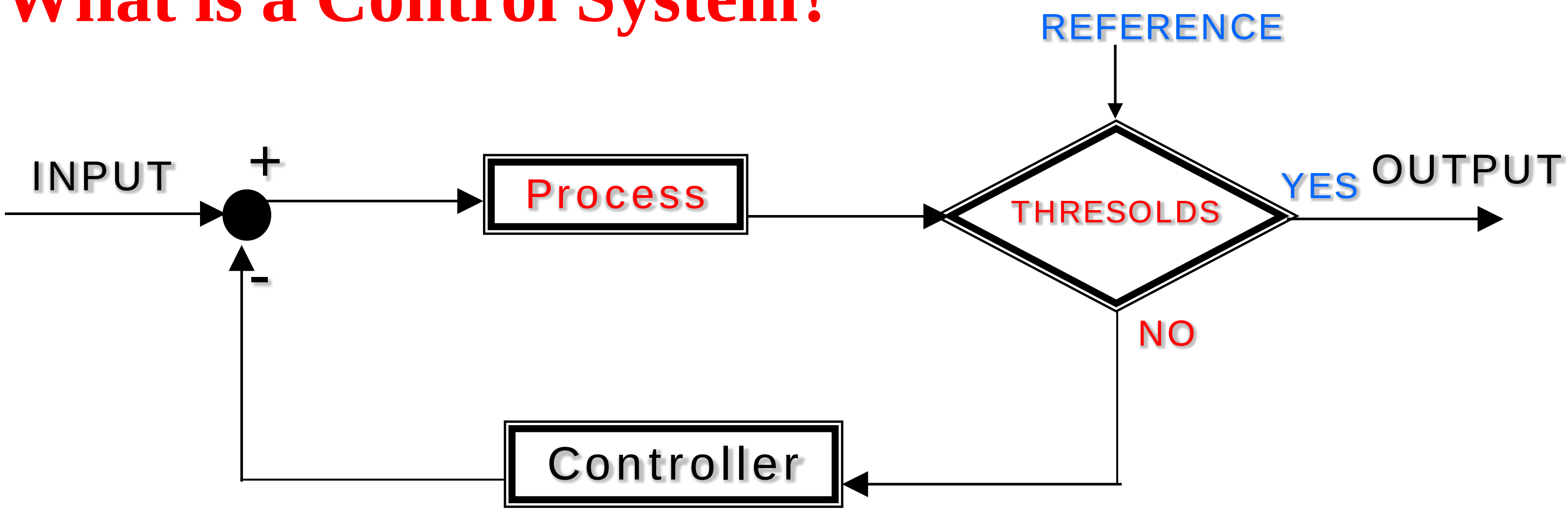
- *Variability & uncertainty in geological, geotechnical and hydrological conditions;*
- *Deviation of ground behavior from predicted;*
- *Lack of excavation process control, due to:*
  - *Lack of timely interpretation of monitoring data;*
  - *Lack of (adequate) counter-measures*
- *Human factors.*

Thus, a more consistent approach is required:

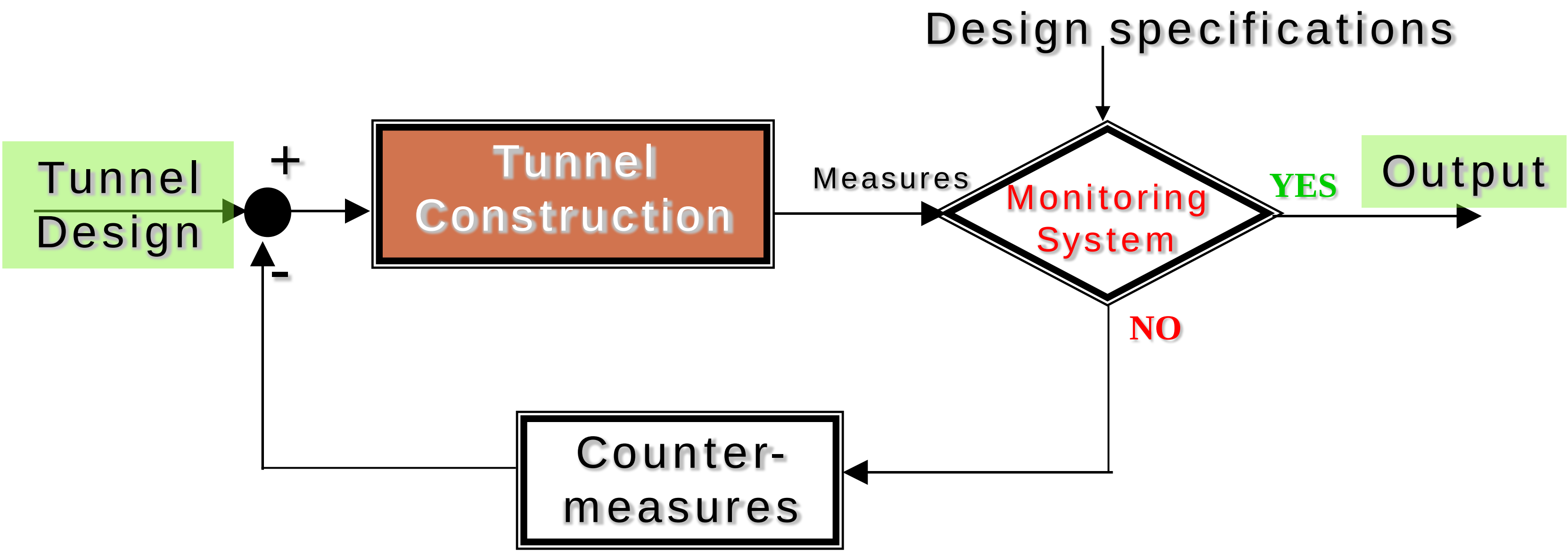
1. Make *a Robust Design* based on *probabilistic (and not deterministic) approach*;
2. Do *a complete Risk Analysis*;
3. Design *a Monitoring Plan* with definition of *thresholds*;
4. Predefine the necessary *counter-measures*;
5. Prepare an appropriate mechanism for the *activation* of the counter-measures;
6. Collect in *real time* the monitoring data, and *share* them among all people involved,
   in order to:
7. Take the *RIGHT DECISION* at the *RIGHT TIME*

All that leads to implement a rigorous Control System

What is a Control System?



The control theory states that in a control system, the output of a process is **fed back** through parameters measurement and comparison with reference values. The controller then takes the **error** (difference) between the reference and the output as indication to **change the inputs** to the system under control. Very simple, isn't it?



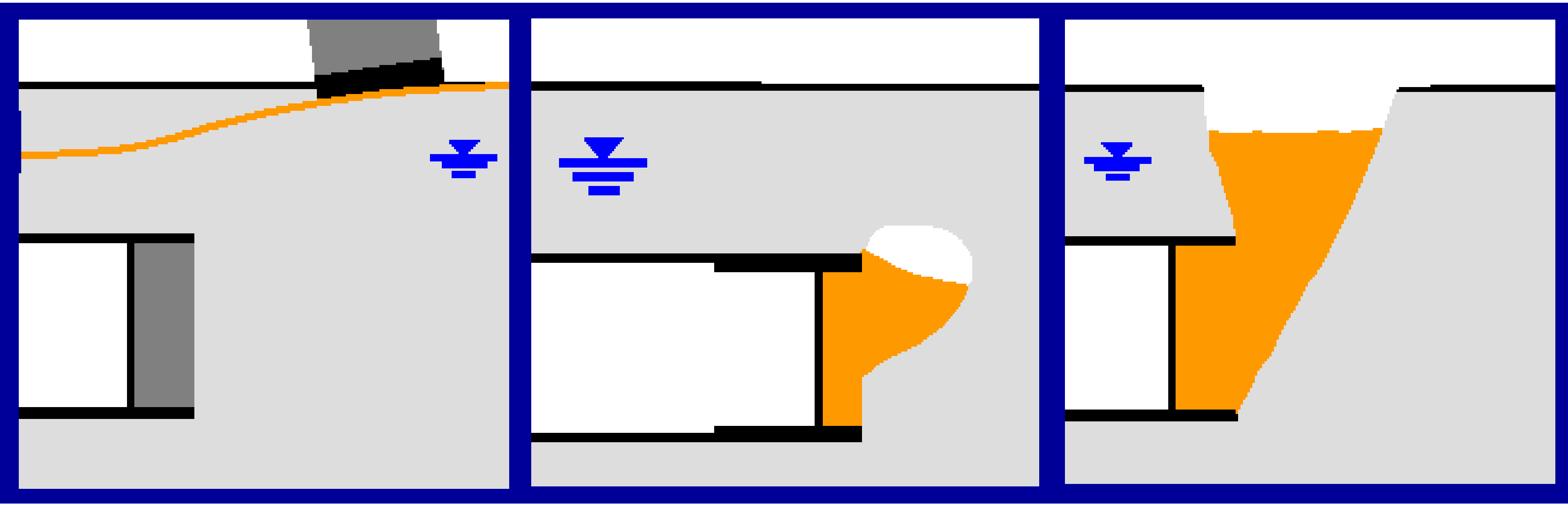
But … ... … when the process is complex like a Tunnel Construction things get harder!!!

Main Risk Scenarios

Damage due to ground deformations (settlements)

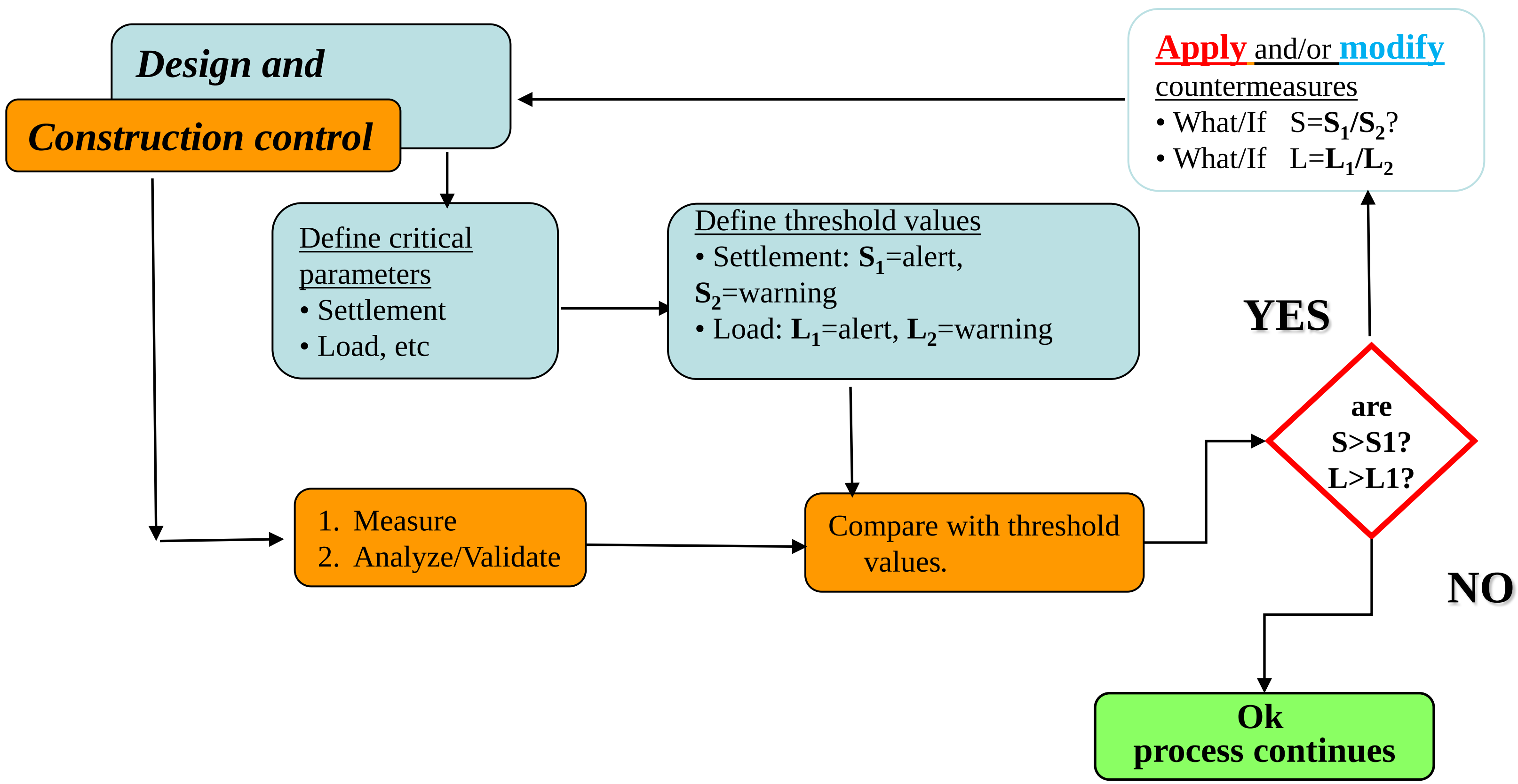
Voids

Collapse to surface



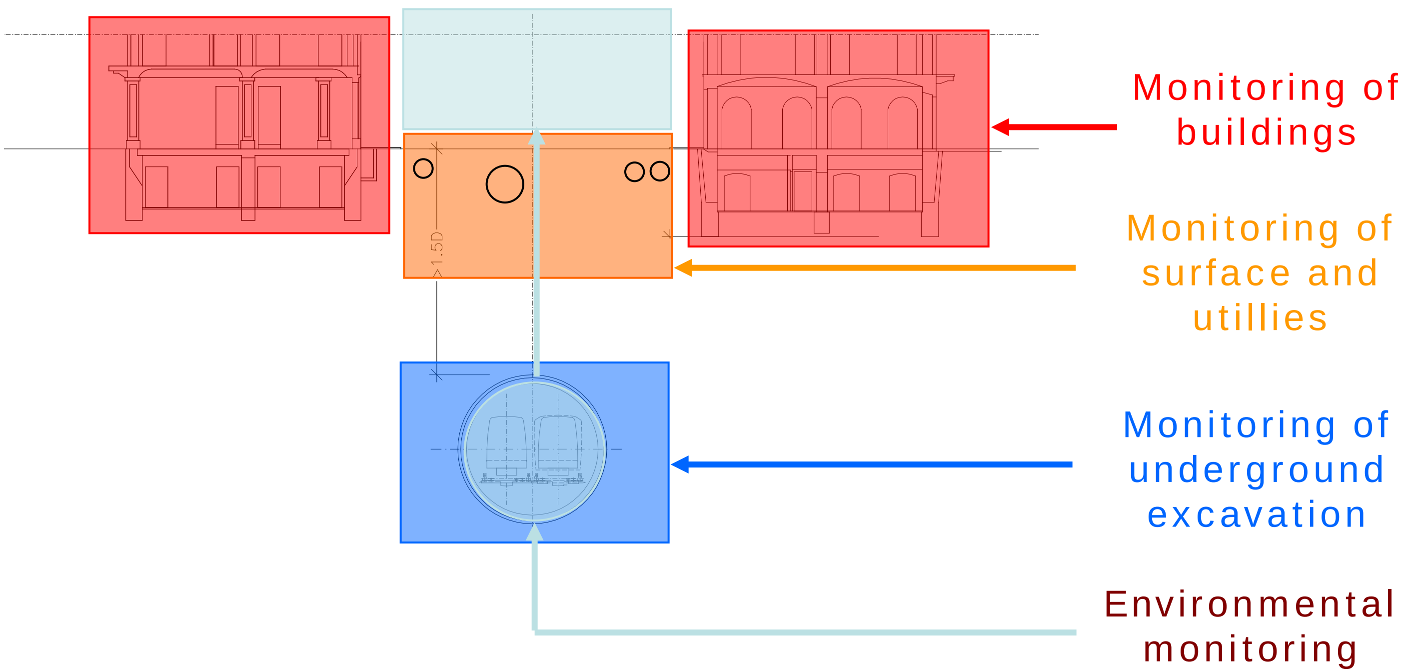
Kovari, 2004

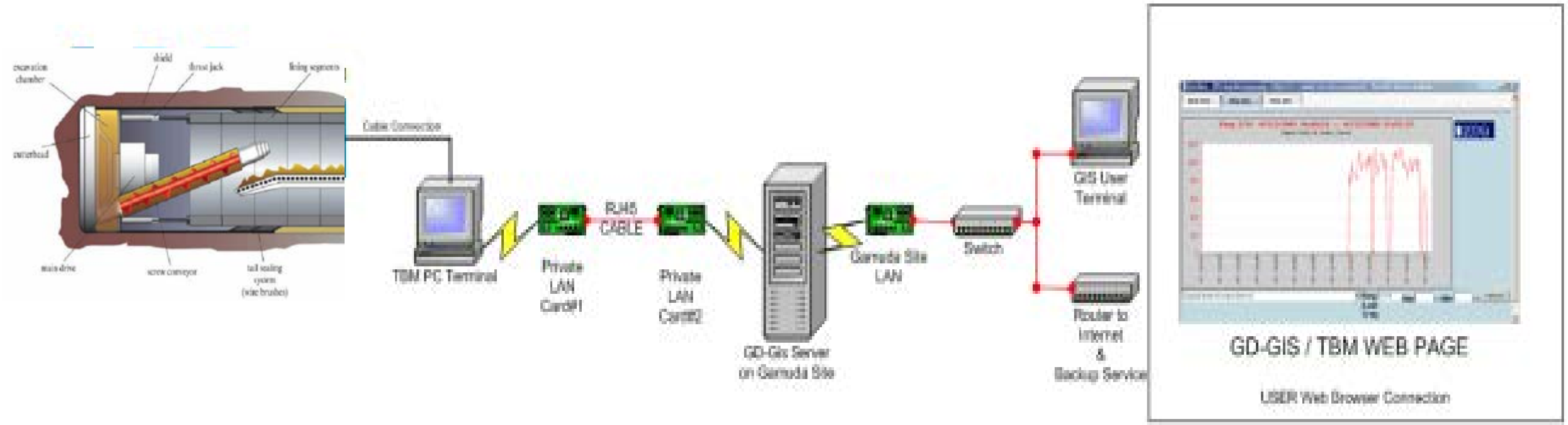
The control system activation gives ***real-time warnings*** to the process controllers, ***even before*** the threshold values are being exceeded, when ***their trend is showing a tendency to the limits***, thus allowing the prompt adoption of counter measures.

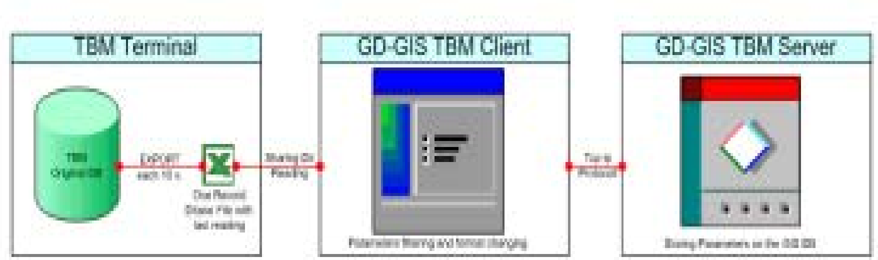


Monitoring and instrumentation can be classified with reference to the object to be monitored:

1. Monitoring of underground excavation;
2. Monitoring of surface and utilities;
3. Monitoring of buildings;
4. Environmental monitoring (air, noise and vibrations);







An example of Real-time Management of TBM monitoring data, with the possibility to transmit values from the data logger to everywhere through a WEB connection for sharing the information, but also for a potential "remote control".

The modern data loggers give us the possibility to control a lot of parameters and are powerful instruments of process control …

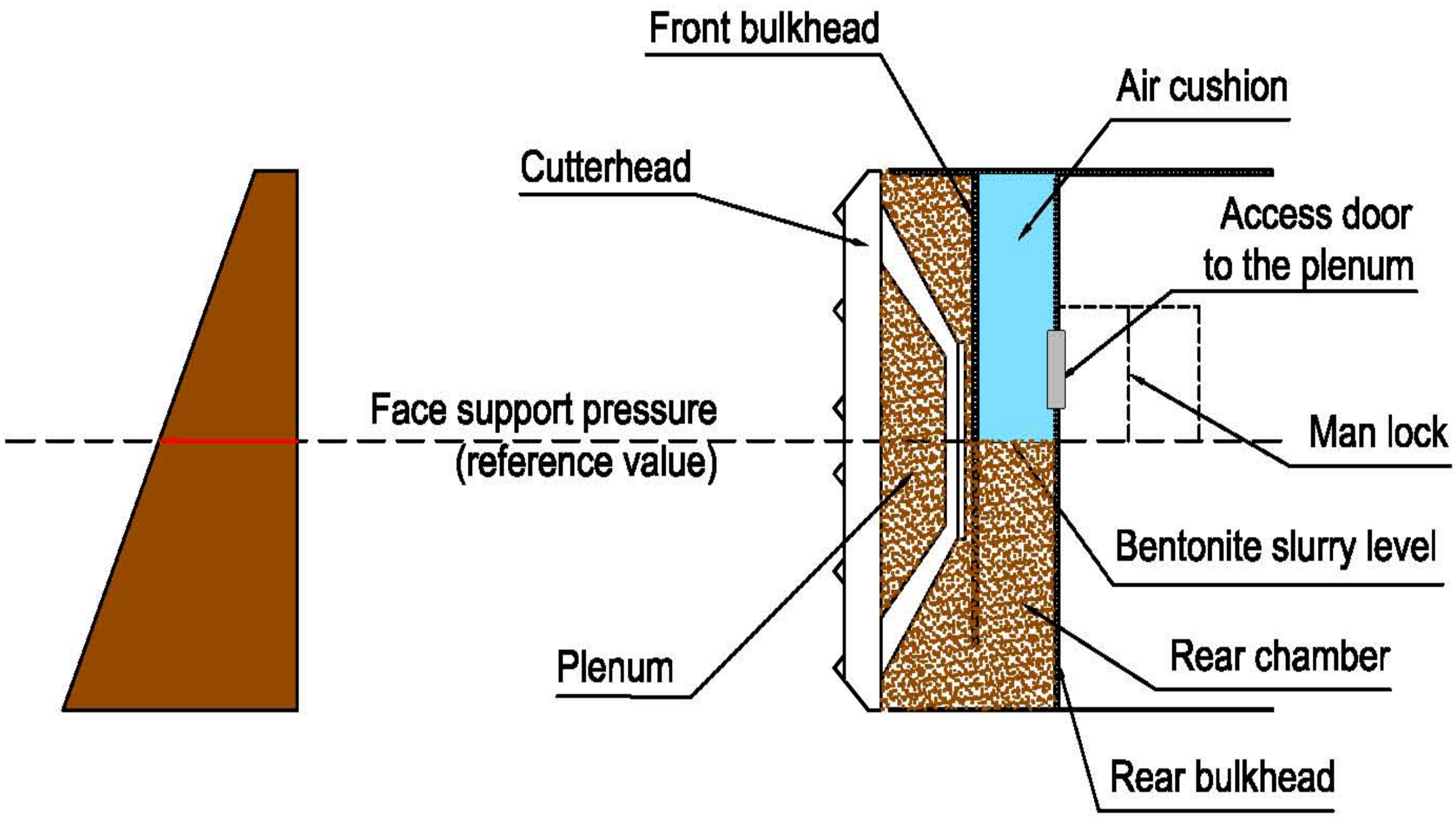
… the monitoring data logger on a TBM is very similar to an airplane flight recorder.

But the purpose of our control system is to prevent accidents not only to explain them "a posteriori", looking for a possible guilty, too often identified in the "*unforeseen & unforeseeable* " behaviour of the ground …

- Let us see now how it can be possible to organize a control system of the two main types of Closed-face Machine available for urban tunnelling:

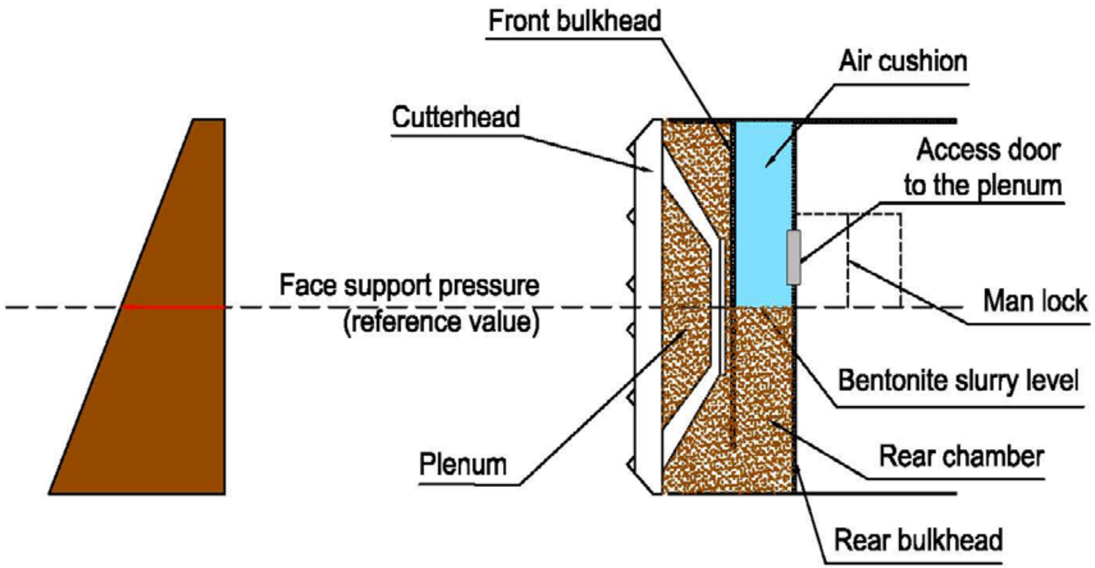
- **The Slurry Shield, and**
- **The EPB Machine**

The control of a SLURRY SHIELD



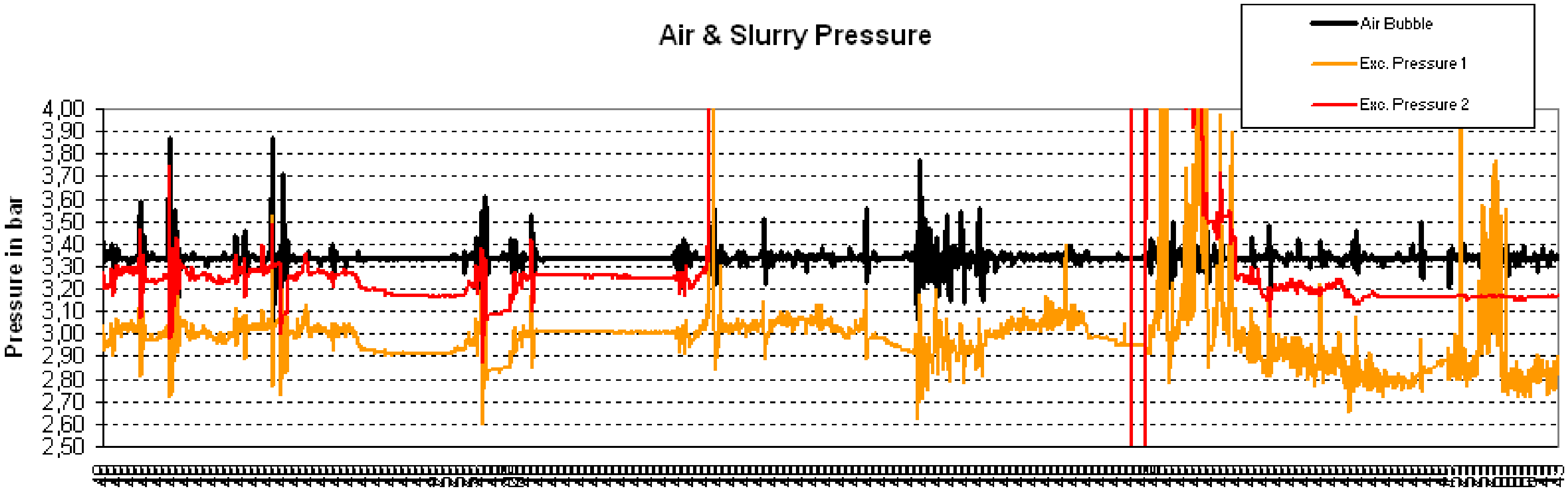
The control of Slurry Shield

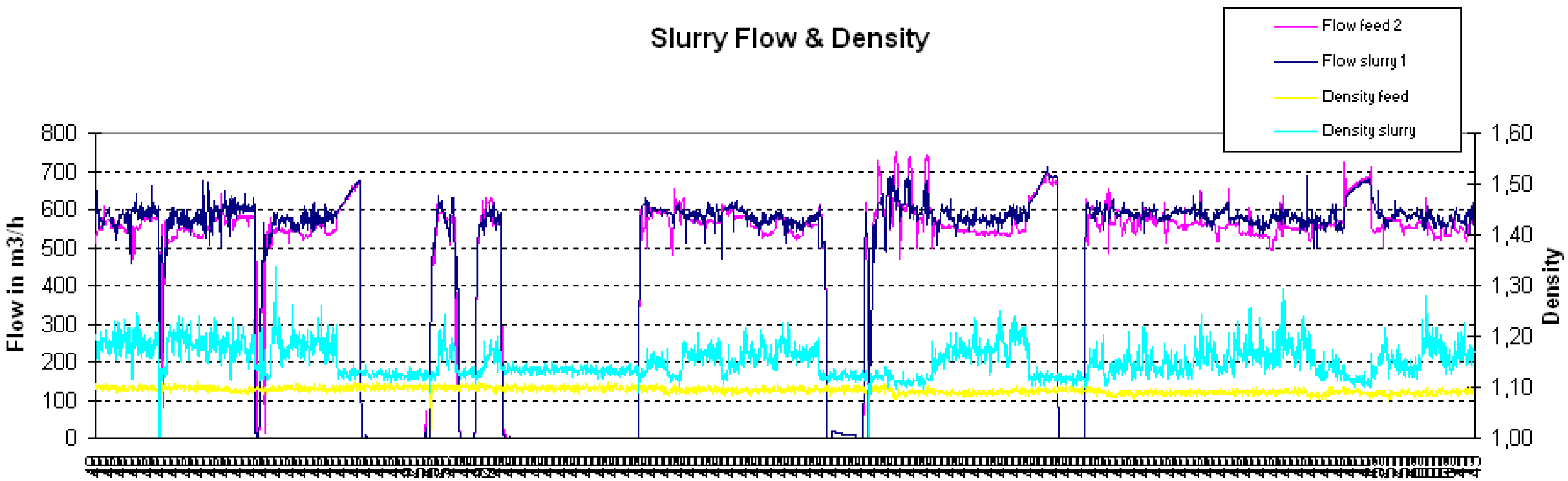
Slurry Shield parameters under control



- **Pressure at the face**: Compressed air pressure and slurry pressure, controlled by TBM automatic system plus slurry level control in the chamber, can be automatic or manual by controlling feeding and extraction pumps;
- **Quality of the slurry**: Viscosity, Yield value, Density, Cake thickness, through the on-site laboratory
- **Quantity and quality of mucked material:** through calculations derived from double measurement system (density and flow) on the in- and out- pipelines, and observations at the treatment plant as well;
- **Segment mortar grouting:** quantity and pressure of injection pumps, through manometers and automatic control system.

The control of Slurry Shield



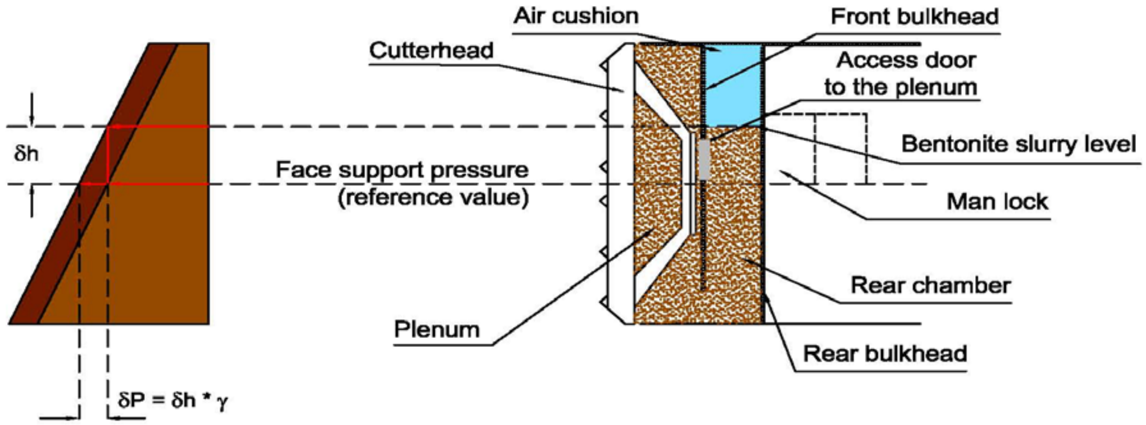


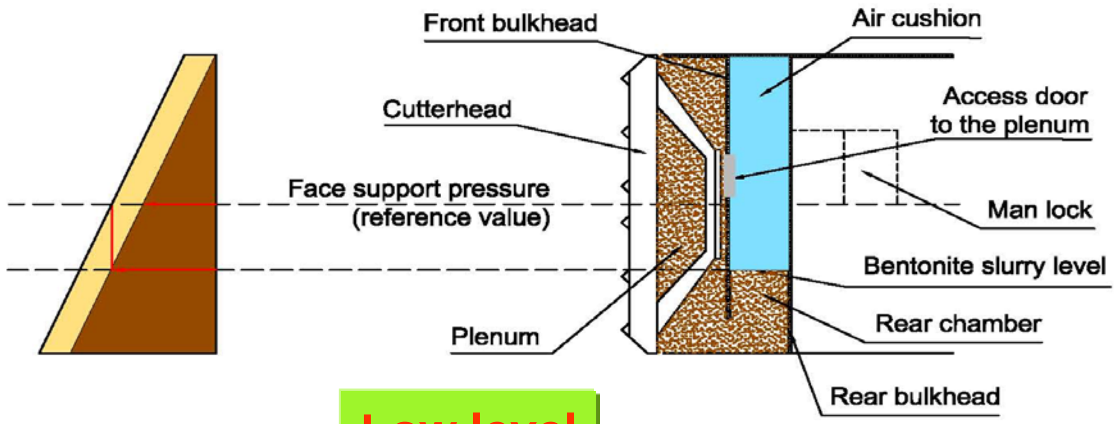
Portland project, South Drive. Excavation parameters at rings 875 to 878.

The control of Slurry Shield

The bentonite slurry level: why it is so important?

High level

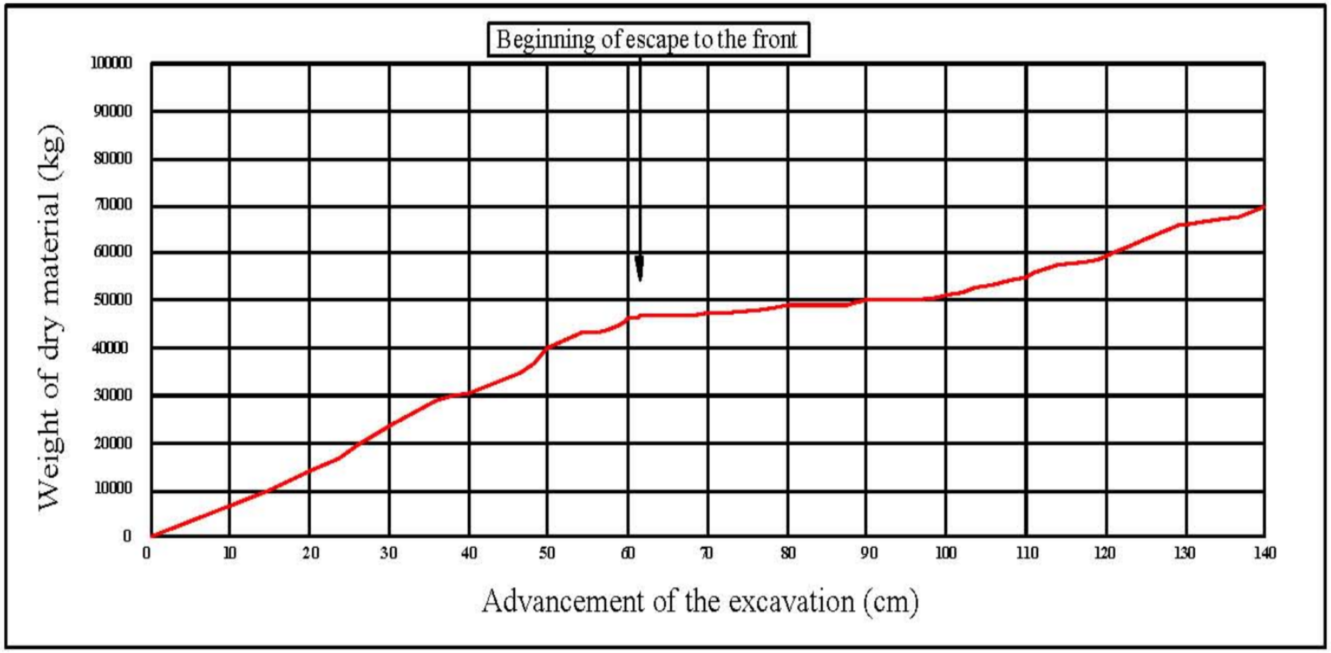




Low level

The control of Slurry Shield

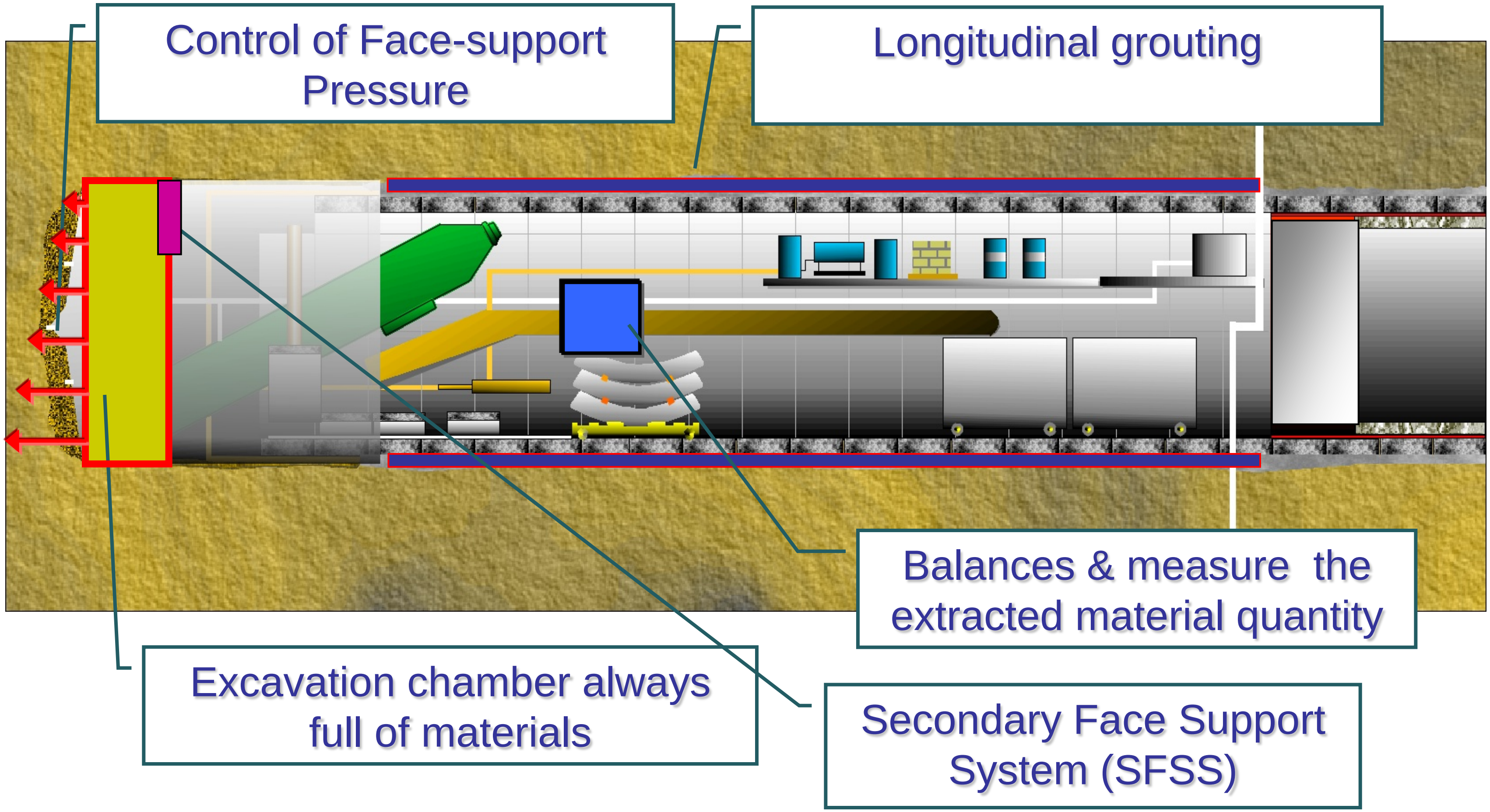
Quantity of "dry extracted material" of a Slurry Shield v/s the excavation stroke



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 plugging at the suction point due, for instance, to the presence of boulders, or sticky material, or (c) the formation of clogging along the first stretch of the pipeline.

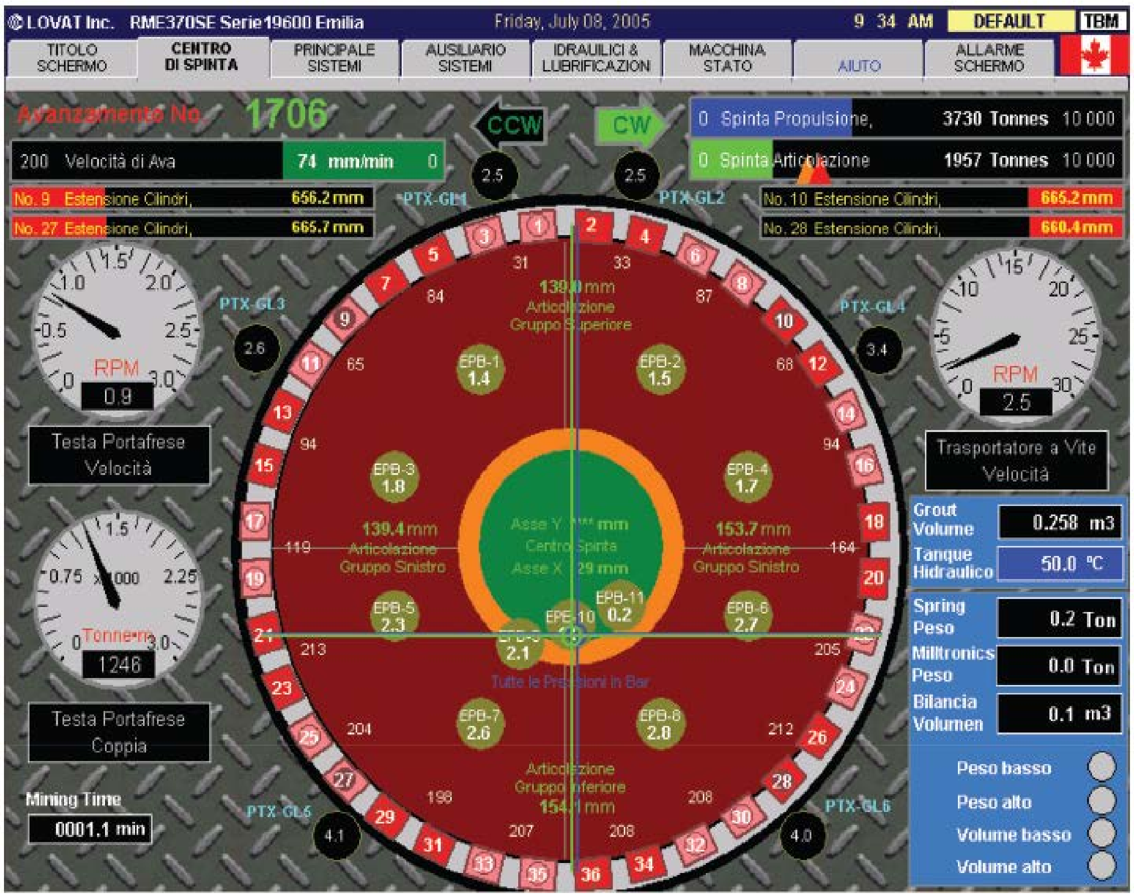
Conversely, a sudden increase of slope of the curve, which is less frequent but even more worrying, would signify a sudden unexpected "inflow" of solid material in the chamber, i.e. the possible beginning of face instability with the danger of collapse, or at least the beginning of an over-excavation.

EPB TBM control: the Key Parameters



The control of EPBM

The control screen of an EPB Machine, with all the key-parameters under the control of the TBM Operator

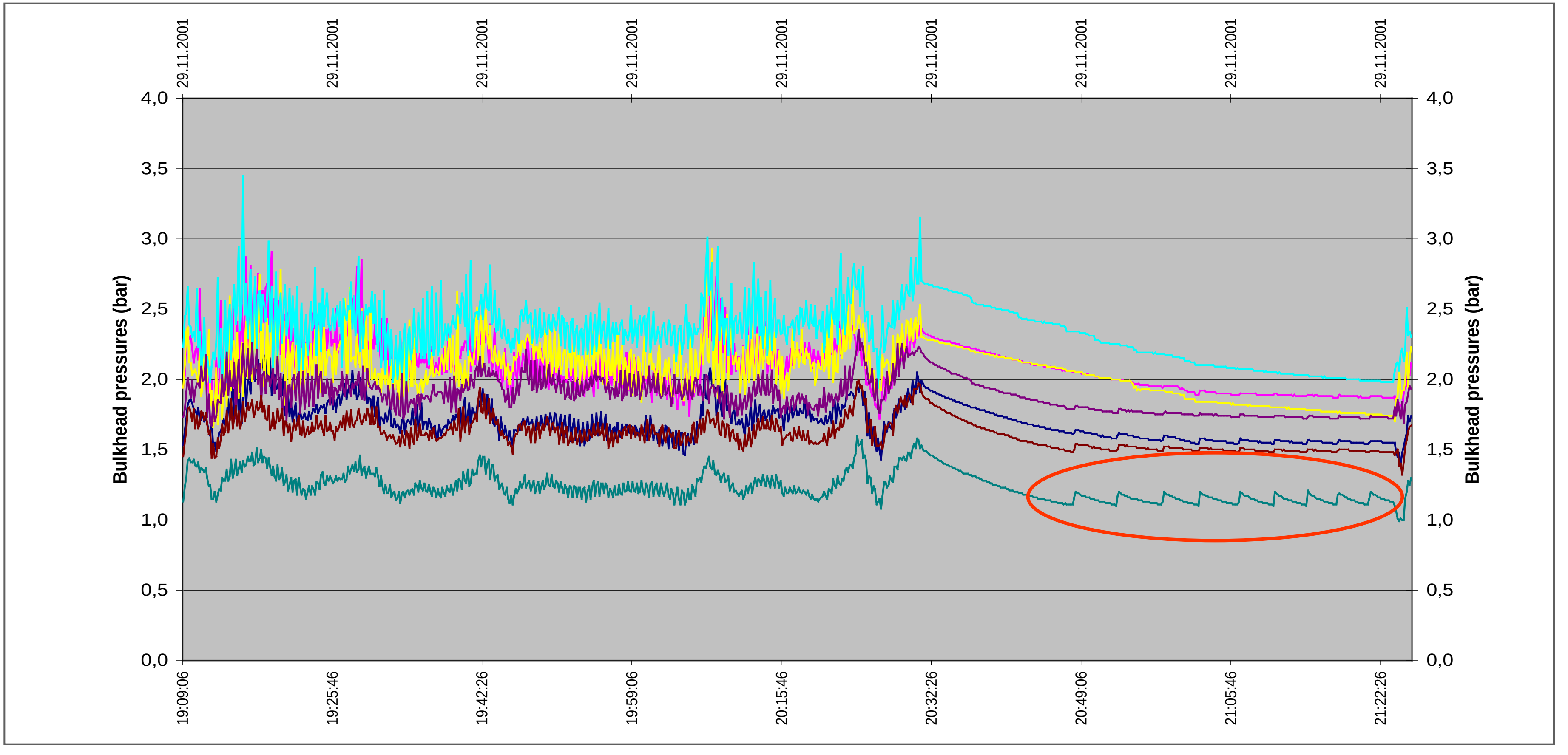


The Key parameters to be controlled are:

- **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 grouting in the annular void behind the lining.
- **Torque, stroke, rotating speed** of the cutterhead, and TBM advancement speed.

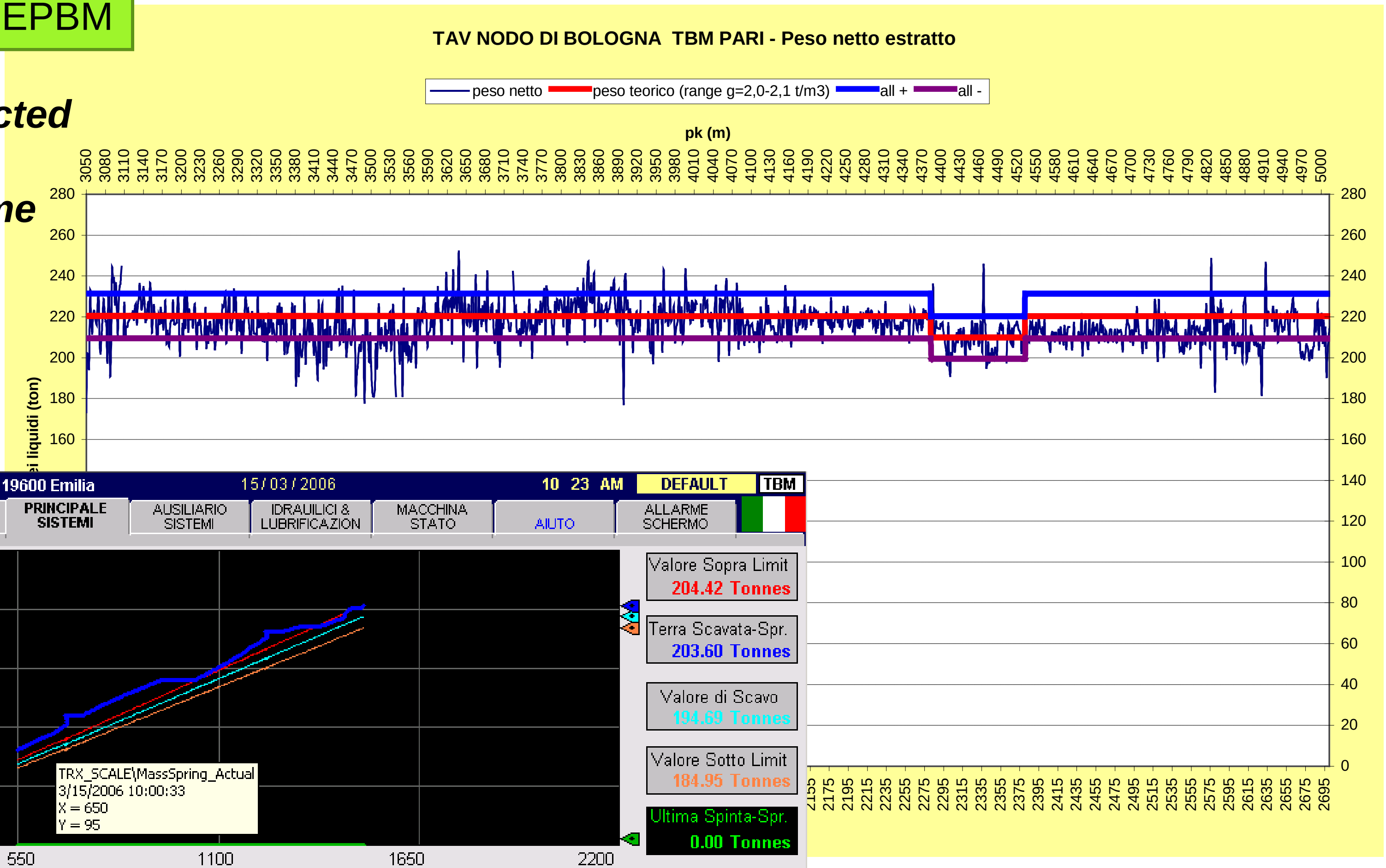
The control of EPBM

Face Support Pressure monitoring



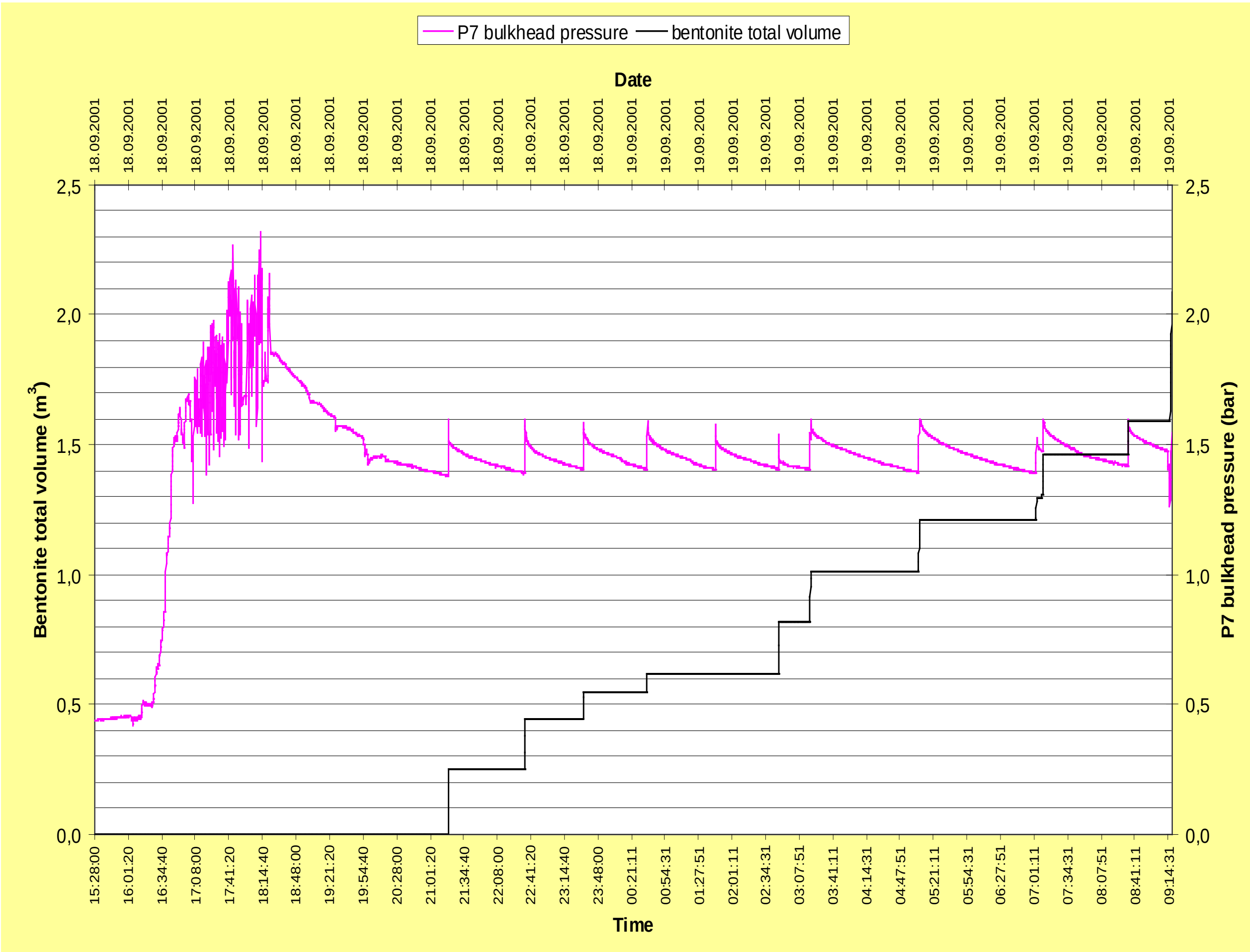
The control of EPBM

Quantity of Extracted Muck: Weight and Volume



The control of EPBM

The face-support pressure during standstill

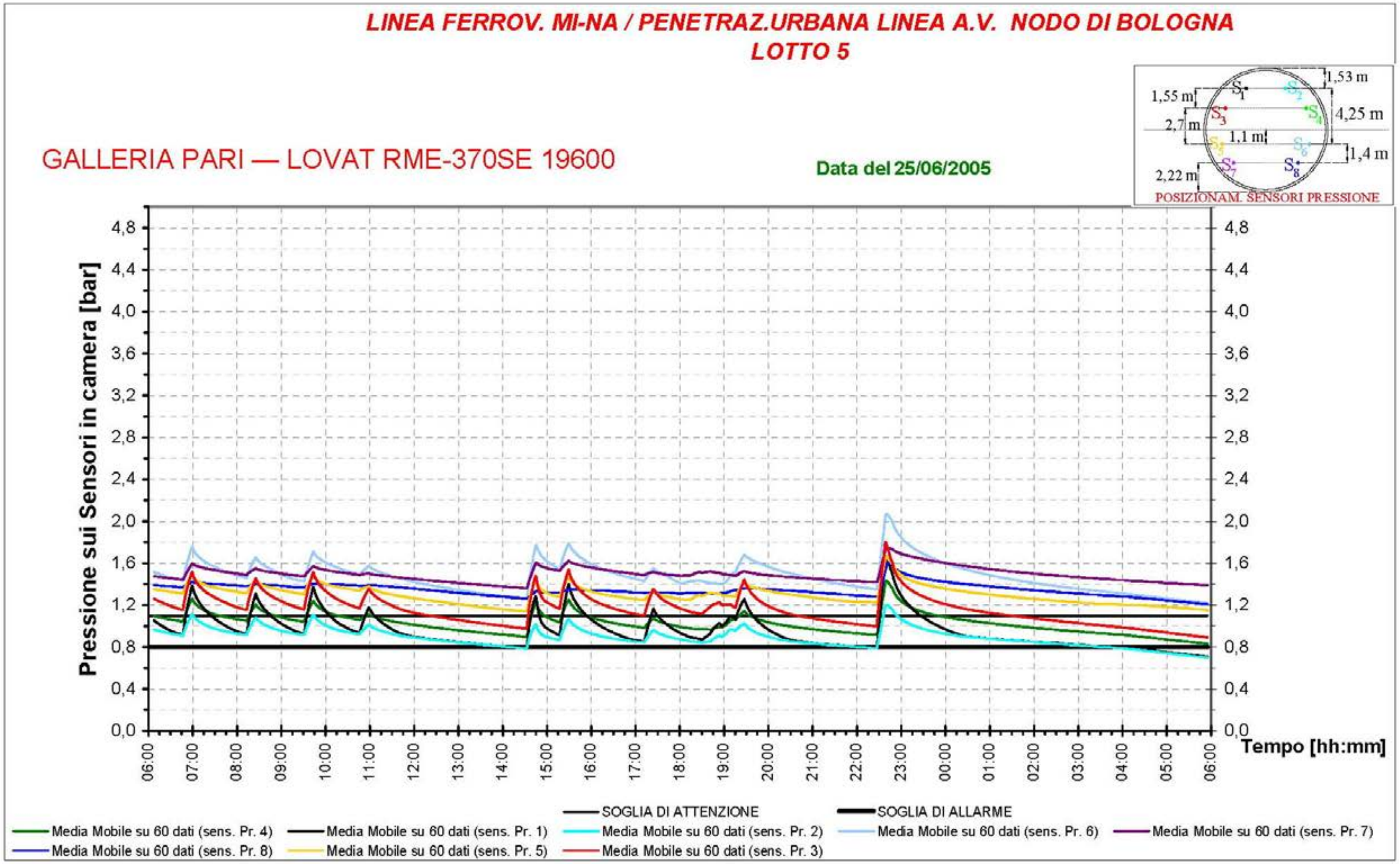


Red line : Face support pressure;
Black line: bentonite quantity injected

An example of the **Secondary Face Support System** **SFSS** application, for controlling the face support pressure during the TBM stoppages.
The intervention of injection pump is here automatically controlled.

The control of EPBM

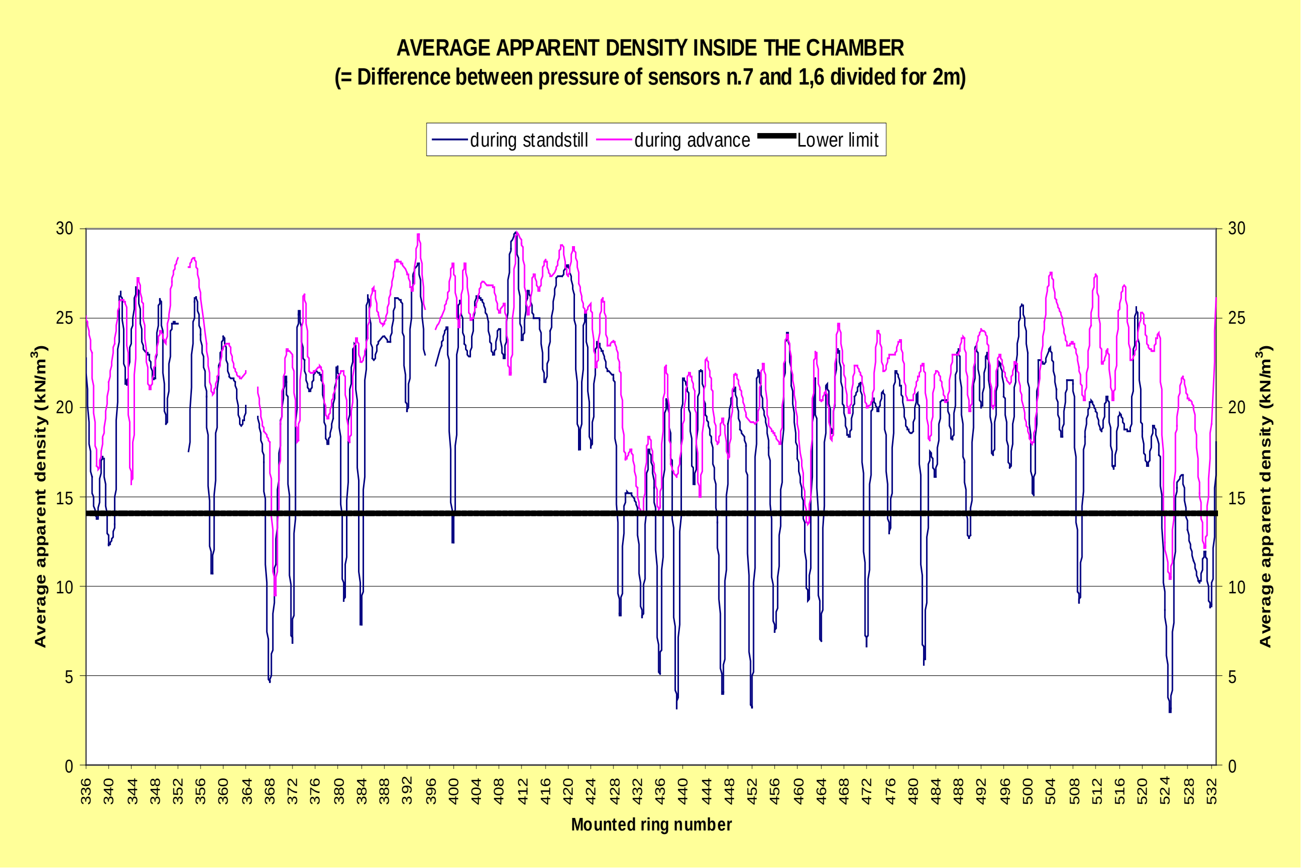
The face-support pressure during standstill



A ***manual*** application of the Secondary Face-Support System - SFSS

The control of EPBM

The Apparent Density Control



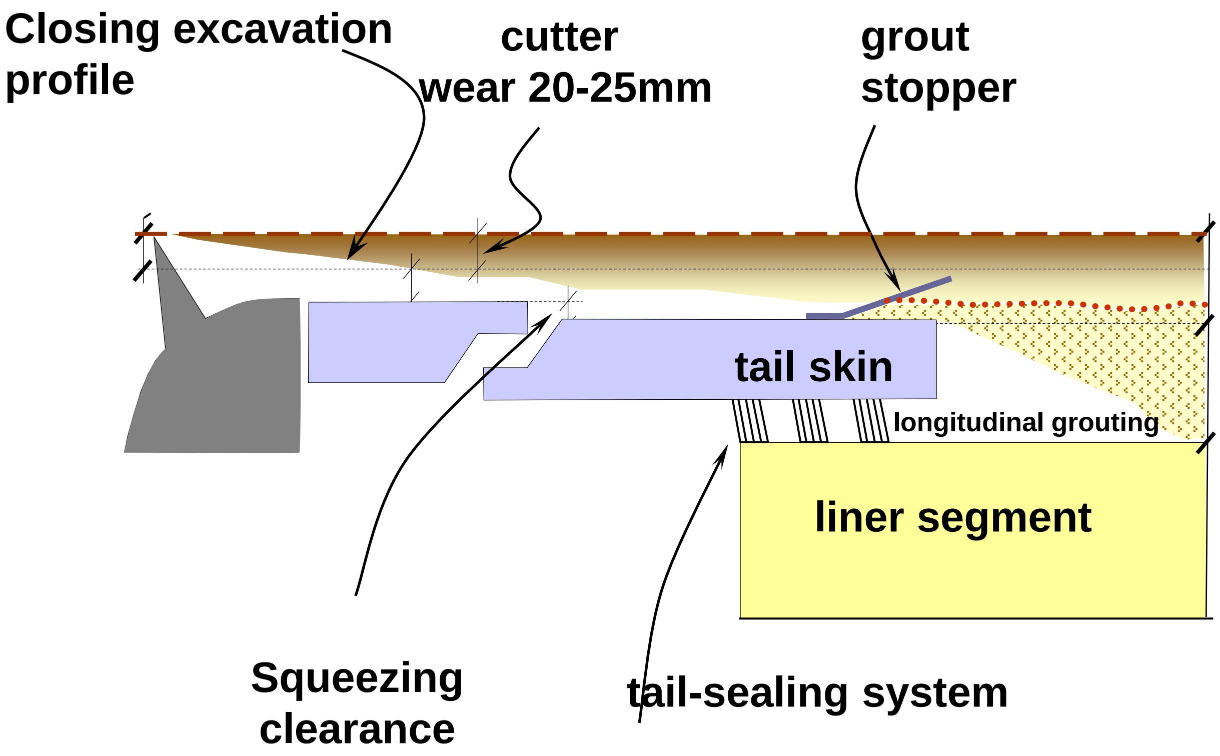
$\gamma_{app} = \Delta P / \Delta h$

Remember:

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

The "apparent density" provides an indication of the consistency of the material in the excavation chamber, 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 control of grouting system is the same for Slurry Shield and EPBM

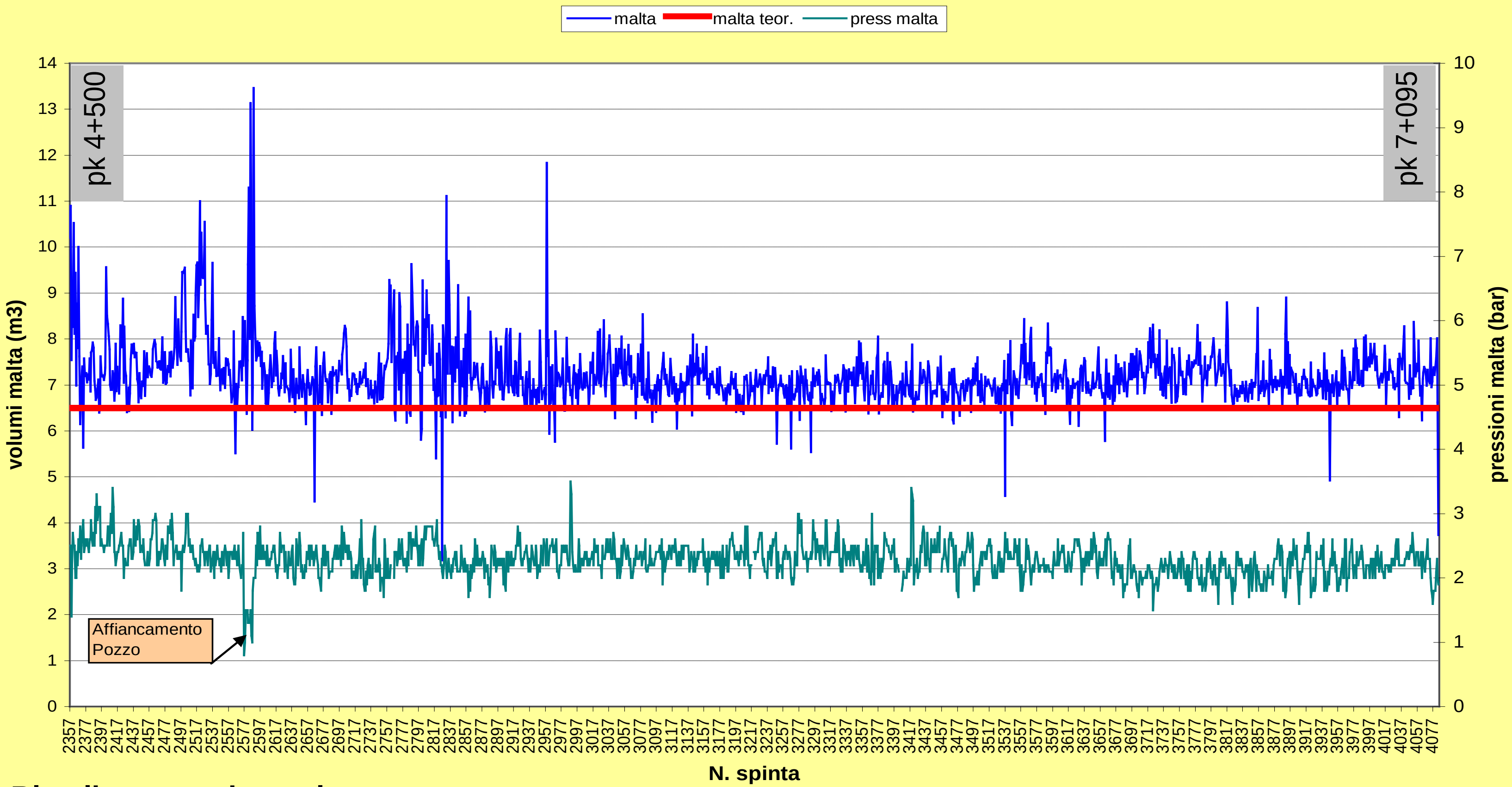


Grouting behind the lining

The control of grouting system

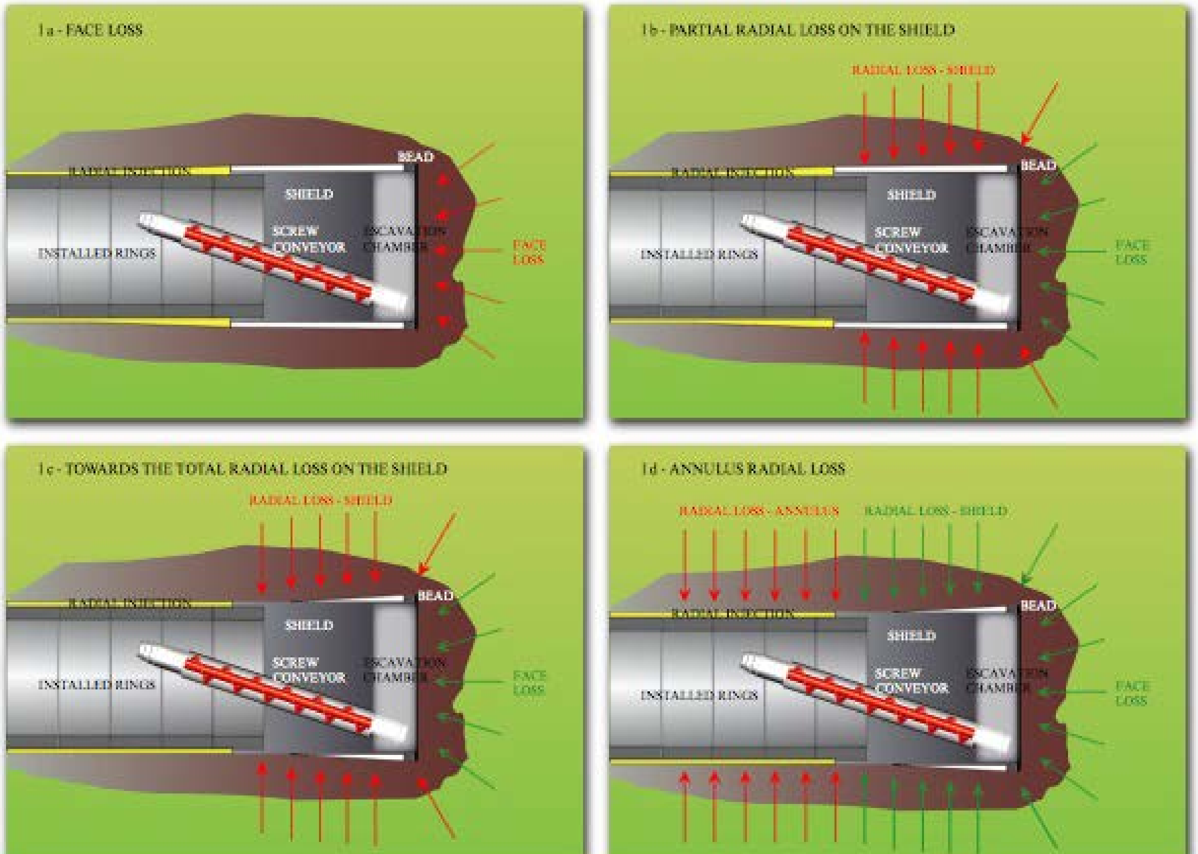
Tail Void Grouting: Volume and Pressures

- Volumi e pressioni di malta



Blue line: grouting volume
Green line: grouting pressure

The results: the control of surface settlements

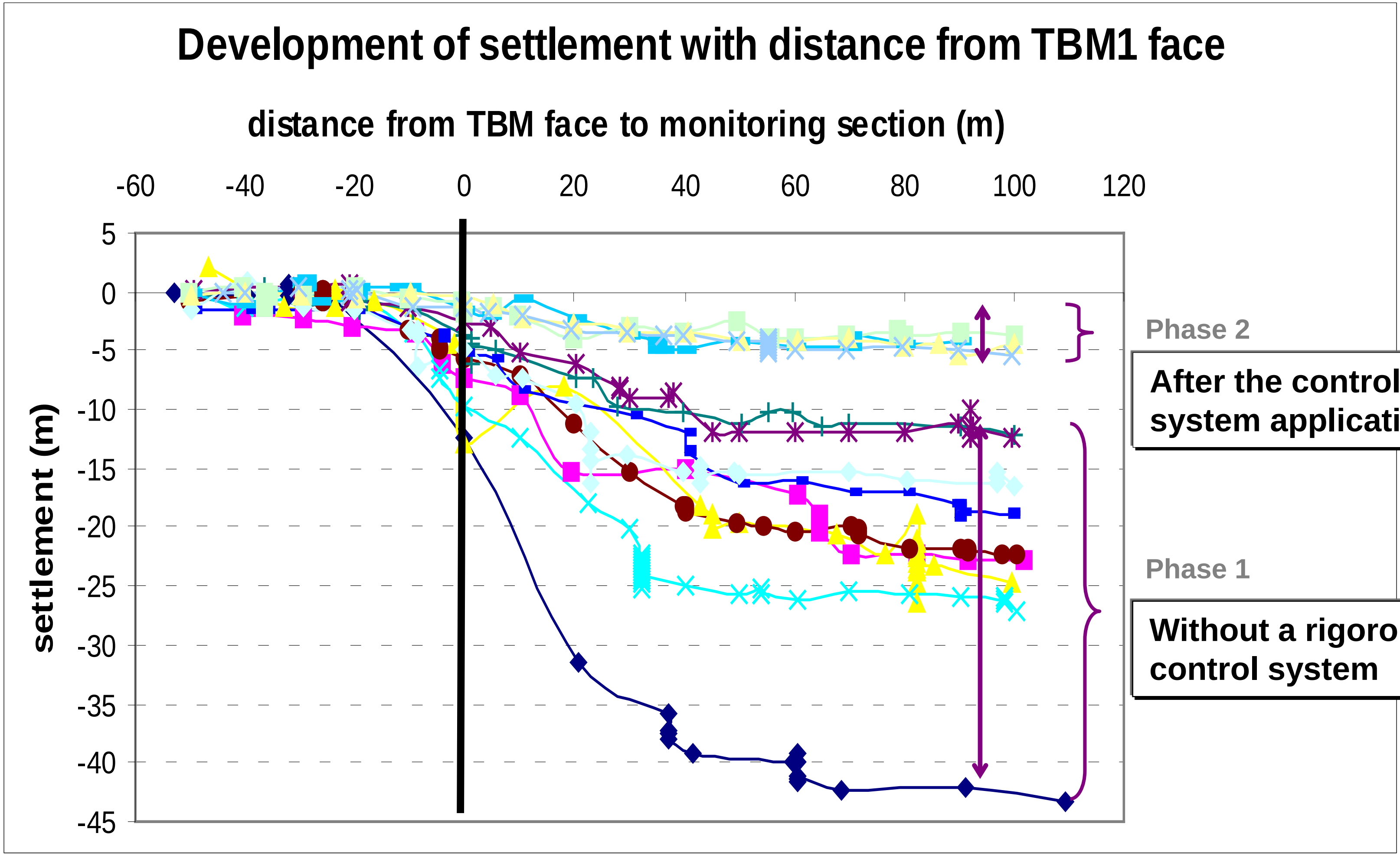


The main sources of settlements are:

Face volume loss
Radial volume loss around the shield
Radial volume loss around the lining

If we are able to control the key-parameters of the excavation process, we can also control the surface settlements.

The results: the control of surface settlements



An example: The “Nodo di Bologna High Speed Railway” project in Italy

Lessons learned:

1. **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).

2. **Be wise a priori:**

   Nowadays the "unexpected" is no longer acceptable from a strict "risk management" point of view.