Face stability in conventional tunnelling and EPB soil conditioning

TRAINING MATERIAL PREPARED BY

D. Peila and C. Oggeri
Face stability in conventional tunnelling

Part 1

Prepared by “C.Oggeri”

Prague - 2007
Face stability in conventional tunnelling and EPB soil conditioning

1 Introduction

2 Face stability control

3 How to reinforce the ground

4 Design approaches

5 Conclusions and References
Why to control face stability:

- Increase the free span and the stand up time to enlarge the size of the excavation section
- to cross “geo” or preexisting problems which can compromise the performances of non suitable TBM or enable the face support capabilities in conventional methods
- to control settlements and chymneying, and to protect buildings during tunnelling excavation in urban areas; to allow surface for road transportation
- to control water inflow
Which are the main actions that can be applied to increase stand up time or the unsupported span:

- to reduce of the excavation section into smaller portions
- to apply a counter pressure against the face
- to improve or reinforce the ground properties
- to use preventive supports of the rock mass installed ahead of the face

**Face stability in conventional tunnelling and EPB soil conditioning**
Face stability control

1) to reduce the excavation section into smaller portions.

If the face is smaller, the control of the stability is easier, the characteristic time is shorter, smaller is the amount of waste rock to be removed and fewer supports have to be installed.

Face stability in conventional tunnelling and EPB soil conditioning
2) to apply a counter pressure at the face
- mechanized tunnelling

Face stability control in conventional tunnelling and EPB soil conditioning
Face stability control

2) to apply a counter pressure at the face
- conventional tunnelling

Face reinforcing at the Bologna Florence high speed railway tunnels

*Face stability in conventional tunnelling and EPB soil conditioning*
Face stability in conventional tunnelling and EPB soil conditioning
The main problem when tunneling through difficult geotechnical conditions with conventional methods is the control of deformations of the tunnel periphery.

Without support or reinforcement the ground plasticizes and tends to move towards the opening and can be cause of:
- fall of ground from the upper part of the tunnel face
- displacement of tunnel boundary
- tunnel face extrusion and failure

To prevent these phenomena it is necessary to use “pre-supporting technique” or to improve and/or to reinforce the ground properties around the tunnel boundary.

**Face stability in conventional tunnelling and EPB soil conditioning**
How to reinforce the ground

Main reinforcing works are based on **IMPROVEMENTS, REINFORCEMENTS, PRE-SUPPORTS, DRAINAGE SYSTEMS**

along the chainage of the tunnel and in the surrounding ground:
- permanent: grouting, structural elements, drainage
  - temporary: freezing, drainage

ahead the face, before the excavation:
- permanent: steel arches, forepoling, grouting
  - temporary: drainage

at the face:
- permanent: radial bolting, invert
  - temporary: drainage, shotcreting, nailing, removable supports

during the excavation, in the surrounding ground:
- permanent: compensation grouting
  - temporary: drainage

**Face stability in conventional tunnelling and EPB soil conditioning**
How to reinforce the ground

IMPROVEMENT

Methods which improve (from the engineering point of view) the mechanical or hydraulic properties of the rock mass: injecting fluids or freezing the fluids already present in the ground

- permeation grouting
- compactation grouting
- jet grouting
- freezing

Face stability in conventional tunnelling and EPB soil conditioning
How to reinforce the ground

REINFORCEMENT

Methods which foresee the insertion, inside the rock mass, of structural elements

- systematic bolting
- micropiles
- cable bolting

Borzoli cavern, Italy

Face stability in conventional tunnelling and EPB soil conditioning
How to reinforce the ground

PRE-SUPPORT

Methods which foresee the insertion, in the rock mass, of structural elements ahead of the tunnel face with the purpose to create a pre-support of the void before the excavation is carried out

1. mechanical precut
2. pretunnel
3. steel pipe umbrella
4. forepoling
5. arch of microtunnels
6. jet-grouting arch
7. reinforced with VTR elements

Face stability in conventional tunnelling and EPB soil conditioning

Courtesy Geodata S.p.A., Torino
How to reinforce the ground

1. Mechanical precut

Face stability in conventional tunnelling and EPB soil conditioning
How to reinforce the ground

steel pipe umbrella

It is possible to cover advance lengths of 12-15 metres, of which 9-12 metres are of excavation, account being taken of the necessary overlap between two sets of pipe umbrella to guarantee the stability of the face.

**Face stability in conventional tunnelling and EPB soil conditioning**
How to reinforce the ground

forepoling

Steel pipe umbrella or forepoling is a pre-reinforcement technique which is obtained by installing steel pipes ahead of the tunnel face.

The steel pipes usually have a dip of 5°-10° (with reference to the horizontal) in a way as to form an umbrella with a truncated cone shape and which allows the overlapping of two adjacent fields.

Many applications have been carried out using self-drilling bolts.
How to reinforce the ground

arch of microtunnels

Face stability in conventional tunnelling and EPB soil conditioning

Highway 285 (Atlanta, USA)

Almaeda (Lisboa, Portugal)
How to reinforce the ground

1. Jet-grouting arch with or without reinforcement of the columns

Face stability in conventional tunnelling and EPB soil conditioning
Example of steel pipe umbrella and face reinforcement with VTR in clay at low depth
Milieu-Gaurain Tunnel (Belgio)

Face stability in conventional tunnelling and EPB soil conditioning
Tunnel face ground reinforcement is obtained by installing on the tunnel face fibre glass elements (such as pipes or plaquettes) fully grouted.

Face stability in conventional tunnelling and EPB soil conditioning.
Face stability in conventional tunnelling and EPB soil conditioning
Ground reinforcement used for the construction of the Bo-Fi highspeed railway (Italy)

Face stability in conventional tunnelling and EPB soil conditioning
Example of some scheme of ground reinforcement using longitudinal fiber glass reinforcement in Tartaiguille tunnel (France) (Lunardi, 2000)

Face stability in conventional tunnelling and EPB soil conditioning
Tartaiguille tunnel
(France) (Lunardi, 2000)

Face stability in conventional tunnelling and EPB soil conditioning
How to reinforce the ground

1. Structural works

2. Railway “Passante” of Turin:
   Grouting for sandy gravel soils and
   construction of precut concrete walls
   for preparation of conventional tunnelling

3. 

4. 

5. 

Face stability in conventional tunnelling and EPB soil conditioning
How to reinforce the ground

DRAINAGE

Technologies which take away water from the rock mass or the ground in a controlled way

Face stability in conventional tunnelling and EPB soil conditioning
How to reinforce the ground

<table>
<thead>
<tr>
<th>TYPE OF INTERVENTION</th>
<th>FIELD OF APPLICATION</th>
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<td>dewatering</td>
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<td>fibreglass elements</td>
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<tr>
<td>umbrella-arch</td>
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</table>

Key: ● Applicable. ○ Applicable with special intervention: 1 – chemical grout; 2 - two or three-fluid jet grouting; 3 - steel rebar or pipe reinforced jet grouting; 4 – active dewatering (vacuum pump required); 5 – additional grouting; 6 – high resistance element; 7 – additional grouting (Russo, 2003).

The interventions listed in this table can be combined in order to guarantee safe tunnelling conditions in almost all geotechnical conditions. Grouting, jet-grouting, freezing and dewatering can be normally be applicable also when tunnelling under water table. The other interventions when the tunnel is under the water table must be combined with impermeabilization techniques.

*Face stability in conventional tunnelling and EPB soil conditioning*
QUESTIONS

a) Which are the settlement modes?
b) Which are the failure modes?
c) Which are the uncertainties in the geological/preexisting conditions?
d) Which are the methods for design?

ANSWERS

a) Settlements can both be localised or distributed, homogeneous or basin shaped, immediate or progressive and delayed. All the combinations arise from the stratigraphy of the soil, the relation between tunnel size and its depth, the occurrence of unexpected old structures, the way of tunnelling and reinforcing. The boundary displacements and stability of a tunnel are always a three dimensional problem.

Face stability in conventional tunnelling and EPB soil conditioning
Design approaches

Face stability in conventional tunnelling and EPB soil conditioning
Design approaches

Face stability in conventional tunnelling and EPB soil conditioning
Design approaches

b) Failure modes

- Safety
- Rock Fall
- Break Down
- Collaps

- Displacements

- Closure
- Settlements

Face stability in conventional tunnelling and EPB soil conditioning
A difference can be put in evidence between cohesive and cohesionless soils
Tunnel near the surface - collapse mechanism: sliding of the ground

Failure bulbs for different ratio Diameter/depth (Chambon and Corté, 1990)

Face stability in conventional tunnelling and EPB soil conditioning
Tunnel near the surface - collapse mechanism: sliding of the ground

Influence of tunnel unlined length on extent of failure mechanism for C/D=4 (Chambon and Corté, 1990)

Face stability in conventional tunnelling and EPB soil conditioning
In urban areas the uncertainties arise both from the geology, i.e. the occurrence of different layers of soils (clay, gravel, sand, boulders), local phenomena (karst, alteration of outcrops), and also to man made structures (building foundations, old underground facilities). The water level and old fillings can also contribute to make more complex the ground conditions.
Example of steel pipe umbrella and permeation grouting in a tunnel portal Doria Tunnel (Genova, Italy) (Courtesy Geodata S.p.A.)

Face stability in conventional tunnelling and EPB soil conditioning
Design approaches

Face stability in conventional tunnelling and EPB soil conditioning
d) Which are the methods for design?
Theoretical determination of settlements and face stability remain difficult. However both analytical and numerical methods can be of great help.

Analytical: Peck, Leca, Dormieux, Rowe, Panet, Sagaseta, Attewell, Kovari, Mair, O’Reilly, New, Lunardi et al.

Numerical: FEM, FDM, PFC, implementing large displacements and interface behaviour.

In the design emphasis should be put on the expected failure mode and on the potential consequences on the structures above the ground.

Face stability in conventional tunnelling and EPB soil conditioning
Temporary support pressure on the face

\[ \sigma_t = \min \left[ \frac{4N_b A \sigma_b}{\pi D^2}, \frac{4N_b S_l \tau_a}{\pi D^2} \right] \]

where:

- \( N_b \) = number of VTR pipe;
- \( A \) = cross section of the VTR pipe;
- \( S_l \) = lateral surface of the pipes;
- \( \tau_a \) = shear stress on the lateral surface of the pipe;
- \( \sigma_b \) = yielding stress of the pipe material

Peila, 1994

**Face stability in conventional tunnelling and EPB soil conditioning**
Evaluation of face reinforcement action

Improvement of cohesion of the ground

\[ \Delta \sigma_3 = \frac{n \cdot T_{\text{max}}}{S} \]

\[ \tau^* = c + \frac{1 + \text{sen} \varphi}{2 \cdot \cos \varphi} \cdot \Delta \sigma_3 \]

\[ T_{\text{max}} = \text{max force of sliding between the reinforcement and the ground} \]

Face stability in conventional tunnelling and EPB soil conditioning
Horn model (1961) which was assumed by Anagnostou and Kovari (1994,1996) as the base for the stability analysis of the face ahead of Slurry Shield and EPB machines. The some model can be applied for face nailing calculation.
Stability analysis below the pre-support

Evaluation of the forces in the nails based on Soil nailing approach

(Racommendation Cluterre, 1991)

Face stability in conventional tunnelling and EPB soil conditioning
Evaluation of face reinforcement action

Cohesion increment

Rock reinforcement (a)

Applied pressure (b)

Modelling of the single pipes (c)

$P_{face} = \min\left\{ \frac{n \cdot A \cdot \sigma_{adm}}{S}, \frac{n \cdot S_f \cdot \tau_{adm}}{S} \right\}$

Face stability in conventional tunnelling and EPB soil conditioning

San Vitale tunnel (Italy)
Example of 3D numerical computation

Face stability in conventional tunnelling and EPB soil conditioning

Depth 5m
Example of 3D numerical computation

**FLAC3D 2.00**

Step 139000  Model Perspective
16:10:44 Tue Oct 10 2000

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<td>Z: -5.826e+000</td>
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Contour of Y-Displacement
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-2.5000e-003 to -2.0000e-003
-2.0000e-003 to -1.5000e-003
-1.5000e-003 to -1.0000e-003
-1.0000e-003 to -5.0000e-004
-5.0000e-004 to 0.0000e+000
0.0000e+000 to 5.0000e-004
5.0000e-004 to 6.4141e-004
Interval = 5.0e-004

Job Title: Realizzazione della fase 27
View Title: MGB1/F27 - Vista ingrandita sulla sezione - Spostamenti lungo l’asse y

*Face stability in conventional tunnelling and EPB soil conditioning*
Example of 3D numerical computation

**FLAC3D 2.00**

Step 139000 Model Perspective  
16:44:20 Tue Oct 10 2000

Center:  
X: 2.526e+001  
Y: 7.209e+001  
Z: -5.826e+000

Rotation:  
X: 13.000  
Y: 0.000  
Z: 45.000

Dist: 2.979e+002  
Mag.: 7.6  
Ang.: 22.500

**SEL Geometry**

**cableSEL Axial Force**

- Positive
- Negative

Maximum = 1.859e-001

**Sketch**

**Linestyle**

**POLITECNICO DI TORINO**  
Dip.di Georisorse e Territorio

*Face stability in conventional tunnelling and EPB soil conditioning*
Contour lines of total displacement for overburden of H/D=0.5 for different length of reinforcement left: 12m right: 4m (Schweiger and Mayer, 2004)

Face stability in conventional tunnelling and EPB soil conditioning
Design approaches

All the methods for design are linked to an operative phase:

the following main actions of the reinforcing techniques can be defined and designed:

- methods which modify the convergence-confinement curve
- methods which modify the radial displacement at the face
- methods which guarantee the stability of the free span
- methods which guarantee the local stability of the face
- methods which guarantee the stability of local volumes
- methods which control water inflow

*Face stability in conventional tunnelling and EPB soil conditioning*
Conclusions and references

In order to obtain a comprehensive control of tunnel face stability, it is helpful to consider:

- the boundary conditions (tunnel size, interferences, water conditions)
- the geological - geotechnical model (detailed characterization, with emphasis on the investigation and testing)
- the adoption of proved reinforcing methods
- the validation of both analytical and numerical methods of design
- the monitoring of both the tunnel excavation and of neighbouring structures
- the availability of data base of case histories, which represent the true tool to maintain the sensibility to the variety of actual conditions in urban or shallow tunnelling.

Face stability in conventional tunnelling and EPB soil conditioning
Conclusions and references

Among the others, it is possible to list the following titles:

1. R. Peck “Deep excavations and tunnelling in soft ground”
2. P. Chambon, J.F. Corté “Shallow tunnels in cohesionless soils: stability of tunnel face”
3. C.W.W. Ng, G.T.K Lee “A three dimensional parametric study of the use of soil nails for stabilising tunnel faces”
4. E. Leca, L. Dormieux “Upper and lower bound solutions for the face stability of shallow circular tunnels in frictional materials”
5. E. Leca, M. Panet “Analysis of tunnel front stability using the yield calculation approach”

C. Yoo, H.K. Shin “Deformation behaviour of tunnel face reinforced with longitudinal pipes; laboratory and numerical investigation”

C. Yoo “Finite element analysis of tunnel face reinforced by longitudinal pipes”

P. Lunardi “The design and construction of tunnels using the approach based on the analysis of controlled deformation in rocks and soils”

L. Cornejo, “Instability at the face: its repercussions for tunneling technology”

G. Anagnostou, K. Kovari “The face stability of slurry shield driven tunnels”

G. Anagnostou, K. Kovari “Face stability conditions with Earth pressure balanced shields”

ITA AITES WG Research, “Settlements induced by tunnelling in soft ground”
Face stability and EPB soil conditioning

Part 2

Prepared by “D. Peila”

Prague - 2007

4th of May 2005
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1. Introduction

2. Tunnel Boring Machine  face stability control

3. EPB soil conditioning

4. Laboratory tests

5. References

Face stability and EPB soil conditioning
Full face TBM tunnelling is undergoing great development throughout the world.

In long tunnels and/or in difficult geotechnical conditions as exist in many urban areas, the use of TBM is imperative:
- to reduce the risks for the urban environment
- to increase the safety of the working site
- to reduce excavation time

*Face stability and EPB soil conditioning*
TBM face stability control

1. When tunneling with full face machines in urban areas there are some specific aspects that influence the tunnelling risks and that must be taken into account in the design and the construction procedures.

2. **Urban environment**
   - Shallow overburden
   - Structures on ground surface
   - Foreign objects in ground
   - Constraints for alignment
   - Restriction for: impossibility of road closure; place of attack, material transport, access to TBM, exploration and carrying out of auxiliary measures (i.e. ground reinforcements), high visibility of damage

3. **Geological and hydrogeological conditions**
   - Properties of the recent geological formations
   - Presence of a man made filling (sometimes of unknown depth)
   - Frequently changing „geo“ conditions
   - Presence of ground water

4. Non-perfect (i.e. not as designed) performance of the tunneling method, i.e. of the TBM

5. **Face stability and EPB soil conditioning**
An optimal design must be based on risk analysis and risk management which must address the decision and choice to be taken and also influence the construction management.

In fact this approach permits after the identification of all potential hazards, to assign to each of them a probability of occurrence and to allocate an index of gravity-severity to the consequences.

With this picture in mind is possible to define:

- the solutions to be used to reduce the probability of occurrence of negative events
- the counter measures for reducing the gravity of the consequences of a negative event.

(Kovari, 2000, 2004; Guglielmenti et al., 2002; Guglielmetti, Mathab, Xu, 2007)
TBM face stability control

The most relevant risk scenarios in urban area when tunnelling with full face machines inside a soft soil are:

- Limiting condition for the machine (that is to say a condition for which the machine is not working as designed)
  - excessive wear of the tools
  - excessive wear of conditioning agents, grease, ect.
  - etc.

- Interferences with the local environment and accidents
  - face collapse which can reach the surface
  - damage of already existing constructions
  - underground water pollution
  - etc.

Face stability and EPB soil conditioning
TBM face stability control

In the present lecture we will analyse the problem of face stability which can cause the following type of accidents:

- face collapse which can reach the surface
- damage of already existing constructions both on surface or underground (i.e. subsidence)
TBM face stability control

First option for risk reduction

The first set of choices which permit the activation of countermeasures to be adopted to face these risk scenarios are:

1) the choice of a correct machine for the local urban environment and geology;

2) the correct management of the excavation process (control of face counter-pressure, evaluation of the amount of extracted material to avoid overexcavations, correct and proper filling of tail void, etc.)
TBM face stability control

First option for risk reduction

With specific reference to the correct choice and management of the full face machines it is necessary to control the face stability:

a) to correctly evaluate the face pressure to be applied to guarantee the stability and correctly apply with reference of the local environment;

b) to properly treat (condition) the ground to permit the face pressure to be applied by the machine;

c) to control the excavation process to avoid over-excavation (monitoring of the ground and of the machine performances)

If these options are not sufficient it is necessary to use a second set of options for risk reduction

Face stability and EPB soil conditioning
TBM face stability control

Most used face support methods

- Slurry
- Excavated soil
- Compressed air
TBM face stability control

Face stability and EPB soil conditioning

1. Precast concrete lining
2. TBM face stability control
3. Cutting head
4. Screw conveyor
5. Excavated soil

Additives nozzles
Pressure chamber
Head motors
Thrust jacks
Iron shield
Backfilling injections

Material scale
Precast concrete lining
TBM face stability control
EPB machine suggested ranges of applications

Face stability and EPB soil conditioning

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### Face stability and EPB soil conditioning

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TBM face stability control
EPB machine suggested ranges of applications

These granulometric curves are only indicative since very often the machines are used outside these ranges to face different ground types by varying the type and the amount of conditioning agents.
TBM face stability control

EPB machine example of applications

Face stability and EPB soil conditioning
TBM face stability control

1) Definition of the stabilizing pressure to guarantee the stability

2) Definition of the failure mechanism

Face stability and EPB soil conditioning
The definition of the appropriate EPB face pressure need to be considered on a project-by-project basis taking into proper account the soil properties, the groundwater content and the TBM design.

**Groundwater pressure**: in some types of rock such as weak or broken rock the principal reason for using a closed-face machine is to control groundwater.

The operating pressure should be a small margin, perhaps 10%, above the existing hydrostatic pressure.

In water bearing granular material it is necessary to apply operating pressures to resist both hydrostatic and soil pressure.

In both cases it is necessary to ensure that no risk of ground loss from the crown

(BTS, 2005)
TBM face stability control

Design aspects

1. Unstable ground: In non-water bearing granular material where there is no water pressure to balance and where the soil pressure may be small it is difficult to determine the operating pressure.

   It is necessary to operate the machine at a pressure that ensures the bulk chamber remains full at all the times to guard against loss of ground from the tunnel crown.

   In soft clays and silts that can flow it may be appropriate to use a pressure that approximates to full overburden pressure

   (BTS, 2005)
Modification or conditioning of the excavated material is a process for both slurry and EPB tunnelling system.

For EPB shields conditioning agents, usually foam or foam/polymer solution are injected under pressure into the spoil as it is excavated to assist the tunnelling process in two ways:

1. When mixed with the soil the conditioning fluid reduces the permeability and the internal friction of the material which flow through the bulk chamber and the screw conveyor for discharge into the muck-haulage skips at the atmospheric pressure;

2. The reduction of permeability of the material enables the creation of the plug in the screw conveyor to form and ensure that earth pressure balance support of the tunnel face is maintained.

Face stability and EPB soil conditioning
TBM face stability control

Monitoring of buildings and of the surface

Torino metro – courtesy GTT-Torino

Face stability and EPB soil conditioning
TBM face stability control

Monitoring of machine performance

To monitor an EPB machine the following parameters are used:
- the pressure inside the bulk chamber and along the screw-drive;
- the weight of extracted material;
- the amount of material injected in the tail void and the injection pressure.

Many pressure sensors are applied inside the bulk chamber to measure and keep under control the pressure of the spoil. This control is a key parameter for the correct management of the machine and for the control of tunnel face stability.
TBM face stability control

Monitoring of machine performance

Face stability and EPB soil conditioning

Average value of earth pressure at the face and of the weigh of the extracted material

Guglielmetti et al., 2002
TBM face stability control

Secondary option for risk reduction

a) Constructional measures
   - Ground improvement from the surface
   - Ground improvement from underground works
   - Prepared grouted blocks for stopping the machine
   - Preventive structures

b) Additional measures
   - evacuation of buildings
   - closure of roads

Face stability and EPB soil conditioning
TBM face stability control

Ground improvement

Torino Metro

Face stability and EPB soil conditioning
TBM face stability control

Ground improvement

Torino Metro

Face stability and EPB soil conditioning
TBM face stability control

Face stability and EPB soil conditioning

Zimmerberg Tunnel
Zurich; Kovari, 2004
TBM face stability control

Ground improvement around the tunnel to be excavated

Face stability and EPB soil conditioning

Torino metro
TBM face stability control

Preventive structures

Zimmerberg Tunnel
Zurich; Kovari, 2004

Face stability and EPB soil conditioning
TBM face stability control

Prepared grouted blocks for stopping of machines

Longitudinal section

Cross section

grouted body

tunnel

Face stability and EPB soil conditioning
In order to fulfill all the requirements for a successful EPB technology application, as well as to extend the applicability of such technology over a wider range of soils, it becomes necessary to inject some additives that “transform” the soil into a material that shows the required features:

- Good plasticity
- Low permeability
- Pulpy consistency

For EPB system spoil conditioning is an essential part of the tunnelling process.

**Face stability and EPB soil conditioning**
EPB soil conditioning

Main goals to be obtained with soil conditioning

1. Reduction of the wear for all mechanical parts of the machine in contact with the soil
2. Better uniformity of the pressure distribution in the bulk chamber and consequent improvement of the face stability, with better control of the subsidences
3. Control of the flow of the excavated material through the cutter head
4. Reduction of the required power for the cutter head due to the reduction of friction
5. Reduction of the friction forces in the bulk chamber with consequent reduction of the generated heat;
   • Reduction of the permeability with consequent better control of water inflow;
   • Smoother flow of material along the screw conveyor and creation of the plug in the screw;
   • Easier spoil handling
EPB soil conditioning

SOIL CONDITIONING: WHERE

The additives are injected in several points of the machine:

- ahead the cutting head
- in the pressure chamber
- along the screw conveyor

Face stability and EPB soil conditioning
The most used additives for soil conditioning belongs to following families:

- **Foam** (surfactants and are delivered to site as concentrates. These are mixed with water and compressed air in a specific ratio to create a foam).
- **Polymers** (to improve the foam stability and the consistency of the spoil)
- **Anti-amalgams** in ground with high clay content to avoid amalgamation and improve their characteristics
- **Abrasion-preventers**
- **Bentonite**
- **Filler**

Water can also be injected in order to plasticize the finer part of the soil (clay, silt).
EPB soil conditioning

Average composition for a normally used foam:

- Foaming agent: 0.5-1%
- Water: 5-10%
- Air: 90-95%
- Polymer (eventual): <0.1%

Foaming agent can have inside a small amount of polymer to stabilize the foam bubbles.
EPB soil conditioning

Foam properties assessment

1. Foam expansion ratio (FER): to measure the ratio of concentrate to expand foam. Should be carried out using foam generator that is intended to use on the TBM.

2. Foam density: to measure the density of various foams in their expanded state.

3. Foam stability (half time): to measure the durability of the foam at atmospheric pressure (different foams can change their properties in 3 min to 1 hour).

Face stability and EPB soil conditioning
SOIL CONDITIONING: HOW

By now, no procedure nor protocol or guidelines have been developed for the conditioned soil features assessment: “At present, soil conditioning in soft ground tunnel boring machines remains very much a “black art”, determined largely by experience or trial and error”

as reported by EFNARC, “Specification and Guidelines for the use of specialist products for Soft Ground Tunnelling, November 2001 and the latest EFNARC specifications (dated April 2005) the issue “Test methods for conditioned soil” is not largely discussed.
Laboratory tests

FOAM Design parameters

normally used ranges

\[
FER = \frac{V_{\text{foam}}}{V_{\text{generation} \_\text{liquid}}}
\]

FER = Foam Expansion Ratio

\[
FIR = \frac{V_{\text{foam}}}{V_{\text{excavated} \_\text{soil}}}
\]

FIR = Foam Injection Ratio

(8 - 20)

(20 – 80 %)

Face stability and EPB soil conditioning
### Laboratory tests

#### Face stability and EPB soil conditioning

<table>
<thead>
<tr>
<th>Soil</th>
<th>Foam types</th>
<th>Polymer additives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clay</strong></td>
<td>A</td>
<td>30-80 Anti clogging polymer</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>FIR</strong></td>
<td></td>
</tr>
<tr>
<td>Sandy clay – silt</td>
<td>40-60</td>
<td>Anti clogging polymer</td>
</tr>
<tr>
<td>Sand – clayey silt</td>
<td>20-40</td>
<td>Polymer for consistency control</td>
</tr>
<tr>
<td>Sand</td>
<td>30-40</td>
<td>Polymer for cohesiveness and consistency control</td>
</tr>
<tr>
<td>Clayey ravels</td>
<td>25-50</td>
<td>Polymer for cohesiveness and consistency control</td>
</tr>
<tr>
<td>Sandy ravels</td>
<td>30-60</td>
<td>Polymer for cohesiveness and consistency control</td>
</tr>
</tbody>
</table>

Product types for EPBM relative to different soils (FIR values are indicative only)

*EFNARC (2005)*
Laboratory tests

Test on the conditioned soil

1. Foam penetration test
2. Slump tests
3. Mixing tests
4. Permeability test
5. Screw drive extraction tests
Test on the conditioned soil

Foam penetration test

The purpose of this test is to determine the depth, beyond the cutterhead to which the foam can be injected.

During the test the foam is made to penetrate under pressure in the sample contained in a cylinder to which is also applied a water counter-pressure. The ability of the foam to penetrate inside the ground is then measured.
Slump test on conditioned soil

The purpose of this test is to determine a global and plastic behaviour of the treated ground.

The conventional slump cone standard as for fresh concrete is used.

Values of cone fall between 10 and 15 are usually suggested as optimal in technical literature.

Vinai et al. (2007) proposed an assessment chart for interpretation of cohesion less soils.
Laboratory tests

Slump test: soil assessment

The assessment of the quality of the additivation has been carried out both measuring the cone fall height and observing the final consistency of the mix:

- Good
- Fair
- Too dry
- Too wet
Laboratory tests

Face stability and EPB soil conditioning

Slump test: soil assessment

Relationship between water content and FIR for an uniform sand

Peila et al. 2007
Laboratory tests

Face stability and EPB soil conditioning

Vinai, 2006

Foam mix stability

W=10%
FIR=40%

Cone fall [cm]

cone fall [cm]

time [h]

0 10 20 30 40 50 60 70 80 90 100

0 2 4 6 8 10 12 14 16 18 20

Cone fall
log. approx

Vinai, 2006
Laboratory tests

Foam effect on drainage time

\[ td_{50} = \frac{t(250\text{ml})_{\text{cond}}}{t(250\text{ml})_{\text{nat}}} \]

Face stability and EPB soil conditioning
Laboratory tests

1. The use of simple tests as slump test for the definition of the quality of the soil treatment is necessary both for a matter of simple and quick execution as well as the possibility of check the results on job-site;

2. The global understanding of the behaviour of the conditioned soil calls for a deeper investigation based on big size tests analysing precise aspects of the EPB operations;

3. Geometry and dimension of an experimental apparatus should be as similar as possible to reality, as well as monitored parameters should be the same recorded during real excavation;

4. The whole chain of pressure transmission, from pressure chamber to the discharging point of the screw conveyor should be monitored.

Face stability and EPB soil conditioning
Laboratory tests

<table>
<thead>
<tr>
<th>Component</th>
<th>Dimension: mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conveyor casing length</td>
<td>1050</td>
</tr>
<tr>
<td>Conveyor casing internal diameter</td>
<td>108</td>
</tr>
<tr>
<td>Unrestricted discharge outlet diameter</td>
<td>85</td>
</tr>
<tr>
<td>Restricted discharge outlet diameter</td>
<td>50</td>
</tr>
<tr>
<td>Screw length</td>
<td>1200</td>
</tr>
<tr>
<td>Screw flight diameter</td>
<td>102</td>
</tr>
<tr>
<td>Screw shaft diameter</td>
<td>43</td>
</tr>
<tr>
<td>Screw pitch</td>
<td>80/130</td>
</tr>
</tbody>
</table>

Device used at Cambridge University - Merritt and Mair, 2006

Face stability and EPB soil conditioning
Laboratory tests

Lab screw conveyor devices

Device used at Politecnico di Torino - Vinai et al., 2006

Face stability and EPB soil conditioning
**Laboratory tests**

**Lab screw conveyor devices**

1. Displacement wire transducer
2. Pressure cell on the top of the tank
3. Pressure cell on the bottom of the tank
4. Torquemeter
5. Pressure cells along the screw conveyor
6. Precision scale
7. Tank height: 800mm
8. Tank diameter: 600mm
9. Screw length: 1500mm
10. Screw diameter: 168mm

Device used at Politecnico di Torino - Vinai et al., 2006

*Face stability and EPB soil conditioning*
Laboratory tests

Lab screw conveyor devices

Better transmission of the pressures from the tank to the screw conveyor and along the screw conveyor itself.

Saturated sand

Conditioned sand

Vinai et al., 2006
Laboratory tests

Lab screw conveyor devices

Conditioned soil

Wet sand

Face stability and EPB soil conditioning
Laboratory tests

Face stability and EPB soil conditioning

screw torque measured values
Laboratory tests

FIR = 25%
\( w = 10\% \)
FER = 16

Face stability and EPB soil conditioning

Natural soil
103/111
Laboratory tests

Face stability and EPB soil conditioning
Laboratory tests

Face stability and EPB soil conditioning
References


Face stability and EPB soil conditioning
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