Construction of bored tunnels in urban areas – Essential techniques for success

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1 Introduction

The requirement to develop basic infrastructure in large, densely populated cities has led many transport projects to be constructed below ground. Singapore, Hong Kong, Shanghai, Chengdu and a number of other major Chinese cities are examples of Asian cities where increasing populations have led to the Mass Rapid Transit Railways being constructed underground to avoid the occupation of expensive land on the surface as well as to minimize traffic congestion both during and after construction.

The most common method to construct large diameter tunnels in urban environments has been by bored tunnel since this method is considered as relatively safe with regard to the risk to adjacent structures. This is due to the capability of boring machines to limit surface settlement by ensuring that earth and water pressures are balanced during excavation therefore reducing or eliminating over excavation. In addition the use of two component backfill grouting through the boring machine tail skin has reduced settlement directly behind the ring build area.

This document will describe the use of soil conditioners that assist in ensuring that Tunnel Boring Machines can operate within expected design parameters and ensure that settlements due to tunnel construction is minimized. It will also describe the latest backfill grout techniques with examples of typical backfill grout design mixes.

2 Bored Tunneling – selection of Tunnel Boring Machines

The selection of a tunnel boring machine is made based on information usually obtained from soil investigations carried out either pre or post contract award. The most important soil characteristics when choosing a TBM are the soil grain size distribution, un-drained shear strength and density/consistency.

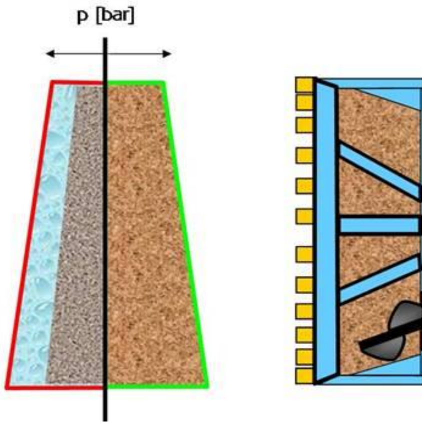
In the case of most highly populated South East Asian cities, which are located near to the coast or in flat areas associated with large river flood plains, the soil conditions are classified as soft and would not accommodate the use of manual or partially mechanized methods such as the New Austrian Tunneling Method.

Pressurised Face Shield TBM's, which are used in soft ground, "are capable of exerting a balancing pressure against the tunnel face "which can "control excavation rates and ground water inflow as well as stabilise the tunnel face". (*1) The amount of pressure required to stabilize the excavation face is calculated based on parameters such as tunnel depth, soil characteristics and hydrostatic pressure.

Their are two main types of Pressurized Face TBM's.

2.1 Slurry TBM

Typically in relatively non cohesive soils with high water pressure and large particle size a slurry, often containing bentonite, under pressure is used in the excavation chamber to counterbalance the soil and water pressure. This slurry is also used to transport the excavated soil to the surface where the soil is separated from the slurry and disposed off site. The slurry is then reconditioned and returned to the excavation chamber.

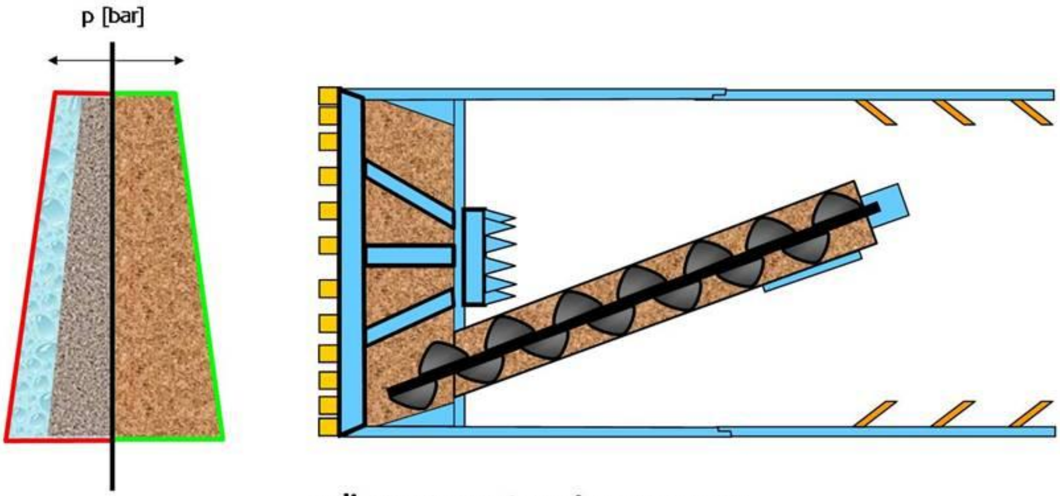


Soil Pressure + Water Pressure

= Slurry Pressure in working chamber

2.2 Earth Pressure Balance TBM

An Earth Pressure Balanced TBM differs from Slurry since the soil and water pressure exerted on to the TBM excavation face is balanced by the soil inside the working chamber, as oppose to a liquid slurry. The pressure of the soil inside the working chamber is controlled by the timely release of soil through the screw conveyor. The design of the screw conveyor allows for the loss of pressure in the soil so that it is eventually discharged under atmospheric pressure at the screw discharge gate.



soil pressure + water pressure
=
earth pressure in working chamber

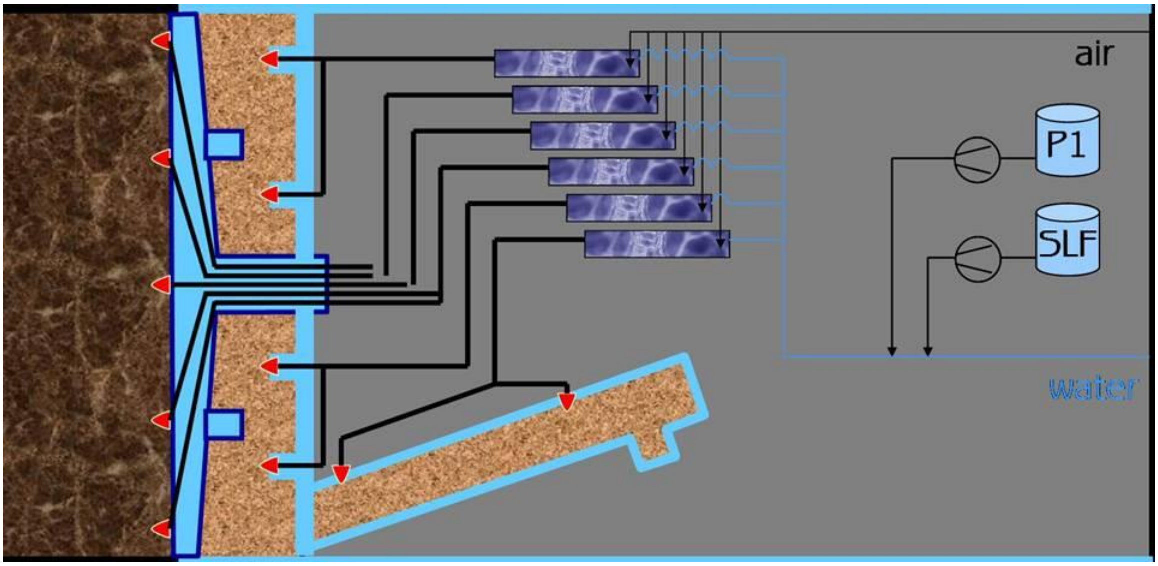
In order for the excavated soil in the chamber to provide adequate support to the excavation face and so that it has the consistency not to travel along the screw conveyor under its own weight it should have certain characteristics.

The ideal soil behaviour for EPB drives generally includes

- Good plastic deformation
- Low permeability
- Low angle of friction
- Pulpy to soft consistency (*2)

In reality the excavated soil seldom demonstrates these properties therefore the soil needs to be conditioned. The soil is conditioned by the injection and subsequent mixing of the soil at the cutter face, directly in contact with the excavation face, working chamber and sometimes the screw conveyor.

Depending on the soil type different soil conditioning technologies can be used to get the most satisfactory results.



Conditioning layout showing injection at cutterface, working chamber and screw conveyor.

Typical discharge of soil conditioner from several ports at the cutterhead.

2.3 Soil Conditioners

Soil conditioning technology is continuously being developed so that EPB machines can be used successfully in ever more challenging soil conditions.

Their are three current conditioning technologies which can be used alone or in combination to treat the soil into the required condition.

2.3.1 Foams

Foam is the “physical state of air dispersed in a liquid” (*3) and is achieved using chemicals called “surfactants”. The surfactants act as fluidizing agents when mixed with the excavated soil.

Sandy Gravel

Sandy Gravel with Foam

Other benefits of the introduction of foam include a reduction in the energy required to rotate the cutter head and less risk of the soil sticking to the cutter head and causing blockages which result in poor performance of the TBM.

There are many different types of foams with varying properties which include

- Air incorporation
- Half life time
- Anti-clay behavior
- Ion sensibility
- Rheological behavior
- Soil draining behavior

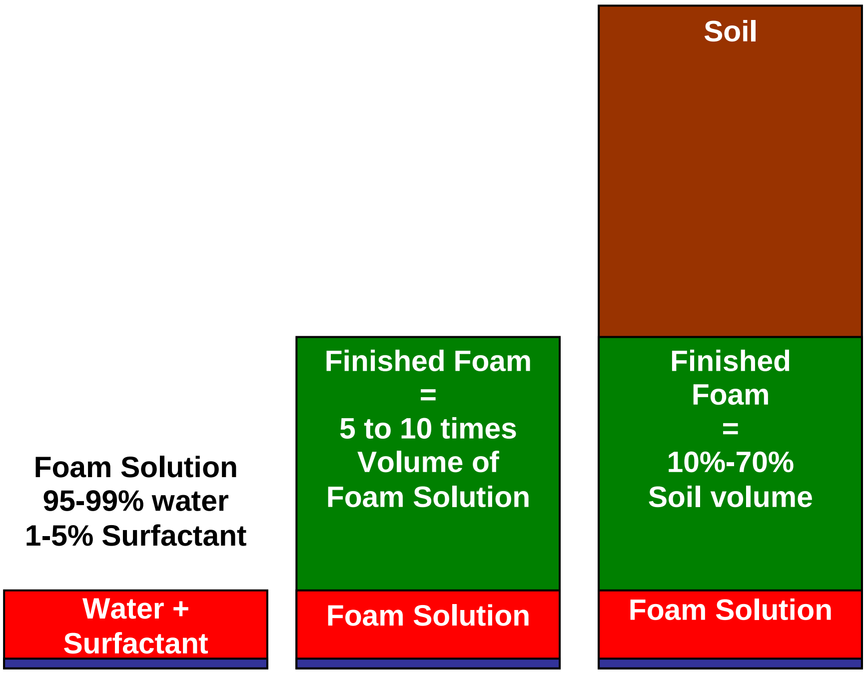
It is therefore vital to carry out laboratory tests on soil samples before the TBM operation commences in order to save time and unnecessary site tests. It is common for soil samples from the shaft or station to be collected and tested well in advance of TBM commencement.

Apart from the characteristics of each foam type the following properties of the injected foam can be varied

Surfactant Concentration – this will affect the quality of the foam and the amount of molecules in the final foam and is described as a % of the Surfactant against water. The mixture of surfactant and water is called the foam solution. Typical concentrations might vary from 1 to 5%.

Foam Expansion Ratio- will define the ration between liquid and air in the foam. This is measured by comparing the volume of the foam solution against the expanded foam and usually varies from 5 to 10 times.

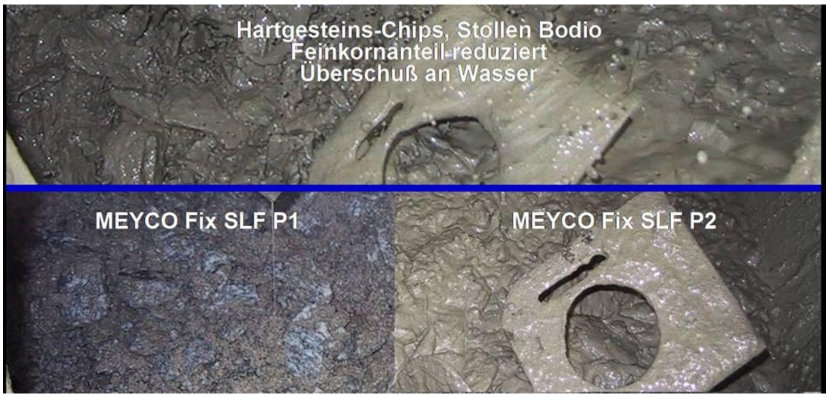
Foam Injection Ratio- this is the amount of the finished foam which will be introduced into the mixing chamber. This is normally presented as a % of the soil volume and can range from 10 to 70%.



Typical usage of foam for injection

2.3.2 Polymers

The first Polymers used for tunneling were polyacrylamides however recent developments have led to the use of hydrocarbon chains which are water soluble and biodegradable. By introducing polymers into the excavated soil the cohesion is increased therefore producing more stable soil for face support and to ensure that a plug is formed in the screw conveyor. Some Polymers can also absorb ground water in the soil therefore reducing the liquid characteristics of the excavated soil. Polymers are “particularly recommended for poorly graded and low fines ground, saturated ground, and high water pressure ground in EPB shield machines” (*4)



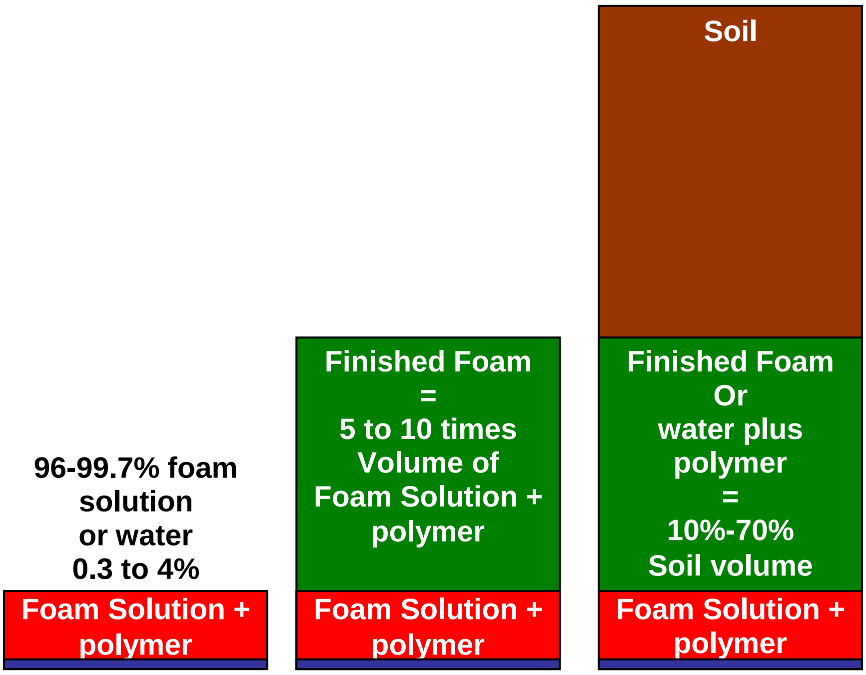
The excavated soil is loose and non cohesive in the upper picture however after addition of polymers the soil is uniform and cohesive similar to a low slump concrete.

Polymers can be introduced into the excavated soil in several ways

- By adding the polymer to the foam solution
- By injecting the polymer directly into the cutter chamber or screw conveyor
- By adding polymer to water that is injected into the cutter chamber.

In very dry soils it is common for some water to be injected into the cutter chamber to assist in producing a plastic material however the mixed soil is often not cohesive therefore the addition of polymer to the water helps bind the mixed soil together.

Typical rates of polymer usage range from 0.3 to 4% of the foam solution/injected water.



Typical usage of polymer for injection

2.3.3 Anti Clay agents

Anti Clay agents are also liquid polymers which have been designed to specifically tackle the problems associated with heavy soils such as clays.

The main function of the polymer is to reduce the “stickiness” of the clay to the metal surfaces of the TBM as well as to improve the soil consistency. The effect on the TBM is to reduce clogging of the TBM cutter face which allows the TBM to excavate at increased speeds.

Bologna cay +
water & foam

Bologna clay +
foam & Rheosoil

Left picture shows clay stuck to the metal mixing paddle. Right picture shows the soil particles have adhered to each other and the mixing paddle is clean.

Anti Clay agents can be introduced into the foam solution or into the water which is injected into the cutter head(similar to Polymers). Typical consumption of Anti Clay agents is in the range of 0.1 to 0.5% of the soil volume.

Soil Conditioning Example- Toulouse Metro Lot 2

Toulouse Metro Lot 2 is a 4.7km long tunnel constructed using a 7.785m diameter EPB TBM. The geology along the tunnel route is predominantly clay with some sand lenses with high water pressure. The tunnel route passes below heavily built up areas where excessive settlement issues could prove problematic to the success of the project.

The TBM was launched and operated without soil conditioning and with partial compressed air in the cutter chamber which proved reasonably successful in dry and homogeneous soil.

However when sand lenses were encountered the sand and ground water entered the cutter chamber uncontrollably despite the air pressure.

Following laboratory tests to determine the best soil conditioning regime a combination of water, Foam and Anti Clay Agent was used to produce a homogenous and non sticky soil which could fill the cutter chamber under pressure and prevent uncontrolled ingress of sand and ground water.

Toulouse Metro -Plastic and Non clogging conditioned soil

The injection regime was a follows (*5)

- Foam Concentration SLF 30 2-3%
- Foam Expansion Ratio 8
- Foam Injection Ratio 70%
- Anti Clay agent Rheosoil 211 0.8 to 1kg/m3 of insitu soil
- Water 5-20m3/ring.

The resulting TBM performance was satisfactory and surface settlement was controlled as the excavation face was fully supported by the conditioned soil in the chamber. The cutter head was also free of clogging which ensured good advance rates for the TBM of 40-50mm/minute.

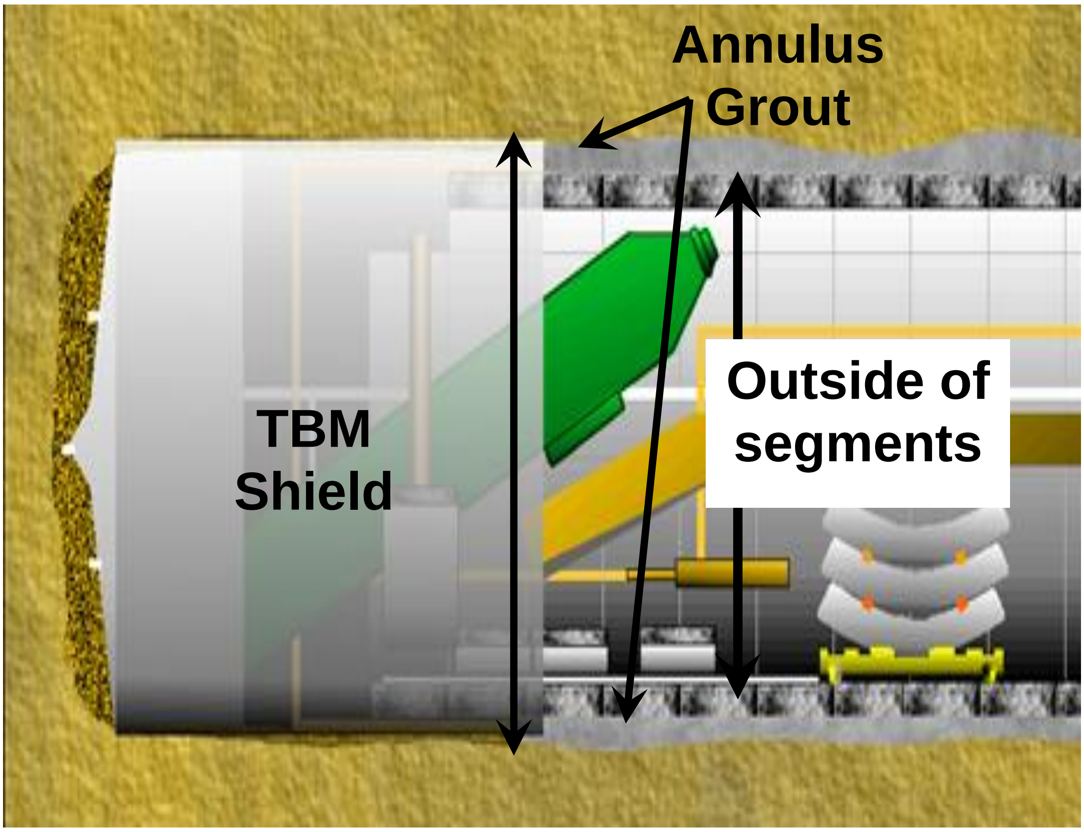
Toulouse Metro TBM cutter head with all openings clear and cutter bits clearly visible.

2.4 Annulus Backfill Grouting

"As a shielded TBM advances, an annular void is inevitably created behind the concrete lining. This void has to be completely filled with an appropriate material as soon as operationally possible." (*6)

The thickness of this void is predominantly dictated by the structural thickness of the shield which is designed to withstand the soil and ground water pressure as well as forces which result from TBM thrust. Typical thickness of annulus grout range from 60mm to 120mm. This void is filled with material, usually a cement based grout with the following benefits.

- To give early stability as construction occurs
- To prevent heave / flotation of the segment lining
- To take early load in the build area
- To reduce settlement, especially in non-cohesive soils
- To prevent segmental misalignment
  and the rupturing of gaskets
- To eliminate / reduce water ingress
  to avoid secondary injection



"Research findings so far have shown an evident qualitative correlation between the quality of the grouting process in the annular tail void at the back of the TBM and settlements."(*7)

In the case of soft soils as encountered in the region their have been two traditional methods of injecting the grout into the annulus void.

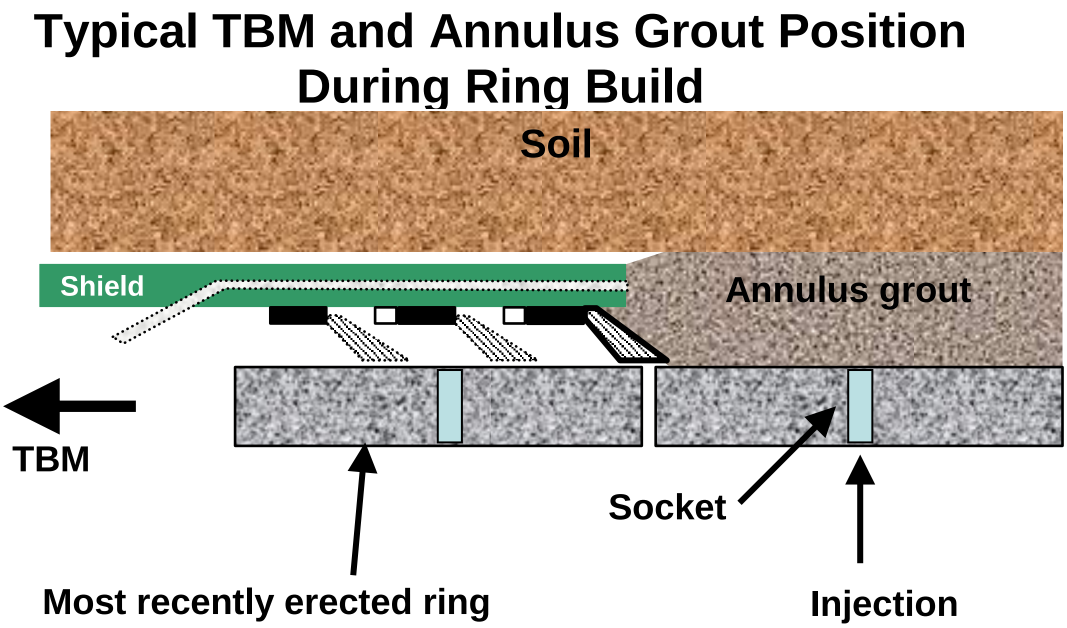
2.4.1 Injection through the Segment Lining

Historically the most commonly used method of injecting the annulus grout has been through a socket in the pre cast concrete tunnel segment. The socket is normally fixed with a non-return valve to prevent the injected grout from leaking back into the tunnel.

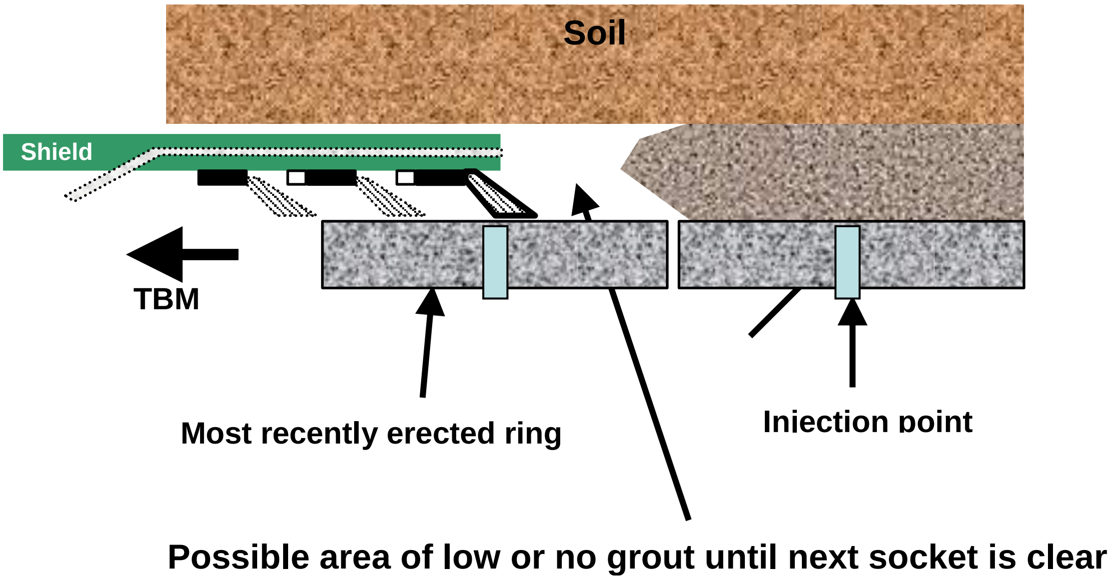
Grout hose fixed to socket on inner surface of tunnel segment.

This method has the advantage of being easy to control the grouting operation and cleaning of the grouting hoses etc. In the event of a blocked hose or grout socket a spare hose can be connected to another segment socket and grouting can continue.

The main disadvantage of this method is the failure of the grouting operation to keep pace with the TBM movement.



Typical Position during Early Stage of Excavation Stroke

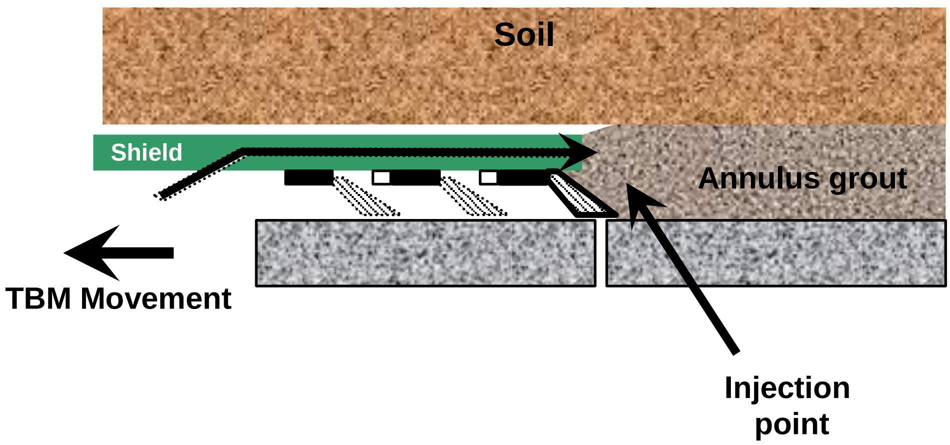


Due to this reason it has become increasingly popular for the annulus grout to be injected simultaneously through the TBM Tail Skin

2.4.2 TBM Tail Skin Grouting

Following research to improve the annulus grouting operation and reduce surface settlement the technology was developed to inject the annulus grout through the TBM Shield Tail Skin simultaneously with TBM movement. This is achieved by installing pipe lines inside the structure of the tail skin.

Typical TBM Tail Skin Annulus Grout Arrangement



This method provides several advantages over injection through the segment such as

- In unstable ground the grout provides support immediately reducing possible settlement
- The grout is introduced instantaneously as the TBM moves.
- No requirement for sockets through the segment, which provide the opportunity for ground water to enter the tunnel, therefore segment durability is increased.

However due to the location of the grout pipes directly behind the segments it is difficult to maintain and repair the grout pipes.

It has now become common on most tunnel projects in the region to grout through the TBM Tail Skin.

2.4.3 Backfill grout mix designs

Backfill grout requires several properties including

- Good flowability
- Good pumpability over pumping distance
- Workability may be required from 4 - 24 hours
- No bleeding (<1% bleed of free water)
- Anti-washout properties
- Easy to mix and transport
- Easy cleaning of the grout channel (tailskin)
- Durable with no shrinkage

In order to achieve these properties several ingredients are used such as

- Cement
- Fine aggregates
- Water
- PFA (fly ash)
- Limestone dust
- Blast Furnace Slag
- Bentonite
- Colloidal silica
- Admixtures

The development of a suitable mix design for a specific TBM and Geological condition requires laboratory and site trials well in advance of the TBM starting work on site. This mix design development is often carried out together with a construction chemical company as the performance of the grout is difficult to achieve without the use of one or more admixtures.

Their have typically been two separate classifications of mixes based on the concept of the injection process.

2.4.4 Single Component

A single component mix was the most commonly used mix and provides a grout which retains its flow characteristics for a period of several hours while it is mixed, transported and injected into the annulus void. While this type of grout is easily handled it has the disadvantage of having a slow set time which can lead to failure to provide adequate support for the soil immediately after injection.

Typical Single Component Backfill Grout requirements

- Bleeding at 3 h < 3.0 %
- Marsh cone (10 mm) 40 – 50 sec
- Open time 2 h
- Compressive strength at 24 h 1.5 MPa
- Compressive strength at 28 d 15 MPa

In order to make the mix economical it is common for the grout to contain a filler such as limestone as well as sand. In this case the backfill grout would be more accurately described as a liquid mortar.

Mix	Composition
OPC	180 kg/m^3
water	300 l/m^3
Fly ash	330 kg/m^3
limestone	230 kg/m^3
sand	900 kg/m^3
Admixtures Rheobuild 1000 Glenium Ace 38	6.5 l/m^3
Air entrainer Micro Air 200	2,5 l/m^3
Retarder Delvo	0.3 – 0.8 l/m3

Typical Single Component Mix

2.4.5 Two Component

Two Component systems were developed primarily to allow for a very early strength grout so as to provide support to the soil directly behind the TBM Tail Skin. This is achieved by using an accelerator as the second component to speed up the set of the cement based grout.

Typical Two Component Backfill Grout requirements

- Bleeding : Less 5%
- Flow : 6-12 sec
- Open time : 6-48hours
- Gel time (after mix accelerator) : 8-15sec
- 28 day Compressive Strength : 2.0 MPa

Typically this mix is a pure grout and does not contain sand or a filler however bentonite is often used to help reduce bleeding in the mix.

Typical Two Component Mix Design Kg/m^3

Cement	Bentonite	Water	Retarder Pozzolith 89	Accelerator GA-10
230	30	830	2.0 ltrs	80

The mixes are generally very fluid and can be pumped for several kilometers in the tunnel eliminating the need to transport the grout into the tunnel by locomotive.

Disadvantages of this system include the increased cost of the accelerator and the maintenance of the delivery system which is more likely to choke with the use of an accelerator.

In the South East Asia region the vast majority of TBM projects specify Two Component systems.

3 Conclusions

With the increasing need to construct underground infrastructure projects in densely populated cities it is essential that the works are executed with a minimal affect to traffic and property.

This document has detailed some of the technologies which are available to assist in smooth and safe TBM operation in the field of soil conditioning and backfill grouting. By using the latest available technologies and partnering with leading companies to ensure the correct decisions are taken before and during construction the risk to the project can be significantly reduced.

List of References

*1 Luke Erickson, Peter Raleigh, Victor Romero. Geotechnical Conditions and TBM selection for the Bay Tunnel

*2 Dr. Qiu Ling Feng (2004), “Soil Conditioning for Modern EPBM drives ”Tunnel and Tunnelling International Page 18 December 2004

*3 S.Jancsecz, R. Krause, L. Langmaak (1999) “Advantages of Soil Conditioning in Shield Tunneling. Experiences of LRTS Izmir” ITA 1999 Page 3

*4 BASF, Meyco SLF P2 Technical Data Sheet.

*5 Albin Martinotto, Lars Langmaak,(2007) “Toulouse Metro Lot 2: soil conditioning in difficult ground conditions” ITA 2007 Page 5.

*****6 Two-component backfill grouting on Rome’s Line C, Packaging Today June 2011.

*7 Ir. J.G.S. Pennekamp, Dr. IR A.M. Talmon, (2004) “Backfill Grouting” http://www.narcis.nl/research/RecordID/OND1300808