Railway Procurement Agency

METRO NORTH

ORAL HEARING

Response to questions from the Inspector on the Technology of Closed face Tunnel Boring Machines

December 2009

Railway Procurement Agency

Metro North Oral Hearing

Responses to questions from the Inspector on the Technology of Closed face Tunnel Boring machines

December 2009

Metro North Oral Hearing

Responses to questions from the Inspector on the Technology

of Closed face Tunnel Boring machines. December 2009.

Introduction

Please find enclosed a written submission of the presentation made by Dr. Alastair Biggart to An Bord Pleanála on 17th December 2009 with regards to closed face tunnel boring machine technology.

During the week commencing 14th December 2009, several tunnelling related issues were discussed and answers provided to the Board to which RPA would like to take this opportunity to provide further clarification. A summary of the issues discussed, and the clarified responses are provided below.

Clarification of Tunnelling Responses

Date Question Raised	Summary of Issue Discussed	Clarification
15th December 2009	The use of closed face tunnelling machines. Mr. Rory O'Connor indicated that the Contractor will operate the tunnel boring machines (TBM's) in closed face mode.	It is possible where ground conditions permit that the Contractor may choose to operate the TBM's in open face mode. An example of such operation would be through the limestone bedrock in areas where significant inflows of groundwater would not be encountered.
16th December 2009	In response to the Inspector, Mr. Geoffrey Featherstone indicated that it is estimated that it would, depending on shift patterns, take two to four months to excavate the underground emergency crossover beneath St. Patrick's sports fields.	As indicated in RPA's response to An Bord Pleanála's further information request of 26th June 2009, Item 1 Part 5, Impact Assessment No. 71 Ferguson Road, 4.4.2, it is estimated that excavation and construction of the emergency crossover will take four months. The cross passage located just north of the emergency crossover is estimated to take three weeks to excavate, and three weeks to line and finish.
17th December 2009	Dr. Massarsch asked Dr. Alastair Biggart how long he had been working on the Metro North project, to which Dr. Biggart replied "since last month".	Prior to employing Dr. Biggart to advise on TBM issues, RPA employed Mr. Peter South in this capacity from Autumn 2008. Mr. South has over 40 years practical experience of tunnelling and TBM's with major UK contractors Nuttall, Mowlem, Cementation, Balfour Beatty and Amec, which included the procurement and operation of major tunnelling machines. Peter was the Project Director for the Woolwich Docklands Light Railway crossing of the River Thames, Tunnels Director for Jubilee Line Extension Contract 102 and was the tunnelling Director for the Channel

		Tunnel drives. Due to project commitments it was not possible for Mr. South to continue in his role advising RPA, and hence Dr. Biggart has now been employed by RPA in this role. RPA also confirm that a recognised TBM specialist will be employed throughout the project by RPA to review contractor's proposals.

Metro North Oral Hearing

Presentation to the Board on the Technology of

Closed face Tunnel Boring machines. December 2009.

Introduction

I am Alastair Ross Biggart.

I have been employed by RPA since 1st November 2009 as an Expert on TBMs and tunnelling.

I am a Civil Engineer, a Fellow of the Royal Academy of Engineering (FREng), a Fellow of the Institution of Civil Engineers (FICE), a Member of the American Society of Civil Engineers (MASCE) and a member of the British Tunnelling Society (BTS).

I am a Doctor of Technology from Loughborough University

I chaired the BTS Committee in 2005 which produced "Closed Face Tunnelling Machines and Ground Stability". *A Guideline for Best Practice*.

I have been involved in underground construction for 52 years, 35 years as a contractor and 17 years as a consultant.

Amongst other things I have been involved in a number of major projects in a senior capacity. These include:

- The Cairo Wastewater Project, where we used 3 Slurry Machines in sands and gravels at slurry pressures up to 2 bar. I was Technical Director on site for the contractor.
- The Channel Tunnel between England and France, where we used 5 open face TBMs on the UK side for excavating in the Chalk Marl. I was Operations Director for the UK Contracting Consortium.
- The Storebaelt Tunnel in Denmark, where we used 4 large diameter EPBM's for excavating below the sea in the Glacial Tills and the Copenhagen Limestone at up to 7.5 bar earth pressure. I was Project Director for the Owner.
- The Hollywood Metro Extension in Los Angeles, where we used a main beam rock TBM for excavating through a large variety of conditions in a highly seismic area. I was Project Manager for the Owner.
- Currently I am acting as an advisor to Banverket (Swedish rail) in Sweden on the Hallandsaas Tunnel. Here a 10.5m Slurry Machine is being used, which can work in twin modes, either as a rock TBM or a Slurry Machine at up to 13 bar.
- During the last 20 years I have advised on 16 tunnelling projects, the vast majority of which have involved the use of Closed Face TBMs. On many of these I have experienced similar ground conditions to those on Metro North.

Within the general specialisation of tunnelling I have in particular specialised in the use of Closed Face TBMs.

My presentation today is on the development and use of Closed Face TBMs and their relationship with the environment.

There are two types of closed face TBM, Slurry Machines and Earth Pressure Balance Machines.

Slurry Machines

The original patent for a Slurry TBM was taken out by John Bartlett of Mott Hay and Anderson in 1964. In essence it said, "A liquid thixotropic suspension … to contact and support the working face…" A thixotropic liquid has the particular properties that when it is still it forms a stiff gel and when it is stirred it goes liquid. This is an infinitely variable state.

In the UK the original Bentonite Tunnelling Machine experiment based on the Bartlett patent was carried out in 1972 in London. I was in charge of that experiment.

Concurrently the Germans were developing the Hydroshield. This has a unique method of controlling the slurry pressure in the excavation chamber. There are two bulkheads. The front bulkhead covers the top 75% of the face and the rear bulkhead covers the whole face. A bubble of air is trapped between the two bulkheads, the pressure of this air is strictly controlled and exerts a pressure on the horizontal face of the slurry between the two bulkheads.

The Japanese were ahead of us all and had the first slurry machine working by the end of 1964. Coincidentally this was the same year of the Bartlett patent.

Let me give you a brief explanation of how this type of TBM works:

- It uses a thixotropic suspension (bentonite) which is pumped under pressure into the excavation chamber ahead of the bulkhead.
- Because the liquid penetrates the ground if forms a filter cake on the face and the pressure of the liquid against the cake supports the face.
- The excavated spoil mixes with the liquid slurry and is then transported to the surface in large diameter pipes.
- On the surface the spoil is cleaned out of the bentonitic slurry and the clean slurry is pumped back down to the TBM for re-use. If the slurry cannot be cleaned the process becomes uneconomic.
- So the bentonite slurry has two purposes, a) to support the tunnel face and b) to transport the excavated material.

By the end of the '70's over 1,000 Slurry TBMs had been used worldwide, but the vast majority were in Japan.

Gradually the tunnelling world discovered that the envelope of ground that a slurry TBM could excavate was limited in accordance with the grading curve of the ground. In other words if there was too much silt or clay in the ground it could not be cleaned by the surface separation plant, to allow re-use of the slurry.

Earth Pressure Balance Machines (EPBMs)

So in the very early '80's the Japanese came up with the idea for the EPBM which was able to cope with clays and silts. This type of closed face TBM traps the excavated spoil ahead of the bulkhead under pressure, conditions the spoil to become more flowing and viscous and removes the spoil under control through a large diameter screw.

At first these machines used bentonite and polymers as the conditioning agent, but this was not entirely satisfactory and did not allow the ability to control settlement as well as Slurry machines. So towards the end of the '80's the Japanese introduced the use of a surfactant foam (soap).

This had a remarkable effect in terms of the EPBMs being able to control settlement. In fact it brought the ability of the EPBM up to the ability of the Slurry Machine in terms of controlling settlement.

By the middle 1980's EPBMs were being used much more than Slurry Machines, but bearing in mind the limits on both types in terms of dealing with a wide range of ground conditions, Slurry Machines are still frequently used for granular conditions.

Tunnelling on the Metro North Project

I know you are all aware that the ground conditions on this project are mixed. Some lengths of the tunnel are in a full face of limestone bedrock, some in a full face of glacial till, some in glacial sands and some in mixed faces of bedrock and the tills and sands.

In my opinion the use of EPBMs would be very appropriate on the Metro North project. In my experience this would be a good way of doing it.

So if EPBMs are used they will be used together with a gasketted pre-cast concrete segmental lining built in the tail of the TBM. The steel shield cans of the TBM will be pushed through the ground by a series of heavy hydraulic jacks pushing against the pre-cast lining in the tail. 3,500 t to 4,000 t of thrust will be available. It should be noted that at 2 bar earth pressure 660t of this thrust will be absorbed by the backward force of the earth pressure.

The cutterhead will be equipped with both pick cutters to cut the soft material and disc cutters (17”dia.) to cut the limestone and the boulders.

The rotating cutterhead, which will rotate at 1 to 2 RPM, will excavate the ground, the excavated spoil will fill the excavation chamber and will mix with the surfactant foam. Typically the quantity of foam can be up to a 50% mixture with the spoil, but it can be more.

As the TBM advances, the screw conveyor will turn at a regulated speed and will allow the spoil to be removed from the excavation chamber at such a rate that it will control the “Earth Pressure” in the excavation chamber. This earth pressure will have been calculated by the engineers for the whole length of the tunnel. The earth pressure will be required to resist both the hydrostatic head of water and the active pressure of the ground around the tunnel arising from the overburden depth. It is obvious that the pressure will vary along the whole length of the tunnel, due to the varying depth of cover and the variability of the ground water level.

As the tunnel advances, the annular gap between the outside of the pre-cast lining and the excavated profile will be continuously grouted with a sand cement grout through the tailskin of the TBM. This is vital in terms of controlling settlement and is a fairly recent innovation.

TBM Operating Parameters

All the functions of the TBMs will be continuously monitored by the datalogger. This information can be made available, via telemetry, to the contractor, the RPA and the Independent Monitoring Engineer. The various parameters that will be monitored will include:

- Thrust
- Torque
- Penetration rate
- Cutterhead rotation speed
- Screw speed
- Earth pressure
- Conditioner quantities
- Grout quantities
- Power
- Excavated spoil quantity – this is particularly important!

All of the above parameters are important to the contractor’s management in terms of controlling the effect that the TBM has on the environment.

Control and Mitigation of Environmental Impacts

Settlement

Settlement is caused by ground loss arising from the operation of the TBM. The ability of a TBM to control settlement is judged by what is called Volume Loss. That is the percentage of the excavated face area that is reflected at the surface by a settlement trough. RPA have selected the following parameters for this Volume Loss percentage:

- Mixed face of glacial sands and gravels and limestone – 1.5%
- Glacial till – 0.6%
- Limestone bedrock – 0.2%

There is much anecdotal evidence to support these figures and I am personally happy with the figures from my own experience.

The main parameters of TBM control to achieve settlement within the above figures are:

- Use of the correct earth pressure.
- Use of a minimum gap between the shield body and the excavated profile of the ground
- Continuous annular grouting through the TBM tailskin.
- A well designed TBM with the ability to inject the correct quantities of conditioner into the face - foam, bentonite, polymer and pulverised limestone if there is a need to supplement the amount of fines in ground that has < 10% of natural fines.
- A properly designed screw conveyor that has the ability to hold the correct earth pressure (the correct pressure dictated by the tunnel engineers). There is the option of having - Long Screws – Double Screws – Double Piston Pumps, all dependent on the fines content of the ground, which dictates the screws ability to hold the pressure.
- Proper management.
- Good monitoring as already mentioned.
- Accurate measurement of the excavated quantities is vital! In the good old, bad old days we just counted the muck skips, which was a pretty inaccurate method of control. Nowadays with modern technology we use Belt Weighers and Laser Profilers on the conveyor belt which receives the spoil from the screw conveyor. These are accurate to less than 10%. Measurements are looked at on a comparative basis on a 5 ring rolling average.

Control of Settlement in a Mixed Face

The main area of concern on Metro North regarding settlement is when the tunnel is in a mixed face of bedrock and either glacial sands or glacial till. There are a number of strategies that the contractor can employ to minimise the settlement in these circumstances as follows:

- Take extra care in measuring the volume of excavated material.
- Apply an additional earth pressure over and above the theoretical, but less than the pressure that could cause heave.
- Apply additional thrust (there is 3,500t to 4,000t available) – this gives additional mechanical support to the face.
- Make sure the cutter discs are in good condition, so that the hard ground does not slow up the forward progress of the TBM.

Noise

Generally the tunnels are fairly deep. The tunnels will probably advance on average 15m per day. Noise will be produced by the TBM cutting boulders and rock. Nothing can be done regarding the cutting of the boulders and rock. But there are various ways of mitigating the noise from the TBM, although this is a minor element of the total noise.

Possible ways of reducing noise from the TBM are a) to use Variable Frequency Drive (VFD) for turning the cutterhead, instead of hydraulic drive, b) Reduce the rotational speed of the cutterhead so that any impact with boulders or limestone is reduced, c) Reduce the instant penetration rate of the TBM which will reduce the impact with boulders or limestone, d) mount the trailing sledges, which hold all the electrical, mechanical back up for the TBM, on sound absorbing wheels. All of these measures have to be balanced against the need to excavate at a rate that will minimise settlement.

Vibration

The risk of TBM vibration inducing settlement has been covered in the evidence submitted by Geoff Featherstone of the RPA in his submission of 23rd April 2009.

There are some actions that can be taken on the TBM to mitigate vibration effects:

- Control the cutterhead speed.
- Control the forward penetration rate.
- Use an energy efficient power source for the powering of the cutterhead. On the Metro North TBMs the total installed power for each TBM will be of the order of 2 MWs, 1.5MW of which will be used to turn the cutterhead.

These will all be a minor contribution to reducing vibration levels and using these mitigations will need to be set off against the over-riding need to control settlement.

Gas

Continuous monitoring will be installed on the TBMs. On an EPBM this is normally at the rear end of the screw conveyor, which is where gas will first enter the tunnel. Gases monitored would normally include, CH_3, H_2S, NO, NO_2, CO, Oxygen Deficiency. It may not be necessary to monitor all of these on Metro North.

If trigger levels are reached the TBM will be automatically shut down.

The main way of dealing with gas in the tunnel is by ventilation and dispersion.

The Excavated Spoil

This will contain the following:

- Conditioner, made up of foam, bentonite and polymer. All these will be supplied as biodegradable. It is best if the spoil is first laid out in relatively thin layers at the disposal site, before being used as bulk filling material. This will allow it to both dry and biodegrade.
- Very small quantities of main bearing seals grease. The quantities are extremely small as a percentage of the excavated spoil and would not be harmful.
- Fibrous tailseal grease. This is left as a very thin layer, <1mm thick, on the back of the pc segments. This layer is locked in by the annular grouting which is approximately 100mm thick and this protects the groundwater from any pollution.

The Tunnel Effluent

It is inevitable that some oils and greases may be spilt in the tunnel, particularly hydraulic oil. All the waste water from the tunnel will be passed through settling lagoons and weirs and flocculants will be used to separate out particulate matter, oils, greases etc.

The Use of Compressed Air

Although the use of closed face tunnelling machines has largely superceded the use of compressed air, there are occasions when it is still needed. This is mainly for the maintenance and repair of the cutterhead and cutting tools. If the tunnel is below the water table in soft ground personnel will have to enter the face under compressed air pressures. As the soft ground is generally dense the escape of compressed air will be very limited. Pressures will probably not exceed 2 atmospheres above normal atmospheric pressure.

TBM Control and Achievable Volume Losses

It is my opinion that if the contractor manages the project properly and diligently he will be able to control the volume losses to the levels or below those assumed by the RPA i.e.:

- In a mixed face of glacial sands and bedrock – 1.5%
- In glacial till – 0.6%
- In bedrock – 0.2%

I have recently been researching this subject and have been most encouraged by the results being achieved today by the tunnelling industry. I also say this from my own personal experience. On the Warrington project in the UK in 1975 we used a prototype Slurry Machine to excavate a 1.4km long by 3m diameter tunnel. The geology was loose sands overlying a dense layer of boulders sitting on sandstone in the lower part of the tunnel. The Volume Loss, which was measured independently, was 1.37%, i.e. less than the figure assumed by RPA for mixed face conditions, but on a tunnel using a very early prototype TBM.

Ultimately the contractor will be responsible for managing the tunnelling operation and this is one of the factors that will be considered by the RPA when selecting the successful bidder.

Railway Procurement Agency
Ghníomaireacht um Fháil Iarnród
Parkgate Business Centre,
Parkgate Street, Dublin 8, Ireland
Phone +353 1 646 3400
Fax +353 1 646 3401
www.rpa.ie

Responsible for LUAS METRO Integrated Ticketing System

With funding and support from transport21 progress in motion NDP National Development Plan 2007 - 2013 EUROPEAN REGIONAL DEVELOPMENT FUND