IMIA Working Group Paper WGP 60 (09) Tunnel Boring Machines

Table of Contents

1. Introduction
2. State of the art and new challenges
3. Loss exposure
4. Loss Prevention
5. Review of insurance coverage available
6. Examples of losses
7. Conclusion
1. Introduction

The tunnel boring machine is a machine which has been developed in recent years and has revolutionised the tunnelling industry both making tunnelling a safer, more economic solution for creating underground space and opening the possibility of creating tunnels where it was not feasible before.

The development of this machine has however presented insurers with a set of new challenges many of which have already been presented in an earlier IMIA working group paper WGP 18

1.1 Goal and Scope of the Paper

The goal of this paper is to give underwriters an understanding of what is a TBM and to build up an awareness of the wide variety of perils TBMs are exposed to during their utilisation for a tunnel project, to help underwriters carry out a risk analysis relevant to the type of TBM proposed and the environment in which it will be expected to work.

This paper is only at this stage in draft form and the team drafting the paper would like to issue an update in 2010.

The paper explains in the first part various types of TBM it then looks at the various perils it is exposed to during transport, assembly, erection, testing, boring of a tunnel and disassembly.

1.2 History

The first successful tunnelling shield which is commonly regarded as the forerunner of the tunnel boring machine was developed by Sir Marc Isambard Brunel to excavate the Rotherhithe tunnel under the Thames in 1825. However, this was only the invention of the shield concept and did not involve the construction of a complete tunnel boring machine, the digging still having to be accomplished by the then standard excavation methods using miners to dig under the shield and behind them bricklayers built the lining. Although the concept was successful eventually it was not at all an easy project. The tunnel suffered five floods in all. It is also noteworthy that Marc Brunel’s son who was the site engineer went on to become what is generally thought of as Britain’s greatest engineer, Isambard Kingdom Brunel.
Diagram of tunnelling shield used to construct the Thames tunnel

Improvements on this concept were used to build all of the early deep railway tunnels under London in the early 20th century and lead to the name ‘tube’ which is the nickname all Londoners call their metropolitan railway and give tunnels made by this method their characteristic round shape.

In other countries tunnel boring machines were being designed to tunnel through rock. The very first actual boring machine ever reported to have been built is thought
to be Henri-Joseph Maus' Mountain Slicer designed in 1845 dig the Fréjus Rail Tunnel between France and Italy through the Alps, Maus had it built in 1846 in an arms factory near Turin. It basically consisted of more than 100 percussion drills mounted in the front of a locomotive-sized machine, mechanically power-driven from the entrance of the tunnel however it was not used, and the tunnel was finally built using conventional methods.

In the United States, the first boring machine to have been built was used in 1853 during the construction of the Hoosac Tunnel. Made of cast iron, it was known as Wilson’s Patented Stone-Cutting Machine, after its inventor Charles Wilson. It drilled 10 feet into the rock before breaking down and the tunnel had to be completed many years later, using less ambitious methods.

We need to move on nearly 100 years when James S. Robbins built a machine to dig through what was the most difficult shale to excavate at that time, the Pierre Shale. Robbins built a machine that was able to cut 160 feet in 24 hours in the shale, which was ten times faster than any other digging speed at that time.

The modern breakthrough that made tunnel boring machines efficient and reliable was the invention of the rotating head, conceptually based on the same principle as the percussion drill head of the Mountain Slicer of Henri-Joseph Maus, but improving its efficiency by reducing the number of grinding elements while making them to spin as a whole against the soil front. Initially, Robbins’ tunnel boring machine used strong spikes rotating in a circular motion to dig out of the excavation front, but he quickly discovered that these spikes, no matter how strong they were, had to be changed frequently as they broke or tore off. By replacing these grinding spikes with longer lasting cutting wheels this problem was significantly reduced. Since then, all successful modern tunnel boring machines use rotating grinding heads with cutting wheels for boring through rock.

Below is an example of a tunnel boring machines which is equipped with a back hoe. Whilst the cutting head has been a breakthrough on soft material the shield with a backhoe is still a cost efficient and well utilised solution even today.
1.3 Different Types of machines

The description of the types of TBM derive from what type of soil is being excavated.

1. Slurry Machine

This is used for soils usually of varying hardness. The excavated soil is mixed with slurry to create positive face pressure required to sustain the excavation. This is known as a closed machine. The system for the removal of the soil involves pumping the soil mixed with slurry to plant located outside the tunnel that separates the slurry from the muck allowing its recirculation. See sketch below.

![Slurry Machine Diagram](image1)

2. Earth Pressure Balance machine

This is a closed machine and is used usually for softer fairly cohesive soils. In this case the positive face pressure is created by the excavated ground that is kept under pressure in the chamber by controlled removal through the rotation of the screw conveyor. The muck is thereafter removed by a conveyor belt and/or skips.

![Earth Pressure Balance Machine Diagram](image2)
3. Rock Machine

This is used for excavating rock. The rock is crushed by the cutters (often discs) and removed on conveyors and/or skips. Cutters are specifically designed to resist hard abrasive material.

Description of the machine

A tunnel boring machine (TBM) typically consists of one or two shields (large metal cylinders) and trailing support mechanisms. At the front end of the shield is a rotating cutting wheel. Behind the cutting wheel is a chamber. The chamber may be under pressure (closed machine) or open to the external pressure (open machine).

Behind the chamber there is a set of hydraulic jacks supported by the finished part of the tunnel which push the TBM forward. The rear section of the TBM is braced against the tunnel walls and used to push the TBM head forward. At maximum extension the TBM head is then braced against the tunnel walls and the TBM rear is dragged forward.

Behind the shield, inside the finished part of the tunnel, several support mechanisms which are part of the TBM are located: soil/rock removal, slurry pipelines if applicable, control rooms, and rails for transport of the precast segments.

The cutting wheel will typically rotate at 1 to 10 rpm (depending on size and stratum), cutting the rock face into chips or excavating soil (usually called muck by tunnelers). Depending on the type of TBM, the muck will fall onto a conveyor belt system or into skips and be carried out of the tunnel, or be mixed with slurry and pumped back to the tunnel entrance. Depending on rock strata and tunnel requirements, the tunnel may be cased, lined, or left unlined. This may be done by bringing in precast concrete sections that are jacked into place as the TBM moves forward, by assembling concrete forms, or in some hard rock strata, leaving the tunnel unlined and relying on the surrounding rock to handle and distribute the load.

While the use of a TBM relieves the need for large numbers of workers at increased pressure, if the pressure at the tunnel face is greater than behind the chamber a caisson system is sometimes formed at the cutting head this allows workers to go to the front of the TBM for inspection, maintenance and repair if this needs to be done.
under pressure the workers need to be medically cleared for work under pressure like divers underwater and to be trained in the operation of the locks.

Shields

Modern TBMs typically have an integrated shield. The choice of a single or double shielded TBM depends on the type of rock strata and the excavation speed required.

Double shielded TBMs are normally used in unstable rock strata, or where a high rate of advancement is required. Single shielded TBMs, which are less expensive, are more suitable to hard rock strata.

Urban tunnelling and near surface tunnelling

Urban tunnelling has the special challenge of requiring that the ground surface be undisturbed. This means that ground subsidence must be avoided this is discussed in much greater detail in Section 6. The normal method of doing this is to maintain the soil pressures during and after the tunnel construction. There is some difficulty in doing this, particularly in varied rock strata (e.g., boring through a region where the upper portion of the tunnel face is wet sand and the lower portion is hard rock).

TBMs with positive face control are used in such situations this means the pressure in the chamber has to be balanced with the water and soil pressures ahead of the machine. There are three common types: Earth pressure balance (EPB), Bentonite slurry (BS) sometimes called hydroshield, and compressed air (CA). The compressed air method is the oldest, but is rarely used today because of the health and safety issues Both types (EPB and BS) are clearly preferred over open face methods in urban environments as they offer far superior ground control. This is discussed in more detail in section 6

Situation Today

There are now several manufacturers of tunnelling machines in Europe, North America and Asia and they continue to develop new and improved machines whilst the technology has moved on greatly since the 19th century each new development needs to be carefully considered by underwriters to be sure there are no adverse risks associated with each new development.

2. State of the art and new challenges

2.1 Maximum diameter for slurry and EPB

The biggest shields ever built to date are the 2 Shanghai slurry TBMs of 15.43m diameter. They were designed for a road tunnel.

The biggest EPB shield is one that bored the M30 road tunnel of Madrid. Its diameter was 15.20m. It was fitted with a double cutter-head aligned on the same axis. The inner one was of 7m diameter. These cutter-heads could operate independently of each other.

The size of the shield is limited by:
a) The cutter-head. Indeed the bigger the size the stronger structure of the head must be. As a result there is less room for openings and therefore more difficulties to let the bored materials located closed to the axis of the head

b) Movement from the cutting chamber. This is why the double head system was helpful to solve this problem. The rheology of the muck in the cutting chamber in an EPB system. If the muck is too dry it is difficult to remove it from the cutting chamber. If it is too wet the pressure at the entrance of the screw conveyor (hydrostatic behaviour but with a high density) is too high and the ability to keep a proper pressure gradient along the screw not achievable. This means there is no pressure drop through the screw conveyor therefore a very high risk of collapse of the front face.

2.2 Maximum water head

Beyond 3.5 bars (35m water head) at the crown of the shield the pressure is an issue in respect of the maintenance in the cutting chamber. Indeed with a pressure above 4.5 bars the working hyperbaric conditions are not easy with air: short working period, narcotic effect of the nitrogen, toxicity of the oxygen. Saturation diving is possible (Westerschelde tunnels) by breathing heliox (mix of helium and oxygen) or trimix (mix of nitrogen, oxygen and helium) but it needs special equipment and professional divers.

See also section 3.2

2.3 Use of TBM in squeezing conditions

This is a main issue. In that case the cutter-head should be equipped in its periphery with an over-cutting tool to let the body of the shield to move. This one has not a perfect cylinder shape but a cut conic shape to be able to escape from the squeezing effect behind the cutter-head.

See also section 3.5

2.4 Maximum speed of excavation reached

In a closed mode (under pressure) the speed is lower than in an open mode (no pressure).

With an EPB the contractor can afford to bore under open mode subject to his assessment of the stability of the front face. Underwriters should check that contractor's assessments of the stability of the front face are consistent with the stability assessments of the designer team and their geologists.

The speed of the shield depends on how it is driven (thrust, cutter-head rpm, ...) but also by the geotechnical parameters of the soil or rock (compressive strength, degree of fracturing,..), its abrasivity and how its ability to keep stable the pressure in the cutting chamber.

In a closed mode the speed is in the range of 0 to 8cm/min

2.5 Operational Measurements

In contrast with the traditional way of tunnelling the contractor can’t see the front face
when using pressurised TBM during boring operation except with the fully air
pressured technology but this is a special case (Bessac shield) and is now rarely
used.

This means the contractor is therefore not in a position to adapt the excavation
method with the change of the soil and/or rock conditions by a visual review. He can
assess changes in the soil by analysing the change of the drilling parameters.

The main sources of information he can use are: the speed of the shield, the torque
of the cutter-head, the thrust of the jacks of the shield when moving forward, the
parameters linked to the stability of the pressure inside the cutting chamber and the
quantity and quality of removed muck from the cutting chamber.

What is crucial is not only the actual values of these parameters but their variability
with the progress of the shield:

The speed of the shield
This depends on the pressure to the cutter-head and is linked to available power for
the torque demand of the cutter-head. Of course the speed is also highly related to
the compressive strength of the soil or rock and how it is fractured in case of rock.
The wear of the cutting tools will reduce the advance rate of the shield.

The torque of the cutter-head
The torque of the cutter-head can dramatically rise up if the shield is in squeezing
ground conditions. For instance if the shield enters a fractured area or meet boulders
this affects the rotation of the cutter-head and as result increases the torque. The
same phenomenon may be found cohesive clay.

The thrust of the jacks of the shield to move forward
Decreased thrust values and increased advance rates mean the shield is entering
softer ground and visa versa.

The parameters linked to the stability of the pressure inside the cutting chamber
The shield operator has to keep stable the fixed pressure inside the cutting chamber.
This is usually automated but it is important to analyse what has changed.

With a slurry shield, if there is a loss of bentonite into the soil because of an increase
of its permeability the pump will have also to increase the inflow in the cutting
chamber. In that case it could be also helpful to change rheology of the bentonite.

If an EPB shield enters a water-pressured sand lens, the viscosity of the muck in the
cutting chamber will be lowered leading to a lower pressure gradient in the screw
conveyor. If low pressure gradient trigger levels are reached the conveyor door must
be quickly closed to avoid face loss which in the worst scenario can lead to sinkholes
or chimneys.

The quantity and quality of removed muck from the cutting chamber
This is a key parameter. During the boring operation the quantity of removed muck
should proportionally increase with the progress of the shield. If this increases
suddenly there is a face loss under progress

There are different means to measure the quantity of muck removed from the cutting
chamber. For instance with an EPB shield if the muck is carried by wagons their
numbers are always the same per kind of ground conditions. If the muck is removed
with a belt conveyor the weight of the muck should be monitored with progress of the shield.

With an EPB shield the pilot can easily see the muck coming out the screw conveyor. So he can visually monitor changes in the nature of the muck. Parameters he can identify are changes in granularity and/or the colour and water content. In fractured and weathered rock the muck consists in bigger stones with green or red colour. Competent rock is usually a grey colour.

Obviously there are strict procedures which are preset as to how to drive properly the shield, but it also highly linked with the education and the background of the pilots who will be the first to deal with change of the soil and/or rock conditions. The use of proper risk assessments and training of operators for contingency procedures is essential.

3. Loss Exposure

3.1 Introduction

In this chapter we would like to briefly assess the risk exposure of a TBM from the moment it is assembled the manufacturer’s premises until the moment in which excavation works have been completed and the machine has been dismantled and shipped away from the site.

During this period of time it is possible to identify different types of risks which can lead to a damage to the TBM, and impact the project under execution. Whilst these damages are not necessarily covered by the “All Risks” Policy issued for the project and extended to cover the TBM, it is nevertheless important for underwriters to have a full picture of the risk exposure run by this type of machine to inform them of the effect of risks that they have agreed to include in the cover or to decide which ones instead must remain excluded.

All these risks will be presented in accordance of the time sequence they are found:

1. TBM fabrication and delivery at site;
2. TBM assembly at site;
3. Excavation works;
4. Disassembly and re-shipment.

3.2 TBM Fabrication

Once the characteristics of the required TBM have been defined, the period of time needed to manufacture the machine, can take up to twelve months (refurbished ones should take less). This takes place at the TBM fabricator’s premises which is usually distant from the site so a serious loss at this point, such as a fire, can have a huge impact on the critical path of the project, but will not impact a classic Engineering “All Risks” Policy covering the execution of the project at the work site.
If the Policy includes ALOP and with a “Suppliers’ extension” there is a potential source of loss for underwriters. This is a typical Contingency Business Interruption clause covering the consequences of delays due to losses affecting items important for the project during their period of fabrication outside the site.

Once fabrication has been completed and the TBM has been assembled and cold tested at fabricator’s premises, it is disassembled and shipped. Normally the insurance of the shipment is not included in the “All Risks” Policy. In consideration of the difficulties in delivering these machines at site due to their dimensions and to the heavy weight of their components, underwriters must clarify when the period of insurance for the TBM starts as in some cases the extension to inland or marine transit can apply also to the components of these machines. This becomes particularly important for tunnels where the access to the portals is via steep and narrow access roads, which is the typical case for tunnels in hydropower schemes.

3.3 TBM Assembly at site

Risk exposure during this phase depends on the location of the alignment of the tunnel to be excavated and on its depth. The start excavation can in fact be located in areas exposed to flooding and landslides. Sometimes the location of the portal of the tunnel can even require a land reclamation to have enough room available for the assembly and launching of the TBM.

If this happens mostly for tunnels crossing mountains, in the case of tunnels for metro line the access most of the times can be reached only through a shaft of several tens metres of depth.

From the moment the TBM arrives at the site it is possible to distinguish the following exposures:

- exposure to flooding, fire and theft during the period of storage (if any);
- exposure to damages caused during the assembly due to the lifting and movement of the heaviest components;
- Exposure to flooding or landslides during the assembly of the machines.

Underwriters should therefore make sure that storage and assembly areas are not exposed to flooding and equipped with proper fire fighting facilities. These areas should be fenced and guarded to reduce the risk of thefts.

Assembly operations must be carried out under the supervision of skilled technicians preferably including those from the supplier of the machines.

These operations can be risky when carried out in a shaft. In this case lifting operations are more exposed. Shafts increase moreover the exposure of the TBM to the risk of flooding caused by the run off water created by torrential rains. The measure of prevention is very easy and quite cheap. Underwriters should make sure that the shaft is protected around its access with a small wall of adequate height, calculated on the level of run off water expected for a certain return period. The shaft bottom should in case also be equipped with de-watering pumps.
Once the assembly and the cold testing are completed the TBM is ready for the hot testing, that is the check of the TBM during the excavation of a tunnel length agreed with the TBM supplier. The phase of assembly can last up to three months.

In order to shorten overall delivery times to supply these machines some suppliers have recently introduced the so called OFTA (Onsite First Time Assembly), consisting in operating only one assembly directly at site. This procedure, allowing the saving of several weeks, clearly increases the risks of possible problems arising during the testing.

New machines are usually under guarantee during the testing and the initial drive by the supplier. This is normally carried out over a length of 50 or 100 metres under the supervision of supplier’s engineers. The duration and extent of this guarantee is a quite important piece of information that rarely is supplied to underwriters.

3.4 Excavation Works

Elements of risk exposure during excavation works are several. The most important ones are:

- submersion by water;
- fire and explosion;
- difficulties due to geotechnical external factors:
  - damages due to tunnel collapse or detachment of rocks
  - damages due to unexpected geological conditions;
- difficulties due to an inappropriate choice of the machine;
- difficulties due to the inexperience of the operator;
- difficulties due to the choice of the tunnel alignment;
- difficulties due to machinery breakdown,
- Breakthrough location.

We will go through all of them. We would like to comment that some of the events described not necessarily are losses recoverable under the “All Risks” Policy or its section covering the TBM this will depend on the extent of cover purchased.

3.5 Submersion by water

Exposure to submersion by water can happen when the TBM must operate below the water table or when excavating through tunnel sections where presence of water pockets can be expected.

If despite all precautions water inflows are possible into the tunnel the best control method consists in keeping available de-watering pumps dimensioned for an adequate capacity. Stand by spare pumps are also very important as the water
entering the tunnel can be mixed with silt or mud that can obstruct or clog up the main pumps. These elements become essential when project constraints dictate that the TBM must advance downhill. This can happen during the opening of access tunnels or when a long hydraulic tunnel is excavated in different non aligned sections. In these cases de-watering must be accurately controlled as any water inflow will accumulate at the tunnel front with the risk of loss of life to the operators as well as damage to the machine and tunnel.

For TBM drives below the water table, there can be different situations going from a tunnel alignment crossing layers of permeable soil under a water head of several metres, up to the excavation of tunnels located below rivers or the sea at several tens of metres depth. Machines used in this case are closed machines of the EPB type that can operate under several bars of pressure. If in the past pressures of 3 bars (30 metres of head) were already considered as challenging, machines that can operate up to 6 are now commonly used and recently some machines able to reach up to 12 bars have been produced (see also section 2)

One of the most difficult moments during these works is when the machine is stopped for the maintenance or due to an unforeseen situation. Typical operations, such as substitution of cutting tools, or, more rarely, the substitution of the main bearing, in the event of a sudden inflow of water, become particularly complicated and in some cases even hazardous. As the TBM is continuously under pressure, the use of expensive hyperbaric chambers or watertight shafts is needed. The first one requiring very specialised workers with underwater diver type qualifications, operating in difficult conditions assisted by doctors. The second one implies instead the opening of a shaft only for carrying out the reparation required.

When working under water table simple mistakes can lead to tragic consequences. In one famous case of an undersea tunnel a worker left one of the TBM watertight locks open to allow the passage of a cable during maintenance of the shield. The opening of a crack in the tunnel ceiling in front of the machine produced a water inflow that flooded two tunnels causing damages to both works and machines.

Rigorous procedures need to be implemented and that all workers operating in the tunnel and on the machine need to be satisfactorily trained.

The most susceptible part of the whole machine to muddy or salty water is the control room where electronic panels and devices are installed. The submersion of these can cause considerable damage that can easily exceed EUR 1 ml and as well a long period of stoppage required for the necessary reparations and re-testing.

3.6 Fire and explosion

On a TBM there are several items that can cause an exposure to fire. There oleodynamic circuits under pressure that in case of a break can spray oil on other parts at high temperature. There are also transformers on the TBM back-up.

Prevention can be granted by adequate maintenance and controls. TBMs must nevertheless also be equipped with proper fire fighting facilities able to extinguish a fire.
BS 6164 is a standard which is used worldwide for safety of TBMs and includes recommendations on fire safety.

During the crossing of different geological layers coal can also be encountered. These sections can retain pockets of damp, a gas that can explode when the required stochiometric mixture with oxygen is reached.

To prevent this eventuality TBMs are usually equipped with gas detectors carrying out continuous analysis of the atmosphere of the tunnel.

3.7 Difficulties due to external factors

Difficulties found during the excavation due to unexpected or under-evaluated geological ground conditions represent a common cause of damages. Adequate geological information is the key factor for the tunnel support design and for the choice of the TBM; it is obvious that the reliability of this is essential for a successful project. Unfortunately costs for geological investigations increase in line with the reliability and the level of detail of the information. This results in Principals and Contractors always looking to find a compromise between reliability and costs. Depending on the compromise made at this stage there will be an increased risk later on in the project, this residual risk may be transferred to a certain extent to Insurers.

When the geological report is not detailed or there are some doubts on the ground conditions that might be found in a certain section, we would therefore expect prudent contractors to advance the TBM cautiously checking the situation ahead with an intensive use of probe-holing or similar techniques. Taking into consideration that this type of investigation requires several hours, this happens rarely due to the time pressure under which most of Contractors operate and to the quite high costs associated to keeping a TBM in standby whilst further geological assessment are undertaken. These costs can easily reach EUR 100,000 per day (2008 costs).

Types of difficulties that can be encountered are:

- detachment of block of rocks from the tunnel;
- opening of chimneys or over excavation;
- sinking of the head or difficulties in steering the TBM;
- large tunnels deformation due to squeezing;

These adverse conditions will vary depending on the geological conditions of the tunnel existence of fault zones, overburden and on the type of TBM chosen for the excavation.

These difficulties do not always direct damage to a robust TBM, nevertheless they slow down the TBM progress and if adequate measures are not taken in time, they can result in a damage to the tunnel under construction.

Detachment of rocks: this affects mainly hard rock TBMs. The detachment of large blocks of rock due to the presence of fractured layers can block the head or cause a
localised overload of tunnel segments, originating in the worst case scenario their cracking.

TBMs used in hard rock are usually shielded or double shielded machines. The detachment of blocks can cause some minor damages to the TBM but requires most of the times expensive and time consuming measures to be taken for the tunnel consolidation before restarting the boring.

Underwriters’ should make sure that proper risk assessments have been carried out following investigation of the geological situation in front of the TBM and if required following the risk assessment process probe-holing or other techniques are carried out.

Opening of chimneys or over excavation: they can occur both in the case of tunnels driven through mountains or in the case of metro projects in urban areas. Opening of chimneys is usually more frequent when boring through very fractured or loose grounds under limited overburden. In both these cases if an adequate support of the front of excavation or of the tunnel walls is not available, large volumes of materials can move creating cavities that in case of a limited overburden can reach the ground surface causing sinkholes depressions and chimneys. In both cases the TBM must be stopped and be freed from the material loading the head. Excavation can restart only after having treated the unstable area. Chimneys, sinkholes and depressions resulting can cause extensive damage to third parties repairs may require extensive measures to reconsolidate the ground.

A robust TBM will not necessarily be damaged by the loose material however operations required to restart tunnelling can be very expensive and they can need several days, if not weeks.

Particularly in case of the construction of Metro lines Underwriters should check that:

- adequate consolidation measures are taken where required before the starting of excavation in areas where the tunnel overburden is limited (less than two/three TBM diameters) See section 4.4;

- on the TBM constant monitoring of some basic excavation parameters is implemented see section 4.2 :
  - actual volume and weight of material excavated against theoretical one;
  - if the TBM is an EPB : pressure variation at the front, changing in the torque;

- Monitoring of ground settlement at the surface is kept under control.

Sinking of the head or difficulties in steering: The head of a TBM is very heavy; when it reaches a tunnel section characterised by untreated soft ground, it can be subject to severe unanticipated settlements producing a localised distortion of the tunnel alignment.

Solutions required to put again in axis the TBM are quite complex as they require usually the construction of supports or particular treatment at the tunnel invert. However there will remain a localised distortion of the tunnel alignment which is extremely difficult to recover completely and usually further specific rectification works are needed, these vary depending on the destination of the tunnel (hydraulic, railway, road, etc.)
In similar conditions might be very difficult to steer the TBM, in which case the design curve of the alignment will not be met.

These events can cause damage the tunnel. In the event of serious sinking the TBM can remain trapped with the possibility of a total loss.

Underwriters should make sure that problem areas identified by geological investigations will be subject by proper treatments and if necessary geological investigations will be carried out in front of the machine in sections where soft ground conditions that will cause problems for the TBM can be expected.

Large tunnel deformation due to squeezing: recently innovations undertaken in the design of TBMs mean that excavation is possible in ground conditions that were considered as prohibitive until some years ago. This has led to some projects being exposed to the phenomenon of squeezing, this occurs in some types of ground under critical pressure, leading in a short time to major tunnel convergence. This has been noted in particular in tunnel sections excavated in deteriorated rocks under high overburden.

TBMs used at present for excavating in these conditions must have a very short head and must be capable to over excavate beyond the standard diameter of the outer tunnel section. In this way, setting properly the speed of excavation it is possible to reach a situation of dynamic equilibrium between the time required by the TBM to pass through a the squeezing section and the time required by the same to reach a level of convergence that could otherwise trap the TBM. These TBMs are also designed with the possibility to exercise very high level of thrust, using if necessary injections of bentonite of other polymers to reduce the coefficient of friction between the tunnel and the shield.

Needless to say this is not an easy scenario for tunnelling using a TBM. In case of a breakdown or the need of an unforeseen maintenance the TBM must stop, or even if it slow down excessively, it can remain stuck. In this case major works will be required to enlarge the tunnel and free the machine. Worst case scenario the TBM can be lost.

Underwriters should check that the maintenance scheme of the TBM has been planned accurately and that Contractors have good experience of tunnelling in these difficult conditions.

Other type of problems: here are some examples noted by insurers and on the number:

- damages to the head or to internal mechanical parts induced by vibrations caused by different type of layers of ground: the random presence of hard blocks in a matrix of soft ground can produce an irregular revolving of the head and therefore vibrations leading to damages,

- Crossing of layers of hard abrasivity: the wearing out of cutting tools is not considered damage as this is only to be expected. In some cases nevertheless Contractors do not to stop immediately to change cutters indeed it may not be prudent for them to do so if they are in an unsafe geological section. The TBM in this cases can forced to go ahead suffering damages to the shield.
- Finding of unexpected obstacles along the tunnel alignment: examples are TBMs that found a bore-hole steel case along the tunnel alignment left by a subcontractor when carrying out the geological campaign king posts from old excavations exiting water mains and other utility pipelines. These can damages the head requiring underground repairs which can be extremely expensive which the TBM is under pressure.

Underwriters when assessing the exposure relevant to the above perils must make sure that the project has carried out full risk assessments including:

- before the starting of tunnelling a detailed geological campaign had been carried out by a competent party,
- after the starting of the excavation if identified as necessary following the risk assessment process:
  - regular probe-holing investigations are carried out in tunnel sections where difficult geological conditions can be expected (e.g. faults),
  - If available, other techniques such as the 3D investigations are carried out in the most doubtful cases. Both this investigations can be done during the period of time required for the installations of tunnel segments or during the TBM maintenance.

### 3.8 Difficulties due to an inappropriate choice of the machine

The choice of the machine to be used depends mainly on the geotechnical characteristics of the grounds, on the level of the water table, rock abrasivity, and maximum settlement allowed at the surface.

Some of these parameters may not be known depending on the level of geological information available. Ground conditions vary, sometimes dramatically, along the tunnel alignment.

The final choice of machine is always a compromise in which one of the key parameters is the speed of excavation.

There may be the choice between a TBM that can proceed safely throughout the tunnel but performing at low speed or another one with a better rate of machine advance for most of the tunnel but with a higher risk exposure when crossing fault zones. In this case the choice could be made to use this second

It is nevertheless very difficult to criticise a choice as even different experts can have different opinions at this regard. This is why the use of formal risk assessments which will go through this kind of process can be a useful tool for underwriters to assess the level of risk of a particular drive.

In some cases the choice can be influenced by the Principal who can have an interest to use an existing machine. If this is the case it might be useful to know the Contractors if opinion of the machine being supplied to them.

Some words must be spent also on the choice of the diameter (see also section 2). Not very long ago the range of diameters was quite standard operating with:

- micro machines up to 2 meters;
- Normal machines from 2 to 9 meters.

In recent years it has been possible there has been a push to increase tunnel diameters.

The largest machine produced to date is thought to be a 15.40 m diameter one used in China.

As a rule of thumb machines up to 7 meters of diameter rarely cause major alteration in the regime of stresses in the ground around the bored tunnel whereas increased diameters must be considered on a case by case (see also section 6) the increase in diameter leads also to a more difficult assembly. The value of the machine moreover increases substantially and with this the exposure for Insurers. A TBM with a diameter of about 15 meter can reach a new replacement value of about EUR 50 ml.

3.9 Difficulties due to the inexperience of the operator

As it happens in all high tech machines driven by man, the experience of the operator and of the team working on the TBM is essential for the success of the project. The operator must know what to do in different type of situations consulting whenever necessary with the geological expert who is most of the times resident at site and, if required, with the engineers of the TBM producers.

At present at many sites data monitored on machines are directly sent by an internet connection to the TBM fabricator who can advise in case of need the most suitable solution to be taken to limit the possibility of a damage to the machine.

The problem that can arise in some of these situations is that excavation can be carried out around the clock on the basis of a three shifts program. Sometimes not all the operators have the same skills and particularly the night shift reveals itself critical when it is necessary to take a decision due to the presence of an unexpected situation.

Underwriters should assess the exposure checking the number of shifts and the experience of the personnel.

There is a key role here for contingency procedures to be put in place following the risk assessment process so that an operator when encountering a situation he has not experienced before has a clear procedure as to what he should do.

3.10 Difficulties due to the choice of the position of the tunnel alignment

The choice of the position of the tunnel alignment is a compromise among numerous parameters on the one side to the function of the tunnel itself (for example for a metro to be near as possible to the people who will use the metro) and to the ease and cost of the construction of the project which will relevant to ground conditions, presence of faults, requirements of the project to be carried out, level of the water table, etc.

Important parameters to be taken into account during construction are:

- inclination of the tunnel section to be bored;
- overburden above the tunnel;
- level of water table;
- Type and extent of faults to be crossed.

All of these have a different effect on the risk exposure for the TBM.

Inclination of the tunnel section to be bored: usually this is very modest but in case of access galleries can reach 6% and for special projects it can event exceed this percentage. Tunnelling in this case can become difficult and requires some particular solutions. Particularly when operating downhill, this can expose the TBM to a high risk of flooding.

Overburden above the tunnel: we can have the two extreme cases. In tunnels under mountains, e.g. the Alps, overburden exceeding 1,000 meters leading to the exposure to squeezing. In Metro construction instead it is preferred to maintain a tunnel alignment as shallow as possible to limit the costs and reduce user travel times. In this way sometimes the overburden is reduced in some sections to below one tunnel diameter, as against the old rule of thumb safe level of three, increasing the risk of third party damages due to ground settlement and worst case scenario opening of chimneys.

Underwriters should check that appropriate risk assessments have been carried out and that if identified, suitable ground treatment is carried out in areas showing low overburden and difficult ground conditions.

Level of water table: nowadays closed machines can easily cope with the excavation under water table. Underwriters should nevertheless be aware of the exposure presented in case repairs are required. They should also check what the maximum water pressure to be encountered is. As a rule of thumb underwriters can consider up to 3 bars (30 metres head) conditions as not challenging, between 3 and 6 challenging, beyond 6 bars extreme.

Type and extent of faults to be crossed: crossing of faults can be difficult and most of the times the inadequacy of solutions taken to consolidate the faulty section before the passage of the TBM remains one of the cause for losses to the tunnel and to the TBM.

Some of the types of accident that could happen have already been dealt with in the previous paragraphs, such as: detachment of rocks and over-excavation, collapse of the front or of the tunnel walls, possibility of sinking of the TBM head, etc.

Underwriters during their risk assessment should always check who carried out the geological campaign, to know the quality and reliability of the relevant information. Moreover full information should always be obtained from Designers and Contractors on the risk assessments they have carried out and measures that they have identified for additional ground consolidation when crossing faults.

3.11 Difficulties due to machinery breakdown

There are several types of breakdown that can affect a TBM during the excavation. The ones that can represent concern for Insurers, depending where the excavation takes place, are:
- breakdown of cutters;
- breakdown of the main bear ring;
- Other breakdowns requiring long period of stoppage.

The “All Risks" Policy covering the TBM is rarely extended to cover the Machinery Breakdown of the TBM due to the heavy working conditions of this machine. Underwriters’ concern is therefore more focused on the fact that from a breakdown can arise consequently an increase in risk exposure.

When operating below the water table, a breakdown or a quick wearing of cutters can result in an intervention using a hyperbaric chamber, as discussed elsewhere.

The breakdown of the main bear ring is particularly feared in consideration of the difficulties to be overcome to substitute this important item. If the excavation is carried out under a mountain a chamber must be open in the ground around the head to substitute the bear ring. The situation can be even more difficult in Metro tunnel open in urban areas.

Nowadays many TBMs allow the possibility to substitute this important component operating from inside the machine. The problem can remain the exposure to squeezing, if any, and the time required to obtain the spare part.

The influence on risk exposure of other types of breakdown (gearboxes, electrical motors etc.) depends as well on how easily the part is accessible for the substitution, the availability of the spare part and the consequent time required for its change.

### 3.12 Breakthrough location (see also section 4.4)

The breakthrough location is not necessarily located in an easy place. Its location depends on several parameters on which basis the tunnel alignment configuration had been chosen.

The breakthrough location can therefore present exposure towards third party liability damages in case of Metro projects, to flooding in case of hydro schemes, etc.

In case of small TBMs performing excavations for outlet sewage tunnels the breakthrough can be even located underwater, requiring thereafter the removal of the TBM to a vessel.

Underwriters should always check where this is located and the consequent exposure to evaluate the possibility of damage at this last point of tunnelling operations.

### 3.13 Completion of excavation and disassembly

Once the tunnel is completed the TBM is ready to be disassembled. Depending on the position of the breakthrough location this operation might not be extremely easy. It can be carried out in a shaft, in a chamber inside a tunnel, in a tunnel, etc.

For each one of these situations there is a different type of risk exposure linked to how the single components are removed and transported up to the deposit area.
What we mentioned earlier in respect of the movement and the storage areas remains still valid in this case. We would need to add that after the completion of the tunnel sometimes the TBM can even remain in storage underground. In this case Underwriters should check that the tunnel section chosen is not exposed to flooding or fire.

Disassembly is quite quick and on average takes about one month.

Cover is usually required until the TBM leaves the site.

4. LOSS PREVENTION

4.1 Mechanical and Electrical

- Breakdown
- Hydraulic oils

"A plan whatever it may be must be made for the bad ground, it must be calculated to meet all exigencies, all disasters and to overcome them after they have occurred" (Remark by M I Brunel on the occasion of proposals for improvement after the flooding of the Thames Tunnel 1831)

In mechanised tunnelling requirements as to safe working conditions can be more easily fulfilled than in conventional tunnelling. The obligation to consider economic and quality assurance aspects has been realised for years.

General safety requirements

In the design of the tunnel-boring machine, the following measures for achieving safety shall be taken into consideration:

- Specification of hazards and assessment of risks
- Elimination of hazards or limitation of risks
- Provision of safeguards against identified hazards which cannot be totally eliminated
- Training level for machine operators

Materials

Materials used in the manufacture or operation of the machinery shall be chosen so as to reduce the danger to exposed persons health and safety and shall not create toxic fumes in case of fire.

Contact surfaces

Accessible parts of a machine shall be designed and manufactured to avoid an exposed persons contact with sharp edges, angles or rough surfaces which are likely to cause injury. The same applies for hot surfaces.

Protection against ruptured hoses and pipes

Hoses and pipes which may become ruptured and thereby cause damage to persons should, where feasible, be firmly secured and protected against external damage and
stresses. Adequate shielding to protect persons and machinery shall be provided in working areas.

Cutter Head on Tunnel Boring Machines (TBM)

If it is necessary to gain access through a bulkhead to the area behind cutter head/shield and similarly through a cutter head to the area in front, the manhole openings of adequate size shall be provided.

The design shall allow for safe access for inspection, service and maintenance work. Face support such as slot gate closures and/or compressed air may be provided. The cutter head shall be equipped with a device to prevent unintentional movement of the head. This device shall be actuated if the cutter head is stopped for other reasons than those normal to its working operation.

Handling of heavy loads

Where the weight, size or shape of parts of a machine prevents them from being moved manually the parts shall be either fitted with attachments for lifting gear or designed so that they can be fitted with such attachments or be shaped in such a way that standard lifting gear can easily be attached.

When the ground support system requires the lifting of heavy units an erecting device shall be fitted. In all cases, winches and drive motors shall be fitted with mechanical brakes, which are powered off during operation.

Loss of stability

All shield machines act as temporary ground support during the tunnelling operations. The shall therefore be designed to withstand the loads imposed by the surrounding ground together with any dynamic loads imposed by the action of driving the machine forward.

All information pertinent to the structural design of the shield shall either be appended to the maintenance manual or be available from the manufacturer throughout the machine lifetime or at least for 10 years, whichever is the shorter.

When grippers are fitted to a full face TBM and are in use it shall not be possible to start the cutter head drive or apply the thrust force until the minimum required gripping pressure has been reached. Should the gripping pressure fall below this minimum the cutter head rotation shall be stopped and the thrust force shut off automatically.

All shields may be subject to slow rotation due to imbalance of loads. Care should be taken in the design and manufacture of the shield machine and back-up equipment to avoid exocentric loadings and all machines shall be fitted with an effective counter rotation system such as an angled plough, for returning the machine and back-up equipment to the correct orientation. Sudden rotation of a shield machine may occur when a cutter head or boom becomes embedded in the face. All such machines shall therefore be fitted with a protective device, which cuts off power to the drive motor in the event of the shield machine rotating in a rapid manner.

There is always a danger of face collapse in open face tunnels in soft ground. All shield machines where open face excavation can take place shall be provided with mechanical face support systems appropriate to the ground conditions envisaged.
These supports may include hydraulically operated poling plates and face plates, sand trays etc.

There is a serious risk of physical injury or drowning to persons working on a shield machine should the tunnel or shaft be flooded. All shield machines shall be designed to accommodate pumping equipment adequate for the conditions envisaged. In every shield, a so-called submerged wall or curtain should be provided. In case of unexpected inflow of water, the air bubble thus formed provides a safety area for a certain period.

**Control devices and systems**

Control devices shall be:
- Clearly visible and identifiable and appropriately marked where necessary,
- Positioned for safety operation, e.g. so that unintentional actuation of nearby controls is avoided
- Located close to each other when the start and stop functions are not operated by the same control device
- Provided with guards when, due to an unintentional actuation, they could cause a hazardous movement

Control system shall be so designed and constructed that they are highly reliable in service in an underground environment and that in case of failure the risk for dangerous situations shall be minimised. They should be able to withstand rigorous handling and severe stresses and shocks.

The control system of the machinery shall be so designed that:
- The switching on of drive motors for hydraulic pumps does not result in any form of hydraulically controlled movements which could be of danger to the machine or persons
- No dangerous operating conditions occur in the case of control voltage failure
- Failure of hydraulic or electrical control circuits shall not cause unexpected or unintentional movements of any part of the machinery, which may cause danger.

At every control point there shall be a key operated switch, which can shut down and prevent the restart of all operation systems controlled from that point and shall operate so that all systems controlled from the control point shall automatically shut down in a safe manner.

**Starting and stopping**

The machinery shall be fitted with a primary start control located at the main operators control point. It shall not be possible for the machine to start or to be started except by the intentional actuation of that control. All starting controls on auxiliary equipment shall be secondary to this control.

Machinery shall be fitted with a primary control whereby it can be brought safely to a complete stop. Each control point shall be fitted with secondary controls to stop some or all of the moving parts of the machinery depending on the type of hazard, so that the machinery is rendered safe. Stop controls shall have priority over start controls.

Emergency stops:
Electrical or electrically controlled hydraulic equipment forming part of a shield machine including back-up equipment shall be fitted with emergency stop devices, which can include trip wires. Emergency stops shall be installed where hazards can be reduced particularly at the main operators control point and at additional control points.

Where central hydraulic or pneumatic controls have no separate emergency stops fitted, they shall automatically return to the neutral position when not in use.

**Fire protection – hydraulic oils**

All hydraulic systems containing mineral hydraulic oils shall be designed so that in the event of rupture of a component, the loss of oil is minimised and early warning is given of the rupture. Hydraulic oil tanks shall be fitted with both low and high level warning alarms.

**Maintenance**

All shield machines and back-up equipment shall be designed and constructed so that adjustment, lubrication, service and maintenance can be carried out without danger. Where possible the machine shall be designed so that adjustment, maintenance, repair, cleaning and servicing operations can be carried out when the machine is at standstill.

**4.2. TBM Launch and Arrival Situation**

The interface between the TBM launch/reception shaft and the tunnel excavation, often at high ground water pressure, is one of the most critical phases of building a tunnel. To perform the launch and the arrival of the TBM from and into the respective shafts a combination of sealing elements has to be installed to prevent water and material ingress into the shaft and consequently ground loss at the surface.

The sealing system typically consists of a gasket system being installed in the sealing ring and a sealing soil/rock block at the ground side of the shaft right behind the retaining wall. The gasket system usually consists of a pair of lip seals - sealing off the annulus at the front end of the shield - and a hose seal at the shield tail. The sealing soil/rock block is commonly either performed by jet-grouting or by lean concrete secant bored piles.

**Launch situation**

After the launching shaft has been completed the concrete structure containing the sealing ring is cast in front of the future tunnel face. Now the shaft retaining wall (usually a diaphragm wall or a secant bored pile wall) can be broken out in the area of the future tunnel face. After that has been done the sealing soil/rock block is the only watertight element between the shaft and any water bearing ground. Its integrity is of utmost importance and needs to be thoroughly tested before the retaining wall can be removed.

After the retaining wall has been broken out the shield is pushed in its final launching position. Then the rigid abutment structure and the pressure ring can be installed and, if space permit, the first TBM backup train attached to the shield. The tunnel drive starts with the erection of the first blind ring.
Arrival situation

In principle, the same sealing elements as for the TBM launch (gasket system and soil/rock sealing block) are used for the arrival situation. Prior to the arrival of the TBM the concrete structure containing the arrival steel cylinder is erected against the retaining wall at the area of the TBM arrival. After the soil/rock sealing block has been tested for impermeability the retaining wall can being broken out. The TBM now approaching is able to drill through the sealing block and enter the steel cylinder.

Once the annulus between the shield tail and the cylinder wall is sealed off by the hose seal installed at the rear end of the steel cylinder the lid of the cylinder is being removed. The TBM proceeds further until the first segment ring outside the tunnel – but still within the shield skin – is being erected. After the annulus between the tail skin and the last segment ring inside the tunnel has been grouted, the system is now sealed off and the shield can proceed onto the shield cradle. The drive is completed and the TBM can be recovered.

A failure of the arrival situation is potentially more disastrous since not only the shaft and surrounding property can be damaged but potentially the entire completed tunnel can be flooded or even severely damaged.

Innovation: Flying launch method

At the beginning of the excavation the TBM moves from its starting pit into the subsurface. In the case of a conventional shield start-up, a fixed rigid structure serves as an abutment for the advancing TBM. This structure and the installed blind ring support constrict the narrow space available within the launching shaft thus hampering the progress of the excavation works.

Based on the collected findings with the operating sequences of various shield start-ups, as previously described, a major European contractor developed the idea of an optimized TBM launch, during which the abutment for the TBM’s driving jacks automatically advanced towards the launching shaft’s retaining wall during the shield start-up.

The so called “flying launch method” mainly consists of a steel structure and a hydraulic unit with hollow piston jacks. Basically the TBM is hydraulically pulled into the ground by means of tension rods – the TBM’s driving jacks only exert a holding function – rather than pushing its jacks against the rigid steel abutment in the conventional launch method.

The shield start-up with the “flying method” affords the following major advantages:

- **Saving Construction Time** – by avoiding erection of the massive rigid steel structure and installation of the blind ring tube. The TBM advance rates can be optimized by having more space within the launching shaft.

- **Production costs** – considerably less steel is required compared with the conventional approach, the number of blind rings (1 to 2) is considerably less than for the conventional approach, where depending on the circumstances as many as 7 to 9 blind rings are needed.
• Health & Safety - Assembly and disassembly jobs in particular represent a high potential danger in terms of industrial safety. Handling heavy and in some cases, pre-tensioned steel parts in confined space and without any direct visual contact between the crane operator and the rigger as well as the removal of the blind ring structure are only two typical examples.

The “flying launch method” has been patented and successfully been adopted in a number of TBM projects.

Loss preventing measures

Testing of the sealing block

The integrity and watertightness of the soil/rock sealing block is of utmost importance for a safe launch and arrival of a TBM in soft ground conditions with high ground water table. Decisive for its quality are parameters like local circumstances at the surface (i.e. accessibility for the drilling rigs in order to ideally perform vertical columns), homogeneity of the ground (i.e. no obstacles which could prevent accurate jet grouting), stability against erosion and last but not least the testability of the block.

The latter is carried out prior the retaining wall is being removed. Tests usually consist of drilling a sufficient number of holes through the concrete wall into the grout block across the face of the future tunnel. The drill holes are equipped with valves in order to measure water inflows and to determine where and with which intensity re-grouting needs to be carried out. Only if all potential water inflows may be prevented can the break out of the retaining wall be performed. During the break out the measurements are continued since due to the vibration caused by the pick hammers new waterways could have opened. These need to be grouted immediately in order to avoid water ingresses. Testing needs to be continued beyond the break out of the concrete wall in practice until the shield penetrates into the sealing block.

The same principles apply to the arrival situation.

“Soft eye” method

The removal of the retaining wall prior to the launch is clearly a high risk activity since after that there is no more safety device left until the shield has passed through the
sealing block, the first segment rings have been installed and the tail skin grouting has been performed.

Very often launching shafts are built to a great depth (20m to 40m below the ground) and have to resist ground and water pressure. For this reason the walls are built with a consistent thickness (1 to 2 m) and are reinforced with enormous steel reinforcing bars. Before the TBM starts boring the tunnel, breaking of the wall is done manually as well as the cutting of the steel reinforcing bars.

This is the reason why nowadays a "smart solution" offered by Glass Fibre Reinforced Plastic (GFRP) – the so called “soft eye” method – is increasingly more adopted. The technique consists of substituting the internal steel reinforcement bars of the concrete wall with composite materials bars having a high tensile strength but low shear strength, which allow the TBM to bore through the wall section easily and without running any risk for the cutting tools and minimizing the risk of water ingresses and ground subsidence.

Dimensions of the sealing block

The design of the sealing blocks is subject to a thorough ground investigation, good knowledge of the geotechnical parameters, the surface situation and the type, size and configuration of the TBM.

In order to find the most cost efficient solution it has become common practice to optimize the dimensions of the sealing block, in terms of width and height in excess of the shield diameter, but also in terms of its length. A minimum length shorter than the shield length is technically feasible; however, potentially more risky than if the block size exceeds the length of the shield.

In some projects with multiple shield drives it has been observed that the first launch is been performed with a sealing block shorter than the shield length, however, after this launch caused problems with ground settlements, a longer block exceeding the shield length has been installed in the subsequent drives for safety reasons.

4.3 TBM tunnelling in soft ground and effects on Third Parties

Settlement

Tunnel construction by TBM will cause settlement. This settlement is a result of ground loss into and around the TBM, commonly known as “face loss”, and this is measured as a percentage of the theoretical tunnel bore volume (% face loss). Face loss occurs during construction owing to stress release of the surrounding ground during the excavation phase and over excavation of the tunnel.

Prediction of settlement

The most common form of assessment for likely settlement is the semi-empirical method based on a 2-dimensional approach transverse to the tunnel. This method approximates the settlement trough to a Gaussian curve. For TBM tunnelling this is usually sufficient to establish the potential settlement that can be expected. The profile of the trough will depend on a number of factors such as tunnel diameter,
tunnel depth, face loss and the settlement trough width factor (a factor that is dependant on soil type and condition).
It should be remembered that settlement does occur in 3-dimensions, so the “bow-wave” ahead of the tunnel needs to be considered. This curve is approximated to a cumulative probability curve.
Where multiple tunnels occur (for instance in a metro system with tunnels for each direction of train travel) the effects of the tunnel construction are considered to be cumulative, and the curves can be superimposed.
For non-TBM tunnels with complex configurations of tunnel construction it is now fairly common to undertake complex numerical analysis to assess likely ground movements.
The area affected by tunnelling induced settlement is known as the zone of influence. For TBM tunnels the zone of influence is centred along the centreline of the tunnel, and as a rule-of-thumb extends to a distance approximately equal to the depth of the invert below ground level, on either side of the centre line.

**Prediction of Damage**

The factors that can lead to damage in buildings are generally rotation, angular strain, relative deflection, deflection ratio, tilt, and horizontal strain.

**Table 1: Classification of Building Damage (after Burland et al., 1977)**

<table>
<thead>
<tr>
<th>Damage Category</th>
<th>Degree of Severity</th>
<th>Description of Typical Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Negligible</td>
<td>Hairline cracks less than 0.1mm wide</td>
</tr>
<tr>
<td>1</td>
<td>Very slight</td>
<td>Fine cracks easily treated during normal decoration. Cracks up to 1mm.</td>
</tr>
<tr>
<td>2</td>
<td>Slight</td>
<td>Cracks are easily filled. Redecoration probably required. Crack widths up to 5mm.</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Cracks can be patched by a mason. Repointing and possibly replacement of some brickwork. Crack width 5-15mm.</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>Extensive repair work involving replacement. Crack widths 15-25mm.</td>
</tr>
<tr>
<td>5</td>
<td>Very severe</td>
<td>Major repairs required including partial or complete rebuilding. Crack widths generally greater than 25mm.</td>
</tr>
</tbody>
</table>

**Table 2: Damage Categories (after Boscardin and Cording, 1989)**

<table>
<thead>
<tr>
<th>Category of Damage</th>
<th>Normal Degree of severity</th>
<th>Limiting tensile strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Negligible</td>
<td>0.000 – 0.050</td>
</tr>
<tr>
<td>1</td>
<td>Very slight</td>
<td>0.050 – 0.075</td>
</tr>
<tr>
<td>2</td>
<td>Slight</td>
<td>0.075 – 0.150</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>0.150 – 0.300</td>
</tr>
<tr>
<td>4 to 5</td>
<td>Severe to very severe</td>
<td>&gt;0.300</td>
</tr>
</tbody>
</table>
The strain is calculated by approximating buildings to being a deep beam located on the ground surface. This beam is then analysed for hogging as it assumes the shape of the settlement curve using Bending theory. This bending causes strain in the building, leading to cracking, differential settlement, and eventually structural failure.

**Underwriting Considerations**

When considering underwriting information related to a TBM tunnelling project consideration of the environment under which the tunnel is going to be built is essential. Third party property that can be affected is not limited to buildings; it can include all man-made structures on, or under, the ground surface, from power cables and sewer pipes, to railways and road bridges.

As part of the engineering process there should have been a detailed assessment of the impact of tunnelling on third party structures. The initial assessment will, most likely, be based on tables 1 & 2 and should highlight structures that are likely to be affected.

This assessment should be provided in the underwriting information in the form of a schedule of properties within the zone of influence and the calculated damage category anticipated. Buildings in categories 3 & above should have a more detailed assessment of their reaction to the anticipated ground movement resulting from the tunnelling. This will

5. **Insurance recommendations**

5.1 **Introduction**

In the previous chapters we have discussed the different aspects of risk exposure that a TBM can face from the moment it is fabricated until the moment when it completes the excavation of the tunnel for which it had been designed for.

In this section, following the same approach, we would like to consider some recommendations for the risk assessment and quoting procedure for underwriters seeking to cover these machines.

5.2 **Period of cover of the TBM**

The first issue for the Underwriter should be to clarify since when he/she is requested to cover the TBM. In most of the cases cover is required to start from the arrival of the machine at site.

The Underwriter should make sure that the CAR Policy section relevant to the TBM is not extended without his being aware to cover the transportation of the machine from the suppliers premises to the site through the “inland transit” clause and to be clear in the event that the TBM, further to the completion of one tunnel section, is required to be disassembled and moved to another tunnel section he has allowed for premium for this transit.
From the moment the TBM arrives at site the type of cover required is of storage until the starting of the assembly operations. The assembly normally takes about three months. Usually there is no differentiation between the period of cover for the preparation phase and for the operational one. During storage and assembly, depending on the location of the machine, the essential aspects of exposure are fire, water damage and theft and if necessary the underwriter may ask for proper warranties to ensure the machines are being properly protected.

Cover thereafter continues until the completion of excavation works and the following disassembly of the machine. To ease the calculation of the correct premium to be charged and monitor its payment rating is calculated on an annual, renewable basis.

5.3 Cover of the TBM during excavation
During excavation the risk exposure to fire, submersion by water and explosion increases. For this phase the Underwriter should make sure that the TBM is equipped with satisfactory fire fighting facilities, adequate dewatering pumps and a system of detection for explosive gases. This can be done through the information gathered during the risk assessment phase or through warranties. A useful benchmark code of practice is BS 6164

When assessing the phase of excavation the Underwriter instead should decide the extent of cover that he/she is prepared to give in consideration of the following aspects:

- expenses incurred for the recovery of the TBM;
- abandonment

Moreover he/she should also consider which Policy provisions should be applied in respect of:

- drill head cutting tools which are usually considered as consumables;
- internal mechanical and electrical failure, breakdown or overheating;
- Preventative measures applied when crossing faults or excavating in other difficult geological conditions.

5.4 Recovery of the TBM and possible abandonment
We already described how, depending on the geological conditions encountered during the excavation, the TBM can be exposed to the risk of remaining stuck. The expenses incurred to free the TBM in these cases can vary substantially depending on the tunnel location (mountain or urban area), its depth, its geology and the level of the water table.

The extent of this can, in the very worst case scenario, lead to the decision to abandon the machine resulting in a total loss. It is therefore essential to clarify in the Policy what is the limit covered for the expenses incurred for the recovery of the TBM and to clarify whether the Policy is extended to cover also the case of the abandonment of the machine and at which conditions.
In the event abandonment is covered, for long tunnels it will be important to state how the indemnity for the total loss of the TBM is calculated a proposal is given in section.

The market has recorded few cases of abandonment of a TBM, the most famous of which is the one of the Ping Ling Tunnel in Taiwan.

To be mentioned also the case of immobilisation expenses that are sometimes covered for items of machinery suffering a loss. The immobilisation of a large TBM can cost up to EUR 100,000 per day therefore Underwriters should consider very carefully this type of extension.

5.5 Residual Value of a TBM
Terms and conditions applied in the Policy normally require that the TBM is insured at the new replacement value. This can vary from a few million EUR for small machines reaching up to EUR 50 m for the largest TBMs.

With refurbishment a TBM can be used several times, by replacing its consumable parts and usually the shield itself.

In the event the tunnel to be excavated is very long, and if abandonment is covered, the Policy should contain a provision for the calculation of the residual value of the TBM during the excavation progress.

With this aim, the Insurance Market applied several times a formula used by loss adjusters, based on the Baugeraeteliste (BGL). This formula calculates the residual value (actual value) referring to:

- \( T \): ratio between the uncompleted length of the excavated tunnel and the original length to be excavated;
- \( E \): coefficient describing the TBM condition at the moment of the loss (value from 0.2 to 1.0);

The Actual value (A) according to this formula can be calculated as:

\[
A = 0.5 \times NRV \times (T + E)
\]

where NRV is the new replacement value.

5.6 Consumable parts and breakdown
Some elements of the TBM (cutting tools) are subject to wear during boring operations. As such it is normal market practice to exclude them from cover.

Taking moreover into consideration the very difficult environmental conditions under which these machines work mechanical and electrical breakdown and overheating are also normally excluded.

Machinery Breakdown covers for these machines remain a controversial issue between Contractors and Insurers. This type of cover is required many times in consideration of the high value of the TBM and of the extent of the loss that can generate from a breakdown.
The most expensive part in the event of a breakdown is the head bearing. This part is expensive and its replacement time can also be long. An example of a bearing loss is listed in 5.9

A key element to check is to check how this bearing can be replaced. In traditional machines its substitution in situ is very difficult, with the best modern machines; the replacement may be carried out inside the tunnel.

In general it must be recognised that the operating conditions for these machines are nevertheless very challenging and therefore it is difficult to estimate the actual reliability of the TBM components.

Underwriters should also be aware that if mechanical breakdown of TBMs is covered this may have an automatic effect on any DSU coverage afforded elsewhere under the policy. The TBM is often on the critical path of a project and delays from machinery breakdowns of TBMs can have an important impact on project completion.

5.7 Safety measures in advancing

Recognising that in many occasions the cost of geological investigations to be carried out before tunnelling is prohibitive the available geological information may be insufficient at the start of the tunnel drive, Underwriters should also make sure of the measures of assessment that are foreseen to be executed from the machine itself are adequate to remove any reasonable doubts on the ground conditions in front of it.

Economic the pressure put on the Contractor to maintain a high progress rate may lead to occasions when the time dedicated to these assessments is limited to a minimum.

If the operational measurements mentioned in Section 2.5 are not sufficient to assess the ground conditions ahead of the face the most common assessment of ground conditions ahead of a machine is probe drilling. In more complex cases there is the possibility to apply a 3D picture of the ground conditions in front of the head up to 100/200 meters ahead of the machines using ultrasonic techniques and/or seismic methods.

The Underwriter should nevertheless make sure that in case of need a technique of investigation is applied to clarify the ground conditions ahead and for standard operations the Underwriter should make sure that the parameters mentioned in section 2 are continuously monitored and kept available for investigation, in the event of a loss.

It is important also to check whether the same are also sent to the TBM manufacturer, whose experts, in case of a problem, can intervene in support to site engineers.

At present there are some suppliers who are able to do this through the internet.

5.8 ALOP

The Insurance Market has several reservations whether to extend cover provided by a CAR Policy to ALOP for tunnelling works, this has been dealt with in a previous IMIA paper (WGP 48) the possibility to extend ALOP to cover consequences of damages to a TBM is probably even more difficult.

In consideration of the high exposure of TBMs, cover is rarely available in the event of a material loss to the machine; one of the worst scenarios is the case of a TBM
getting stuck with only minor damage to the machine, the delay to the project can be extremely long with consequential loss to the ALOP cover...

Even more difficult at present, is it to find cover which extends to ALOP arising from Machinery Breakdown of the machine itself. The team has not been able to find statistics relevant for this type of cover which would allow a premium rating mechanism to be established.

5.9. The Client’s Perspective

Coverage is of course normally provided on an “All Risks” basis, subject to the terms, conditions and exclusions that are applied. From discussion with various risk / project managers responsible for insuring some of the world’s most high profile TBM's, a number of their most common concerns can be addressed by providing them with more detail surrounding how the premium quotations are arrived at. This should then allay much of their concern at ensuring that underwriters have very much taken into account the individual risk and timing factors associated with the specific machine / project that is being insured.

The most obvious and universal comment from the client is that the rates and deductibles are far too high for TBMs, especially from those that have suffered few or only minor losses in the past. Moreover, the following represent particular areas of concern from the clients prospective:

- Has the underwriter differentiated between the TBM itself and the associated equipment (segment train etc) for both rating and deductible purposes?
- Does the basis of indemnity reflect the fact that the machine will almost certainly be used for subsequent projects after refurbishment and is therefore not simply “written down” against the contract price?
- Why do underwriters rarely provide mechanical / electrical breakdown coverage?
- Can cover be extended to include increased cost of working due to adverse ground conditions, including in the absence of material damage to the TBM?
- Have the underwriters taken into account the clients own track record in terms of TBM losses on previous projects?

In addition to the above, part of the rating transparency that clients are looking for revolves around the extent to which the different types / periods at risk have been taken into account i.e. transit, intermediate storage (if any) assembly / erection / positioning, operation and subsequent dismantling etc. In fact, they would also expect that the rating should be different depending upon the exact working cycle of the TBM when in operation (e.g. 2 shifts of 16 hours or 3 shifts of 24 hours).

Reference was already made in 5.8 above to the effect that there is more limited market capacity available for ALOP following a TBM loss. This can of course be a problem for the client, especially where they have a contractual requirement to obtain such coverage (as is often the case for PFI / PPP type projects).

Notwithstanding all of the above, clients are aware of the fact that TBMs are perceived by underwriters as relatively high risk and are therefore keen to work with them to demonstrate why their particular insurance needs should be addressed more adequately and competitively than “standard” risks of this nature.
6. Examples of losses

Thames Water Ring Main - Tooting Bec Inundation

In 1987 Fairclough Tunnelling (now AMEC) was awarded the first stage of the London Water Ring main by Thames Water (now renamed Thames Water Ring Main). The contract was for 4 shafts at Battersea, Brixton, Streatham and Merton and the 100 inch connecting tunnels in-between. The overall 80km of tunnels are for the efficient distribution and supply of water to London. The Fairclough team had selected 2 open face Tunnel Boring Machines (TBMs) for the 3 drives, favoured primarily to suit the London clay which featured over most of the alignment. The Streatham tunnel drive to Brixton was however planned to be driven under 1 bar of air pressure to overcome the anticipated water inflows during tunnelling. The air pressure is intended to counteract water pressure and keep the tunnel dry. Compressed air tunnelling is now very rare, rendered obsolete with Japanese Earth Pressure Balance (EPB) and Slurry tunnelling technology. It’s also associated with long term health problems similar to those affecting divers. Back in the 80’s the Japanese EPB technology was not commonly available outside of Japan, and was certainly not given any merit before the project began.

In November 1988 the clay face of the Streatham drive was catastrophically inundated due to an unexpected highly pressurised lens of Thanet Sand. The 4.2 bar of water pressure flooded almost 1000m meters of tunnel within a matter of minutes rather than hours. Shortly after it had risen up to the surface of the 11m diameter 40 meter deep drive shaft at Streatham pumping station. AMEC and Thames Water, confronted with these dire circumstances, had to rethink their contract and find a solution.

Therefore the “pressure was on” to get it right the second go. A recovery shaft was sunk just ahead of the flooded £400,000 Deacon tunnelling machine. British Drilling
and Freezing were called in to freeze the ground ahead of and around the machine in a £350,000 (1989 prices) operation to recover the drive. Steel tubes were installed from the bottom of the shaft through which salt water was circulated at -30°C from a huge refrigeration plant at the surface. The operation was completed in two stages, the first at the bottom of the shaft before it was deepened again to the tunnel horizon, and the second horizontally outwards to freeze the ground around the TBM.

During this time AMEC travelled to jobsites and manufacturers in France, Germany, USA and Japan in pursuit of a solution. In the end they opted for the first true Earth Pressure balance machine made by Lovat Inc in Canada, which became their 100th order and the very first machine to be delivered to the UK.

The nature and risk balance of contracting at the time led to a specification that at best could be considered a minimum that would do the job. The chosen technology and construction method was not robust. Almost any adverse change of ground conditions would have jeopardised the success of the drive.

A robust method of construction is usually contingent on a robust risk management approach with an effective framework of hazard identification and analysis. The consequent risk mitigation strategies must address the cause and consequence of even the most unlikely scenario. Tunnel inundation was in the absence of a water body above (sea or river) never given any consideration at the planning stage of Ring Main scheme. Such occurrences were in any event very rare, and there was little evidence to indicate such an eventuality. Proper ground investigation would have revealed the circumstances and the necessary project specifications and contingencies.

Great Belt Link

Some 10 years later history repeated itself on the Great Belt Link project! The TBM mechanic working on the cutting head of machine had to straddle his cables and rubber gas pipes across the flood doors leading into cutting head of the TBM. This prevented them from being shut closed when the tunnel face collapsed and the water from the sea bed rushed into the machine and tunnel. The scenario is best compared to one of those depth charge scenes on a World War 2 submarine film. This time the water rushed back to the launch pit from where it also flooded the adjacent tunnel drive. Both tunnel machines had to be completely refurbished.

Socatop

This is the largest known fire in a tunnel during construction. A fire aboard the service train of the TBM damaged the tunnel the loss has been estimated to be around $8,000,000 including damage to the works. In this case the TBM was not itself damaged as it was protected by its on board sprinkler system. Not all TBMs are equipped with on board sprinkler systems.

Machinery Breakdown Losses

There is a small record of Machinery Breakdown losses in the Swiss market. This consists of machines with diameters larger than 4.5 m (Robbins), most of them had a diameter between 9 and 11 m (Herrenknecht). The history is 6 years old and contains 14 different machinery breakdown policies. The insured sum ranges from CHF 8 Mio up to 30 Mio, most of the policies cover fire, natural hazards and erection, Testing and MB. Several policies do have a BI component with sums insured up to
10 Mio. and a waiting period of 20 to 45 days. The deductibles are for smaller machines CHF 50'000.- and for bigger one's 100'000 up to 500'000.-.

So far there are no fire losses in Switzerland over the past 10 years. Nor have there been any BI losses, but there were tow near misses with delays close to the waiting periods.

Table:

<table>
<thead>
<tr>
<th>Number of machines</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of machine years (mach y)</td>
<td>34</td>
</tr>
<tr>
<td>Number of paid losses</td>
<td>8</td>
</tr>
<tr>
<td>Premium written</td>
<td>12.5 Mio</td>
</tr>
<tr>
<td>Paid losses</td>
<td>4.3 Mio</td>
</tr>
<tr>
<td>Losses:</td>
<td></td>
</tr>
<tr>
<td>Main bearing</td>
<td>5</td>
</tr>
<tr>
<td>Motor</td>
<td>1</td>
</tr>
<tr>
<td>Breaker</td>
<td>1</td>
</tr>
<tr>
<td>Gripper and Pad</td>
<td>1</td>
</tr>
</tbody>
</table>

The average of the five bigger losses (> 500'000.-) is 830'000.- with a maximum of CHF 1'200'000.- (main bearing) including all additional covers. Two policies have had two losses during the covered period. There have been no losses during erection.

The main loss reported but not covered was 4.2 Mio. with an additional BI of 2 Mio., this was a total loss of the main bearing after few hundred meter of heading the repair time 4 months but the loss was outside the insurance cover period.

7.0 Conclusion

The invention of the tunnelling machine has revolutionised tunnelling history indeed it had revolutionised the creation of spaces under our cities allowing metro systems, water and sewage systems, and underground cable networks, all to be built in a safe and sustainable manner.

History has taught us that each development of a new machine, which will eventually result in progress of the tunnelling industry, may present short term challenges to the underwriter.
TBMs are very varied and their suitability for different soil conditions means that the correct choice of machine and the level of experience of the operators is critical in their successful use.

Commercial considerations and pressures on the different parties involved in the choice of machine may affect the risk levels an underwriter may face.

Closer cooperation between the tunnelling machine suppliers, contractors and insurers should allow insurers to develop in the future methods of clearly differentiating the levels of risks involved in insuring these machines. More exchange of information about losses will allow insurers to more closely match the industry’s perceptions of the level of risk.

By the very nature of the conditions in which a TBM works, it will always be a relatively high risk piece of equipment that needs to be underwritten by specialist underwriters with knowledge of the tunnelling industry. The lack of enough accurate statistics to date does not allow this type of equipment to be underwritten using standard statistical insurance methodology.