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Tunnel Boring Machine (TBM) applications in soft ground conditions

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Tunnel Boring Machine applications (TBM/SM) in soft ground conditions.

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1. Executive summary

Some major aspects influencing tunnel construction in soft soils have changed considerably during this last decade. In turn, both insurers and reinsurers are now in a very delicate situation regarding the outcome.

The worldwide demand for underground facilities is growing at a rapid rate, and a substantial number of these projects are located in cities where ground conditions are not optimal.

Given the advances in tunnelling technology today, tunnels can be excavated in virtually all types of soil and environment, but there are still numerous unknown parameters. One of the most important is the knowledge of the ground through which the tunnel will be routed. Before the construction starts, a number of assumptions regarding geology, hydrology, soil characteristics, and even the surroundings must be made. The level of accuracy of these assumptions has a direct impact on the final exposure.

There is also a clear trend to shift the burden of geological risk from the principal to the constructor and ultimately to the insurers/reinsurers, producing a clear increase of the final exposure.

The wordings employed are often not ideally adapted to the characteristics of tunnelling projects because of the overlapping of loss mitigation, repair works, and betterment. Hence, they make loss settlements in tunnelling highly difficult.

Last but not least, third parties have become much more claims conscious. Due to the proximity of the tunnel to above-ground properties – clearly the case in cities – and in light of this trend, a major portion of the premium must now be dedicated to the TPL policy section.

The combined effect of all these elements has led to the deterioration of the loss ratio in recent years, and hence, the need for in-depth studies of this situation.

2. Introduction

In contrast to many other civil engineering processes, tunnel construction phases currently used are principally identical or similar to those employed in the last century, but the methods are not. The major changes which have occurred primarily involve more stringent external influences and the advent of new drilling and excavation technologies. Tunnelling projects must now consider numerous underlying political and environmental factors which add to the overall complexity of a given project. Arguably one of the most demanding civil engineering disciplines, tunnelling reflects a borderline situation between safety and economy.

The tunnel itself can no longer be considered as an autonomous civil works entity. Rather, it must be viewed within the context of its integration in existing transportation infrastructures and how it will subsequently comply with prospective network concepts.
Generally, a tunnelling project can be divided into the following five construction phases.

Once the tunnel’s overall purpose is defined, the environment and surrounding regions are evaluated to arrive at a rough decision regarding the tunnel’s alignment or routing. These decisions depend on the scope of the tunnel, and reflect the influence of factors such as governmental regulations, restrictions, accessibility, cost parameters, project deadlines, and possible time restraints.

The second phase involves the evaluation of different design parameters (e.g. diameter, lining) and the respective construction method to be employed (e.g. conventional, staged or sequential excavation coupled with the use of shotcrete lining, hybrid techniques, tunnel boring machine (TBM)).

Once the specific construction technique is selected, the project details are then analysed in depth. During this phase, specialists, suppliers and possibly contractors are involved to arrive at final project specifications.

Phase four involves the actual excavation and construction. Since this phase is of central importance for the underwriter, additional factors also come into play, i.e. soil composition of the tunnelling site, stabilisation safeguards for the excavation which include shotcrete linings, anchor, rock bolts, wire mesh, provisional or permanent section linings according to the respective technique. The loading and discharge of the excavated material into a deposit or silo for future use is also a decisive logistics factor.

The final phase is devoted to the finishing and installation work which is often performed by a different contractor adapting the tunnel to its ultimate use (e.g. railroad, road, sewage, water supply) Technical installations including lighting, signalling, fire detection and safety systems and equipment are provided after construction is completed.

At the beginning of the last century, geological factors were predominantly responsible for determining the overall feasibility of a tunnel project, the determinative factor being the rock or ground conditions. Consequently, the state of the art in engineering at the time limited construction to shorter tunnels.

Tunnels are now built where they are needed or specified. The political and particularly environmental considerations have become vital factors over the years, in some cases vying in importance with engineering and geological factors. The tunnel’s integration in existing transportation networks is also a decisive factor. Due to these restraints, tunnels are often routed through ground compositions which are less than ideal. Geological aspects have assumed a secondary importance and available technology is expected to cope with them.

Today, there are many different techniques available, but certainly one of the major technological breakthroughs is the tunnel boring machine (TBM) for fully mechanised tunnelling, comprising excavation, support, lining, and transportation of excavation material.
3.1 Basic soil classification

Ground categories are broken down roughly according to the following table:

<table>
<thead>
<tr>
<th>Hard rock</th>
<th>Soft rock</th>
<th>Soft soil</th>
<th>Soft soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dolomite</td>
<td>Marl</td>
<td>Expansive or swelling ground</td>
</tr>
<tr>
<td></td>
<td>Limestone</td>
<td>Hard clay</td>
<td>such as clay-stones, anhydrite</td>
</tr>
<tr>
<td></td>
<td>Sandstone</td>
<td>Slate</td>
<td>rock in contact with water,</td>
</tr>
<tr>
<td></td>
<td>Granite</td>
<td>Dolomite</td>
<td>silt</td>
</tr>
<tr>
<td></td>
<td>Basalt</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lava</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gneiss</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quartzite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand, fine gravel, gravel, coarse-grained, stones</td>
<td>Flowing ground = soil with high water content.</td>
<td></td>
</tr>
</tbody>
</table>

These soil classifications are done according to national / international standards and recommendations (e.g. DIN 18196 soil classification for construction purposes)

Only the soft soil categories will be considered in this paper

Soft soils are, contrarily to igneous or metamorphous rock the result of sedimentation and may be roughly classified in two types of behaviour:

- Non-cohesive soils such as gravel and sand are unstable and will, if excavated, achieve a surface inclined according to their internal friction angle. They are permeable and ground water is subject to the hydrological flow laws.

- Cohesive soils such as silt and clay may for some time stand vertically, but threaten to shear off and are often highly compressible. Groundwater does not conform with the hydrological laws, but adheres to soil particles and can be removed only using special point wells.

Generally, soft soils are unstable over a certain period and must be considered as less predictable than hard rock. Hence, adequately describing their behavioural properties requires definition of many more parameters than in the case of hard rock.

Some of the primary analytical parameters include the following: grading curve, angle of friction, cohesion, deposit thickness, strength figures, plasticity, swelling behaviour, permeability, water bearing and water pressure, consistency, and relative density, liquefaction possibility.

The following technical data can be obtained from the cited geotechnical characteristic values and an overall assessment of the geological and hydrological conditions of the subsoil, face stability, proposed face support measures, time lag between excavation and securing the subsoil, and deformation behaviour.
3.2 Methods of investigation

Knowledge of geotechnical conditions is the most important principle for the planning and executing a tunnelling project. Soil analysis requires time and expertise and normally requires 1% to 3% of the overall construction budget.

The preliminary assessment relies on existing documents, topographical maps and feedback from previously constructed civil works in the vicinity to provide an overall evaluation of geological and hydrogeological conditions and is supplemented by further investigation as required. More precise information is required for the design phase, and different investigation techniques are used:
- Investigative boring and the respective core samples
- Exploration and surface samples
- Dynamic penetration tests, pressure probes
- Mechanical borehole examinations (expansion tests)
- Pump and water injection tests, exploratory tunnels or shafts

During construction, additional information is obtained along the tunnel or by additional pilot tunnels. This provides a comparative analysis with anticipated ground conditions and is fundamental for subsequently adapting construction to relevant conditions, which is an ongoing process during the entire project.

3.3 Consequences for Construction

Generally, tunnels built in soft ground are located in metropolitan areas. Their applications range from utility tunnels linked to sewage systems, water transport systems or wider
diameter tunnels - mainly tunnels for highway (city by pass) rail or subways. Stability is a critical aspect of soft ground tunnels and safety measures must be implemented promptly in time and distance from the excavation face so that the support structure is active.

The contractor requires highly detailed geological information, and additional investigations are required if a clear assessment cannot be made.

Geological documentation should provide information on the following:
- Ground structure with indication of material classification and homogeneity (geological map, tables with measured factors)
- Subterranean obstacles to be expected (e.g. boulders, blocks, erratic blocks, underground structures, archaeological artefacts)
- Groundwater conditions indicating the level, ground permeability, flow direction and velocity, chemical values, hydrostatic pressure
- Probable ground reaction after excavation
- Possible use of excavated material, contamination possibility and degree, deposit criteria, waste deposits above and underground
- Vibration characteristics of the excavation method tend to lower the groundwater table, creating settlements.

The respective construction method is determined by relevant geotechnical characteristic values and construction information. Tunnelling classes are then assigned over the routing length which identify the performance requirements per class and describe the level of technical difficulty.

Sometimes alternatives in sequence or construction method might be economically more favourable. The proposal of alternative methods depends on the type of contract between the principal and the construction company. However if an alternative method is adopted, the contractor must assume the full design responsibility.

4.1 Underlying concepts for Tunnel Boring Machine (TBM) / Shield Machine (SM)

In an effort to facilitate and automate tunnelling operations to some extent, the civil engineering industry began developing machines incorporating mechanisation and automation practices similar to those employed in manufacturing processes. During the past 25 years, the industry has continually improved their features and enhanced their application ranges.

Generally speaking, tunnelling machines are circular, they either head the entire tunnel cross-section with a cutter head or cutting wheel full-face or in part segments by means of suitable extraction equipment. During the excavation phase, the machine is moved forward either continuously or incrementally.

Both the TBM (hard rock applications) and SM (soft ground) fulfil the same purpose:
- ensuring systematic and automated subsoil excavation;
- providing an effective protection (the shield) for the labour force at the front;
- stabilising the tunnel through quickly closing of the support ring
- transportation of the excavated material
In this paper, discussion is confined to shield machines (SM). An other limitation is regarding the so called micro-tunnelling techniques / pipe jacking (normally diameter < 3 metres), those techniques are gaining importance, nevertheless they will not be treated in this paper.

The main constitutive items of a SM are the following:
- Front face where the soil is excavated with special tools (shield or cutting wheel)
- Steering mechanism part with drive engines for forward movement.
- Control mechanism for deviation and inclination
- Removal installation for transporting excavated material through the machine to a separator or directly onto an independent transport system
- Installations behind the working chamber permitting either further soil improvements (i.e. with rock bolts, shotcrete or injections) or are used for preliminary investigations
- Support installations within the protection of the shield tail
- Eventually grouting the void at the shielded tail created between the lining and the subsoil.

The support lining erected inside the shield tail consists of large precast concrete segments, weighing roughly 1 ton which require positioning by a power erector arm before they are interconnected.
Behind the shield, excavated material is transported to the outside (depending on the material and excavation method) either by truck (large diameter tunnels) tracked vehicle, conveyor belts, or pumped through pipes.

The backup or tail is part of the systems and provides the necessary underground infrastructure with regard to ventilation, electric power, equipment transport, temporary deposit for segments, injection material, and others support functions. In case of slurry SM (see definition in 4.2.), the pressure liquid is also prepared in this area.

Due to the characteristics of these machines, they are not suitable for all requirements, let mentioned some of the limiting criteria.

Adaptability: In most cases, the SM is customised as closely as possible to the ground specifications which are expected according to the geological assessment. The increasing application of tunnelling machines and the continual improvement of various extraction techniques have led to machine types capable of penetrating more heterogenous subsoil, thereby enhancing their rather limited flexibility.

Transport of cutting head

Assembling a SM

Installation: SM involve high installation/transport costs. Due to its weight of several hundred tons and an overall length of more than one hundred metres, it must be transported to the site in smaller components. Assembling the entire machine is labour-intensive and requires space.

Investment: due to relatively high operation costs, only tunnel lengths of more than 2 kilometres are considered economically justifiable.

Delivery period: Ordering a SM must be scheduled well in advance in view of its custom configuration and long waiting periods (between 6 months and one year).

All SM types used in soft ground are shielded. As a rule, there are two methods applicable for excavating in unstable ground with little or no standup times:
a) Excavation with shield protection. In case of an unstable front face, this area can be protected additionally by platforms and breasting plates. This method is often used when excavating in segments.

b) With a fully closed front shield (cutter wheel, disk). This method is used for full face excavation. The excavated material enters the shield via small openings and is then transported to the rear. When excavating in ground with high water saturation or even under the groundwater level a counterpressure must be generated to prevent liquid soil from filling the excavated hole at the face.

If the ground quality is insufficient, the subsoil must be grouted, vibrator compression, injections or freezing to adapt it to the characteristics of the selected SM.

Compared with the conventional excavation techniques (drill and blast) SM mechanical excavation produces a higher average daily advance rate (between 10 m to 40 m), is more continuous, generates less dust, noise or vibrations, and provides superior protection. The profile accuracy of the cavity cross section is particularly high provided the SM is driven within its operating tolerances.

4.2 Shield machine types

To provide an understanding of the operating characteristics of the SM, a distinction is made between three main types:

**Air pressure:**
The front part of the SM from the face to the working chamber is provided with air locks and generates a pressure strong enough to withhold inflowing liquid. This method is feasible only up to a water depth of 30 – 50 m max, corresponding to 3 – 5 bar. Furthermore, the ground layer above the water must be thick enough to withstand air blowers reaching the surface. This TBM type is no longer frequently in use and is often replaced by more versatile types which feature air pressure as an option.

**Slurry or fluid support machines**
In this case the unstable ground at the front is supported by liquid mixture under increased pressure generating an even counterpressure. A filter between the existing ground and the support liquid (i.e. using bentonite suspension) prevents the liquid from penetrating and disappearing into the ground. Depending on the subsoil permeability, density and viscosity can be varied, pressure can be regulated by controlling the speed of the delivery and feed pumps. The excavation is done by a turning cutting wheel. The excavated ground material and suspension liquid is mixed by hydraulic conveyance via tubes with subsequent separation of the two materials.

**EPB - Earth pressure Balance machines**
Instead of a hydraulic/bentonite suspension the excavated ground is used as part of the supporting liquid and forms a ground slurry. This method request ground which is homogeneous, soft and cohesive. If the water content is too low or if small particles are absent in the grain size distribution, they must be added artificially (bentonite, polymers, foam). In this case, the environmental compatibility of the material for landfill purposes must be taken into consideration.
Increasing application of tunnelling machines and the related continual improvement of the various extraction techniques has led to machines types which have the capacity to penetrate extremely heterogeneous subsoil, that is respectively a mixture of soft soils ground and unconsolidated rock.

5.1 Project Environment

The worldwide demand for underground facilities is growing at a rapid rate, and a substantial number of those projects are located in cities where ground conditions are not the most suitable. Since ground through which the tunnel is routed is the single most important item and has a decisive impact on the feasibility study, the number of preliminary investigations, design, construction method envisaged, estimated advance rate, overall cost as well as cost for material and equipment and last but not least the risk.

Tunnel construction is now considered to be much more technically hazardous than in the past. This is mainly attributed to:
- Trend towards larger cross sections, e.g. 3-lane highways produces greater disturbance of the underground.
- Tunnels are more often built with low overburden constructed close to the surface (subways, underpasses, railways, sewage systems) and beneath overbuilt areas, thereby aggrandising the consequences of a failure
- Tunnels are often part of major projects (new or upgrading networks of transport) and the pressure to match with the time schedule of the others portion, reduces flexibility
- Less impact on surroundings are tolerated (settlement, dust, noise)
- Space on surface for the site, the equipment is often very limited
- Congested underground, often already used over decades if not centuries with installations that are sometimes even still in use
- Due to the requested parameters to fulfil such as minimum diameter, min curve radius or max inclination tolerated etc. bypass unknown or unreported obstacles is impossible

5.2 Characteristics of Tunnel works

The wide range of underground works varies considerably from other civil engineering projects.

In a conventional civil works project, the design is based on established criteria and accurate calculations, the material used is well known, already tested and their characteristics clearly defined with requested safety margins. Overall there are very few open items or grey areas. In the case of underground projects, the opposite is true. The main material is the ground to be excavated; due to the variety of unknown factors, its behaviour and characteristics can only be estimated since its real material behaviour is known only during excavation.

Unlike projects above-ground, incidents often lead to a full halt of the works until the problem is solved. Excavating at a different site is virtually precluded, nor is it possible to alter the excavation sequence. The standard work flow of excavation, removal of material, implementation of safety measures, installation of linings is a single direction process and cannot be changed. The entire project must be considered as one on a critical path. Hence, any disruption of the process (even from external factors) can lead immediately to delays.

Combining the special project feature of having virtually no buffer time and the increasing demand from the financial backers (see section 5.3) for covering Delay in Start Up (DSU), the exposure to financial consequences of such delays are self evident.

5.3 Parties involved

To illustrate the various different challenges faced by tunnel builders, it is important to discuss some of the majors issues the principal parties must confront:

Principal:
Can he obtain the required financial backing and at what terms and conditions?
Will the project be kept on schedule and be completed on time?
Can he transfer some of the obligations? To whom and at what price?
Can the contractor complete the project at the lump sum agreed?
**Financial backers:**
Is the project viable?
What happens if the project is not completed on time or it cannot be commissioned on the scheduled date?
Who will pay the interest and how secure is repayment?
What if an accident prevents project completion and it is abandoned?

**General contractor:**
Can he build the tunnel according to time schedule within cost parameters and with the stipulated construction method and equipment? Have unforeseen conditions been adequately evaluated and can he fully cope with them?
Does he have alternatives for construction methods, equipment, labour force, scheduling?
Does his work force have the required experience and what training is required?
How reliable is the geological information and the conclusions presented? What if differences are revealed?
Can he manage the very complex structure involving many different subcontractors from many different nationalities?

**SM supplier:**
What is his experience with this contractor?
What is his past experience with the relevant geological factors of the project?
How flexibly can the SM cope with changes?
Who is responsible if advance rate falls behind schedule?
What triggers the performance guarantee?

Under such a constellation, it is readily apparent that each partner group may possibly have very highly contradictory objectives. In most projects, financial factors and the related scheduling are the crucial elements for any decision which can compromise both the excavation technique and safety considerations. This, in turn, aggravates risk.

5.4 List of possible major failures

Principal failure mechanisms in soft soil conditions can be classified in two major categories: ground collapse in heading and lining failure before or even after ring closure.

The first category can be divided into 4 subgroups:
- Ground heading is too weak for the excavation method, i.e. invert, bench and crown failures, full or local face failures
- Crown weakness (vertical fissures, pipes, and man-made features)
- Surface collapse (low overburden; craters, mainly in metropolitan areas)
- Ground / running water ingress in tunnel or in shaft (see example on next page)
Ingress of groundwater into a shaft under construction, drop in of groundwater table and subsequent collapse

Once the definitive lining is in place, the second failure category includes:
- Shear failure
- Compression failure
- Combined bending and thrust
- Punching failure
- Watertightness of segments

Based on our experience, the first category is by far the most precarious for insurers. Not only because the reconstruction costs are greater but also because their frequency is much higher.
5.5 Third Party Liability (TPL) exposure

Dealing with third parties is certainly one of the most challenging issues facing tunnelling engineers when building a tunnel in urban centres with soft soil conditions. Since underground works in metropolitan areas disturb existing, often fragile underground conditions, consequences with third parties are virtually unavoidable. Compared with normal above-ground projects, this intervention (dust, noise, vibrations, restricted access) is aggrandised in view of the tunnel’s proximity to the foundations of third party properties.

This TPL exposure is not restricted to above-ground projects since works in a congested underground increase the risk of interfering with underground utilities such as:
- sewage network
- telecommunication
- gas and electricity

In this context, it should be remembered that third party liability cover is meant only to cover direct material damage or bodily injury to third parties and does not cover any immaterial or any consequential financial loss.

Another point for consideration is that the impact of these interferences is not limited to the immediate proximity of the construction site. One component of any soil composition is water. Consequently, the hydrological status is affected in conjunction with modification of the soil structure during tunnel excavation. In some cases, properties some 50 metres away from the tunnel axis can be damaged due to a declining water level, leading to a sudden or gradual settlement of the surrounding subsoil.

One primary factor related to all these technical considerations is that third parties (person or companies) have become much more “claims conscious”. Not surprisingly, the number of TPL claims on projects has increased exponentially during these last years. According to our experience, there is clear trend to divide TPL claims categories into two groups: those with very few TPL claims and others with numerous claims (up to roughly one thousand). These separate distribution categories confirm our impression that TPL claims are influenced more by the general attitude of the involved parties towards risk...
(working method, reputational risk) than by the too often claimed “unforeseen ground conditions”.

All those factors are combined, and today, TPL claims have increased and demand a substantial part of the premium, larger by far than their percentage of the overall premium.

6.1 Loss Experience

Obtaining reliable figures on tunnels claims is somewhat demanding. This is due mainly to the lack of clear surveyability of complex infrastructure transportation projects in which tunnels only form a part. Such projects might include smaller bridges, underpasses or excavation work for subway stations. Often, insurers are aware of this breakdown in values only partially or not at all. On the other hand, claims are often registered within the context of the overall project.

The final results of a careful analysis of this situation – integrating the above-mentioned factors – reveals an interesting picture of tunnelling risks in soft soils.

Based on experiences over the past 15 years, and analysis of more than 300 different cases, the loss ratio is roughly 160% - based on net premium.

This situation has deteriorated substantially considering that until 1992, the loss ratio was only 81%. The worsening of this result certainly reflects the consequences of the decrease in rates, and increased exposure.
The pie chart indicates a breakdown in percent of the loss categories of the total loss amounts in our portfolio (always based on 100%), providing the following results:

**Distribution of losses in % of the total loss amount**

- 48% in 0->0.5 EU mio
- 15% in 0.5->1 EU mio
- 21% in 1->2 EU mio
- 11% in 2->5 EU mio
- 5% in 5->15 EU mio

The aggregate of categories up to (Euro’s) EU 2 m constitute 84% of the loss burden.
Considering that final losses (after deductible) below EU 50,000 (approx. 50% in number, but limited in amount to approx. 1%), medium-sized losses characterise tunnelling in soft soil loss pattern.

Larger loss in excess of EU 2 m only make up the remaining 16%.
Therefore, this case involves more of a frequency aspect rather than a volatile portfolio. Hence, a loss ratio of approx. 160% is even worse since it does not reflect the direct consequence of catastrophic events.

Catastrophic losses as the Heathrow airport tunnel collapse loss of EU 150 m, (not included in the statistics above) rarely occur. Also note that loss payments exceeding EU 100 m are expected only in CAR and DSU combined policies.

Instead of a comprehensive list of losses, the following two cases demonstrate the complexity of tunnels incidents. They have been selected due to technical considerations in addition to their highly complex repairs methods, and because they are relevant to the general situation regarding SM in soft soil conditions.

### 6.2 Case study A ) Wastewater Treatment Project Alpha

**Description**
The project involved the construction of a new EU 360 m wastewater treatment plant and transfer tunnels. The transfer works consisted of tunnels to convey wastewater flow from two pumping stations to the plant and then in an outfall tunnel.
Specifications: tunnel diameter 4.1 m; length 10.3 km average. Tunnel depth below ground level: 20 m – 25 m. The tunnels were constructed by two EPB SM in the closed face mode. Original program: 3.5 years.

Geology
The following findings and conclusions were obtained after numerous boreholes and site investigations. The ground consist of four main layers:
1. Backfill ground, thickness: 1 m to 2.5 m,
2. Recent alluvial deposits, varying thickness: 3 m to more than 15 m
3. Glacial deposits, average thickness: 20 m
4. Chalk bedrock, varying depth: 15 m to 35 m.

The tunnel will be constructed for 2/3 of the length through, full face glacial laminated clay, or full face glacial sand with gravel. The remaining 1/3 is mostly through the upper glacial layer.

Risk Assessment
Very detailed and thorough study by independent company and specialised offices checking the project and providing recommendations.

Technical description of some problems identified:
- change in tunnel route to outfall; further investigation of ground conditions requested
- glacial gravel and sand might lead to excessive wear at cutting face of SM, possibility of large boulders
- potential underground obstructions through fender pillows along the river/dockyard and pile foundation of historic buildings.
- areas of archaeological artefacts around shaft
- 75 buildings or building groups identified with potential of risks of structural damage due to ground settlement. Request for more detailed investigation and mitigation measures.
- tunnelling process rather optimistic and in certain areas ambitious.
- tight schedule
- recommendations given to gain better information in specific areas (geology) and reducing exposure by mitigation measures costing approx. 1% of TCV.

Incident at end 1999

Close to a vertical shaft, distortion was encountered for approx. 15 m of recently completed tunnel, causing seepage of silt and water. Further investigation showed that apart from this distortion, approx. 100 m of the tunnel was still intact but had dropped into the void created by the underlying bed of fine sand that poured into the tunnel due to high groundwater pressure during lining failure. As a consequence, the SM was trapped. Management and all parties involved reacted immediately and tried to stabilise the situation:
- tunnel area stabilised by 2 bar compressed air, followed later by filling the section with water to stop further pouring of sand into the tunnel.
- checking the already completed 8 km of tunnel; no evidence of distortion
- checking the surroundings; no residential properties affected by the subsidence
- works stopped
- parallel investigation started to evaluate possible methods to stabilise the ground and further procedures. Ground freezing selected among several alternatives.
Additional works carried out after immediate measures were in place:
- 3 stage advance (crown, bench, invert) in frozen ground in one metre steps lining by shotcrete with additional insulation-layer between frozen ground and lining.
- heating of mixture aggregates to 40°C.
- secondary lining applied in 20 m steps and featuring original inner diameter.
- SM 2 used on the second contract phase has, after finishing his works, been relocated, in a new additional shaft and will work backwards to gain access to the trapped SM.

Situation now
The wastewater plant is in operation at 50% capacity only.
The other flow, originally scheduled for Nov 2000, should only be in operation August 2001.
The amount for the material damage only (still pending), is expected to be approx. EU 65 m.

6.3 Case study B ) Metro Beta

Project description
Upgrading existing lines and construction of new ones, 7 km are in tunnels, 10 underground stations. Overall construction time estimated before operation: 7 years; 8 years until final handover. Total Project value: EU 800 m.

Tunnel diameter 8.7 m, 22% of line between 0 m and 10 m depth, 60% approx. 15 m, 6% at 20 m and 12% at 30 m.
Construction value approx. EU 360 m, 30% tunnel-related and 70% to other construction works, e.g. stations. Tunnels to be constructed with a EPB SM.

Geology
The geology is very complex, often changing with a wide range of material.
The report distinguishes 4 layers related to the tunnel depth:
1. Residual soils and cobbbers
2. Packing of fluvialtil material,
3. Granitic boulders,
4. Faulty partially granite to blocky granite

Groundwater level about 10 m below subsoil. After heavy rains, percolating water expected due to fractionated upper zones.

Risk Assessment
The underground works project was studied by an independent company and specialised office which checked the project and the documents available at this time.
This assessment was based on a detailed study of 13 zones of 50 m to 500 m length evaluating for underground works the following items: soil type, structure, geomechanics, weathering, water pressure, settlement and for possible surface settlements.
Major findings of risk analysis:

The interfaces between the different formations are generally diffused and impossible to preview precisely.

20% of the project is very close to the surface.

Various weathering phenomena could appear in such a context, without any indication, Weathering due to granite structure (faultiness, lamination), water (permeability, pressure, chemical composition) and surface (geomorphology).

At certain locations, the water pressure more critical due to special ground conditions and is a critical factor with respect to collapse and settlement. In this case, tunnel construction requires particular precautionary measures regarding overall stability.

One line is designed with short radii curves (170 m/50 m), which is close to the maximum estimated capability of the SM. Taking into account the interface of hard rock, soft rock and poor soil within the excavation profile, this configuration will produce a number of guiding and piloting difficulties which could contribute to develop deviation of excavated profile. Possible consequences could be attenuation of the progress ratio, excavated profile stemming from contractual tolerances, poor connection between rings, watertight deficiencies.

High risk level at 3 locations due to either lack of sufficient information, or proximity to historic buildings.

Potential underground obstructions due to existing foundations and underground water utility lines, wells, and cisterns no longer in use.

More than 200 buildings inspected; 50 of them rated at medium to high vulnerability with potential risk of structural damage due to ground settlement and vibration (always high with a SM EPB due to very high torque).

First incident, mid-2000

SM started final test phase by performing an excavation at the tunnel front, consisting of a piled wall.

Rotation of the 700 ton SM by 45% after hard brief vibration period.

Cause is under investigation. Presumably failure of hydraulic system safety valve.

Second incident, autumn 2000

SM advanced some 120 meters at a tunnel depth of approx. 12 m.

Tunnel excavation intercepted a former well resulting of the discharge of its water.

Ground collapse below two buildings produced material damage to structures, ground settlement up to 2.5 meters within an area of approx. 40 m².

Prompt and safe evacuation of tenants according to pre-established contingency plan.

Activities of commercial establishments interrupted for two months and relocation of tenants. Restart of SM some 6 weeks later.

Third incident end-2000

Tunnel depth approx. 26 m. After passage of SM, cracks encountered in the walls of a building followed by a 250 m³ subsidence of the back gardens.

Fourth incident beginning of 2001

Tunnel at a depth of around 25 m. In this area, the buildings and stores are described as historic to some extent. A few days earlier, a minor incident forced the SM to halt to fill a cavity of around 15 m³ due to over excavation. At restart, water ingress on front of excavated tunnel, subsequent water inflow in the SM.

A fatal injury resulted when a third party fell into the crater, roughly 8 m x 8 m x 6 m depth, resulting from the ground collapse.
Two buildings totally destroyed, and major structural damage encountered in two other buildings and to other third parties properties already affected by the previous incident. Relocation of tenants for about one year until the buildings are rebuilt; other tenants in hotels for months.

**Findings from this case**
Investigations on the causes still incomplete, but technical and procedural questions of general importance have been asked and discussed with experts.

Some of the preliminary findings:
- Not all reasonable safety measures may have been adopted in line with the situation, more soil improvement or additional soil investigations should have been performed
- Bearing in mind the high level of exposure for the buildings, the presence of wells should have led to prevention measures for possible instabilities
- SM passing changed the ground conditions by increasing the alteration degree, water ingress under pressure and the occurrence of significant over excavation.
- Worsening ground conditions means a significant divergence from what was foreseen in the project.
- Alarm established for overexcavation, comparing the weight of the theoretical volume to be excavated and the actually extracted excavated weight should have been established.
- Soil indications such as water ingress, ground settlement, change of pressure at cutter wheel deserve interpretation, the question of being under pressure to continue versus security/safety considerations has been raised.
- Vulnerability of these buildings indicated in the survey as low risk, must be revised taking into account the soil conditions
- Questions arose whether halting the SM was a wise decision (fourth incident). Was the option to continue boring an alternative?

**Current situation**
The government intervened after the fatality, interrupting the works and investigating responsibilities. The amount of the material damage is negligible but for the TPL (still pending) is expected to be approx. EU 3 m.

Fourth incident, crater.
6.4 Conclusions on the two cases studied

Out of these two cases we have extracted almost all the issues of concern regarding the difficulties to insure tunnels in soft soil conditions:

- An incident can occur despite sound and professional preliminary studies, careful analysis and above average documentation. Geological factors especially in soft ground pose certain unpredictability.
- A tunnel is always part of a system and might be the bottle neck, therefore the DSU exposure increases, even if in those cases the cover was not granted. Nevertheless a substantial delay caused a considerable financial loss to the principal.
- In general, underground events and even more so, those involving SM demand professional management and pre-determined procedures.
- Independent risk management analysis was correct in several respects, but the necessary conclusions and actions, e.g. more preliminary investigations were not implemented.
- The “repair” of underground works differs from that of above-ground situations. It is seldom possible without improving ground conditions (eliminating the incident cause). Therefore, underground accidents are very costly to repair
- Existing wells/cisterns etc are always dangerous. They demand special attention and detailed preliminary investigations.
- A substantial part of the final losses is the additional cost of working (ACOW), Debris Removal, Expediting costs.
- The TPL exposure is underestimated.

7 Risk transfer

7.1 Insurance

As already been mentioned, unknown geological conditions represent an important factor in tunnelling insurance. In the past, this risk was clearly assumed by the principal, and the contractor could work knowing that he would be compensated for consolidation work on basis of specially agreed unit price basis if he encountered adverse geological conditions.

This situation changed completely as federally subsidised programs for infrastructure projects gave way to private financing schemes and the introduction of lump sum contracts. In conjunction with this, there was a clear trend to shift the burden of the risk from the principal to the contractor and ultimately to the insurers/reinsurers. This trend has significantly aggravated the insurance result.

In others words, insurers are being compelled to an ever greater extent to underwrite entrepreneurial risk. This fact is characterised by the greater demand for such covers as Unforeseeable Soil Conditions, or Increased Cost of Working.
7.2 Wordings

From an insurance standpoint, wordings are very often not ideally adapted to the characteristics of tunnelling projects. As described in the first section of this paper, the major monetary apportionment in the Total Contract Value (TCV) involves ground excavation, and to lesser degree void stabilisation. The sum insured, in fact, primarily constitutes these two elements which are normally restricted to the design profile. However, in the event of an incident, the affected ground area is much larger than that considered in the TCV or Sum Insured (SI).

Another point which is far more difficult to apply in tunnelling projects is the following wording: Adoption of reasonable safety and prevention measures in accordance with professional regulations to avoid damages.

In the first place, design standards are not clearly determined, and secondly if available, they are very difficult to apply, given that local soil conditions may change from one metre to the next.

Two different aspects of the project must be assessed to determine the exposure of the insurer/reinsurer from a practical standpoint. The first involves the technical aspects of the project, and the other, which is more difficult, concerns how the policy will meet the “test” of an event, and how it will be ultimately interpreted.

The wording is drafted during the tender phase for budgeting and subsequently remains the same (unless additional covers are integrated). However, it should be precisely phrased after the construction method is selected and a proper risk assessment has been conducted.

There is very often a lack of understanding with respect to applicable terminology, and the removal of debris may serve as a case in point. On above-ground construction projects, debris is understood mainly as ruined or damaged parts of constructed items and is therefore part of the contract value. The material is known, as is the deposit location and the attendant costs.

In tunnelling projects, however, debris is subject to several interpretations. Does it only entail the material brought into the site, i.e. concrete, anchor rock bolts, etc) or does it
include the excavated material within the tunnel profile or that material intruded from outside the profile? Depending on the scenario, this may result in substantially higher costs just for the removal, meaning that debris removal can be substantially more expensive than the original value calculated for excavation only.

### 7.3 Material change of risk

The risk assessment of a certain project usually considers the type of risk, contract price, its plausibility and the construction period. Furthermore, it is based on the selected and specified construction method, e.g. alignment and other criteria which may have contributed to the specific design and technical calculations. If these fundamentals change, the risk may not be the one assessed or insured before a material change of risk occurs.

Most of the relevant factors are known for above-ground construction projects, and in most cases, design changes with respect to risk assessment are only of limited importance for the overall project. A change is given if the primary construction materials are altered, e.g. from concrete to wood or in the event of adding another level or underground section. Normally, however, the latter case would require a petition for a new construction permit and new negotiations would commence.

In underground construction projects, the situation is quite different in several important respects.

The tender and the officially submitted project design are based on certain facts - insofar as they are already available - and on a number of assumptions regarding geology, hydrology, soil characteristics and surrounding areas during excavation. Design parameters not only include the diameter, alignment, inclination, lining thickness, etc but also prospective safety measures such as anchor, rock bolts, wire mesh, soil improvement measures, monitoring etc. The design is also based on pre-defined soil categories.

Despite prospective drilling and core samples, the distribution of these soil categories are based on certain assumptions. Unfortunately these assumptions prove very often to be inaccurate or they differ substantially from the soil types actually encountered. Time and again, unfavourable ground conditions are encountered in more extended areas than it had been originally assumed. Additionally, unexpected higher ingress or filtration of water is encountered more frequently and require additional measures.
If assumptions are at the border line of soft soil categories, decisive for the choice of SM technology or type (EPB / Slurry) difficulties may occur. All these scenarios will often lead to substantially higher costs, require more time and may even necessitate changing the construction method.

In such cases, principal, contractors, financiers as well as primary suppliers must agree on additional measures, and they may even decide to modify the design and the construction method, but would hardly consider these circumstances as a case of Material Change of Risk. Sometimes such modifications are introduced for a limited period or only for specific tunnel section, but they could well turn out to be those with maximum exposure.

On the other hand, these changes – involving technical factors or a substantial increase in the contract value – may significantly alter the insurer’s exposure and often the risk itself after such a modification. According to most policies, the insured party is obliged to inform the insurer of such changes, but the insurer is well advised to ensure that he is informed regularly about any changes or modifications. Nevertheless, any major material changes will require an adjustment of the insurance cover and conditions.

7.4 Loss settlement

Virtually all tunnelling claims have demonstrated that actual wordings are unsuitable for tunnelling works in most cases. Lacking clear and precise definitions, e.g. wordings such as material damage, additional repair and stabilisation measures, immediate loss minimisation measures put into effect without the insurer’s consent – leave far too many uncertainties and repeatedly and understandably initiate a number of disputes.
Consequently, loss settlement in tunnelling is always highly complex. The overlapping nature of loss mitigation, repair works, works reinstatement, additional soil stabilisation and even improvement, makes it very difficult to clearly allocate costs for these set of measures, not to mention the diverging interests of the individual parties involved.

Indeed, such aspects as: new ground injections, ground removal in excess of tunnel profile, additional excavation, bypasses, temporary measures, longer anchor rock bolts, even constructing a new vertical shaft are excluded from the original bill of quantities and are not part of the original sum insured.

It is a common understanding, that improvements are not included in the cover. Therefore, they should be deducted from the total repair costs which is quite difficult in practice and in the absence of an adequate clause. For example, if a collapse occurs because the temporary retention anchors or rock bolts were only five metres long, repair works include anchors with of a 10-metre length. This collapse would not have occurred had these anchors had a length of 10 metres. These stabilisation measures must be considered an improvement and rockbolts should be indemnified only up to a length of 5 metres. Similar considerations may apply in the event of extensive grouting after the loss, and if this operation were not performed beforehand.

By way of illustration, it should be mentioned that the repair costs in certain recent cases exceeded almost ten times the original costs.

Commercial concessions made on small claims may have repercussions for larger ones; it is important to be precise and strict in handling small claims as well since this practice establishes the framework for handling larger losses and may motivate the insured to take adequate loss prevention measures. While prompt loss adjustment is appreciated, quality should not be jeopardised. Very often a correct and fair loss assessment can be achieved only by close collaboration between contractor, loss adjusters, insurers and tunnelling experts.

7.5 Special tunnelling and underground clauses

It is no secret that the experience gained by insurers and reinsurers in tunnelling insurance over the last 20 years has not been at all encouraging. To ensure that tunnels can remain insurable, some insurers and reinsurers have proposed special technical clauses which should serve to exclude or limit inherent design risks or those of a purely entrepreneurial nature, such as soil risks.

The main approaches are:

1. A clear delimitation of the insurer’s liability by excluding overbreak, the cost of refilling cavities, loss prevention measures, bentonite loss, grouting material, abandonment of shafts/tunnels, etc. and by excluding any cost of improvement or by deducting as-if costs described in section 7.4 (see the complete wording Sect. 9, Swiss Re clause EPI 47 - Underground construction, Munich Re clause 101).

2. Limitation of excess repair costs: Whilst the TSI is based on original construction costs, repair costs may amount up to tenfold of these original costs. In some cases therefore the insured desires to buy against a separate and adequate additional premium, an additional excess cost which may be granted
as a sum per event (SR approach) or in excess of a percentage stated of the original per-
metre construction cost (MR approach). (see sect. 9 clause Munich Re no. 101, Swiss Re
EPI 11 )

7.6 Others recommendations

Very detailed preliminary investigations in such soft soil conditions should be an
absolute must to even obtain insurance. Generally, it is advisable to base risk
assessment and underwriting on a neutral technical project report authored by a
tunnelling specialist. All relevant project data should be part of this report and special
consideration must be given to exposed areas such as the tunnel entrance, vertical
shafts, adjacent properties and backfilled areas. Furthermore, a detailed soil
investigation report is mandatory for precise risk assessment.

Case studies and long experience shows that even the best risk assessment is not a
guarantee against unforeseen losses. However, foreseeable losses should be addressed
and clearly excluded from the very beginning and before granting CAR cover and issuing
the policy.

Some additional technical clauses may prove to be necessary, depending on the location
and other risk aspects, such as :

**Dewatering system**
excludes loss or damages to the works due to breakdown of the groundwater pumping
system unless sufficient standby pumping facilities are installed and ready for immediate
use

**Vibration, Weakening and removal of Support Cover**
this extension applies for tunnelling excavation and vertical shafts and covers adjacent
property; it is based on a neutral survey report on the structural condition of certain
named adjacent properties.
Underground Facilities Cover (TPL)
delimits the liability for underground facilities such as cables, ducts and pipes and the like to physical loss or damage and excludes consequential loss of any kind

Very often, especially in the case of lump sum contracts the sum insured may prove insufficient once the method is changed albeit, in limited areas only or simply that additional measures have had to be taken. The insured is obliged to inform the insurer about any change to the total contract price in order to avoid underinsurance.

In view of the exposure to larger losses - even minor damages may cause unpropotional repair costs - a reasonable deductible should be agreed. As a rule of thumb and based on the technical assumption that the underground is disturbed in a perimeter of 2 to 4 tunnel diameters, a material damage deductible comprise between the double to the fourfold diameter - (depending on the exposure of the risk) of the original costs per linear tunnelling metre has proven adequate.

Of course, one of the major and often decisive factors is the so-called credibility of the insured parties, which means the insurer should be fully convinced of the contractors’ tunnelling experience, their safety awareness, professional loss prevention, their reputation and quality.

It is also vital for all parties involved to define together with the insured parties their common understanding of certain terms such as works, debris etc. and as a consequence properly phrase the corresponding tailor-made wording according to the needs of the project.

The insured should be made aware in respect of their obligations which are among others :

- constantly undertake investigations and monitor any movement of rock or soil,
- take all reasonable measures to prevent loss or damage - at their costs
- inform the insurer regularly on the progress of works and ad hoc on any change of risk or event which might affect the safety of the risk or give rise to a claim
8 Conclusions

Tunnelling projects in soft soil conditions are always on the borderline between safety and economy. The less known about relevant geological factors, the greater the tendency to make assumptions and unfounded decisions, leading to even more unpredictability. Often, not enough time and money are budgeted for in-depth investigations before and during the construction and instead of appropriating more capital on additional studies, the risk may be transferred to the insurer.

Given the advances in tunnelling technology today, tunnels can be excavated in virtually all types of soil and environment, but there are still numerous unknown parameters. During excavation, the situation can become critical at any minute, metre, and under any circumstance. If the entire tunnelling project is on a critical path, there are no buffers or possibilities to reassign the SM and to shift the work force to other areas if an incident halts excavation work.

The TPL exposure, even if not important in terms of MPL, must be carefully considered in the assessment due to its high frequency.

Future tunnelling projects are certain to become even more demanding from the technical side and more complex with respect to management and control. Insurers are prepared to face the challenge, to consider new trends and methods and to provide cover for such projects. They are prepared to assume material damage risks on the basis of satisfactory and sufficient information and cover potential losses through tailor-made wordings for the risk exposure as well as professional and fair loss adjustments.

However, this is possible in the long run, only if sound underwriting principles are applied, risk adequate terms and conditions are achieved and no concessions are made, regardless of market cycles.
9 Annexes

9.1 Pictures copyrights:
Swiss Re
Munich Re
Babendererde Ingenieure GmbH
Herrenknecht AG

9.2 Sample Endorsements:

Swiss Re

EPI 11 Underground Construction, Additional Costs Cover

It is hereby agreed that as of the inception date of this Policy the following Condition is added to the Special Conditions:

Notwithstanding anything contained to the contrary the insurance under Section 1 Material Damage is in case of total or partial collapse of tunnels, shafts, caverns and similar underground works extended to indemnify the Insured in respect of additional costs of working arising in direct connection with repair or reconstruction as indemnified under Section 1 incurred for

(a) replacement or restoration of rock or soil which supports or contributes to support the Property, if such rock or soil is lost or if its original state and structure has been destroyed and/or

(b) difficult repair working conditions, alternative construction method, additional equipment or work force, change of the works programme or

(c) localised deviation, subject to agreement by the Insurers which is to be obtained prior to commencing any such deviation work.

Sum Insured in respect of each and every accident:

..................................................

Sum Insured in the aggregate for two or more accidents during the Period of Insurance:

..................................................
It is hereby agreed that as of the inception date of this Policy, the following Condition is added to the Special Conditions:

Notwithstanding anything contained herein to the contrary, it is agreed that in respect of tunnels, shafts, caverns and similar underground works:

(A) Insurers shall not be liable for:

(a) the cost of removing overbreak material excavated beyond the minimum net line provided in the plans, nor the cost of filling the cavities produced by such overbreak;

(b) the costs of safety measures taken to support, reinforce, stabilise rock or soil, irrespective of whether loss or damage has occurred, is imminent or has not yet manifested itself;

(c) loss of bentonite, grouting material, or other ground stabilisation fluids and/or materials;

(d) losses incurred due to abandonment or cessation of works.

(B) The Insured shall constantly undertake investigations and monitor any movement of rock or soil, preserve the results thereof and take all reasonable measures to prevent loss or damage, all in accordance with recognised best practice standards.

(C) In the event of partial or total collapse and subject to the Memorandum 3.3.1 Basis of Indemnity and (A) above the Insurers shall be liable for the costs actually incurred in direct connection with accidental physical loss or accidental physical damage for repairs, reconstruction, replacement or other reasonably chosen solutions to complete the Works but

a) excluding such measures which should have been taken prior to the occurrence of loss or damage in order to prevent or mitigate such loss or damage;

b) not exceeding the original cost of the collapsed portion of the construction.

(D) The Deductible in respect of each and every accident is

.............................................
Munich Re

Endorsement 101

Special conditions concerning the construction of tunnels, galleries, temporary or permanent subsurface structures or installations

It is agreed and understood that otherwise subject to the terms, exclusions, provisions and conditions contained in the Policy or endorsed thereon, the Insurers shall not indemnify the Insured in respect of the expenses incurred for

- alterations in the construction method or due to unforeseen ground conditions or obstructions,
- measures which become necessary to improve or stabilise ground conditions or to seal against water ingress unless necessary to reinstate indemnifiable loss or damage,
- removing material which has been excavated, or due to overbreak in excess of the design profile and/or for refilling cavities resulting therefrom,
- dewatering unless necessary to reinstate indemnifiable loss or damage,
- loss or damage due to breakdown of the dewatering system if such loss or damage could have been avoided by use of standby facilities,
- the abandonment or recovery of tunnel-boring machines,
- the loss of bentonite, suspensions, or any media or substance used for excavation support or as a ground-conditioning agent.

In the event of indemnifiable loss or damage the maximum amount payable under this Policy shall be limited to the expenses incurred to reinstate the insured property to a standard or condition technically equivalent to that which existed immediately before the occurrence of loss or damage but not in excess of the percentage as stated below of the original average per-metre construction cost of the immediate damaged area.

**Maximum percentage payable: %**