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# INTERDISCIPLINARY ASPECTS OF TUNNEL DESIGN

## 1. General

ILF's technical know-how in the field of railway lines and tunnelling has been used for the benefit of clients all over the world (Germany, Austria, Switzerland, Poland, Danmark, USA, Italy, France, UK, Greece, Hungary etc.), being involved for decades in building extensive engineering capabilities and competences in order to provide comprehensive engineering and management services. Consulting management, design and supervision services to these institutions for high-speed railway lines and structures is provided on the one hand, but is also involvement in the elaboration of new guidelines and standards (e.g. new standards for tunnel safety), and development of tailored, innovative solutions for any potential problems. The main advantage is that all necessary competences in all disciplines are available within ILF being a competent one-stop-shop solution provider for all issues regarding railway lines and tunnels but also for special issues such as management and operation of railway lines.

The key staff in railway tunnelling and railway design can be divided into different engineering and management disciplines, ensuring the successful implementation of a tunnelling project:

— geology and Hydrogeology (including Engineering Surveys),
— civil Engineering (with special focus on tunnelling),
— geotechnics and Numerical Analyses,
— electrical Engineering and Mechanical Engineering (including tunnel ventilation),
— environmental Engineering,
— risk and Safety,
— construction Supervision and Project Management.

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The more of these tasks are covered by one contractor, the higher the chance of successful design and construction of the project. But even if these tasks are contracted out to different companies (e.g. because of laws or standards), it is necessary for each single company to have acknowledged experts in each discipline to have a comprehensive overview over the project to fit each working package to the general construction targets.

The main targets for each tunnelling project have to be the following:

— check cost-benefit value for the client,
— create sustainable values for the client,
— save time and costs in construction,
— maximise the life-time value of the project,
— manage project risks,
— reduce the interfaces and control them,
— build a positive public image of the project.

## 2. Impact of tunnels on the railway net

Depending on the design speed and the topography, tunnel structures may be required for traversing mountain ridges when building a railway line. These structures comprise the key elements of the route due to their complexity and high cost, and they generally constitute critical factors in the construction time schedule. The operation of the route is substantially influenced by the tunnel structures, since necessary regular inspection and maintenance works lead to restricted operation or require closures of the route. Operation may also be restricted when the safety installations are inspected and the task forces conduct necessary practice drills for incidents.

This means that from project conception to project start-up, in the design and construction phase attention has to be paid to the following — while taking into account economic aspects:

— that the necessary standard as regards stability and personal safety is guaranteed,
— that the material and components have a service life that is longer than that of the structure (generally 100 years),
— that the regular maintenance works are minimised,
— that in case of an incident only short periods for rehabilitation works are required.

## 3. Need for design and construction guidelines

To guarantee that the project is successful it is essential to agree on standards and guidelines for the tunnel structure.

They should at least include the following items:

- routing,
- cross-section design,
- fire and civil protection,
- geotechnical investigations,
- stability analyses (impacts, dimensioning and safety factors),
- geotechnical measurements,
- temporary support (shotcrete, arches, rock bolts, etc.),
- permanent lining (concrete, reinforcement, etc.),
- waterproofing,
- drainage.

The standards provide certainty for the designer, certainty for the contractors that the structure will be accepted by the client, and they enable the client to check whether the agreed service has been rendered or not.

## 4. Safety concept

In railways the users make higher demands on safety than e.g. in private transport. This means that a safety concept geared towards the accepted risks has to be formulated. The safety concept generally encompasses:

- event prevention measures,
- event minimising measures,
- self-rescue,
- assisted rescue.

Especially the measures for self- and assisted rescue have a significant impact on the construction of the tunnel. Experience has shown that the lack of a clear concept at the very beginning of the design process will lead to delays and marked cost increases, at the latest when the tunnel structure is implemented (e.g.: Channel Tunnel, new high-speed railway line Nuremberg — Ingolstadt). This means that it is crucial to define the safety concept as early as in the initial design phases, and to obtain the consent of all involved parties. A typical safety concept for high-speed railway tunnels and low overburden is shown in Figure 1.

Complex numerical analyses have to be performed, investigating different assumptions of incidents.

Figure 2 gives some results in terms of time needed for rescue, assuming different locations of the train stop.

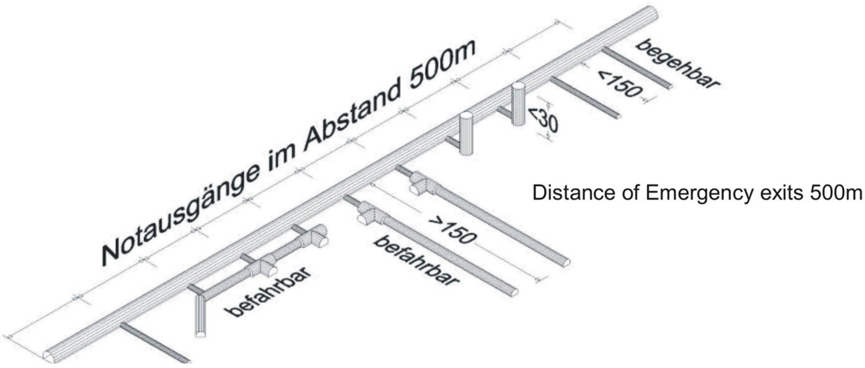



**Fig. 1.** Typical safety concept for high speed railway tunnels and low overburden

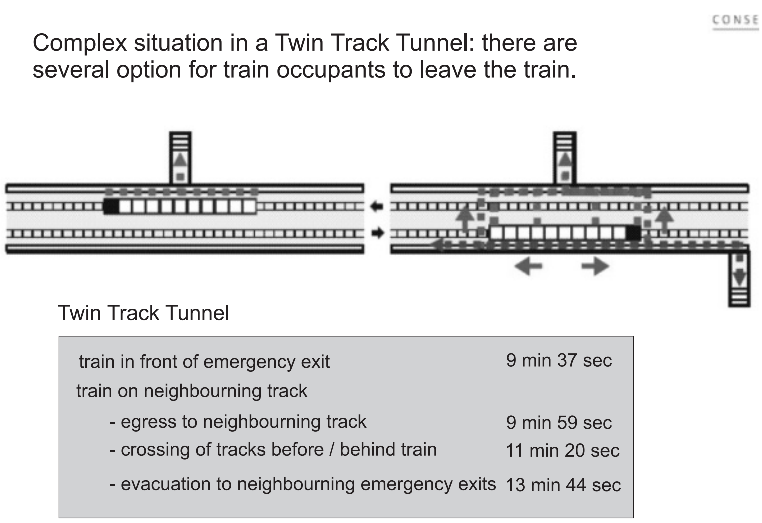



**Fig. 2.** Evacuation Simulation Model: Selected results

## 5. Durability

Railway tunnels have to be designed for a long service life on account of downtimes during rehabilitation or modernisation. The actual tunnel structure is assumed to have a service life > 100 years, the mechanical / electrical facilities and components subject to wear and tear a service life of > 25 years. Such time spans can be achieved when the behaviours of the individually used materials are matched and if all effects expected from tunnel operation, environmental impacts and loading are taken into account in the dimensioning.

## 6. Waterproofing

Tunnel structures of more than 100-year-old lines show that dry areas mostly remain intact while areas with water ingresses in the tunnel vault or invert imply that the tunnel serviceability and stability can only be guaranteed if additional measures are taken. Tunnel records show that wet zones often require rehabilitation works shortly after start-up to catch and drain the water, which generally has little success. This means that new structures have to be permanently waterproofed against the erosive effect of water. When choosing the waterproofing system, expected water pressures, chemical surroundings and suitable application of material and ease of repair have to be taken into consideration. Typical layout criteria for waterproofing systems of high-speed railway tunnels in Germany are shown in Figure 3.

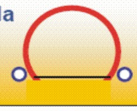
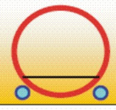
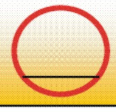
| requirement | waterpressure | waterproofing |
|---|---|---|
| **drained** | **none** | **umbrella**  |
| **partially drained** | **limited to 2 - 5 bar** | **full round**  |
| **watertight** | **actual waterhead** | **full round**  |

**Fig. 3.** Decision matrix for waterproofing systems based on requirements and waterpressure

## 7. Drainage

Depending on the water levels above the tunnel invert and other hydrogeological boundary conditions, the tunnel bore is designed as a structure with watertight lining sustaining the water pressure, or as a drained structure. Especially in the event of high water levels, or groundwater conditions which are difficult to predict, the tunnel bore is constructed as a drained tunnel. In this case care has to be taken that water catchment is effected at the transition between the ground and the tunnel structure and that the water is conveyed to the drainage pipes.

The drainage system can be divided into a primary drainage system which consists of perforation of initial lining dewatering, holes driven into the surrounding rock, pipes and channels, drainage layers (geotextile or studded membranes) and filters. The secondary drainage system is formed by slotted pipes, collector pipes and manholes. The secondary drainage system is regularly inspected and cleaned.

## 8. Maintenance of drainage system

Depending on the chemical composition of the groundwater and the characteristics of the aquifer in conjunction with contact with air, sedimentation in the drainage pipe system may result in clogging and consequently, due to the increased water pressure, in diminished serviceability and stability of the tunnel.

Sintering and clogging depend on the following main factors:

- chemistry and amount of permeating groundwater,
- stress state and temperature of the groundwater,
- type of surrounding rock mass,
- properties of the materials of the tunnel structure.

Counteracting measures include preventing artificial cementation (filter, injections for ground stabilisation) and the usage of concrete made as impermeable as possible. Sintering and clogging makes it essential to adapt and dimension the drainage facilities for the sedimentation tendency and to regularly inspect and clean them, if required. In order to keep the expenses for inspection and cleaning works to a minimum, the drainage facilities must be easily accessible and designed to be suitable for the corresponding inspection and cleaning equipment. Conditioning the water or maintaining a limited water pressure makes it possible to minimise sedimentation and thus to reduce the maintenance costs.

The most effective counteracting measures for the primary drainage system are proper dimensioning, since the system is inaccessible for maintenance. For the secondary drainage system the following is recommended:

- use carbonate-free aggregates for filters,
- use rounded and washed aggregates 16 / 22 mm,
- use high-density polyethylene (HD-PE) pipes,
- pipes shall have 10 mm slots, total 150 $cm^2$ per meter pipe,
- sidewall drain pipes shall have Ø 200 mm, collector pipes Ø 400 mm,
- avoid horizontal and vertical bends of the pipelines,
- water flow: as high and as constant as possible,
- manholes: > 1 m wide, spaced at centres of < 100 m.

## 9. Non-ballasted track

Ballasted tracks in tunnels are extremely problematic. The work conditions for undertaking track position corrections and ballasted track cleaning are unacceptable. That is the reason why non-ballasted tracks (slab tracks) are generally installed in long tunnels. On account of the system the rails can only be adjusted by a few millimetres as regards their location and height later on. The invert of the tunnel must therefore be designed in such a way that after installing the non-ballasted track any deformation of the invert due to changes in loading (water pressure, karst, etc.) is less than the possible post-adjustment of the rails. Three different systems for non-ballasted track have been installed at the Nuremberg-Ingolstadt high-speed railway line [3].

The non-ballasted track had to meet the following requirements:

- crack width ≤ 0.3 mm,
- residual settlements from start of installation of slab track ≤ 1.5 cm.

All three types have in common the principle of single-point support adopted from the ballasted track. Where they differ significantly from each other is in the track bed. RHEDA KLASSISCH is a special construction method where monoblock sleepers are encased in concrete. The concrete trough structure with a width of 3.08 m and a height of 0.38 m was placed directly on the tunnel invert using a slip form paver. RHEDA 2000 consists of bi-block sleepers with lattice girders which are also encased in concrete, however, without concrete trough structure. RHEDA 2000 provides a better bonding of the bi-block sleepers and the concrete track bed (BTS) than RHEDA KLASSISCH. For the installation of the BÖGL slab track system with longitudinally connected precast slabs the necessary installation methods had to be developed first. The BÖGL system has 20 cm thick and 2.55 m wide slabs, prestressed in a transverse direction, which are constructed as precast units and positioned accurately on site, with bitumen-cement mortar poured underneath.

## 10. Interdisciplinary design

Railway tunnels are complex structures where the individual aspects such as routing, cross section (aerodynamics/travel comfort, room for overhead catenary, traffic room, *etc*.), tracks, safety installations, geology/hydrogeology, stability, durability, fire protection, maintenance, cost and schedules, etc. have to be coordinated in an interdisciplinary manner to ensure the success of the project. When changing an individual aspect in the course of the design or construction, it is essential that the impacts on the other individual aspects are taken into consideration. This calls for interdisciplinary design with the corresponding integration of all involved parties as well as strict quality control during design and construction.

## 11. Choose of excavation method: TBM — NATM decision

One of the most crucial points for the success of tunnel excavation is the right choice of tunnelling method, either NATM or TBM (Tunnel Boring Machine). When choosing TBM there are different types of tunnel boring machines which may be used. When studying the literature one will find decision trees, as shown for the high speed railway tunnel in Austria (Perschling Tunnel; Fig. 4) and it seems to be simple and the decision is only guided by 1 or 2 aspects.

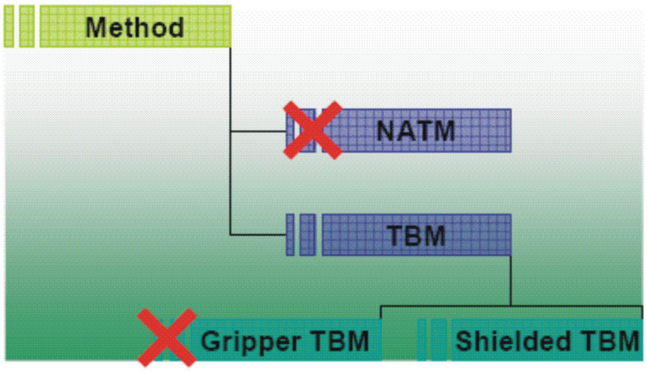



**Fig. 4.** Decision tree and main data (tunnel perschling)

In reality, each decision is based on a complex risk analysis taking account of different risk scenarios, their impact in terms of time and money have been provided [1]. Typical risk scenarios for NATM drives are listed in Table 1 [2]. The risks have been monetarised and result in a risk distribution. The risks have to be combined using mathematical formulas (Fig. 5).

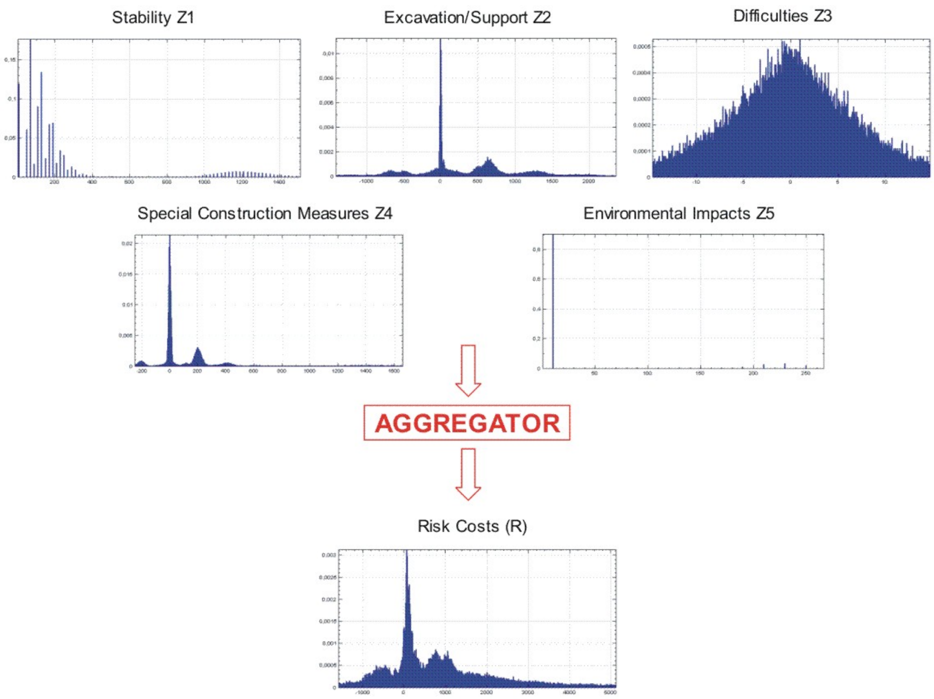



**Fig. 5.** Distribution of total risk, cost in 1000 € [2]

TABLE 1

**Examples of the identification of risks and risk scenarios**

| Identified risk | Risk potential | Risk scenarios |
|---|---|---|
| Stability of the construction site **($Z_1$)*** | — Locally confined failure – such as outbreaks from the crown area or small-scale failure of the excavation face | — Outbreak up to 5 m³ **($X_1$)***<br>— Outbreak up to 20 m³ **($X_2$)**<br>— Local face failure up to 20 m³ **($X_3$)**<br>— Local marked deformation (> 50 mm heading, $L$ = 20 m) **($X_4$)** |
| | — Extensive failure – from collapses (scope 500 m³) to cave to the surface or extensive failure | — Collapse 500 m³<br>— Extensive face failure >20 m³ **($X_5$)**<br>— Cave to the surface |
| | — Geogenic and anthropogenic phenomena | — Blowout<br>— Discharge of suspension |
| Excavation and support **($Z_2$)** | — Impairment of excavation – such as alteration of the calculated lengths of rounds of the excavation classes | — Change of excavation classes **($X_6$ / $X_{10}$)**<br>— Clogging of excavation tools<br>— Machine defect/breakdown of mechanical equipment and vehicles |
| | — Support requirements – such as alteration of the calculated lengths of support classes | — Stresses and strains due to large swelling pressure **($X_7$ / $X_{11}$)**<br>— Stresses and strains due to small swelling pressure<br>— Water pressure on primary lining<br>— Water pressure on secondary lining<br>— Uncontrolled loads **($X_8$)** |
| | — Excavation and support concept | — Failure of the excavation method<br>— Failure of support method **($X_9$)** |
| Difficulties **($Z_3$)** | — Impairment by water or gas | — Water ingress >10 l/s<br>— Water ingress 3–10 l/s<br>— Gas-impairment<br>— Discontinuation of excavation |
| | — Obstacles – such as unexpectedly frequent appearance of boulders and/or anthropogenic inclusions (steel, tree trunks, wells, etc.) | — Boulders up to 1.5 m Φ<br>— Boulders > 1.5 m Φ<br>— Anthropogenic foreign bodies (steel well pipes)<br>— Wood (trunks 20 m long / crossways to the direction of advance) |
| Special construction measures **(Z4)** | — Above-ground measures, non-scheduled – such as local groundwater lowering, soilcrete columns (vertical jetting) etc. | — Lowering of local groundwater level ($L$ = 100 m)<br>— Local freezing<br>— Soilcrete columns (50 m) |
| | — Below-ground measures, non-scheduled – such as pipe arches, soilcrete columns (horizontal jetting), pressure relief measures, etc. | — Pipe arch ($L$ = 30 m)<br>— Soilcrete columns ($L$ = 30 m)<br>— Water pressure relief<br>— Injections/Grouting |
| Environmental impacts **(Z5)** | — Unexpected environmental impacts – such as oil leaks, impact of construction method on the environment, noise, vibrations, dust, etc. | — Groundwater impairment (oil accident)<br>— Truck collision with fire |
| | — Expected environmental impacts – due to noise, vibrations, dust, etc. | — Noise during excavation<br>— Vibrations (obstruction over a length of 200 m)<br>— Air in the tunnel<br>— Water<br>— Settlements |

* $Z_i$; $X_i$: referred to example Figure 5

All these investigated risks and the risk analysis depend heavily on the geological strata along the tunnel. In case the strata differ, or if there is no great variety of strata, the decision on the excavation method might be different. An oversimplification of the problem may lead to wrong and at the end catastrophic results in terms of construction progress, time, money and quality. The final decision for the Perschling Tunnels was to use a TBM (Fig. 6).

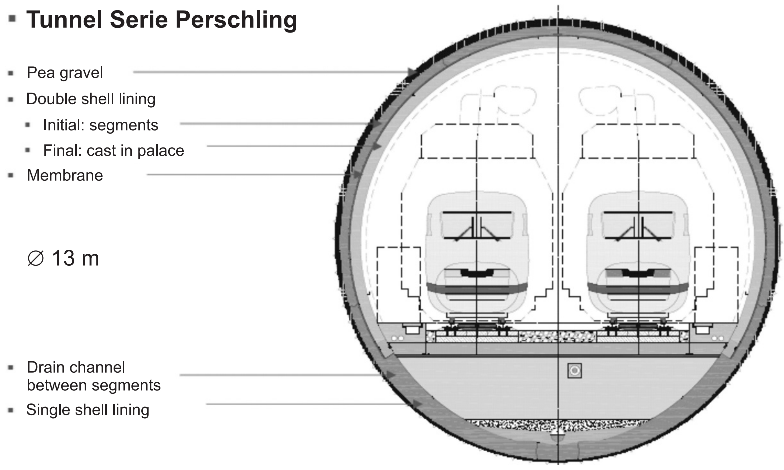



**Fig. 6.** Regular Cross-section of TBM Tunnel Perschling (High Speed Railway Austria)

## 12. Conclusions

Design of a tunnel is a very interdisciplinary task. Only when taking account of all relevant boundary conditions such as needs of overall infrastructure, geological, geotechnical and hydrogeological aspects, lay out of primary and secondary support measures, electro — mechanical design, durability and serviceability, safety aspects, local and international market a tailor made design of the tunnel can be done. Problems either already in the design phase, construction phase or during operation will definitely occur when vital aspects are neglected. Only high experienced consulting company can guaranty the client to be satisfied by the project he will get.

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