

# FORENSIC ENGINEERING IN TUNNELLING

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**ABSTRACT:** What post-mortem review is on the individual project level that is forensic engineering for international sharing of experience from structures. This can apply to collapse (ULS), including construction phases, but also to loss of serviceability (SLS), e.g. excessive deformations as in squeezing rock, or settlement of buildings above shallow tunnels. In the introduction the broad range of purposes of forensic engineering and particularities of underground works are discussed. Based on a webinar for the Indian Association of Structural Engineers (IAStructE 2024) three different types of cases are presented: a cut-and-cover tunnel close to rupture; the famous collapse of the Heathrow Airport tunnel in NATM; and the excessive deformations of the Lötschberg Base tunnel encountered in carboniferous rock. The conclusions address some aspects of risk analysis and project management, but also monitoring, prepared interventions, and stable hold points.

## 1. OBJECTIVES OF FORENSIC ENGINEERING

In Roman times, criminal trials were conducted publicly in the marketplace, the *forum*. Hence the investigation, analysis and reconstruction of criminal cases is known as forensic applications of natural sciences (like medicine) or engineering disciplines. In fact, the best practices of safeguarding evidence on the 'crime site', of subsequent laboratory investigations, and of the statements in court are discussed among forensic experts at the annual congress of societies such as the Forensic Engineering Division (FED) of ASCE. Engineers are usually not familiar with the way judges look at technical matters; preparing technical experts for all kind of unusual questions in court trials is therefore essential. The general advice is that the expert opinion should concentrate on the technical aspects and leave the allocation of responsibility and accountability to the judge to decide.

As part of the 'crime site' investigation, expert engineers may also be asked to assess the remaining safety of damaged structures on behalf of the rescue teams, to issue trespassing restrictions, and to recommend demolition or refurbishment. This also applies to geotechnical assessments, when villages are to be evacuated due to imminent slope failure or rock fall (Fig. 1). A comparable expertise in tunnels is the investigation of e.g. historical brick linings, giving opinions on their temporal stabilization and safe rehabilitation.



Figure 1: Map of restricted area 2025/26 for unstable rock slope endangering the village of Brienz in Grison / Switzerland

A rather different attitude is learning to advance the state of the art – for instance, the construction of increasingly robust tunnel boring machines, coping with a variety of unexpected ground conditions to avoid blockage of the TBM e.g. by an erroneous prognosis of fault zones. Back analysis of failures and the improvement of modelling techniques is a particular aspect, pursued for concrete mechanics in fib's Forensic TG 3.5, with a certain tradition in dam engineering, but also in tunnelling (e.g. Barton 2016). Nonetheless, inadequate education and training, misguided cost-cutting (incl.

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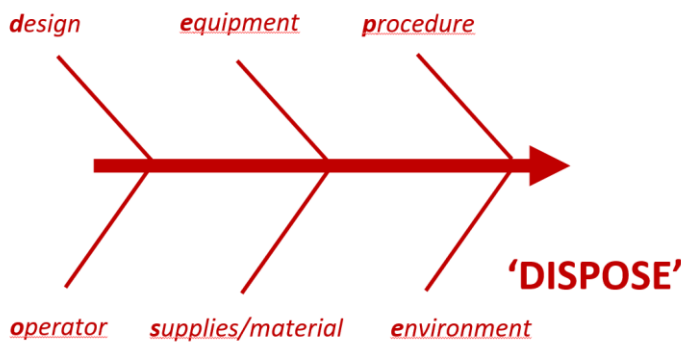


Figure 2: Fishbone diagram as schematic failure tree in engineering (like creeks sending water downstream in a flooding event)

Most often it is not a single mistake leading to catastrophic failure, but a combination of several adverse factors or long tolerated malpractices, which (with some bad luck) align to permit the failure to happen. This phenomenon of safety barriers with holes in an unfortunate combination is called the “Swiss-cheese model” (Hohberg 2017). This attitude of not looking for the culprit but identifying the lessons (to be) learned is different from ‘forensic’ investigations in court. For example, the FED of ASCE has a “Commission on Practises to Reduce Failures” (CPRM).

Tunnels and underground structures are less amenable to forensic engineering than structures like bridges and buildings, because the ruins in case of collapse can often not be accessed (or only with destroying evidence). An example of millions spent on an “evidence recovery pit” is the failure of the diaphragm wall of the metro in Cologne/Germany, where the medieval archive was lost. Another particularity is the fact, that tunnelling practitioners are used to handling uncertainties and to suffer minor drawbacks like local collapse near the tunnel face – which may be tolerated if no injuries occur and just construction time is lost. However, if a TBM gets blocked, like in the case of insufficient ground freezing at the Rastatt tunnel of the German Railways in 2017, the economic consequences may nevertheless be disastrous (Fender 2017).

## 2. THREE EXAMPLARY CASES STUDIES

A well-documented case is the access ramp to a new metro tunnel in Singapore in 2004, known as the Nicole Highway Collapse (named after the road affected by ground failure), Fig. 3. It is very illustrative in terms of soil mechanics errors as well as problems in structural detailing and flawed management decisions. Since this failure does not concern the tunnel proper, it will not be discussed here. However, a cut-and-cover tunnel is taken as first case study.



One of the intermediate tunnelling access points for the Lötschberg Base Tunnel was situated in Mitholz on the northern ramp, where the exploration gallery ended and an access gallery was built. When filling up the valley with excavated material unsuitable as aggregate, the cantonal road was relocated into a 640 m long gallery embedded in the landfill. The idea for this project, serving as avalanche protection, was born quite late with insufficient ground investigation.



Figure 3: Collapse of metro construction pit due to buckling of struts in Singapore 2004 (Source: Hee Yang Ng, Structure Magazine 2021)

### 3. MITHOLZ GALLERY

The concrete gallery with a horse-shoe profile was cast in situ and the crown reinforcement spliced with the wall reinforcement. Unfortunately, the splices were not staggered but all situated at the same height as indicated by the point of zero bending moment in an analysis with characteristic loads, employing a partial safety factor on the bending moment and the ring force alike (output factoring). Soon after opening, in July 2004 the continuously growing overburden caused a severe flexural shear crack in the tunnel shell. The geodetic measurements revealed torsional twisting of the entire gallery, pivoting around some hard rock inclusions embedded in a dominating peat subsoil.

In an emergency response the gallery had to be stabilized by wooden props (Fig. 4), the overburden was removed to grout the cracks and an additional 20 cm thick inner r/c lining was cast, reducing the clearance of the tunnel by sacrificing the bicycle lane. Closer examination of the expert from EPF Lausanne revealed that not the 40 cm settlement of the peat had caused the cracking, but that the earth pressure was grossly underestimated by the 2D finite element analysis. Because the modelled width of 45 m was too small, the lateral overburden and the inclined thrust on the wall could not fully develop. (Fig. 5)



Figure 4: Temporary propping of the gallery to stabilize the flexural shear crack

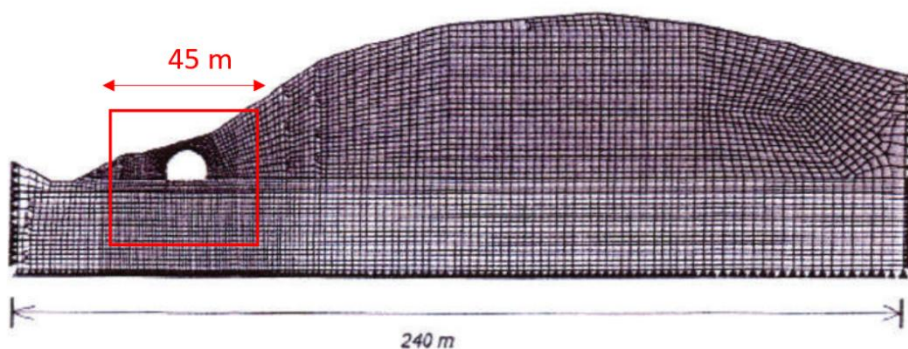


Figure 5: Insufficient width of the modelled domain in FEM analysis to give a realistic estimate of the unilateral earth pressure

Instead, the roller bearings on the vertical boundaries, mimicked a symmetry condition (i.e. invisible identical galleries adjacent to the left and the right side of the model boundaries).

In his PhD thesis Silvan Plumey (2007) applied the convergence-confinement method to plastic hinges developing in tunnel linings, identifying the problem of

insufficient ductility of concrete shells without shear reinforcement. This was further investigated in shear tests at EPFL (Campana 2014), (Fig. 6), and resulted in a guideline of the Swiss Federal Office of Roads (OFROU) stipulating input

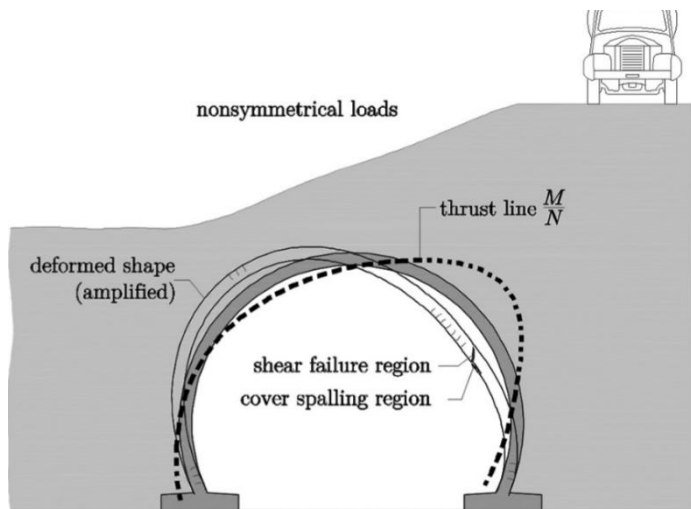


Figure 6: Failure of arch-shaped member in combined bending and shear under non-symmetrical load

factoring of earth pressure by reducing the strength parameters in the load bringing (active) part of the slope. In this manner the inflection point of the moments between wall and crown would shift with increased loading and indicate the sensitivity of curtailing and splicing the wall reinforcement.

Although this research was triggered by a cut-and-cover tunnel problem, the challenge of ovalization and the issue of undesirable shear reinforcement also applies to mined tunnels with a primary stress ratio strongly deviating from the hydrostatic  $K=1$ , either due to geotectonics, valley topology or squeezing rock.

### 3.1 NATM HEATHROW AIRPORT TUNNEL

The collapse during construction of the railway express station under the Heathrow Airport in October 1994 triggered an intense discussion on the suitability of the NATM construction for shallow tunnels in clay (i.e. without using rock bolts), but also an ardent debate between Switzerland and Austria about the 'intellectual property rights' of the concept of a rock support ring forming around a cavity, ridiculing the "new Austrian swimming technique based on the concept of buoyancy" (Kálmán Kovári of ETHZ). It illustrates further the question of ductility in concrete linings when a tunnel is exposed to ovalization.

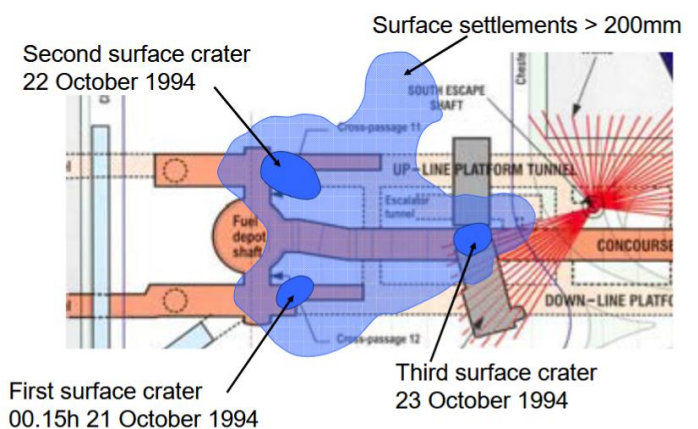
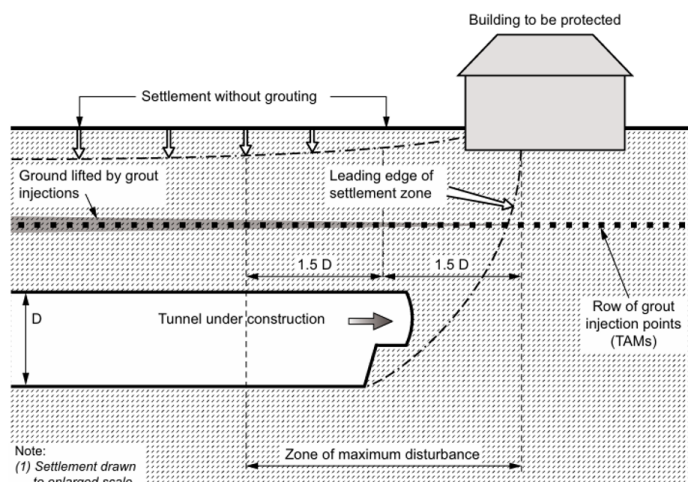


Figure 7: Principal concept of compensation grouting (left) and situation with sequence of tunnel collapse (right); in orange the excavation state at the time of collapse

The three tunnel tubes (two single track platform tunnels with a concourse tunnel in between) were designed with 21 m of overburden and horizontal grout injection pipes (tube-à-manchette) at half height, 10 m above the tunnel crown (Fig. 7 left), as an option to compensate any settlement of buildings, incl. an airport fuel depot. The concourse tunnel was excavated first from an access shaft, followed by the platform tunnels, excavated with an advance side gallery ('eye') followed by a three-step enlargement (crown / bench / invert) with gradual demolition of the temporary shotcrete partition (Fig. 8).

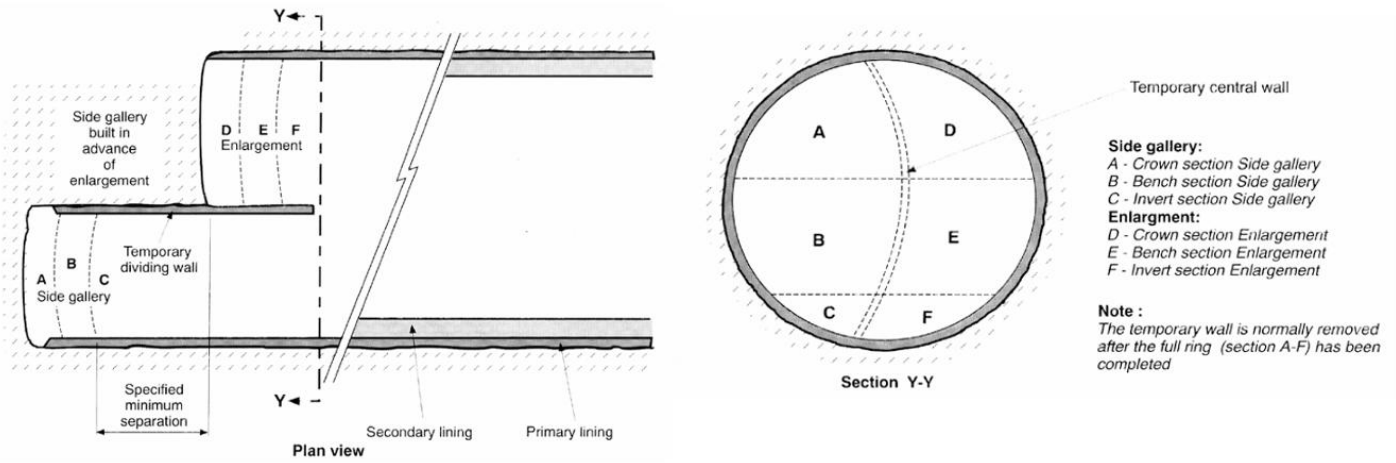


Figure 8: Excavation sequence with advance side gallery and following enlargement

The final lining was designed by the Austrian consultant, while the construction stages were under the contractor's authority. In hindsight this was considered a misunderstanding regarding the terminology of "temporary works" (Golser 2025): The first reinforced shotcrete layer, which serves as H&S protection of workers, may be disregarded in dimensioning for long-term stability ("rotting scenario") but is nonetheless part of the convergence control.

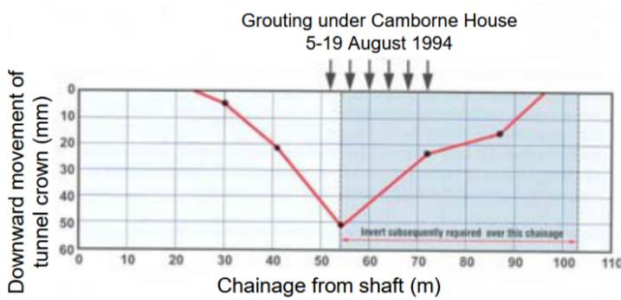


Figure 9: Downward movement of concourse crown due to compensation grouting

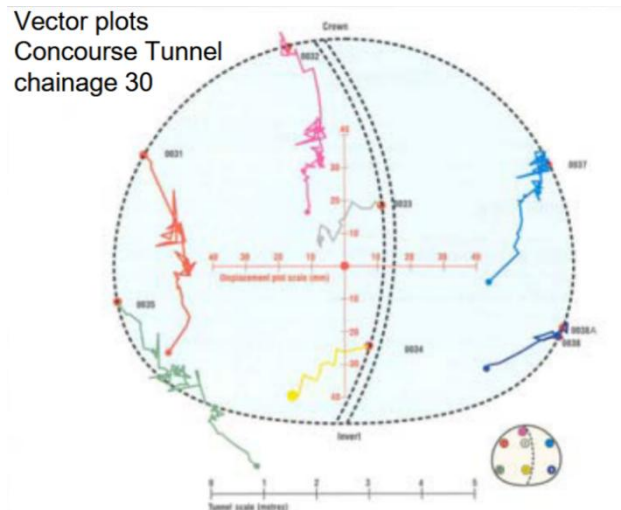


Figure 10: Reflector measurements showing overall downward depression of shotcrete shell

When in July 1994 the settlement limit of 25 cm was reached, compensation grouting began and produced a 50 mm deep depression trough in the concrete lining over a length of 72 m (Fig. 9), accompanied by downward and inward movement of the shotcrete shell and cracking of the invert. However, only about 50 m – the dark blue area in Fig. 9 – were repaired (Clayton 2008). The concrete quality of the invert was poor due to considerable shotcrete rebound, and the curvature of the invert had been reduced further by the overall tunnel settlement (Fig. 10).

Due to pressure by the contractor to increase progress, the repair was stopped in September and the enlargement of the platform tunnels started on 7 October with several attack point at the same time, advancing in already disturbed ground with reduced passive earth pressure at the tunnel walls. Convergences started to accelerate, but the evaluation of results – in Excel without software for real-time processing – reached the Austrian consultant too late. A second invert repair was ordered by the consultant on 18 October and still underway ("in an erratic and uncoordinated manner", ripping out parts of the concourse invert during a night shift) (Golser 2025), when the progressive collapse started three days later in the lower platform tunnel close to the shaft (Fig. 7 right). The 7 m thick clay pillar with the adjacent open invert in the concourse tunnel could not provide sufficient lateral support.

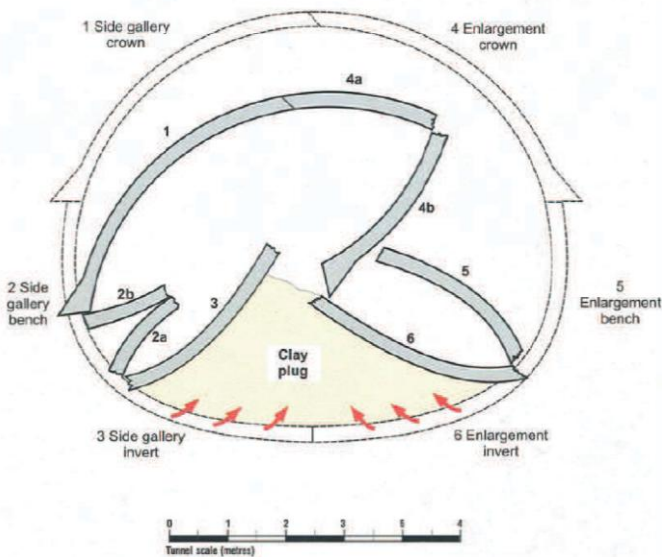


Figure 11: Debris of the concourse tunnel

Apparently, the cold joint in the invert between the side gallery (#3) and enlargement (#6) failed first (Fig. 11), where the reinforcement detail had been changed by the contractor (Clayton 2008). With the ground moving inwards through the invert, the side gallery bench (#2) failed, and the side gallery crown (#1) came down, followed by a crack in the enlargement crown (#4).

Apart from the lacking instrumentation of the invert and focus on the ground settlements rather than the tunnel behaviour during compensation grouting, the contributing factors were mostly of the nature 'organisational environment'. According to the Austrian consultant, he had offered four experienced tunnel foremen, which the contractor replaced by three inexperienced young engineers for cost reasons. Progress had priority over quality control.

The Austrian consultant was mandated by the contractor and not reporting to the client. Quality audits by the project management team (with representatives of the client, the contractor and a British engineering consultant) were conducted by young engineers and did not adequately address the technical risks of NATM construction. The principal problem was that the consultant did not terminate his contract when realizing that the contractor did not follow his advice (Wood 2000).

### 3.2 CARBONIFEROUS ZONE IN THE LÖTSCHBERG BASE TUNNEL

The 35 km long Lötschberg Base Tunnel (LBT) in Switzerland was built in two lots: from the north (Ct. Berne) by drill & blast, and from the south (Ct. Valais) by TBM. In advancing with drill & blast, the cross-section was of a horse-shoe shape with an open tunnel floor as material transport route.

In March 2004 an unpredicted carboniferous rock was hit at chainage 30.2 km with 1,500 m overburden (Fig. 12).

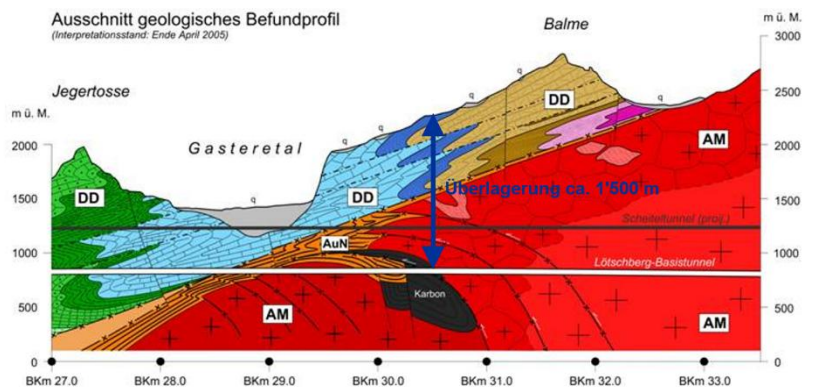


Figure 12: Geological profile (as amended 2005), anthracite in black

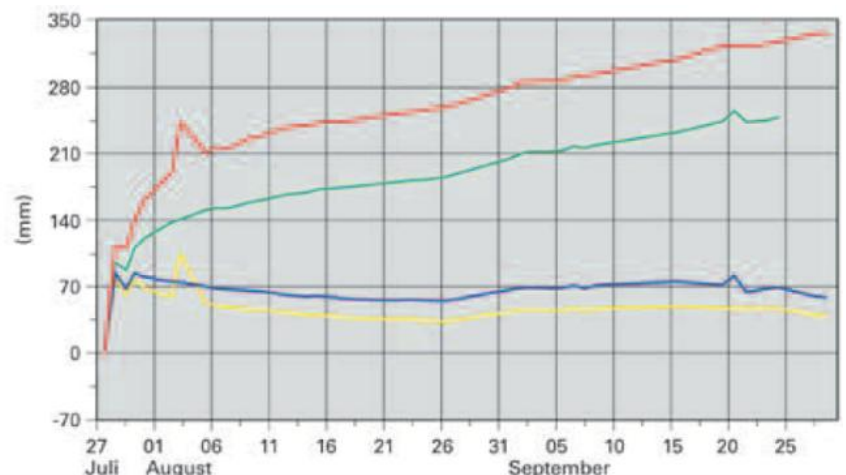


Figure 14: Geological face mapping with typical development of radial deformations (geodetic reflector measurements)

The problem was that large radial deformations developed in an asymmetric manner, with no apparent asymptotic trend (Fig. 14). To protect the shotcrete shell against crushing, several techniques from the mining industry were tested: sliding joints in the steel profiles, spring pots, and precast crushable concrete blocks – the spring pots tilted due a substantial longitudinal displacement against the direction of the tunnel drive, whereas the high-yield concrete blocks remained stable and controlled the shotcrete stresses effectively (Fig. 15). Still, the radial inward displacements continued to grow up to 70 cm.



Figure 15: Behaviour of convergence slots – sliding joints (left), spring pots (centre), crushable concrete blocks (right)

The formula by Sulem & Panet (Sulem 1987) was fitted to the measurements against space and time and served to estimate the expected convergence (Fig. 16). The tunnel was reprofiled to a circular shape with longer rock anchors, and the additional lateral space was used to cast a thick concrete inner lining. The crown thickness could not be increased without removing the overhead protection and was kept as 50 cm. Till October 2004, several cross-sections had to be refurbished more than once (Fig. 17).

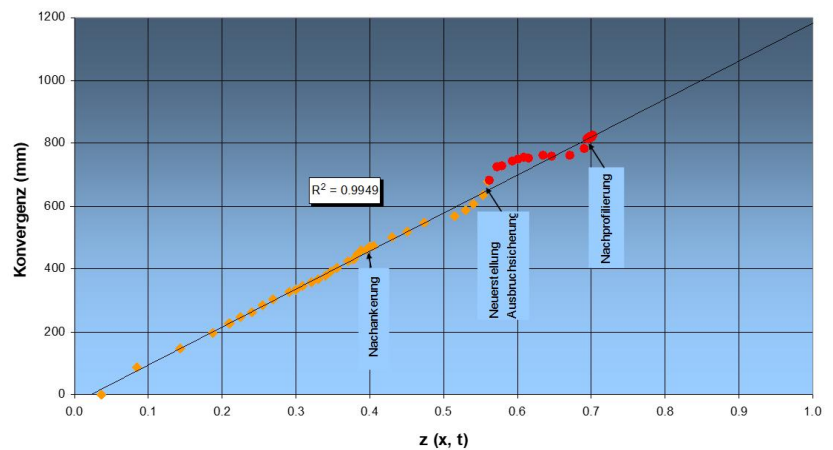


Figure 16: Logarithmic development of convergence

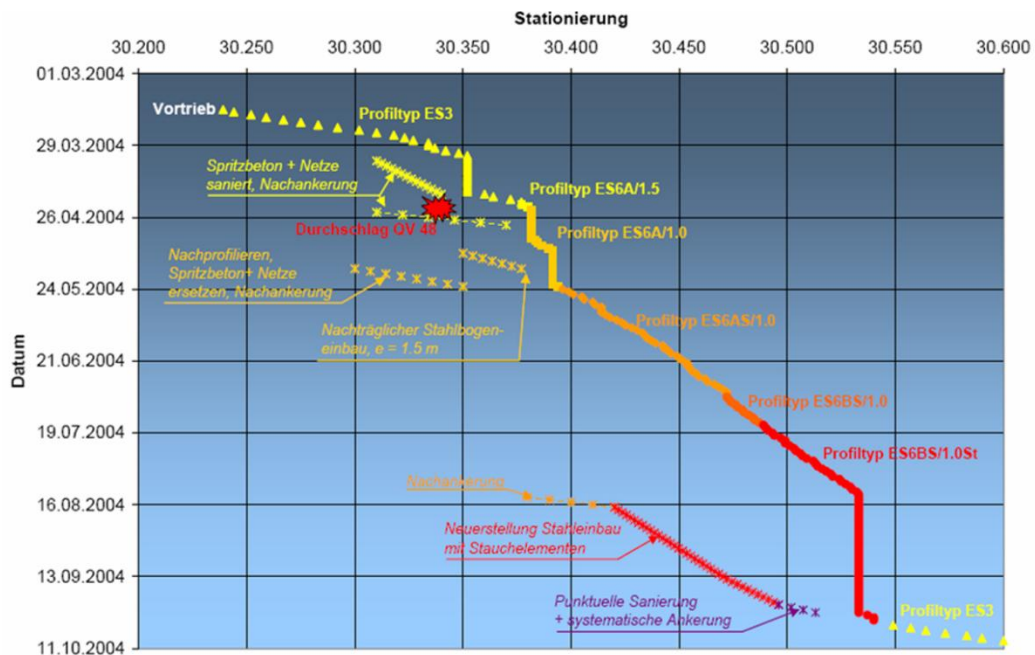
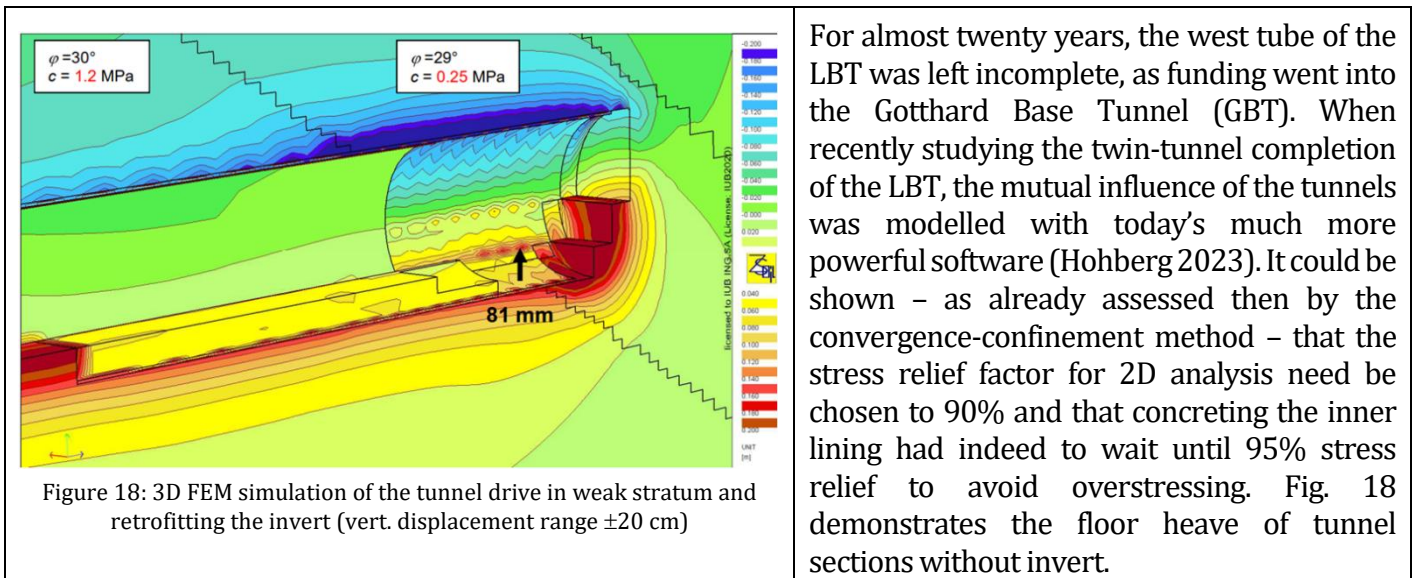


Figure 17: Overview of strengthening measures with reprofiling, additional anchoring and convergence slots



#### 4. CONCLUSIONS

Clients may not wish to see their asset as an object of dispute, but this is not unique to tunnelling. What matters more is that problems may not be visible, unless an underground stability problem reaches the surface. The more it is to be welcomed that the number of published construction problems slowly increases, for instance at the World Tunnel Congress (Bosshard 2017, Jesel 2017). Even a case study from the Czech Republik was found (Srb 2015).

Also, the willingness to address issues of risk management, procurement and project management appears to grow. The HSE report (1996) on the safety of the NATM not only discussed inherent risks and decision making, but also means of error avoidance, detection and correction. (Error detection is an important criterion in FMEA.) While avoidance is linked to the question of ground investigation and exploration – e.g. by drilling and exploration gallery, as done for the Lötschberg Base Tunnel –, error detection is linked to the observational method, based on good instrumentation. However, causes and effects must be distinguishable – as seen in the Heathrow case, multiple attack points at close distance may overstrain the human capacity of realizing, what is going on.

The crucial factor is time for analysis and reaction (Fig. 19).

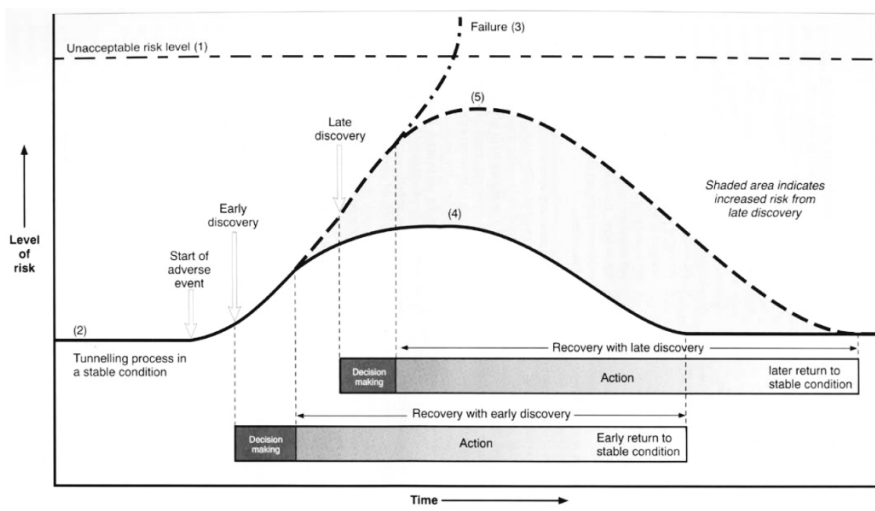


Figure 19: 'Discovery - recovery' model of timely intervention (HSE 2019)

Stopping ongoing work is not enough in underground construction, but the safe shutdown to reach a stable state may well require predefined (even exercised) emergency procedures and stand-by provisions, particularly in the presence of water, erosion and loss of confinement. Therefore, the concept of secure hold points from which to depart only after thorough checks (Monemvasioti 2022) is good practice, like pilots do before take-off.

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