Collapse of Březno railway tunnel made by prevault (perforex) method in the Czech Republic

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ABSTRACT

A single track railway tunnel was constructed by prevault (Perforex) method in tertiary sedimentary ground conditions as a by-pass of an open coal mine. After excavation of about half of the 1,7 km long tunnel, sudden, daylight collapse happened and destroyed about 100 m of the tunnel with prevault shotcrete lining, leaving the excavation machine buried as the crew left to safety.

Consequent investigation and re-design delayed construction for 2 years and doubled construction costs.

Investigation on the causation was performed on several levels, including involvement of experts of local and international insurers, focused on the following aspects:

- geology, site investigation and interpretation;
- adequacy of the tunneling method;
- adequacy of the design;
- adequacy of the construction and geotechnical monitoring;
- adequacy of the tender and contractual conditions and respective organizational and control arrangements.

Discussion includes project history, specifics of the financing, tendering, and construction arrangements. Main topic is the decision for using Perforex technology and its suitability for given geological conditions, as well as organizational aspects and financing specifics, which did not respect tunneling requirements.

Tunnel was finally completed using conventional tunneling based on principles of the NATM. During completion, some tunneling problems occurred as well; therefore comparison of the two used methods is possible.

Both authors were acting as experts for insurers and reinsurers.

1. INTRODUCTION

North-West Bohemia is an area in Central Europe with rich sources of tertiary coal deposits being randomly exploited since medieval ages and systematically from industrial revolution in Europe, i.e. mid of 19th century A.D. After the Second World War this low quality "brown" coal was the main energy source for extensively developing heavy industry of the Czechoslovak Republic, that time part of Soviet block of the East European countries.

Coal deposits were extracted from large open pits, creating huge dead areas of open and vast depressions in originally historically populated land, destroying agricultural land, historical monuments, towns and villages. Systematic rehabilitation effort started only since the end of the 20th century.

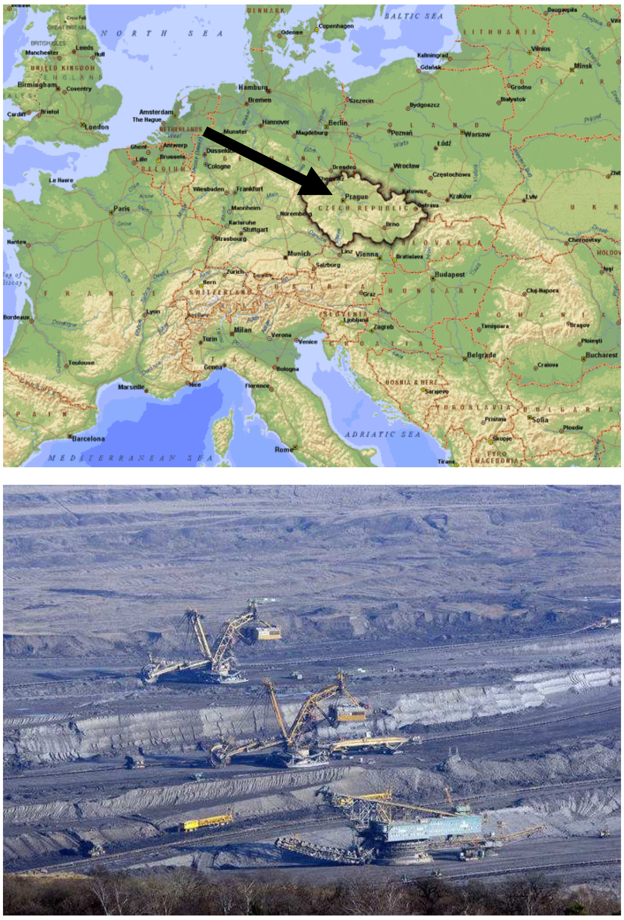

Figure 1. Location of the Project and open coal mines

Social and environmental aspects considered by political representations after changes in 1989 led to regulation of coal mining, defining space limits of coal exploitation as well as rehabilitation measures after finishing mine exploitation. For remedial measures and reduction of the mining impacts, financial reserves had to be created by mining companies, being used for specific measures under strict state control.

Open pit mine "Tušimice" supplies power stations located in vicinity with total output of 1,6 GW energy and future mining activities would extend its area to existing railway line. This was the reason for re-location of the railway line to a new alignment. Financing of the relocation was done from financial reserves by the mining company "Severočeské doly". In the 1990s, alignment studies for new single track line were performed and, finally, a variant with 1,7 km long tunnel was selected. For this tunnel geological/geotechnical investigation was performed in 2 phases, coming to different interpretation of the existing geotechnical conditions for tunnel excavation varying from "rather bad" to "reasonably good". In 1999 tendering of the tunnel construction project took place, with strict definition of the excavation method "prevault/perforex" and no alternatives allowed. This requirement, based on unclear reasons, was discussed and questioned within tunneling community; however, tender conditions defined by financing mining company were not changed.

After long tendering process, Contractor was awarded the contract and started commissioning the Perforex machine, design of the tunnel and, finally, in late 2000, construction. Tunnel excavation started consequently in 2002. Instead of planned completion of the construction in 2003, in May 2003 sudden daylight collapse buried the Perforex machine, destroyed 80 m of the tunnel and left the project with questions:

- what was the collapse reason?,
- how/if to continue?,
- who is going to pay?,
- and who is guilty and be called to responsibility?

Authors of this paper acted as externally chosen independent experts for insurance and re-insurance companies and are in good position to give objective opinion on the reasons, and recommendations for preventing similar accidents in the future.

2. GEOLOGY

The region is situated in the realm of a large Tertiary graben called Eger Graben or Ohre (Oharecky) Rift. More specifically, the tunnel area is situated in one of its sub-basins designated Most Basin, as stressed in the published geological literature [1, 2]. The graben is a long tectonic structure lying south of the Erzgebirge (Krusne hory mountain), related to a major subsidence along faults striking N60 - 70E. The graben in the area of the Most Basin is filled mainly with fluvio-lacustrine continental sediments, some of them coal bearing. In large scale, the region is strongly faulted and still being affected by present day compressive tectonic stresses, which have reactivated some of the main regional faults [3]. In terms of weathering, the region shows evidence of prominent ancient (Pleistocene) permafrost related to the glacial periods. The effects of frost action including freeze-and-thaw processes are today more conspicuous along the topographic highs, such as that in the surroundings of the collapse area.

For the Březno tunnel, geological conditions were known in broad terms and localization of weaker zones (fault zones) predicted in certain locations.

2.1 Performed investigations

In order to define the geological conditions of the tunnel alignment, 11 boreholes were drilled at tunnel portals and 10 along the tunnel alignment, but not strictly in the tunnel axis. The number and depth of the boreholes can be considered adequate to study and postulate the stratigraphy of the site; they do not contribute to the analysis of the potential existence of subvertical discontinuities due to the vertical direction of drilling. Complementing the borehole data, different techniques of geophysical survey were used, including dipole - DRP, vertical electrical sounding - VES and combined centric gradient – CCG resistivity surveys; spontaneous polarization SP, ground penetration radar GPR, very long waves electromagnetic survey VLW, magnetometry and shallow refraction seismics.

2.2 Local geology

Stratigraphy and Structural Geology

The horseshoe single-track rail tunnel (Fig. 3), with a height of 9 m and a width of 9.2 m, was initially driven into a sequence of coal-bearing *Holesice* Member and, from Station km 1,320 onwards, into overlying *Libkovicke* Claystones. Both of these units belong to the upper part of the Tertiary age filling the *Eger* Graben, being part of the *Most* Formation. Neither coal layers, nor mining activities were identified, close to or at the location of failure.

Entrance portal is located at sta. km 1,243 and exit portal at sta. km 2,720. The tunnel grade is slightly ascendant (9‰), following approximately the gradient of the topographical surface. The collapsed stretch, between Station km 2,029 and km 2,106, lies about 14 m above the upper coal seam with about 25 m of crown cover. The claystones have subhorizontal bedding. The main faults in the region were described to follow trends NE-SW and NW-SE.

The Libkovice Claystone in the TunnelStretch km 1,984 – 2,135

The Libkovice Claystone is composed dominantly of type F8, intercalated by F7 clay/claystone. The F8 claystones are considered as of firm consistency according to the Czech Standard CSN 73 1001, with higher geotechnical/geomechanical parameters than the equivalent F7 stiff claystones.

Structural geology - it was interpreted that a NE to ENE striking fault crosses the tunnel approximately around progressive Station km 2,000 (on the surface), with a relative subsidence towards NW. This fault, and the related brecciated zone, could be responsible for the loosening of the ground and groundwater infiltration around the collapse area.

Geophysical Data

Geophysical transverse seismic refraction profiles indicated that from Stations km 1,900 to 2,050 there is a significant difference in seismic velocity with depth, with an increase of this parameter in the tunnel alignment due to a shallower 1200 m/s seismic velocity at Station km 2,050, potentially indicating a sounder massif in the later Station.

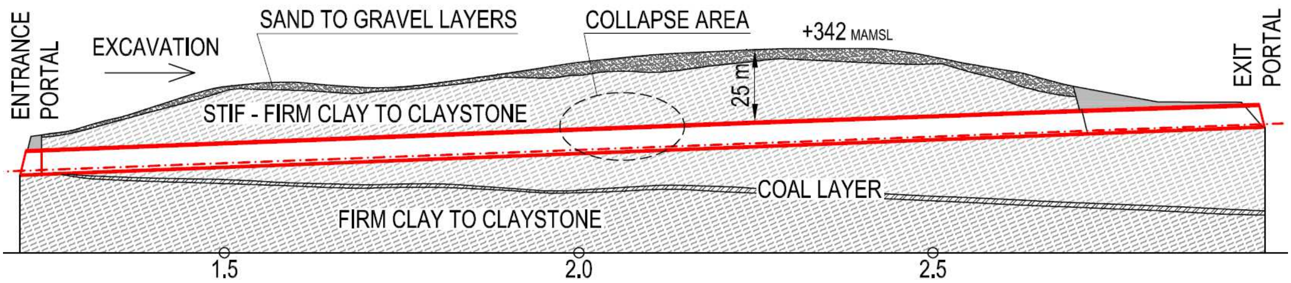

Figure 2. Tunnel profile

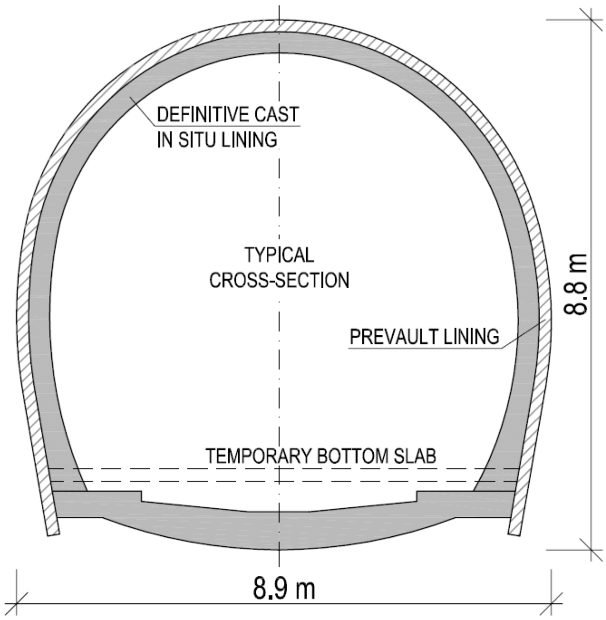

Figure 3. Tunnel cross section – primary and final lining

3. DESIGN

The basic task of tunnel design is to define a tunnel structure specified by geometric and material parameters, as well as a construction method able to materialize this structure in existing geological conditions with the necessary safety and economic parameters.

For verification of adequacy of proposed structure and construction procedure, different methods may be used. These may vary from empirical experience and case history projects based designs, to sophisticated numerical models considering variety of ground-structure interactions and parameters used for the design and its verification.

Specifically for the Brezno tunnel design was imperative to use the prevault/Perforex method (Fig. 4) of excavation and primary support installation. Verification of this method did not consider the actual construction method used. One reason may be that it was the first (and so far the last) use of this method in the Czech Republic and, therefore, no experience on the Client's, the Designer's and the Contractor's side. Method and technology for excavation and primary support was probably considered as a "ready made" mechanized tunneling and designer's attention was focused on definitive final lining made of reinforced concrete with closed invert. Disproportion between geometry, dimensions and requirements on primary lining and final lining is obvious (Fig. 3). And practical impossibility to close the tunnel's cross section with invert vault in adequate time after excavation of the advance step is crucial.

Designed solution of a thin bottom slab could not act as an invert element closing the tunnel profile (Fig. 5). Closing of tunnel profile in a ring-like structure, i.e. using a structurally acting invert, was, however, a requirement of the investigation performed in 1994.

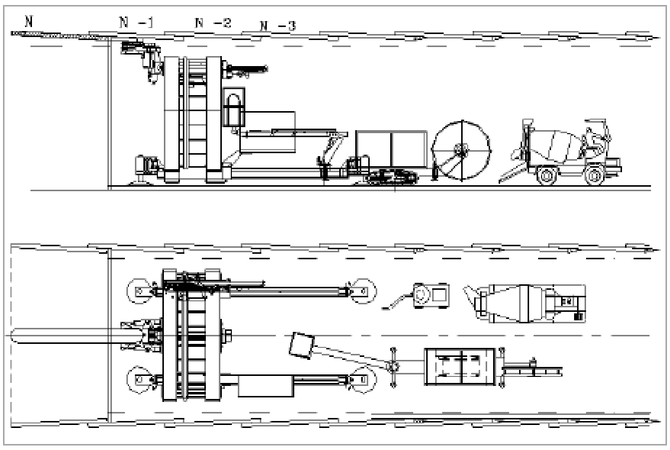

Figure 4. Prevault/Perforex method and machine

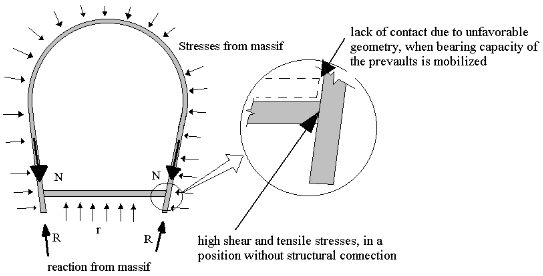

Figure 5. Bottom slab function

4. CONSTRUCTION, MONITORING AND COLLAPSE

Excavation of 1477m railroad tunnel started in March 2002 and was scheduled for completion in March 2003. Approximately 77 m of the tunnel, between station km 2.029 – 2.106 at a depth of 27 m, collapsed on 05th May 2003, when construction progress was already significantly delayed. Prior to the tunnel failure, only approximately 860 m of the tunnel excavation had been completed. Excavation rate of advance indicated problems with the schedule and progress.

Due to the expected influence of old mining activity under the tunnel alignment during the first 300 meters (1st Section) of tunnel excavation, systematic strengthening of the tunnel foundations and tunnel face was performed by grouting and application of fiber glass anchors. Tunneling progress was, therefore, rather slow at the beginning, combining a learning period of a new technology with the additional works for strengthening the massif. After entering into geological conditions considered as optimum for the method (2nd Section), monthly progress reached an average of approx. 90m/month in the period September 2002 – February 2003. This progress rate proved to be a realistic maximum for excavation in the existing conditions.

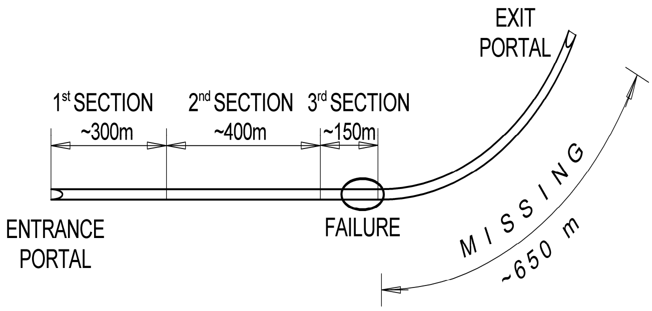

Figure 6. Schematic tunnel layout

Construction progress in March to May

Starting in March 2003, deformation behaviour of tunnel sections excavated in February (prevaults no. 160 to no. 172) generated serious concern as a non stabilizing tendency was recorded by the instrumentation program (Fig. 7).

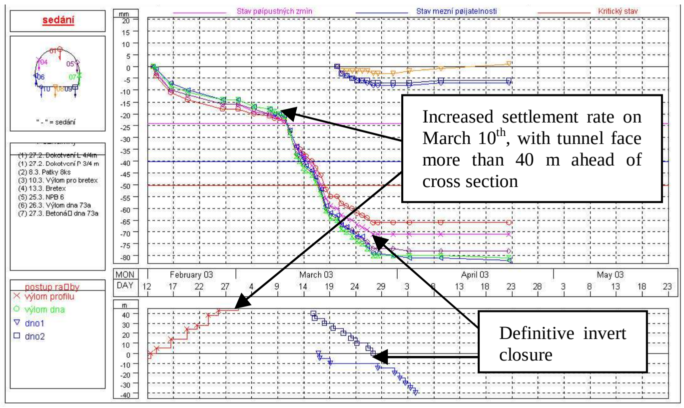

Figure 7. Monitoring of tunnel deformations

A series of measures, not foreseen in design and listed beneath, were applied/tried in an emergency on site decision process:

- stop excavation;
- support two prevaults by steel support
- install additional measurement profiles;
- install 3,5 m fiberglass anchors, 4 pcs on each side;
- the immediate construction of the definitive invert;

- before excavation for the definitive invert, 6 m long anchors/dowels shall be installed at foundation level of the prevaults, 4 pcs at each side;
- installation of lattice girders at connections of prevaults;
- deformation measurement shall be per formed approx. 2 x in 24 hours.

These stabilizing measures, mostly not predicted by the design, were adopted in order to stabilize the tunnel prevault lining. The tunnel, in this area (sta. km 1,922 to km 2,002) of foreseen worsened geotechnical conditions, suffered unexpected deformations in a magnitude beyond the critical design limits. Design did not provide, at that time, enough details/procedures for stabilization. Solutions were sought in an ad-hoc, on site decision making process initiated by the Contractor.

The only effective solution to stabilize the tunnel finally proved to be the invert closure. Deformation behavior of the tunnel stabilized only after completion of the definitive invert in section sta. km 1,922 to km 2,002 (Fig. 7).

The tunnel construction continued on 5.4.2004 with excavation and anchoring of the sides of prevault with 10 pcs. of 6 m and 8 m long anchors.

Construction progressed moderately well during April with regards to advance rate; however, geological conditions as monitored did clearly indicate continuation of adverse conditions. The deformation measurements indicated behavior not leading to stabilization during the whole April period.

On April 30, 2003, closure of the invert was recommended by geotechnical advisor, but the Client stated that it would be convenient to continue tunnel driving.

On May 3, 2003, deformations as measured indicated "*extreme*" increase and following measures were agreed upon:

- to finish cutting of the last prevault no 196;
- to complete radial anchor installation in prevault no. 195;
- to move Perforex machine to sta. km 2,000 (closed invert);
- to perform deformations monitoring on 24 h period.

On May 4, 2003, on the basis of a more detailed evaluation of the technology of construction and the deformations development, the Contractor and Client agreed on the following progress of works:

- the Perforex machine was to be left at the face;
- excavation of the invert was to start on May 5, 2003, with subsequent closure of the final invert to be performed in direction opposite to the direction of driving.

On May 4, 2003, at 7 p.m. on the basis of the latest deformation measurements, dated May 4, 2003 at 5 p.m. and indicating acceleration of deformations, the following measures were agreed:

- immediate support of prevaults 184–191 by means of I-profile steel arches;
- the installation of supports to be performed in the following order: prevault nos.188, 187, 186, and 189, 190, 191 and then 185, 184;
- development of deformations to be monitored on a 24 hour frequency.

On May 5, 2003, at 4:30 a.m. the tunnel experienced large and accelerating deformations leading to breaking of the prevault lining starting with bottom slab upheave at prevault no. 188, progressing in domino-like effect over the prevaults no. 177 to 195, leading to total tunnel failure in this section and progressing to the surface (Fig. 8).

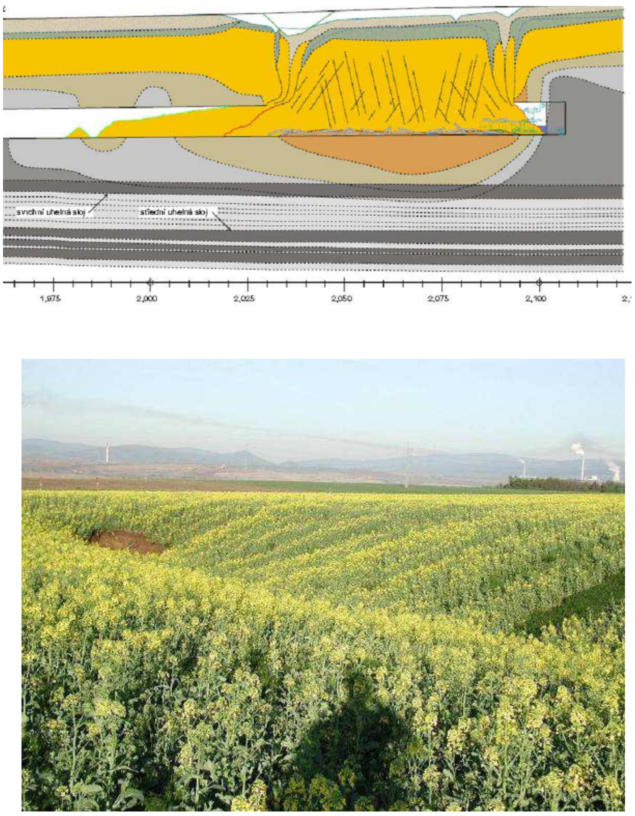

Figure 8. Collapsed tunnel profile and surface depression

5. CONTRACT,FINANCING, ORGANIZATION AND CONTROL OF THE PROJECT

Tunnel construction requires organizational, contractual and control arrangements suited for specifics of tunnel construction as:

- contract should consider deviations in the construction due to real (different from predicted) conditions encountered, and financial reserves should be considered;
- project organization and system should clearly define competences and responsibilities;
- decisions should be made by joint agreement of competent representatives of involved parties;
- control (supervision) during tunneling should be continuous and parallel to construction (24h/day, 7 days/week).

In general, none of these requirements was fully met. Following main project parties were involved (Fig. 8):

- Financing Organization (private mining company)
- Client (public railway company, awarding construction contract)
- Contractor
- Designer (for all design stages incl. detail design for Contractor)
- Monitoring (geotechnical)

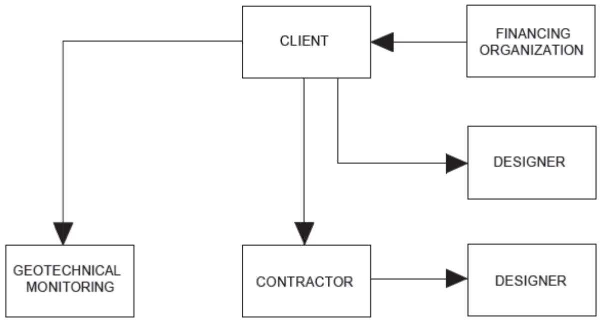

Figure 9. Parties of the project and their relations

There were systematic problems related to Czech tunneling due to limited experience with modern tunneling in new conditions after political and economical changes in 1989. These were missing regulations (standards, directives, and guidelines) suitable for tunneling, capacity and competence of Clients, and tradition and examples of tunnel projects preparation and realization.

For Brezno tunnel project, there were additional systematic features contributing to problems during tunneling. The most important, influencing the whole development of the project was financing arrangement. Financing organization (private mining company) had power to define tunneling method and has full control of cash flow with one obvious interest – minimize costs of the project. The Client (public railway company) had to organize and administrate project with limited decision competence about financing, but with full responsibility for safe and effective project realization and later operation. All decisions about necessary measures to be adopted during construction were therefore lengthy and difficult and definitely did contribute to problems ending later in tunnel collapse.

Following were main systematic contributing factors leading to tunnel collapse:

- definition of tunneling method prevault-Perforex (no alternative allowed)
- lack of independent check of the design
- lack of proper construction supervision (24h, 7days/week)
- limited flexibility in decision making process required by real encountered conditions (geology, technology)
- conflicts of interest of some involved parties (same designer working for both the Client and the Contractor, monitoring company – same arrangement)
- Client's limited capacity and professional competence

6. SUMMARY – CONCLUSIONS - RECOMMENDATIONS

Collapse of 1,7 km Brezno railway tunnel in May 2003 was a major setback for tunnelling in the Czech Republic. The project schedule was extended for more than 3 years and cost doubled.

Technical reasons of the collapse were connected with the used technology (prevault/Perforex) and lack of design verification of the primary support in existing geotechnical conditions. Construction reasons were of smaller importance. Method itself can be effectively used only in very specific range of "optimum" conditions with soft (for chain cutting) but stable geology. Other than optimum geology leads to either slow progress (if quick closure of the profile is required) or stability problems in weaker grounds and to slow progress (due to cutting) in strong grounds. Reference projects show problems on many of them.

Besides technical reasons (construction method and performance and geology), major influencing factors were systematic, i.e. project preparation, project tendering, project financing, and organization and control of construction. Lack of capacity on Client's side, non existing independent control mechanisms for both design as well as for construction were important contributing factors. However, unique financing arrangement (financier without responsibility and client without money) was probably the start of the problems.

Project was finally completed by excavation through collapsed part strengthened by piling, micropiling and grouting in original excavation direction, and a consequent counter drive from the exit portal. Both drives were performed based on principles of the NATM.

Project contributed to better understanding of the unknown tunnelling method and principles of the design verification and tunnel project organization in the Czech Republic. Lesson learned will hopefully prevent unreasonable systematic arrangements for tunnel project preparation and realization in the future.

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