SOME OBSERVATIONS ON THE CONSTRUCTION OF THE M6 MOTORWAY TUNNELS

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INTRODUCTION

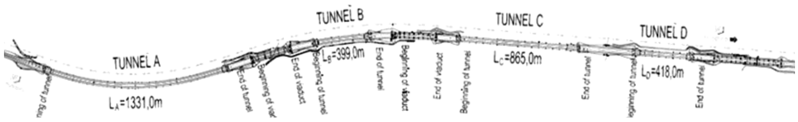
The tunnels of the M6 motorway were built using The New Austrian Tunnelling Method (NATM). The main characteristics of which are large cross section free excavation areas, the use of mechanical excavation methods, steel strutting and shotcrete supports. The high level of mechanisation is of key importance in terms of the technology used.
A collapse occurred in Tunnel 'A' affecting the southern side of both tubes at dawn on 24 July 2008. The incidence affected a ~120m section of the tunnel in the east tube and ~90m in the west tube. Later the incident was followed by further collapse of ~80m stretches of the two tubes. The evacuation of the tunnel was successfully completed as the collapse had been preceded by loud cracking noises and visible deformations. Detailed analyses were carried out on tunnels in order to understand the reasons of the collapse, and to ensure the possibility of further construction.

1. THE DESIGN, ALIGNMENT AND ENGINEERING STRUCTURES

The design of the M6 Motorway section connecting Szekszárd to Pécs was commissioned by the National Motorway Corporation and began in 2003. The route of the motorway sees a much more difficult terrain beginning at Bátaszék: the flat land of the Sárköz region along the river Danube turns to an undulating landscape with valleys and hills, and loess soil. (Fig. 1.) Complying with the maximum of 4% longitudinal inclination allowable for motorway construction is not easy with such a terrain. Furthermore, it also needs to be considered that the motorway runs across the historic vineyards of the Szekszárd wine growing region. The original plans, which included 17-40 m cuts with slopes, were later in the design process modified and the cuts were replaced with tunnels. Excavating, transporting and disposing of huge amounts of soil are costly and time consuming, and land purchase for the cut and slope construction greatly increases the costs.

Figure 1. Map of the M6 highway.

Slope stability in deep cuts in clay-silt soils prone to erosion poses serious technical problems to be addressed. The extent of injury to be inflicted on the natural environment and the long soil compaction period following the excavation of millions of cubic meters of soil are important factors in the decision making when choosing the method of tunnel construction. There had been several proposed alternative alignments for the motorway, which did not require tunnel construction, but these were eventually abandoned.



There are four tunnels in this subsection of the motorway marked ‘A’, ‘B’, ‘C’ and ‘D’. The tunnel project consists of the following parts: 8 pre-cuts with the excavation of 323,000 m³ of soil, 797 m of cut and cover tunnel, 5419 m of NATM tunnel with a cross section area of 101 m². Tunnel ‘A’ is 2 × 1,356m long, Tunnel ‘B’ is 2 × 423 m long, Tunnel ‘C’is 2 × 766 m long, Tunnel ‘D’ is 2 × 441 m long, there are 5 cross passages in Tunnels ‘A’ and ‘C’, and there are 2 emergency bays of a 120 m² cross section in Tunnel ‘A’.
Our analysis extends to the geotechnical and construction aspects of Tunnel ‘A’, however it should be noted that the construction of the other tunnels was carried out along similar principles.

2. GENERAL GEOTECHNICAL FEATURES OF TUNNEL ‘A’

For the purpose of the geotechnical expert opinion initially 29 borings and later further 6 static cone penetration tests (CPTs) were carried out in different depths, the results were analysed and as a result 5 different layers of soil were identified in the soil profile. *(Figure 2.)*
The excavation class for each section was determined on the basis of the penetration test results, extending from Class *A* to the strictest Class *H*. The excavation class for each particular section was specified on the basis of the deformation modulus (E_s) and cohesion (c) of the soil profile and on the basis of the surface soil cover.

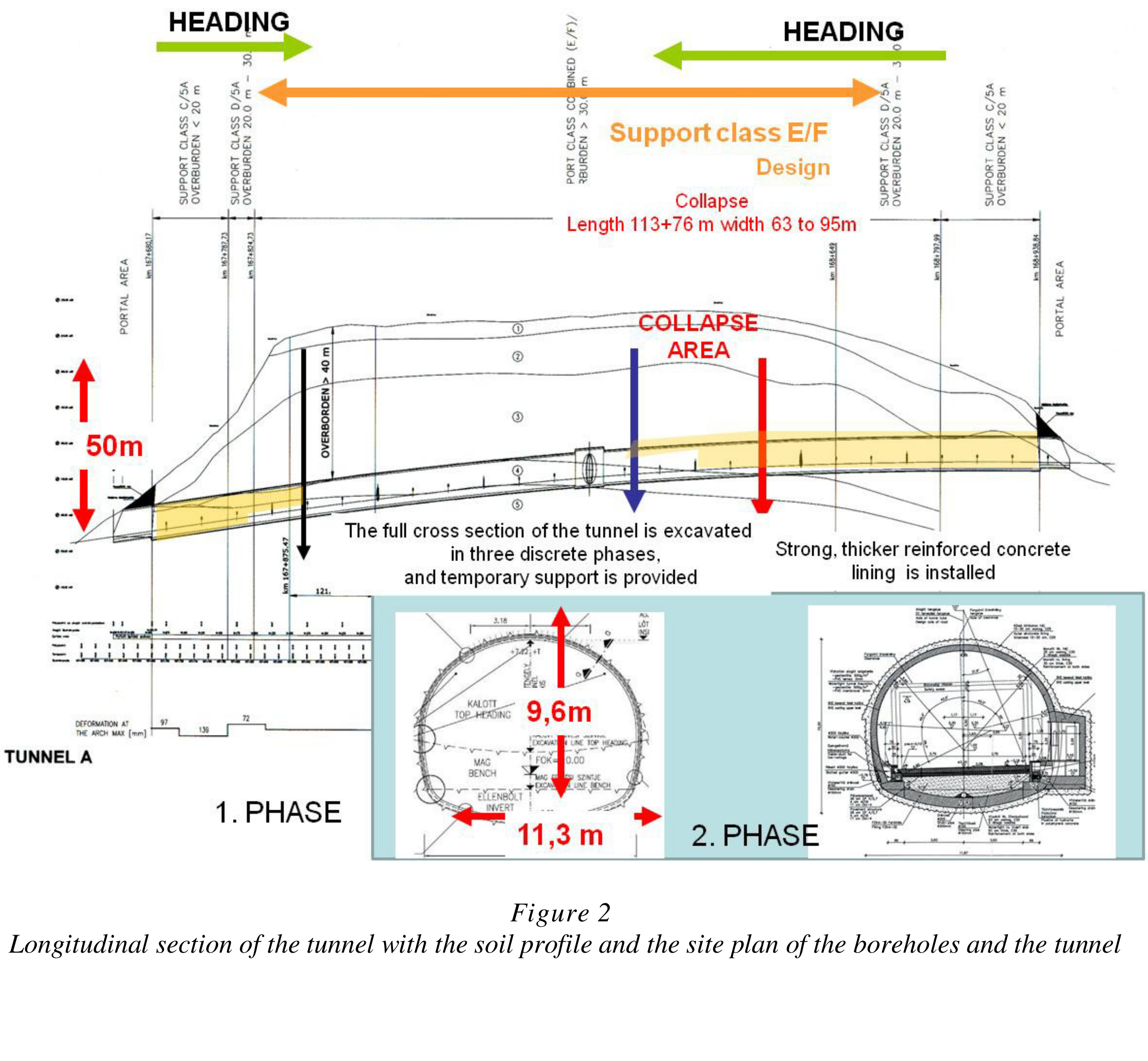


Figure 2
Longitudinal section of the tunnel with the soil profile and the site plan of the boreholes and the tunnel

Over the tunnel the Baltic Sea level height of the ground is 213-217 m, while the Baltic Sea level height of the road pavement is between 160 – 174 m (R=35000 m, L=1207 m). It means that the motorway runs 43-48 m below the ground level. The tunnel is joined by a viaduct, which passes at the height of 8-10 m.
In the examined area the Pannonian strata are covered by a cover layer of 35-40 m originating form the Pleistocene epoch of the Quaternary.
In the thicker loess sections one or more reddish-brown and brown clay layers can be observed, which developed in periods of higher temperature and increased precipitation during the Ice Age in the course of the chemical weathering of the surface loess layers. Upon loess weathering the sandy silt content gets reduced while the rate of clay fraction increases and may reach as much as 40%.
According to analyses conducted by the Geological Institute of Hungary (Hungarian abbreviation: MÁFI) the iron-oxide content increases along with the intensification of weathering and mostly appears in the form of limonite. Therefore the paleosoil that once covered the ground surface is of reddish-brown, greyish-brown colour. This paleosoil, also called loam zone, is a clay formation of crumb structure. Its thickness may vary from 0.5 m to several meters. Due to the fact that several periods of higher temperature are known to have taken place during the Ice Age, the formation of paleosoil may have been followed by further loess deposition and further soil formation periods.
The different strata of loam zone – paleosoil can be clearly observed in the examined area.
The *Red Clay – Tengelic Red Clay* stratum is a special soil type, which overlies an uneven stratum. The *Pannonian* strata are disintegrated by erosion. According to an analysis conducted by the Hungarian Institute of Geology (MÁFI) it is a product of a lengthy weathering process of prevailingly local substances under a warm climate with high precipitation. At the bottom of the stratum a thin limestone layer or its debris is settled. The limestone is of dingy white colour and of cavernous, porous structure. It is overlain by a bright red fat clay layer, which is coherent, firm and unstratified. Due to its montmorillonite clay mineral content it has a strongly expansive nature.
As the geological expert opinion also pointed out, rock formations may vary both horizontally and vertically even within a relatively small area, due to the above modes of formation, the different environmental conditions (ground surface, plant cover) and climatic fluctuation.
The allogenic, weathered variations appear in a depth of 28.7-44.2m in the lower zone of earlier drilled boreholes on the Birka-hill. The allogenic, weathered nature of loess in this area is indicated by clay that formed within the loess beds in an unusually thick layer, by the lime concretion debris („containing limestone”) and, in certain boreholes, gravel intercalations. (Fig.3.)
The profile based on the different soil profiles excavated in the area of the tunnel under examination justified the preliminary geological assumptions.

Geological-geotechnical conditions of tube 'A' summarised as following:

- Geological descriptions did not indicate loess deposits typical of the area, but heterogenic strata with clay intercalations,
- The slope loess was probably in movement after its geological formation – the clay stratum is not continuously distributed but discontinuously deposited.
- The intercalated red Tengelic clay is of rather unfavourable nature showing volume change behaviour and it is of low shear strength; above and under it are layers of mixed composition soils.
- The high rate of substances of gravel grain size appearing in the strata indicates an unstable geological structure.
- Above the tunnel soil types of higher permeability and of loose structure can be found.
- The soil under the shoulder of the tunnel is of mixed composition, relatively loose and compressible.

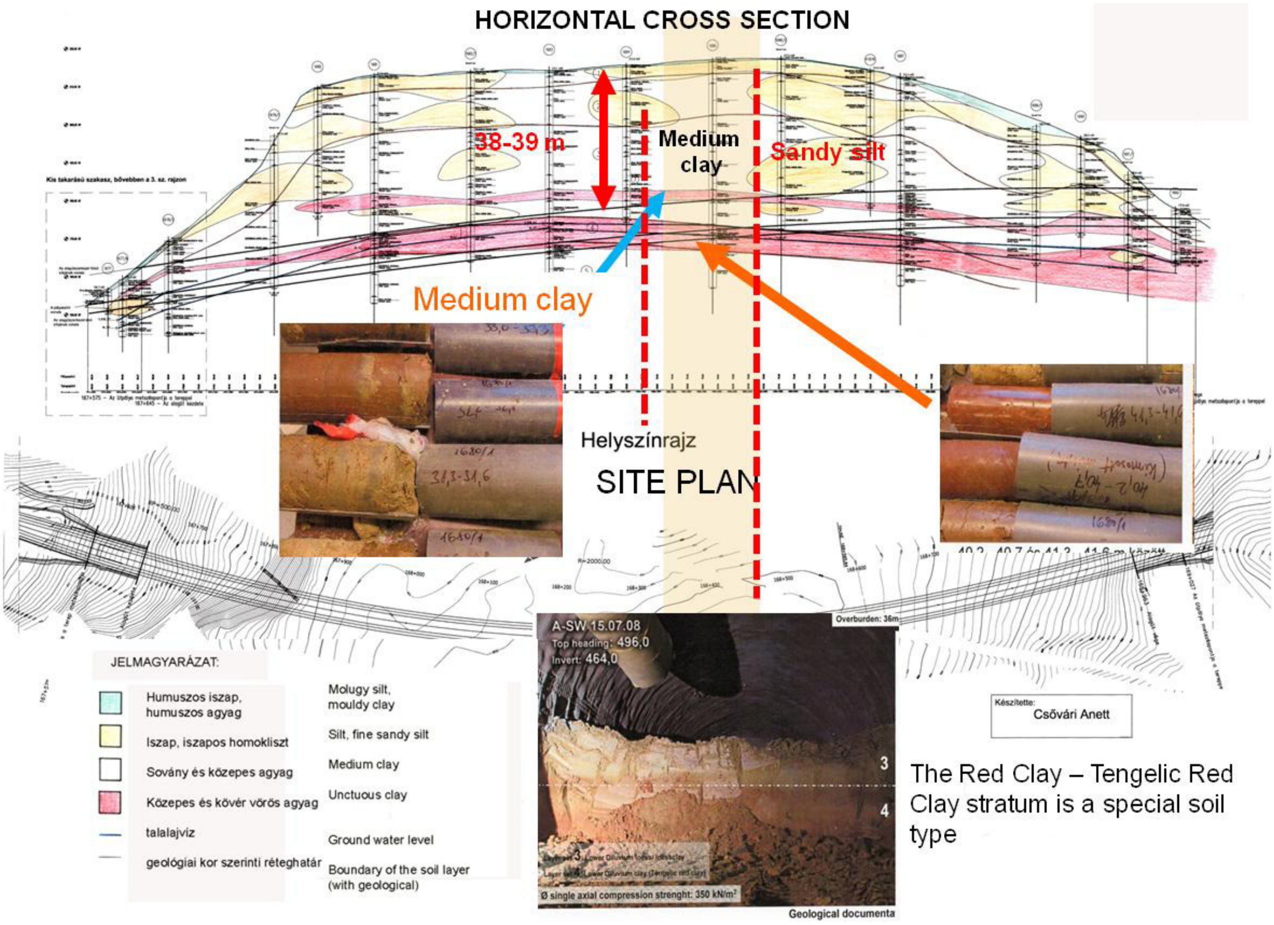


Figure 3
Longitudinal section of the tunnel with the soil profile and the site plan of the boreholes and the tunnel

3. THE COLLAPSE

A collapse occurred in Tunnel A affecting the southern side of both tubes at dawn on 24 July 2008. The incidence affected a 120m section of the tunnel in the east tube and 90m in the west tube. The evacuation of the tunnel was successfully completed as the collapse had been preceded by loud cracking noises and visible deformations. The increased air pressure was so high that it knocked down workers waiting at the entrance of the tunnel. Later the incident was followed by further collapse of 80m stretches of the two tubes. According to the first assumptions the two collapses were closely related. Following the incidents work in the four tunnels was stopped and a thorough investigation began to find the contributory causes.

The original design of the tunnel was reviewed, and based on the expert opinions a decision was made that the tunnel construction was to be continued with the technology used but the safety levels had to be increased. Detailed specifications were drawn up addressing technical, construction organisation and construction management issues. It was asserted that the original design for the permanent support lining of the tunnel was structurally adequate, and no modifications to it were needed.

Detailed reports and analyses were carried out on all the four tunnels, while a new design was made for the collapsed stretch of the tunnel. (Gebauer B., Mecsi J., Schwartz J.) The District Mine Inspector and the competent authority both granted permission for the continuation of the tunnel construction.

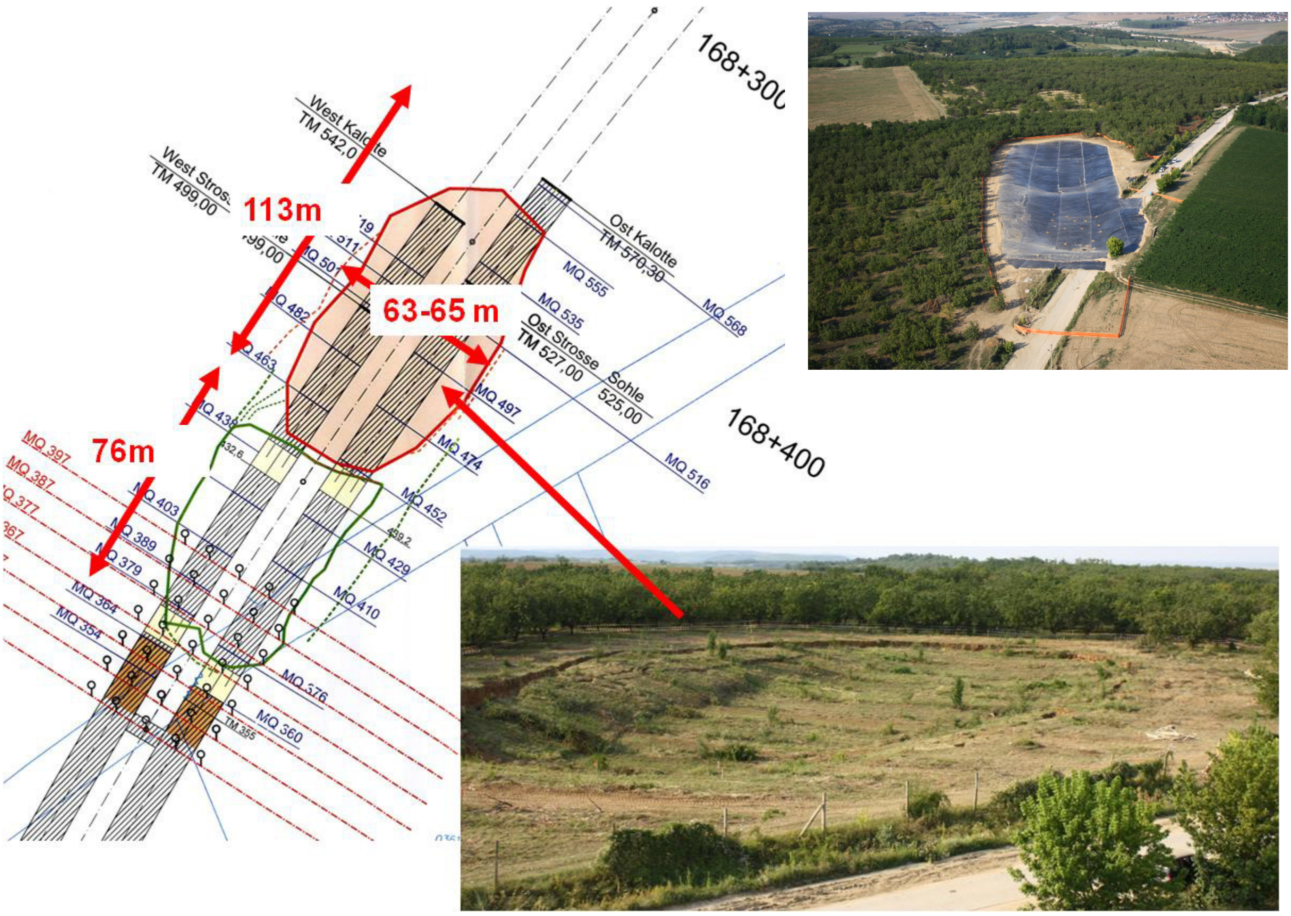


Figure 4 Surface of the collapse area

The main points of the expert opinion, regarding the continuation of the construction work:
The working plan should be considered as a framework plan, which can be modified according to required changes in the technology used, to geological and geotechnical conditions and to other conditions affecting the implementation.
The following measures are aimed at improving the technology:

- enlarging the foot of the top heading to provide for better bearing and support, and to relieve the low load bearing capacity piles of the loading,
- using connecting bars at the bottom of the top heading to ensure lateral load distribution,
- introducing strict technological specifications and control for the excavation distances between the faces of the two tubes during the excavation of the top heading and the construction of the invert,
- checking the strength of shotcrete against the required specifications, and indirectly decreasing the speed of the excavation, ensuring the time needed for the adequate instalment of support structures or a temporary propping system when necessary,
- tying the required strength of shotcrete to the assumed highest value of the soil's unaxial compressive strength (800 kPa = 0,80 N/mm^2), which determines the lining of next excavation span,
- ensuring the stability of the ground between the two tubes by anchoring the inner sides of the tubes together,
- draining the occasional infiltrated water (which accumulates in small quantities at the top of the clay layers), for which the specifications are given in the Method Statement.

If these measures are introduced as minimum conditions, the excavation class to be adopted must be one stricter than Class *D*.

For the implementation and control of above technical measures the adequate expert and technical background must be ensured, with special emphasis on the following:

- Increasing the effectiveness of the risk analysis evaluation and supervising the implementation of measures. Extending the scopes of responsibility of persons participating in the risk analysis evaluation and compulsory compliance with them,
- Extending the powers of the Independent Engineer entitling him to take measures in the event of proven non-compliance with requirements of the technology,
- Requesting approval from the Mining Inspectorate for the Method Statement to be applied and worked out in accordance with the expert opinion
- Continuous supervision by and power of action for the geotechnical site manager must be provided for the period of the excavation work

  The performance and documentation of daily in situ analyses, as well as a regular dissemination of information are of special importance.

  Documentation should cover the observation of tunnel cross-sections, soil stratification, the nature and quantity of ground water infiltration, the standard geological and soil mechanical description of soil types, soil stability and probing results.

  Data processing and analyses should also be executed in respect of the longitudinal section of the tunnel.

The supervision, evaluation and technical intervention measures described above ensure that risks shall be reduced to the minimum and personal security shall be prevailing.

4. ANALYSIS OF POSSIBLE REASONS FOR THE COLLAPSE

In the course of the analysis it had to be considered that the work phases of the NATM have different effects on the soil environment. The so-called “ability of the soil to remember” had to be regarded as an important factor. It means that before the construction began the vertical loading was 650-800 kN/m^2 as a result of the compressive stress of a soil layer of 40-45m, while as it is typical of static conditions, there was a significant horizontal stress in the soil. With the excavation of the tunnel, part of the compressive stress of the soil is taken over by the yielding temporary support. The increased stress around the cavity secured by the temporary support is mostly taken over by the soil around the tunnel. All this occurs in a soil which has special features; it is inhomogeneous due to its geological formation, it has tilted strata and its formation was characterised by intense internal movements in the geological era of its development.

Several questions arose concerning the development of the incident, the answers to which might have contributed to the understanding of the reasons for the damages:

- To what extent are the geological and geotechnical conditions of the collapsed tunnel section different from the conditions revealed in the other sections? Are there any special circumstances that may explain the special behaviour?
- What may explain the fact that the tunnel section entirely secured by the temporary support was also affected?
- What role do the construction technology, the pace of construction and the consolidation periods play in the processes in question? Are there any effects that traditional engineering calculations were not able to reckon with?

- Have problems arisen, and if yes, what kind of problems have arisen? Caused by the management, unclear competencies, insufficient relationship between implementation-design-technical inspection…? To which extent have been considered the design specifications? Have the relevant technical leads sent an appropriate signal about the anomalies found? etc.
  (These questions do not fall within the scope of the present paper, but shall not be neglected in the overall analysis of the issue.)

5. SPECIAL GEOLOGICAL-GEOTECHNICAL CONDITIONS OF TUBE ’A’

Geological descriptions did not indicate loess deposits typical of the area, but heterogenic strata with clay intercalations. The slope loess was probably in movement after its geological formation – the clay stratum is not continuously distributed but discontinuously deposited. The intercalated red Tengelic clay is of rather unfavourable nature showing volume change behaviour and it is of low shear strength; above and under it are layers of mixed composition soils.
The high rate of substances of gravel grain size appearing in the strata indicates an unstable geological structure. Above the tunnel soil types of higher permeability and of loose structure can be found. The soil under the shoulder of the tunnel is of mixed composition, relatively loose and compressible.

Details of geotechnical conditions:

- The soil stratification of the collapsed tunnel section is rather unfavourable and is significantly different from conditions of the other tunnels and tunnel sections.
- It is of crucial importance that there is a 6-8m thick Tengelic clay stratum in the area of the tunnel section in question.
- ***The position of the stratum as related to the tunnel is extremely unfavourable.*** The stratum stretches into the tunnel section along the direction of the excavation and extends up to approximately half of the height of the tunnel within the section where the collapse occurred.
- **The stratum therefore had a determining and fundamental effect on the construction of the tunnel.**
- Average probing resistance values characterising the different excavation sections measured on the tunnel face during the tunnelling.
- Cohesion values calculated on the basis of the probing resistance values are also indicated. In situ probing does not provide absolute and exact values for the characteristics of the soil mass but show changes in the soil condition as comparative indicators.

Observations:

- In the collapsed tunnel section the probing resistance measured on the tunnel face and, parallel with that, the average cohesion of the soil significantly dropped, from the earlier value of 75-125 kPa to a permanent 50 kPa value.
- Along section between 300-400m intense shear strength conditions were observed indicating probable sectional disintegration.

Examination results also indicate that mostly lean and medium fat clay soils are deposited above the tunnel in the area of the collapse.

6. EXCAVATION CONDITIONS

The analysis of the construction process and of the pace of the different construction phases are of great importance within the general analysis process.
In the control of possible deformations the examination of the pace of excavation and construction, as well as the continuous geotechnical observation and supervision of the different construction phases, of the sections between the excavation faces are extremely important.
To examine the construction process, a typical cross section of a tunnel construction phase has been selected and is shown on the horizontal axis. (Fig. 6.) The positions of the faces of the other construction phases are shown on the vertical axis. Presenting the distance between the two top heading excavations, the sections of the construction of the benches and the inverts, a spatial picture is presented of the tunnel construction. The temporal changes of the selected construction position being also indicated, a clear picture is given of the tunnel construction process advancing in time and space and thus information is obtained as to whether the construction technology was properly applied.
As a result of the analysis it can be presumed that the excavation of the bench and the invert was advancing in the two tubes parallel with each other, more or less in the same section, which is considered unfavourable. Furthermore, the soil excavation of the bench and the invert section was presumably carried out in an unfavourably long segment within a short period of time.
The effects of the soil excavation and the unfavourable geological conditions were further strengthened by the weakness of the tunnel sealing.

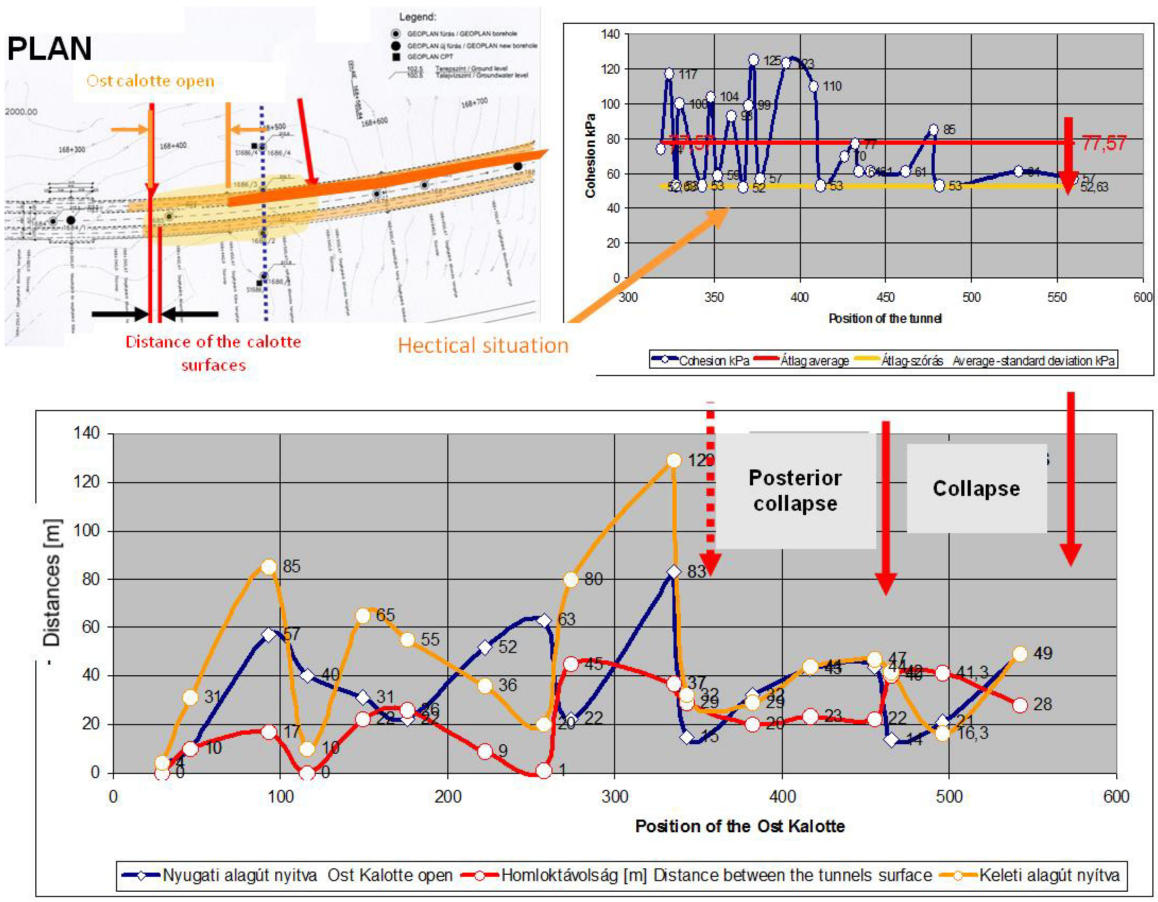


Figure 6. Construction process. Position of the different building position from the Ost kalotte surface [m]

7. STATIC ANALYSIS

After the incident independent experts analysed the structure using a finite element programme, modelling the circumstances that existed at the time of the collapse and taking into account the tunnel section geometry as described in the plans and as required by Excavation Class 'D'.
Results of the static tests also confirmed that the most sensitive work phase of the tunnel construction is the excavation of the bench, partly because the excavation of large quantities of soil entails a sudden relief of load, and party because soil stress redistribution may require more time in clay soil. A large horizontal deformation was visible by the side wall of the tunnel which led to the fracture of the concrete and indicated serious deformations of the tunnel. (Fig. 7.)
It must be noted that along the long tunnel this is the area where soil stratifications proved to be the most unfavourable; the red *Tengelic* clay stratum is situated partly at the bottom of the tunnel and mostly under the tunnel. At other parts of the tunnel the clay stratum is situated either in the whole soil section of the tunnel or deeper under the bottom of the tunnel, therefore the above effect cannot occur or occurs only moderately.

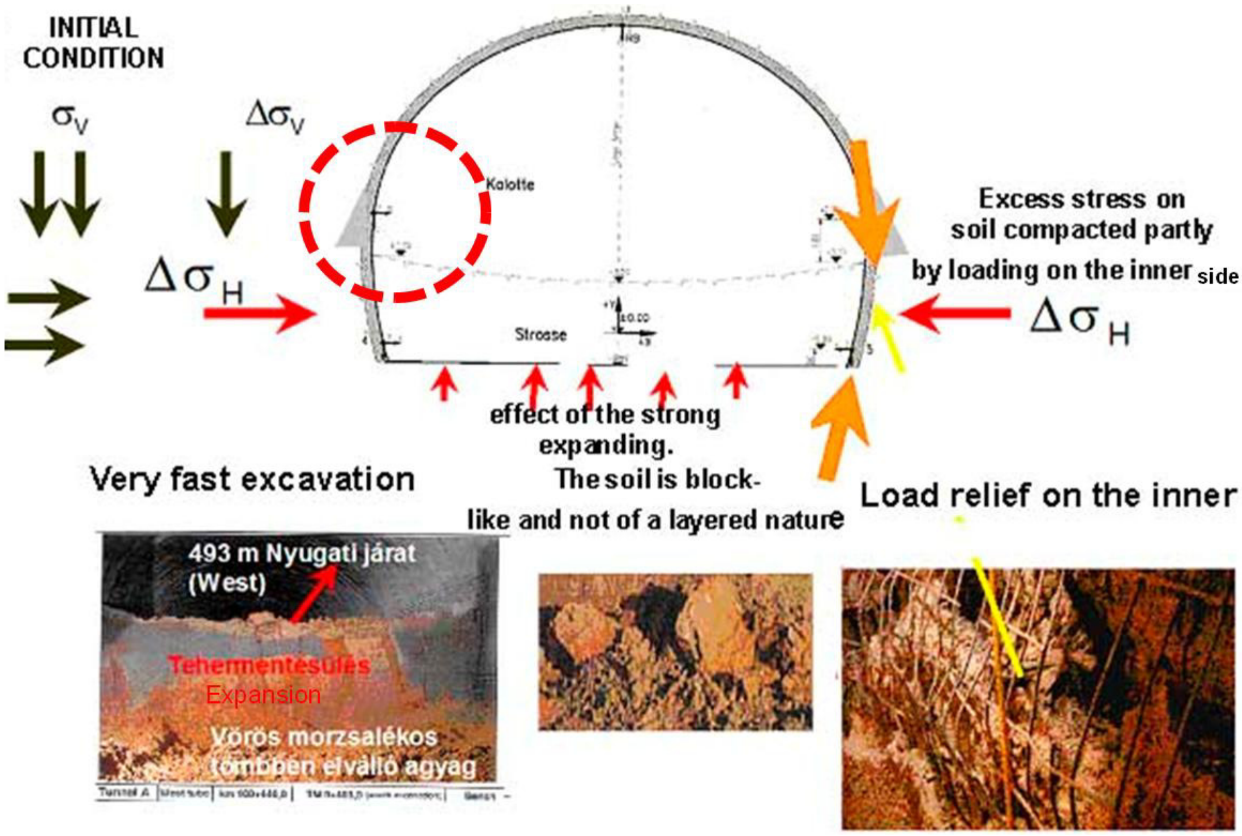


Figure 7 Presumed effect of load relief on clay stratum

Summarising the important technical effects of the collapse were the following:

As a result of the analysis it can be presumed that the excavation of the bench and the invert was advancing in the two tubes parallel with each other, more or less in the same section, which is considered unfavourable.
Furthermore, the soil excavation of the bench and the invert section was presumably carried out in an unfavourably long segment within a short period of time.
The effects of the soil excavation and the unfavourable geological conditions were further strengthened by the weakness of the tunnel sealing.

8. TUNNEL CONSTRUCTION IN THE AREA OF THE COLLAPSE

Safe conditions had to be established for the continuation of the excavation work and the soil to be extracted had to be homogenised while continuously maintaining a specified level of soil strength. Therefore a stabilising row of cemented jet grouting piles was constructed in both tubes of the collapsed section of the tunnel. Stabilisation was started from a depth of 43m in the length of 8m. The minimum designed diameter of the piles was 150cm.

Further excavation in the collapsed section was carried out under the protection of a tube umbrella. The 33 steel tubes with casings were drilled at 45cm intervals into the excavation face, which was supported with concrete, and the voids were grouted. The length of the tube umbrella was 15m and the next tube umbrella section was built in after an excavation length of 10m, therefore there was a 5m overlap between the sections following each other.

As a result of the strict construction discipline and the precise technical implementation, Tunnel A was completed with the application of the temporary supports on 19th August 2009 and the tunnels will be handed over for test operation in December 2009.

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REFERENCES

Csővári A., (2006), The "Bátaszék" tunnel design. Thesis work. Budapest University of Technology and Economics, Department of Geotechnics, Consultant: M. Müller

Mecsi J. [2009]. "Some problems of the Less Soils at Geotechnical Emplaiments" -A lösz eredetű talajok néhány problémája a geotechnikai jellegű károsodásoknál) 13th International Conference on civil Engineering and architecture Hungarian Technical Scientific Society of Transylvania, ISSN 1843-2123 pp. 364-370 (In Hungarian)

Mecsi J., Gamper C., [2011]. "Az M6-os autópályán épített közúti alagútak néhány építési tapasztalata, koncentrálva a talajviszonyokra és az építési sebességekre. - Some construction experience about the M6 motorway road tunnels, with a focus on soil conditions and construction speeds." In Collapse Understanding to Solution Book (In Hungaian: Káresetek a megértésen át a megoldásokig"), Edited by: J. Mecsi, Mérnöki Kamarai Kiskönyvtár 2nd edition ISBN 978-963-88358-1-9, ISSN 2062-5081 pp.30-51 (in Hungarian)

Schwartz J, Mecsi J., Gebauer B., (2008) Expert report about the "Bátaszék" tunnel A.

Szilvágyi et. al: (2009) Geological and geotechnical conditions of the first Hungarian motorway tunnels on M6 Szekszárd—Bóly project. Proceedings ITA-AITES World Tunnel Congress 2009, Budapest, May 23-28, 2009