THE DEGREE OF DETERIORATION OF THE TUNNELS OF THE PRAGUE METRO BASED ON A MONITORING ASSESSMENT

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Abstract

Understanding the ageing of structures is a very important issue from the point of view of assessing the risk inherent in those structures. Geotechnical structures, of course, have their own specific risks. This paper is focused on the tunnels of the Prague Metro, looked at from various aspects, i.e., geology, construction systems, and the influence of flooding. The section of the tunnels that was selected for monitoring is one of the most affected, and has a large system of cracked segments. However, even for this affected section the monitoring systems, based on macro- and micro-approaches, showed no significant deterioration was taking place. Nevertheless, for long-term monitoring a wireless system for data collection and transfer was installed and implemented. The results so far have been very positive.

Keywords

tunnel, metro, deterioration, ageing, geology, construction, monitoring assessment, MEMS, geophysical, wireless data transfer, metro flooding

1 INTRODUCTION

Recently, the owners of infrastructures have started to become concerned about the life expectancy of engineering structures that were designed for lifetimes of about 100 years and are now beginning to approach such an age. This concern is very much connected with the risk of a sudden collapse of these structures and the consequences of such an occurrence. In this sense geotechnical structures have specific differences compared to other structures, like concrete, steel, timber, masonry, etc. Geotechnical structures include old dams and the protective embankments around settlements. As is evident from these examples, old earth structures have a much longer lifetime than other engineering structures. To simplify the issue we will not touch on the problem of pore-pressure development, which takes place shortly after the end of the construction of earth structures, rather we will consider the long-term behaviour, when the pore pressures are steady with respect to the stress-field changes, due to the construction of the earth structure.

Earth structures are increasing their strength and stability with time, as is clear from the age of the examples mentioned above. However, this is only true if the conditions for the internal and external erosion limit states are fulfilled. In most cases this improvement is given by the strengthening of the inter-particle connections, and in this improvement the composition of the liquid phase plays a significant role. Unfortunately, a change in the chemical composition of the liquid phase can significantly affect the potential risk of an earth-structure collapse. A classic example of such a negative change is the “quick clays” from Norway, where the fresh water washes out the salt that was present during the deposition of the clay layers on the sea bed.

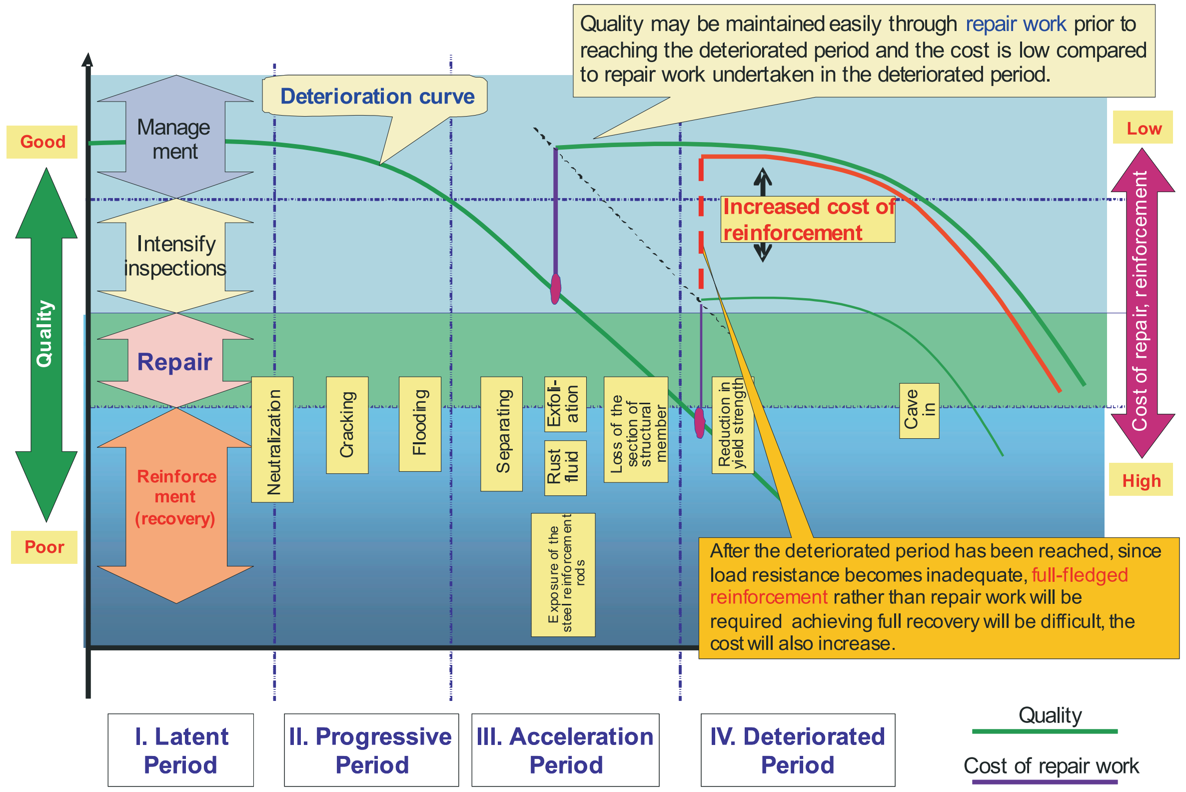
A completely independent problem is associated with the weathering of the surfaces of geotechnical structures, such as the slopes of excavations or tunnels without linings. Here, the most significant role is played by the stress change due to unloading, which can initiate the opening of micro-cracks and start the process of physical weathering. In the case of foundation engineering we do not have any examples of the deterioration of the ground underneath shallow foundations or around deep foundations. The problems of the aging of geotechnical structures are therefore mainly becoming the same as the problems of ageing with other structures, e.g., concrete structures like foundations, retaining walls, and tunnel linings. In this paper we will concentrate on an example of the last of these, the deterioration of the tunnel lining of the Prague Metro. In our case the monitoring is not directed at determining the potential risk of collapse, rather it is to confirm that the tunnel is still in a stable state and to help us determine the appropriate moment to schedule minor repairs in order to significantly extend the expected lifetime of this underground structure. As an example, we can use the approach to this problem mentioned by Soga [1] (see Figure 1).

With underground structures there is always the problem of access, which is leading to the use of remote monitoring based on wireless technology.

2 BRIEF DESCRIPTION OF THE PRAGUE METRO

The design of traffic flow in Prague on two vertical levels started as early as 1898, when a Prague entrepreneur, Ladislav Rott, submitted the first proposal to build an underground railway to improve the traffic connections in the historic district of the city. In 1912–1941 a series of plans for new routes of the underground railway were developed; however, these plans were never implemented (see Figure 2). Starting in 1958, the design of an underground railway using a system of subsurface trams with a subsequent transition to metro trains began to be developed.

In 1967 the final decision to begin the construction of the Prague Metro was made. On 20 January 1969, driving operations on the first underground tunnel were launched, and on 9 May 1974 regular passenger operations began on the first line of the Prague Metro – line C, 6.57 km in length, and with 9 stations. One of the most recent metro sections put into operation was the



Quality may be maintained easily through repair work prior to reaching the deteriorated period and the cost is low compared to repair work undertaken in the deteriorated period.

After the deteriorated period has been reached, since load resistance becomes inadequate, full-fledged reinforcement rather than repair work will be required achieving full recovery will be difficult, the cost will also increase.

Figure 1. Life cycle of an ageing structure.

extension of line C as far as Ládví Station: two additional stations and a length of 3.981 km. The highlights of this section are the first double-track driven Metro tunnel (Figure 3) and Prague's first single-nave driven Kobylisy Station, which is also the deepest station on line C, being situated 31.5 m below ground.

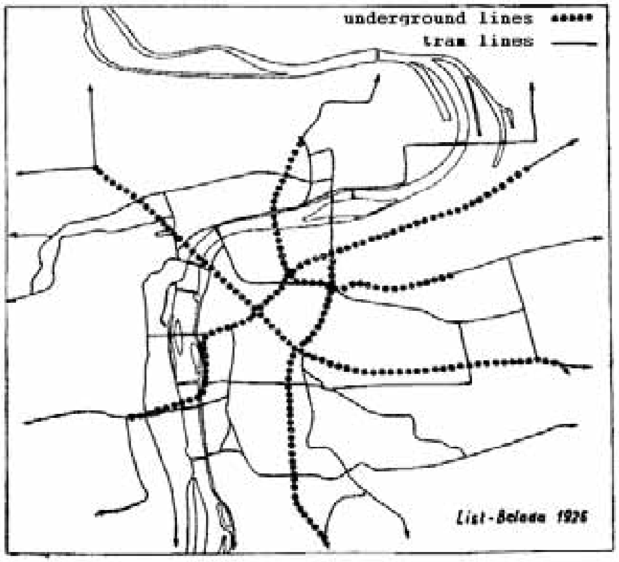


Figure 2. Plan of an underground railway network designed by Vladimír List and Bohumil Bellada in 1926.

The Prague Metro system presently (Jan 2008) operates 3 lines (A, B, C) with 54 stations and a total length of 54.7 km (see Figure 4 on next page). Line A has 13 stations and is 11.0 km long; line B is the longest, with 24 stations and a length of 25.7 km; and line C has 17 stations and is 18.0 km in length.

2.1 GEOLOGY

The area of interest in the vicinity of metro lines A, B and C is predominantly formed by sedimentary rocks from the early part of the Paleozoic era (during the Ordovician period), but also partly from the later part of the Proterozoic era, which are overlaid by soils of quarternary superficial deposits and made ground [2].

2.1.1 Bedrock

The tunnelled sections of the Prague Metro pass through a vast complex of sedimentary rocks of the Barrandien, from the late Proterozoic to the early Paleozoic eras, with the most numerous locations from various formations of the Central Bohemian Ordovician period. The entire succession of strata shows the predominance of clayey, silty-to-sandy shales and siltstones with different physical and mechanical properties and a varying degree of tectonic failure. The bedrock is also rich in sandstone-

Figure 3. Double-track metro tunnel on line C.

Figure 4. Present system of the Prague Metro's lines.

to-quartzite rock types, with the sporadic occurrence of subsurface forms of paleovolcanic activity. The whole area was intensely folded and tectonically deformed. One example is Můstek Station, in the city centre, the point of a prominent tectonic failure – the so-called Prague fault – where clayey-to-sandy shales of Šárka strata and quartzites and siliceous sandstones of Skalka strata are found. This area was subject to intensive tectonic failures, and the rocks are heavily fragmented into chips or cuts. The tunnelling operations here faced many difficulties.

2.1.2 superficial deposits

Over the whole territory, the bedrock is overlaid by soils of superficial deposits. In the central part of the city, in the flood plains, these are mainly fluvial terrace deposits of the lowest Vltava River terrace benches, which are composed of sands and sandy gravels. Their thickness ranges from 6 to 12 m, and sporadically up to 18 m.

The overlying stratum of the terrace deposits contains Holocene alluvial plain deposits. Predominantly, they take the form of fine sandy, loamy and clayey sediments, at places with organic interlayers and separate horizons of re-deposited sandy gravels. The thickness of this alluvium is generally 1–3 m, and exceptionally up to 8 m.

Outside the flood plains, in the areas now occupied mainly by the outskirts of the city, there are eluvial, deluvial and deluvial-fluvial sediments, consisting predominantly of clayey-to-sandy loams, often with fragments of underlying rock.

A part of the territory is also covered by eolian deposits, reaching up to several metres in thickness, as well as loess and loess-like loams.

Close to the surface of the territory, man-made deposits are often found – backfill, made ground, and the remains of structures – with thicknesses of 1–5 m, and occasionally even greater.

2.1.3 Hydrogeological situation

The hydrogeological situation directly reflects the complex geological composition of the geology of Prague. There are groundwater horizons with distinctively different characteristics of the hydrogeological regime. In the sands and gravels of the lowest Vltava River terraces with considerable pore permeability, there is a continuous horizon of groundwater that can be called alluvial water. In other covering formations, groundwater of the pore type with an unconfined level is found. Another groundwater horizon is found in the bedrock of the predominantly Ordovician sedimentary rock mass. This is mostly a very poorly permeable-to-impermeable medium with fissure permeability. Here, the water also tends to show increased aggressiveness, mainly of the sulphate type.

2.2 CONSTRUCTION OF THE PRAGUE METRO

The tunnelling methods used during the construction of the Prague Metro had to respect the difficult geological conditions of Prague and minimize the impact on the structures on the surface, mainly in the historically valuable parts of the city. The rock was excavated mainly by blasting. The horizontal transport of the spoil was mostly by rail, and the vertical transport made use of winches in the access shafts.

The running tunnels were built using the following technologies:

a) The "Prague" ring tunnelling method with an erector (in the solid rocks),
b) The non-mechanized tunnelling shield (in the soft rocks and soils),
c) The mechanized tunnelling shield TCSB-3 (Soviet made),
d) The NATM method (from the 1980s),
e) The cut-and-cover technique,
f) The immersed tunnel (used for Vltava River crossing at Nádraží Holešovice)

2.2.1 The "Prague" ring tunnelling method

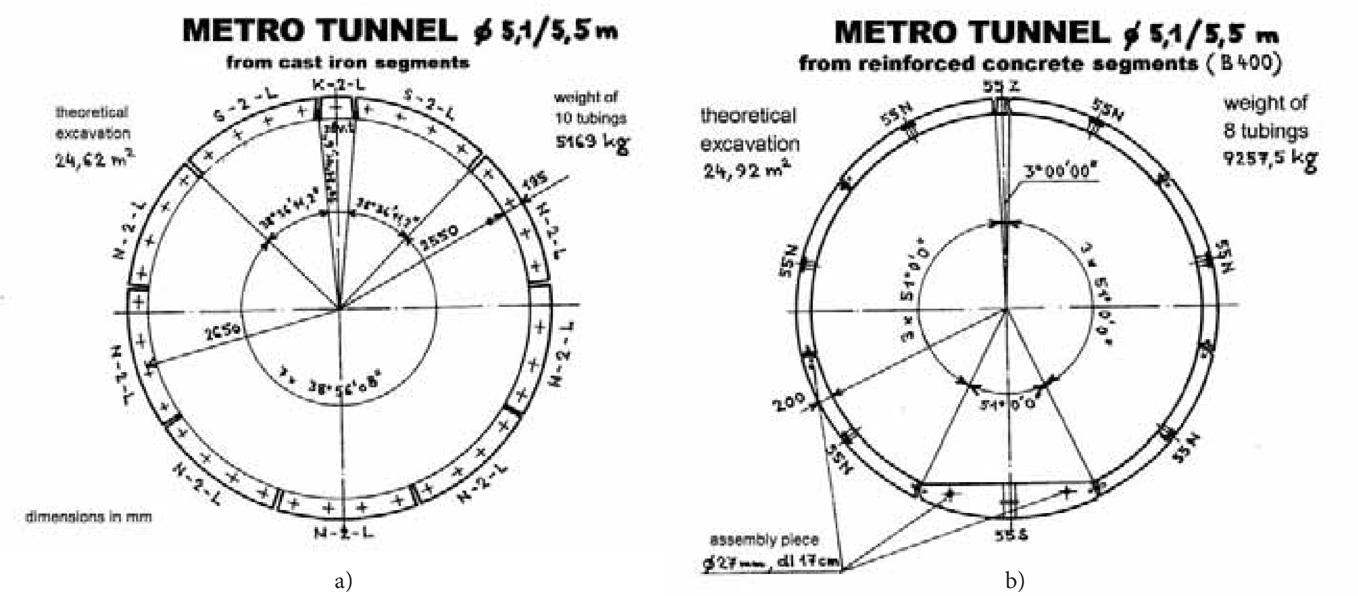
This method used an erector for the mechanical assembly of the lining from cast-iron or reinforced-concrete segments (Figure 5) in the blast-excavated tunnel. The prefabricated lining was activated against the rock mass by injection filling; the protection against water in the reinforced concrete segments was made by sealing injection, and in the cast-iron segments the calking of joints was used.

2.2.2 The non-mechanized tunnelling shield

The excavation of the tunnel made use of a shield with an Alpine roadheader (see Figure 6 on next page). This method also used mechanical assembling of the lining from cast-iron or reinforced-concrete segments. The activation of the tunnel lining and the water sealing of the tunnel was done in the same way as for the "Prague" ring tunnelling method.

2.2.3 The mechanized tunnelling shield TSCB-3

This shield had a full-profile cutting head for the tunnel excavation, and compressed concrete was used as the lining (see Figure 7 on next page). The tunnel was excavated by a tunnelling machine in full profile. The tunnel lining was created with concrete that was placed between the formwork and the excavated rock. The tunnelling



a) b)

Figure 5. Cross-section of the tunnel with a) cast-iron segment b) concrete segment [3].

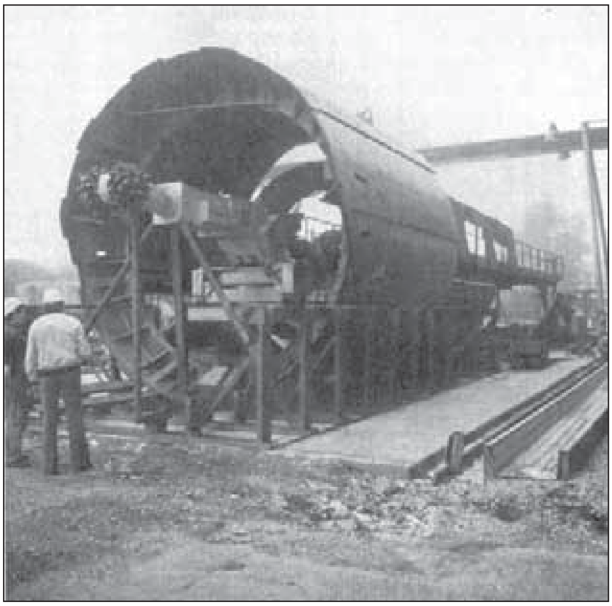


Figure 6. Open shield with roadheader.

machine (shield) was moved forward by pushing the pressing ring, using hydraulic jacks, against the just-concreted lining, which creates a highly compressed concrete tunnel lining.

2.2.4 The NATM method

This method was first used in the 1980s and is typical for a two-shell lining – the primary lining is made from shotcrete and the secondary lining is made from monolithic reinforced concrete, with a sealing in between (see Figure 8).

2.2.5 The immersed tunnel

The basic principle of this technique consists of constructing individual tubes in a dry dock, which was dug in the Troja bank at the location of future tunnels (see Figure 9) [7]. When the concrete structure of the tube was completed, the internal balance tanks and the

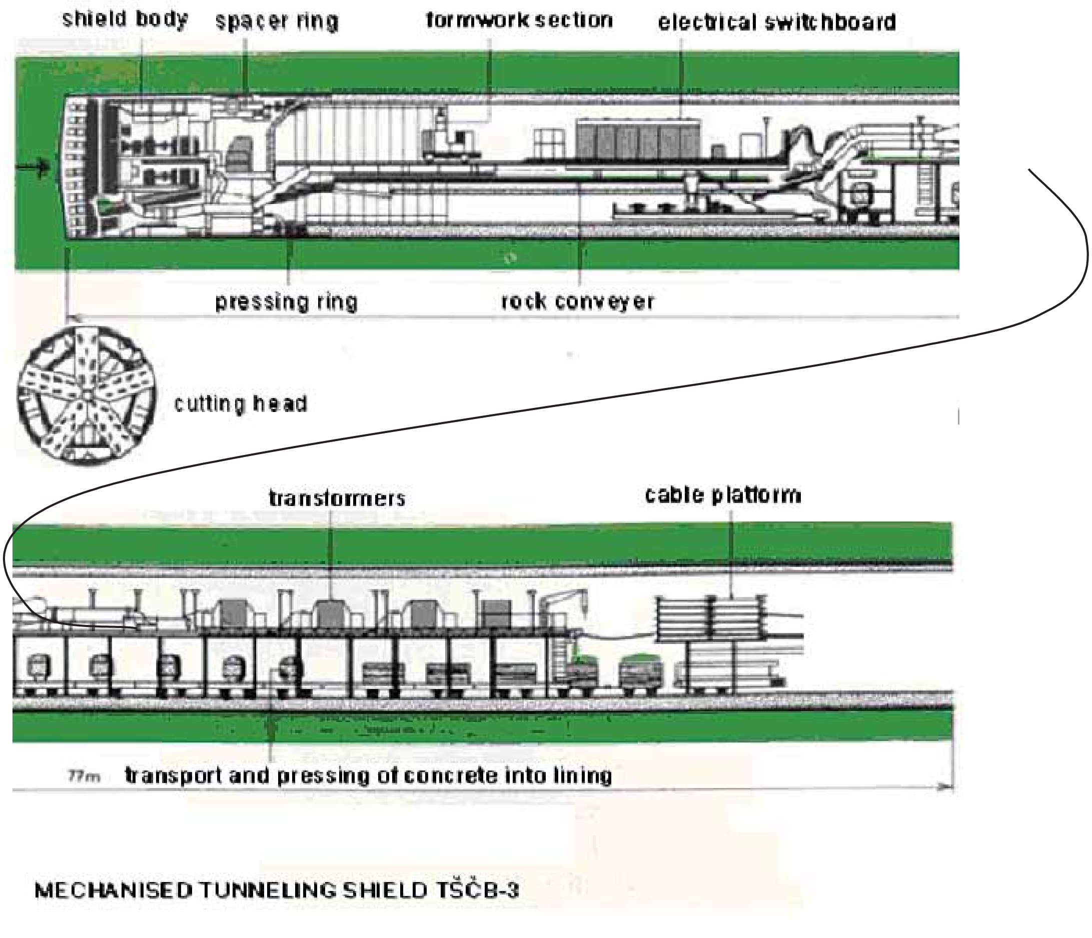


Figure 7. Cross-section of the mechanized tunnelling shield.

Figure 8. The building of the Kobylisy station.

Figure 9. Immersed tunnel – the concrete tube still in the dry dock.

steel bulkheads at both ends were installed. A suspension system was connected to the tubes in the form of anchoring elements cast into the tubes. After the installation of the tunnel outfit the dry dock was then flooded, allowing the shifting of an individual tube into its final position in a trench dug in the river bed. Two tow steel cables anchored on the opposite bank drew the tubes forward. The rear support of the tube, sliding along the track, carried the major part of the weight, and ensured the stability of the whole body. When the support in the Holešovice bank was reached, the tunnel position was stabilized, and then the tunnel was fixed to the river bed by anchoring.

2.2.6 Details of section Vltavská-Nádraží Holešovice

Both tunnel tubes were driven using the "Prague" ring method. During tunnelling an overbreak (approximately 50 m^3) developed under a railway-car repair shop, with a consequent depression in the surface. The hollow space was filled with concrete, but the construction was delayed for 6 weeks.

2.3 THE INFLUENCE OF THE FLOODING IN 2002 ON THE PRAGUE METRO

The first rainfall struck parts of the Czech Republic on 6–7 August 2002, affecting mainly Southern Bohemia, and to a minor extent West and Central Bohemia and Southern Moravia. The second rainfall came between 11 and 13 August 2002. This time the entire territory of Bohemia was struck, and on 13 August there was heavy rainfall mainly in Eastern Bohemia, including the Orlice Mountains and parts of Northern Moravia.

The August flood in the Czech Republic took a relatively unusual course, unprecedented in the past. During a relatively short time, two flood tides were generated.

The rise of the first flood wave on the Vltava River was, to a large extent, eliminated by the reservoirs of the Vltava River cascade, so that the flood flow recorded in Prague reached only a five-year high. At the same time, considerable saturation of the affected territory occurred during this first flood wave, leading to the exhaustion of its retention capacity. This is why the start of the second flood surge was followed by a rapid rise in the water levels on watercourses and in reservoirs. The subsequent flood on the Vltava River was the result of a collision between the flood wave from the Vltava River cascade and the flood wave from the Berounka River. The resulting flood wave on the Vltava River in Prague occurred on 14 August 2002 at 12:00, with a water level of 782 cm and a discharge of 5130 m^3.s^{-1}, which is a value corresponding approximately to a five-hundred-year flood. It was the most devastating natural disaster recorded in Prague since 1827 (see Figure 10).

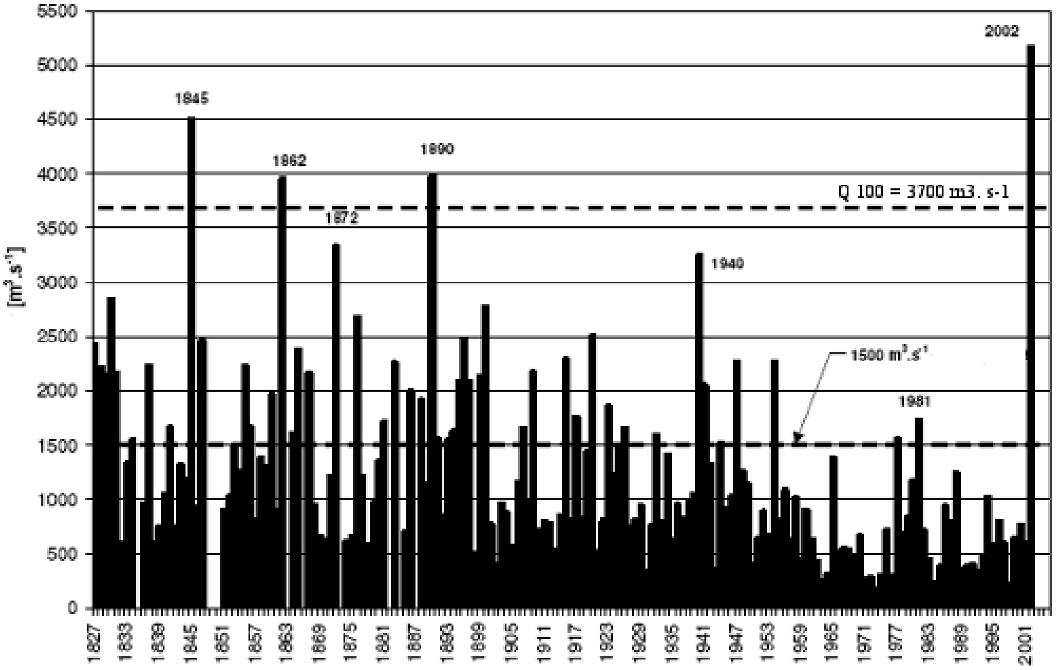


Figure 10. Floods on Vltava River, 1827–2002 [4].

The Prague Metro was flooded for approximately two days, from the evening hours of 13 August 2002 to the afternoon hours of 15 August 2002. The following sections of the Prague Metro were flooded:

Line A – for a length of about 3.8 km, including 4 stations (total operating length of 10.0 km, including 12 stations)

Line B – for a length of about 11.2 km, including 12 stations (total operating length of 25.7 km, including 24 stations)

Line C – for a length of about 2.3 km, including 3 stations (total operating length of 14.1 km, including 15 stations)

At that time (August 2002), the metro had a total of 51 stations, of which 19 were completely flooded (see Figure 11). The total volume of water in the stations and tunnels was estimated to be about 1.2 million m^3.

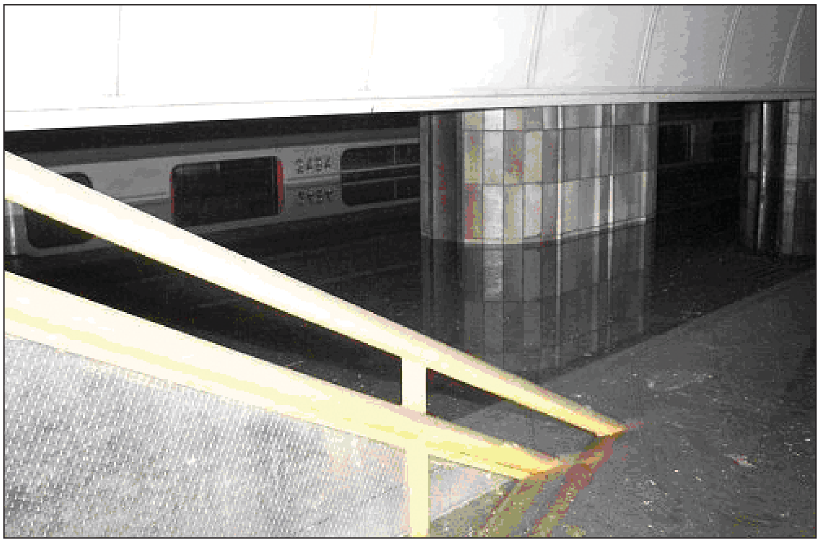


Figure 11. Submerged metro train in Florenc Station (after some of the water had been pumped out).

The conclusions from the inspections carried out after the events of the flooding, which were part of the investigation into the causes of the flooding, showed that the main structural systems of the metro were not affected by the flood [2]. The only affected systems were the non-structural ones, like floors, partition walls and facings. Also, there was some damage to the steel linings of the ventilation shafts and at localised points that suffered greater levels of water infiltration. During the walkovers the inspection teams also found some older faults, which had not been caused by the floods and which did not affect the serviceability or the stability of the running tunnels. The teams of experts stated that the metro system was, in general, safe for operation.

More details of the history, geology and construction systems of the Prague Metro have been described by Romancov [5].

This flooding accident clearly demonstrated the need for remote wireless monitoring, as the decision about the speed with which the water should be pumped out of the metro tunnels was connected with some uncertainties relating to the safety of the Prague Metro's underground structure.

3 MONITORING THE PRAGUE METRO

The research activity of monitoring the underground structures of the Prague Metro started in the frame of the European research project Micro-Measurement and Monitoring System for Ageing Underground Infrastructures (Underground M^3), with the Engineering Department of Cambridge University as the project leader. The experiences gained during the first monitoring stage from the Prague Metro will be used for metro systems in London, Barcelona and Madrid. As a result, representatives of these metro authorities were also involved in the project, because close cooperation is a necessity when monitoring these tunnels.

After a detailed visual control carried out on several kilometres of the Prague Metro's tunnels, the most appropriate places for locating the instrumentation were selected. Different methods for the monitoring measurements were proposed, agreed on, and are described in more detail below.

The tunnel lining of the Prague Metro is affected by cracking at different locations (see Figure 12). The tunnel section Vltavská–Holešovice at the chainage 18+725 km was selected for the pilot instrumentation as part of our monitoring project. The techniques selected for this pilot consist of traditional macro-scale measurements, geophysical measurements as well as wireless data collection and transfer [8].

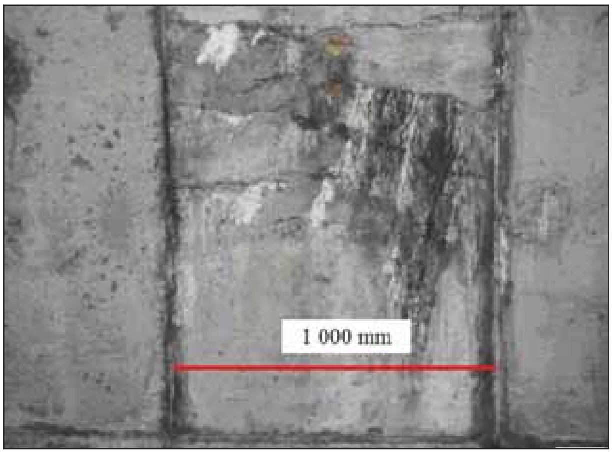


Figure 12. Set of cracks in the tunnel lining on line C.

3.1 MACRO-MONITORING

For the macro-scale measurements we determined the following requirements:

a) The monitoring of the overall deformation of the selected tunnel section should determine whether the development of the deformation is either important or negligible for the characterization of the tunnel lining's behaviour and for the numerical modelling of the stresses' distribution and the ageing of the lining.

b) The monitoring of the lining detail affected by the cracks should determine the crack activity and provide a basis for the cross comparison of the monitoring results on the "macro" and "micro" scales.

The macro-scale instrumentation was designed in two stages (see Figure 13 on next page). Standard methods of monitoring were used in the first stage of the instrumentation. The monitoring was based on convergence type measurements and the application of a portable tilt meter.

For the second stage, Geokon crack-meters were selected because of their long-term stability with respect to the requirements stated in point b), above.

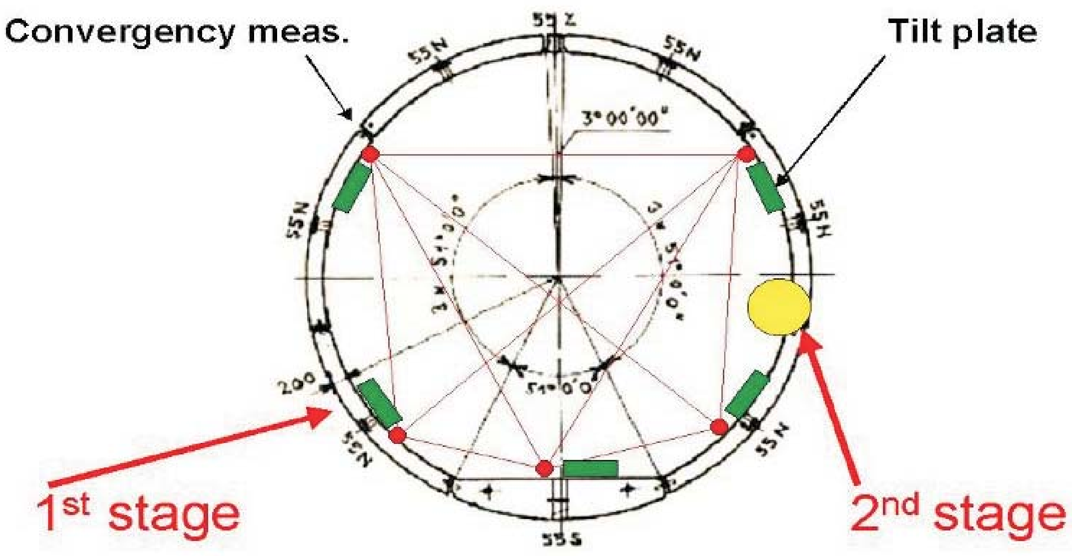


Figure 13. Typical section of the tunnel lining and the placement of bolts and plates (second stage = crack-meters).

To begin the strain monitoring, a segment with a “simple” crack was selected. The instrumentation for the overall deformation monitoring of the lining (stage 1) was completed at the end of 2006. The measurements indicate very small variations in the measured values, mainly due to seasonal variations rather than due to any deformations of the tunnel. The repeatability of the measuring equipment is better than 50μm for the convergence measurements, better than 40 arc seconds for the tilting, and better than 3 μm on the 300-mm base of the crack-meter.

3.2 GEOPHYSICAL MONITORING

3.2.1 In the tunnel

The geophysical systems for determining the structural condition using MEMS (micro-electro-mechanical systems) sensors that are now implemented in the Prague Metro use two different techniques. The first technique is seismic velocity sampling; this is based on measurements of the elastic wave velocity passing through the tunnel lining. The other technique is an analysis of the time-development frequency spectra of the structure’s vibrations under traffic loads. For seismic velocity sampling we used MEMS accelerometers that are attached to fixed points on the lining in a 200 x 200 mm grid. Figure 14 shows a view of the final arrangement of the monitoring profile. The accelerometers measure the response to the other fixed points’ excitation. The damping of the signal represents a potential gap or crack within the lining. In this way it is possible to determine the locations of cracked zones of different sizes. These measurements are carried out during night inspections at more or less regular intervals, and the changes in the responses are compared so potential micro-crack development can be detected. The disadvantage of this method is the need for physical access to the measuring location in order to take the measurements, because there is no automatic system for the excitation of the lining at the fixed points. As the fixed points on the measurement profile were installed in the region of visible cracks, we will be able to monitor the changes with time and hence the rate of deterioration of the structure.

An example of the successful use of this technique, for the location of weak zones in the old masonry tunnel lining of the sewerage system in Prague, was presented by Macháček and Barták [6].

The analysis of the time-development frequency spectra of the structure vibrations under traffic load uses geophones installed in the Prague Metro’s lining measurement profile (see Figure 14). The geophones measure the development of changes in the frequency spectrum and the damping parameters of the tunnel lining with time. These measuring points are inaccessible while the tunnel is in operation, due to traffic loads;

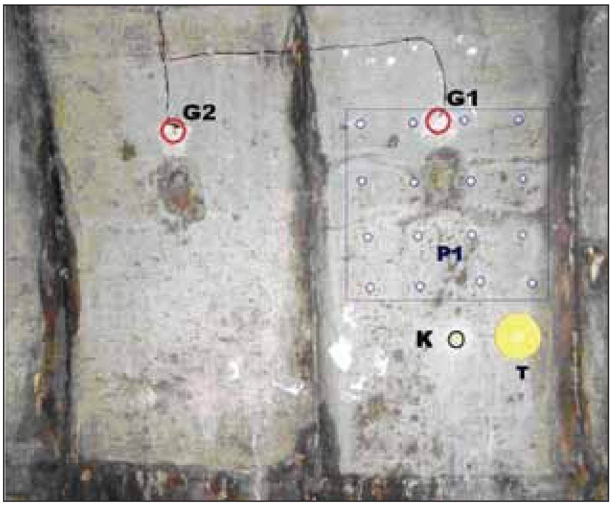


Figure 14. Final arrangement of the monitoring profile.

G1 = monitoring geophone
G2 = reference geophone
P1 = field for seismic velocity sampling
K = convergence bolt
T = tiltmeter plate

therefore, a remote data-collection system is required. For the time being we are using long cables running from the measurement point to the station, where it is possible to gather the data instantaneously during the metro's operation using a high-sensitivity digital oscilloscope. Using this technique we want to obtain a direct relationship between the measured data and the deterioration status of the lining.

3.2.2 In the laboratory

In parallel with the monitoring in the Prague Metro's tunnel we also started to study the dynamic response accelerograms of a reinforced concrete slab in laboratory fatigue tests (see Figure 15).

We measured the acceleration of a single point movement at one-third of the span of the specimen's supports. Our main concern was the development of changes with time in the course of deformations, as there is no doubt that the specimen must gradually lose its elasticity with the increasing number of loading cycles it has undergone. As the laboratory test is currently only half way through, there is not yet enough data to process and determine the overall degree of deterioration of the slab. However, there are results from accelerometers that indicate some ageing of the tested member, and the results from the frequency spectra analysis indicate some fatigue development. At the time of writing there is no visible macroscopic failure whatsoever on the specimen.

3.3 WIRELESS MONITORING

Another part of the monitoring project is to deploy a wireless system for data collection and transfer from the tunnel to the monitoring office. The aim of the wireless system is to reduce the amount of wiring in the tunnels, in order to collect the data from monitoring points and also because the wires in the tunnels are affected by the strong electromagnetic fields that are present there. Another advantage is that the system is redundant, and so even if some points fail the system will continue to work. It is also possible to insert additional monitoring points if this will be required in the future.

a) b)

Figure 15. The experimental arrangement (a) and the measuring line (b).

Up to now we have installed a pilot network of wireless points with temperature and light sensors in the vicinity of a metro station. The wireless monitoring points are configured around Intel motes working on a ZigBee platform (see Figure 16). This pilot installation serves several purposes, including being able to define the optimum distances between points to be able to guarantee the redundancy in the system for safe data collection at real locations. Another reason for the pilot is to determine if the system will interfere with wireless systems already being deployed in the Prague Metro for signalling purposes. We discovered during the initial stages that the optimum distance for the conditions in the Prague Metro's tunnels is about 15m, and that from the reliability point of view we should employ at least 2 to 3 motes in every profile along the tunnel.

Last, but not least, is the issue of how to wirelessly transfer the data from the tunnel to the monitoring office, in order that the data can be available in real time. The wireless monitoring system has a gateway in an embedded PC that is connected to the internet and hence to the monitoring office via a multi-protocol router. The router and the gateway are placed in a single box that is fixed to the tunnel lining. For the time being the transfer system is based on the mobile-phone GPRS platform, as the stations in Prague are covered by the mobile-phone signal and there is a plan to cover the tunnels in the near future. This system was not very stable at the beginning, mainly because we tried to find the longest possible distance from the station, where we could still achieve a good and reliable connection. We discovered – which should not have been a surprise – that the GSM signal is also affected by the electromagnetic fields in the running tunnels. For this reason we have chosen a location closer to the station and better antennas have been selected.

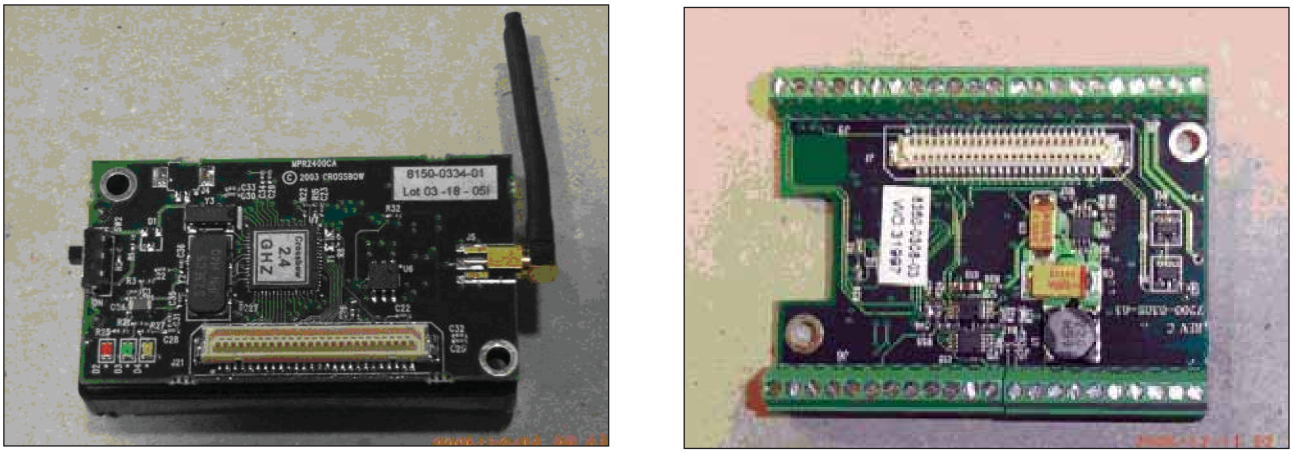
4 A BRIEF ASSESSMENT OF THE MOST UP-TO-DATE RESULTS

Our monitoring showed that even for a highly cracked lining the behaviour is very stable, as there we monitored mainly just the seasonal effects on the lining, more so than anything else. The geophysical measurements from the tunnel showed, in combination with the laboratory measurements, that the lining is in a stable state and is not approaching the acceleration period (see Figure 1). We can also say that the wireless approach to monitored data collection and transfer selected for the Prague Metro seems to be both reliable and useful.

Our experience leads us to believe that in the near future we will be able to achieve results on the micro-scale deformation measurements in the range of 10^{-4} mm and then be able to use those results for a comparison with numerical modelling using creep models and the theory of micro-crack development for concrete.

5 CONCLUSIONS

This paper is a reaction to the demands of infrastructure owners who want to determine the quality of their structures and the potential risks posed by the aging of those structures. Three different approaches to the evaluation of this problem, applied to the Prague Metro, are described in detail. Firstly, we have direct deformation measurements; secondly, we have geophysical methods of monitoring that utilise the vibration response to train passes and manual excitation, and, thirdly, we have wireless technology for data collection and transfer. The



a) b)

Figure 16. Main board of the wireless mote (a) and the circuit board of the A/D converter.

latest results indicate that the Prague Metro's tunnel lining is in very good condition; nevertheless, some additional features should be added for subsequent long-term monitoring.

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