Monitoring of tunnel lining deformation and deterioration

Surveillance de déformation et de détérioration de doublure de tunnel

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ABSTRACT

In recent years the infrastructure owners are getting more involved in the determination of the level of deterioration of underground infrastructure in order to predict future performance and to optimize the plan of care (repair, refurbishment, reconstruction). Especially the tunnels for transport infrastructure are of the most importance. Therefore international research project was established to study these effects. In Prague metro tunnels monitoring of tunnel lining deformation and deterioration started in 2006 and the results of these monitoring activities are presented in this paper. The monitoring techniques used are wide from traditional convergence measurements, through crack behaviour monitoring by crackmeters, geophysical observation of lining segment properties changes in time by geophones and velocity sampling method to novel monitoring techniques like micro sensing using MEMS sensors – strain gauge and inclinometer, computer vision – comparison of photos / videos from the same location in time to detect new cracks and movement of existing ones. All possible monitoring techniques were combined into system of wireless data collection and transfer for further evaluation. The wireless system is very useful to avoid regular visits in the tunnels for data collection and can provide online data during some critical events. The monitoring methods mentioned in this paper proved to be useful for the purpose of determination of the tunnel lining deterioration.

RÉSUMÉ

Ces dernières années les propriétaires d'infrastructure commencent a etre davantage impliqués dans la détermination du niveau de la détérioration de l'infrastructure souterraine afin de prévoir la future exécution et optimiser le plan du soin (réparation, rénovation, reconstruction). Particulièrement les tunnels pour l'infrastructure de transport sont tres importants. Par conséquent le projet de recherche international a été établi pour étudier ces effets. Dans des tunnels de métro de Prague la surveillance de la déformation et de la détérioration de doublure de tunnel a commencé en 2006 et les résultats de ces activités de surveillance sont présentés en ce document. Les techniques de surveillance utilisées sont larges des mesures traditionnelles de convergence, par la surveillance de comportement de fente par des mètre de fente, observation géophysique des changements de propriétés de segment de revêtement de temps par des géophones et de méthode de prélèvement de vitesse aux techniques originales de surveillance comme la détection micro utilisant des sondes de MEMS - jauge de contrainte et inclinomètre, vision d'ordinateur - comparaison des photos/des vidéos du même endroit à temps de détecter de nouveaux fissures et mouvement de celles existantes. Toutes les techniques possibles de surveillance ont été combinées dans le système de la collection des données sans fil et transfèrent pour davantage d'évaluation. Le système sans fil est très utile pour éviter des visites régulières dans les tunnels pour la collecte de données et peut fournir des données en ligne pendant quelques événements catasthropiques. Les méthodes de surveillance mentionnées en ce document se sont avérées utiles pour la détermination de la détérioration de doublure de tunnel.

Keywords: Structure ageing, deterioration, monitoring, metro, underground

1 INTRODUCTION

Ageing of structures represents a general problem and have a little bit different undertone for individual types of structures. At present day there are millions of civil engineering and building structures, where design serviceable life is usually defined in the range of 70 – 120 years (Vaníček & Vaníček, 2008).

Underground structures have specific properties, they are much less accessible and relevant state verification is more complicated. For very good rock massive the dome-shaped roof of the tunnel, gallery, underground spaces generally can be composed directly by this rock massive, sometimes strengthened e.g. by anchors. But for the majority of the underground structures the dome-shaped roof is composed by concrete lining. The basic manifestation of changes on such structures is directly connected with deformation – of all profile, in local cracks or micro cracks on the concrete surface. The chemical degradation of the surface is another manifestation. However changes in the inter particle bonds are not visible on the surface and for theirs observation supplemental methods of monitoring were applied, as non destructive, physical methods.

The problem of life time expectancy has two main aspects - the ageing of respective structure and ageing of internal technology. For some structures the life expectancy can be comparable with life time expectancy of technology as for different stores, supermarkets and so on. Generally for more expensive and difficult respective structure the life time expectancy is longer and during this time the technology can be substituted more times. This case is well known even for building structures, where services can be reconstructed number of times, starting from sanitary facility, kitchen and ending with electrical installation (Vaníček I et al, 2008).

For underground structures this fact is obvious. Basic element – respective tunnel profile with lining – has much higher life expectancy than the technology as e.g. ventilation, safety installation. Understanding of life time expectancy for respective structure or the determination of the phase in which the structure occurs is very important namely for:

- Determination of expected life time expectancy, which can be fundamentally higher than above mentioned 120 years. For underground structures it is not so easy to speak about demolition and about substitution by completely new struc-

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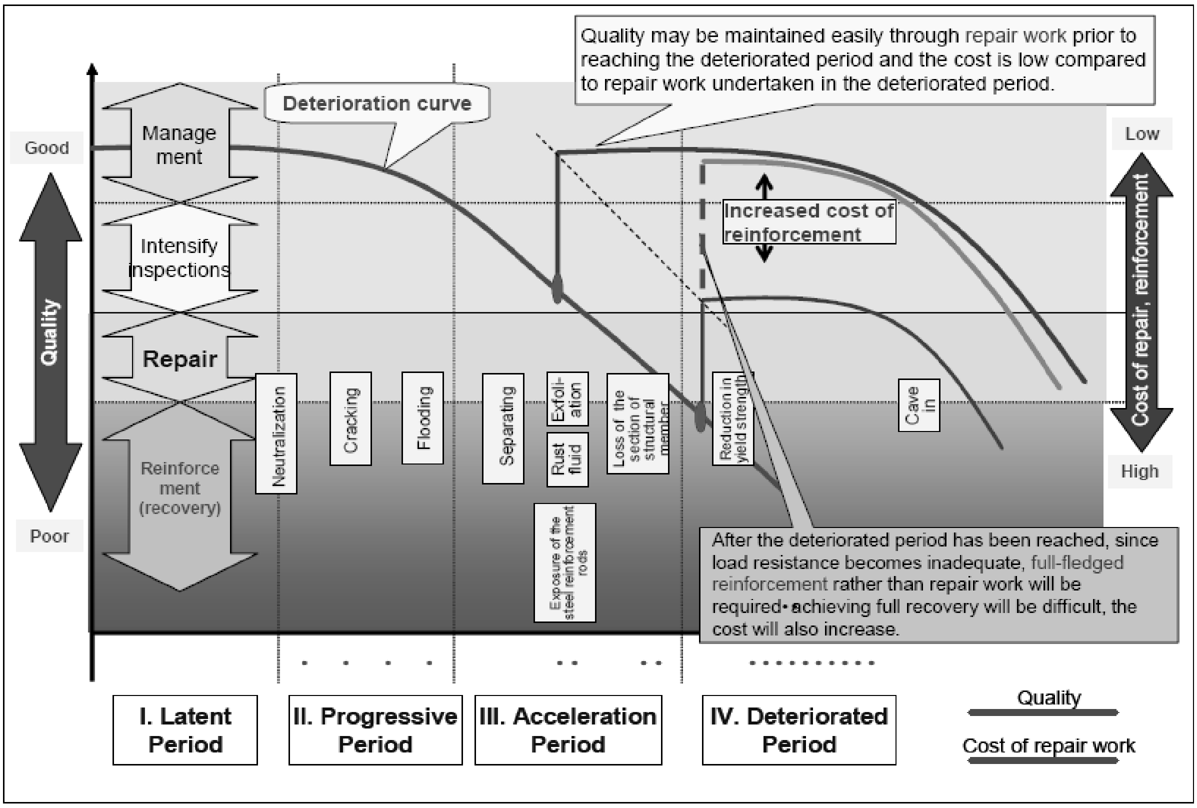

Figure 1: Life cycle of ageing infrastructure. Maintenance, Inspection and Repair. (according to Soga, 2005).

tures. Determination of longevity can significantly help to the planning of the metro system development, including Prague.

- Determination of the particular quality of the respective structure, the phase in which is now, can help us to define the optimal time for reparation or reinforcement.

Theoretical curve of ageing – quality as function of time – is shown in Fig. 1 (Soga, 2005). Two time segments are specified there in which the action to prolong the life time expectancy can be applied.

For the first one duality can be maintained easily through repair work prior to realizing the deteriorated period and the cost is low compared to repair work undertaken in the deteriorated period. For the second one, after the deteriorated period has been reached, since load resistance become inadequate, full fledged reinforcement rather than repair work will be required, achieving full recovery will be difficult, the cost will also increase. Therefore the determination of this curve is so important, to define optimal time for repair work, not to leave the structure to pass the boundary when the strength can decrease under acceptable limit.

However this theoretical curve is valid for general situation when outer loading is close to constant or is changing in expected dimensions. But this curve does not represent significant change in loading, as it was for example for Prague metro during flooding parts of tunnels during heavy floods in 2002 (Chamra, 2006). Significant change can be caused by earthquakes in some regions. But we cannot forget on common situation in large cities when existing underground structure is influenced by other objects on the surface, by other lines of metro, by underground garages, constructed in the vicinity. Loading state can be changed also e.g. by failure of pipelines, as result of pore pressure changes, erosion of soil particles etc.

From the above mentioned it is clear that the initial state of the respective tunnel, which existed before this significant change of loading is important. After that we can more easily distinguish this differences and changes closely specified.

Presented paper is focused on the above mentioned aspects, namely for metro in Prague.

2 SELECTION OF MONITORING PROFILES

When selecting the most appropriate profiles for monitoring, first of all we based this on the visual tunnel inspections done within current and past walkovers through metro tunnels. At the same time we wanted to monitor behaviour of different tunnel lining types that are used in Prague metro. Within monitoring framework we therefore included both section tunnelled using the “Prague” ring tunnelling method with lining from precast reinforced concrete segments and section tunnelled using mechanised tunnelling shield with lining from “press” mass concrete. Other facts like geology with its tectonics were main deciding factors for precise selection of monitoring profiles.

For the profile 1 the bedrock rocks are formed of ordovic letenské layers within flysch formation. This is characterised by interlaying of weaker rocks (clayey-silty schists, siltstones) with hard to very hard rocks (quartzite, siliceous sandstones, siliceous gray wackes). The profile’s depth below surface is about 12.6 m and on the lining there are visible network of fine and thick cracks.

The tunnel lining in profile 2 is composed of mass press concrete of 345mm in thickness. The bedrock rocks are formed of highly tectonically cracked zahořanské, bohdalecké and dobrotivské layers composed mostly from clayey schists. Through selected section is passing one of the main tectonic lines of Barrandien – so called Prague fault of 20 m in width.

3 CONVENTIONAL METHODS OF MONITORING OF LINING DEFORMATION

Testing profile 1 was selected as a base of monitoring. Conventional monitoring was divided into three main stages also with respect to the character of the selected profile, see Fig. 2 and 3:

- In the first stage it was portable tiltmeter and deployment of tilt plates, convergence measurements by tape in between installed convergence bolts for measurements of overall profile deformation together with lining and air temperatures;
- In the second stage monitoring of cracks behaviour by crackmeters;
- In the third stage providing a base for future long-term testing of developed micro-strain MEMS.

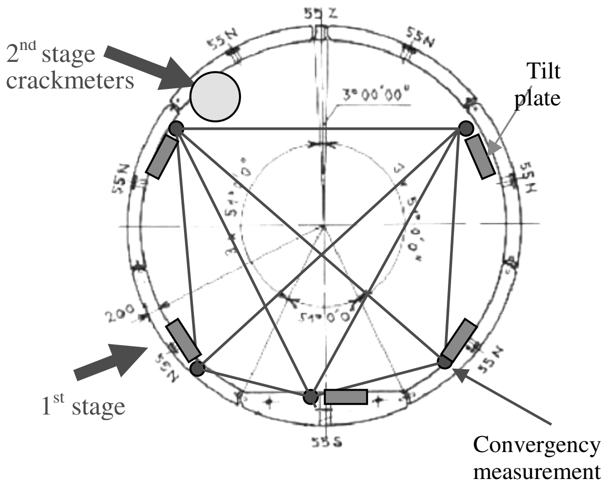

Figure 2: Placement of tilt plates, convergence points and crackmeters in profile 1

Figure 3: View of the test section 1, direction Vltavská station (tilt plates are presented by yellow circles and cracked lining segment by red ellipse where crackmeters, geophones and inclinometers are installed)

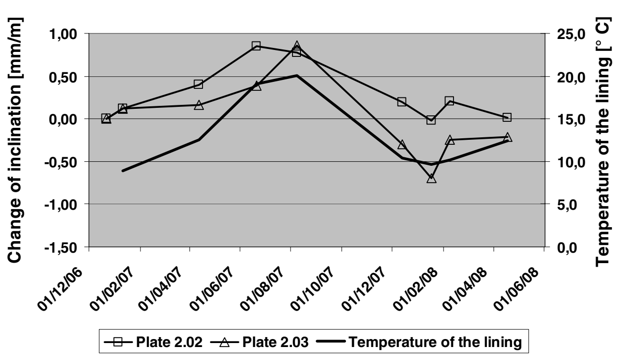

Figure 4: Results of tilt changes monitoring – plates parallel to the tunnel crown

Convergence methods were used for checking of the old tunnel profile deformation in time. The measured deformations were in the range of precision of measuring method (about 0.01 – 0.05 mm) for the monitoring period of two years. The most visible results of profile deformation were proved by tiltmeters, however the deformations in time approximate the temperature changes curve – Fig. 4.

Conventional methods of monitoring proved that selected profile even showing some marks of deterioration is stable; measured deformations are on the highest measurements sensitivity boundary. However pointed out on significant thermal sensitivity of the concrete tunnel lining which can result in faster deterioration of it, especially in case of evidence of active crack system (Bubeníček et al, 2008).

4 GEOPHYSICAL METHODS OF TUNNEL LINING MONITORING

Geophysical methods are aimed at monitoring changes in structural materials related to their ageing during their operating performance. These changes are generated either by physical and chemical conditions of the environment where exposed structures are mounted or by the type of loading which accelerates the process of material degradation.

In terms of their observation scale, therefore, these methods are detailed methods. They are expected to be able to indicate the very first signs of building structures' failure due to their ageing, both under current operating conditions and during extraordinary events (Macháček et al, 2008).

These methods are based on the monitoring of dynamic response and have been implemented using two basic techniques:

- Direct monitoring of the time development of several parameters, indicating the fatigue process development (here, this technique is applied in the monitoring of the laboratory fatigue test).
- Comparative monitoring with a simultaneous observation of the response of a reference unit and deteriorated unit. For this purpose these units should be identically situated in relation to the source of excitation forces. Observations on the reference member will, above all, provide us with the amplitudes and frequency spectra of excitation forces and also the time pattern of its response, including the parameters of elastic wave absorption within its body (this technique is applied in the monitoring of a tunnel lining member).

The monitoring of time related changes in the dynamic behaviour of a tunnel lining unit under operating loads generated by the passage of Metro train units is ongoing for more than two years using electrodynamic sensors (geophones). 2 geophones have been installed in the monitored tunnel lining profile, one on a unit showing a macroscopic failure by cracking (G1 – measuring channel A) and the other on an immediately adjacent unit with no visible macroscopic signs of failure (reference geophone G2 – measuring channel B). They are fixed onto boreholes in the tunnel lining by silicon cement. The output voltage from the sensors is led in an analogue mode into the service premises of the Nádraží Holešovice Station via a five-core cable 350 m in length. The time patterns of the changes in the particle velocities of the oscillatory motion of the observed points during the passage of a train unit have been registered by means of a FLUKE 2-channel digital storage oscilloscope. Using the methods of mathematical statistics in the time domain, effective values of deflections of the monitored points and their time development are evaluated (Fig. 5). The graphic output documents a very similar development in the dynamic response of a failed and undamaged prefabricate, which adequately corresponds to the uniform excitation and low intensity of the defect unit's failure. The tunnel lining's temperature response to the immediate temperatures of the internal climate in the tunnel is averaged and delayed in time. However, a clear dependence of the deflections on the measured temperatures may be seen, and it seems that climatic effects are one of the main factors influencing the time development of the dynamic response amplitudes and the elastic oscillation propagation parameters in the monitored units.

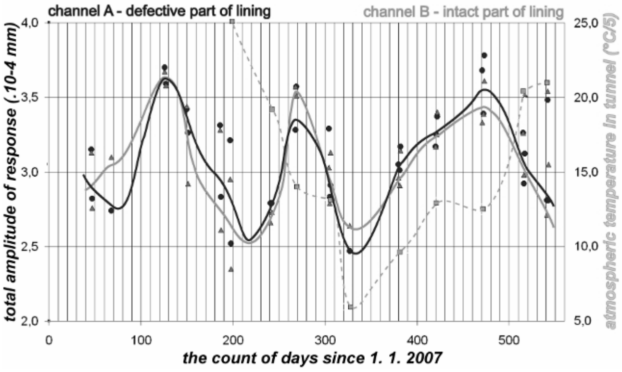

Figure 5: Effective values of total amplitudes of deflections of monitored points for the monitored period.

In the frequency domain, the response is characterized, above all, by the frequency spectrum, which shows that dominant frequencies are mainly found in the range of 0 – 40 Hz. The standardization of the response frequency spectra is aimed at a rough compensation of the differences in the magnitude of excitation forces generated by various train units.

Apart from the basic evaluation parameters of potential ageing manifestations of the tunnel lining monitored units, the tests also cover potential exploitation of summation (or integration) of amplitude contributions of individual FFT frequencies in a selected frequency range. The time development of the sum of amplitudes of standardized FFT in a range of 6 – 16 Hz for both monitored tunnel lining units S(FFT/A) and S(FFT/B) is described in Fig. 6. The chart is also complemented by time patterns of the summed FFT contributions of the S(FFT/A-B) differential channel and time courses of the sums of differential values in the same frequency range, together with the temperature profile for the monitoring time.

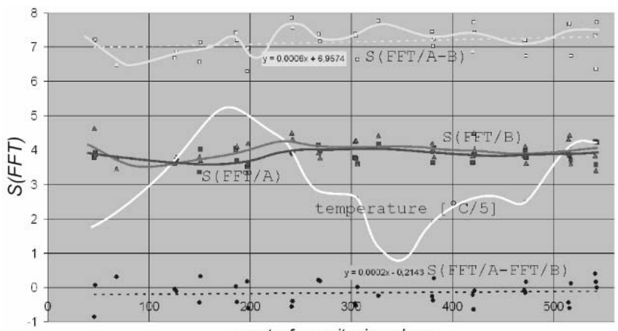

Figure 6: Time development of summed FFT frequency contributions in the monitored period.

The displayed S(FFT/A) and S(FFT/B) values show a very similar development which primarily implies only a global correlation to the climatic conditions in the tunnel tube. The seemingly lesser significance of the effect is caused by the scale of display.

Much more interesting information in terms of the evaluation itself is found in the chart presenting the Fourier transformation values of the S(FFT/A-B) differential channel. Despite the fact that its time pattern is principally affected by seasonal climatic conditions in the tunnel, its development trend still shows a very slight, but distinctly observable growth in the differences of the dynamic reaction of both monitored prefabricates. The explanation may be sought in a different development of the response amplitudes and in the changes of their mutual phase relations. It seems that these values are also determined by the changes in material constants, and we preliminarily interpret them as potential indicators of progressive mechanical, but also chemical degradation.

Geophysical methods are aimed at monitoring changes in structural materials related to their ageing under operating loads. In terms of their observation scale, they represent detailed methods. They are expected to be able to indicate the very first signs of material degradation, either under standard operating conditions, or under extreme circumstances.

5 MICRO-MONITORING OF THE TUNNEL LINING

Micro monitoring methods have two principle aims. They are focussing firstly on point-wise measurements and secondly on the monitoring of the whole profile or its selected points. Point-wise measurements are based on micro electrical mechanical systems (MEMS) sensors and the measurements of overall profile are exploiting Laser scanning or Computer vision.

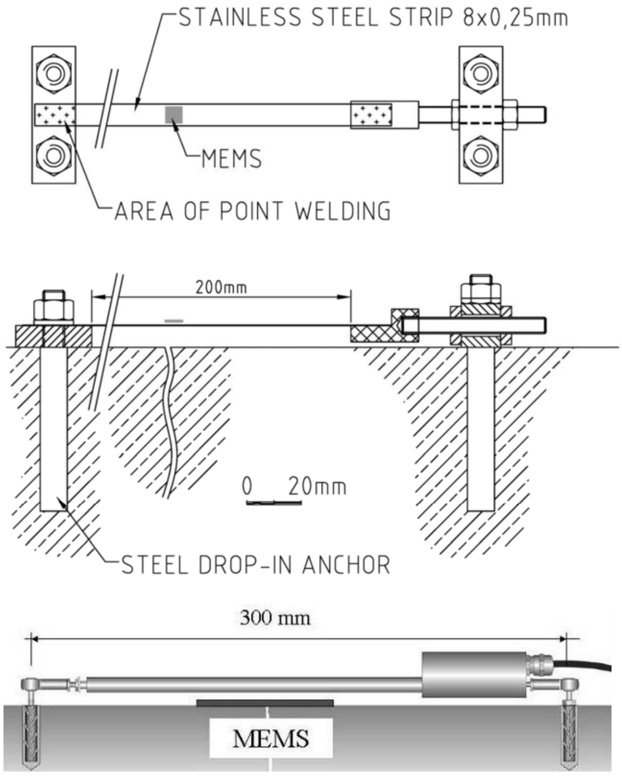

Figure 7: Design of application of MEMS device for steel strip crackmeter and deployment of traditional and MEMS crackmeters for long-term crack behaviour testing.

5.1 *MEMS device for strain monitoring*

This device is able to sense the strain applied to the substrate on which it is realized by means of a shift in its mechanical resonance frequency. Since it can be operated through a self-sustained electrostatic actuation using an electronic oscillation loop, no static bias current is needed for its operation and even dynamic power requirements are very limited because of the very small size of its moving parts (Záleský et al, 2008).

A steel crackmeter has been designed, by our research team, according to the geometry reported in Figure 7, onto which the MEMS sensors can be mounted for crack wireless monitoring. As may be observed in the Figure, the crackmeter has been designed so that the support steel strip shall be pre-stressed over the crack in order to measure both crack contraction / extension especially due to the temperature changes in the tunnel. In order to meet the above requirement, the steel strip base of 200 mm long was designed. In this way, the strip elastic range would be about 0.1 mm of its total extension, considering the elasticity limit of standard structural steel (0.05%). In the crackmeter, the strip is meant to be pre-stressed up to 0.05 mm, leaving a 0.05 mm margin for possible crack expansion. MEMS crackmeter performance is going to be compared to the standard commercially available crackmeter as they are placed above each other (Fig. 7).

5.2 *Laser scanning technique for deformation measurement*

This technology does not reach such accuracy for the individual points as in case of the exact total stations or of the long-term GNSS observation but it overruns this drawback in point density and complexity of surface record. It is possible to reach a level higher accuracy of surface or object displacement than the single point accuracy due to high redundancy of measured data. Scanning of actual shape was applied in the Prague metro tunnel in 2007 near the station Můstek. Next monitoring of the same section will be done after about one and half to two years from the previous scanning to compare the development of the tunnel shape.

5.3 *Computer vision monitoring*

This approach to monitoring is based on nowadays availability of the digital photos comparison. Currently it is possible to compare two photos of the same object even when they are not taken from the same spot and determine the differences between them. Based on this assumption it is possible to create a system that will be capable of comparing the photos of tunnel lining from different time spots and determine the differences between them. In the future it will be possible to automatically determine the features on the lining, if it is a lining defect or not. This task in the frame of our international research project is performed by the team of Prof. Cipolla from the University of Cambridge.

The first step in this task is to map the taken photos of the lining onto 3D space. Stitching of photos for tunnel lining shows several problems, mainly cylindrical shape of the photographed object from different angles and distances. These photos are having serious deformations of their edges and hence there are problems in theirs stitching along the overlaps. Provided we know the shape of the lining (cylinder) it is possible to use mathematical transformations that could eliminate such distortions of the photos edges (Fig. 8).

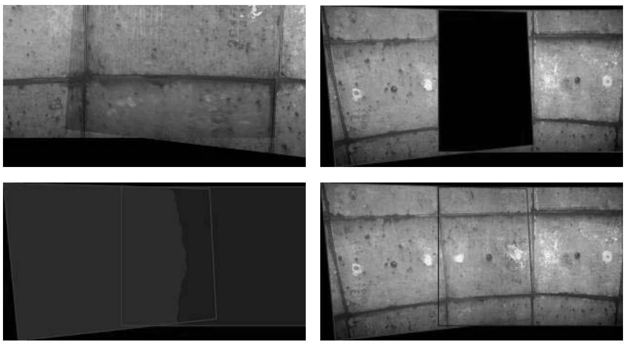

Figure 8: Photos stitching with spatial transformation – overlap finding and determination of the sharpness interface between the photos.

The approach with the transformation of the photos edges proved applicable on the lining that has planar character, on the contrary for the lining that has spatial surface structure is this approach rather problematic. For the case of structured lining segments, e.g. from cast-iron, different approach for mapping the photos into the space has been selected. In this approach it is required for positioning individual points from digital photo in space to perform complicated mathematical transformations over several photos at once. And hence we need several photos of the same object from different views that allow us to position individual photo points into space and create a 3D model of the lining with photos on its surface. Currently we are checking if this approach combination with 3D laser scanning of the tunnel lining can significantly simplify the creation of the primary spatial lining model.

6 NUMERICAL MODELLING OF SEGMENTAL LINING

One of the main aspects of a tunnel design applies to the control the behaviour of the lining and the stress in the vicinity rock, which can involve the ageing of underground structure. Several approaches have been presented in the scientific literature toward estimating maximum tunnel durability and the surrounding mass extension affected by deformation phenomena. The behaviour of the underground structures can be estimated by using empirical, semiempirical, analytical or numerical methods. The main focus is concerned on the acting range of the subgrade reaction in the contact between lining and the surrounding rock mass, the effects of joints between the lining segments, lining parameters and earth pressure coefficient at rest (Pruška & Chamra, 2008).

The modelled sections of the Prague Metro pass through a vast complex of sedimentary rocks of the Barrandien formation. In the analysis we used three combinations of the soil parameters: the worst, average and the best combination. The actual modelling has been done using PLAXIS and ATENA software packages. The ATENA software provides a powerful method for creep and shrinkage analysis for most problems from engineering practice. It is based on so called cross-sectional approach, meaning that the analysis builds upon creep and shrinkage behaviour of the whole cross section. The reason for choosing this method is that at this moment, there is available numerous models for predicting creep and shrinkage behaviour of a concrete cross section. The implemented creep and shrinkage analysis is based on assumption of linear creep, which in other words means that material compliance function and accompanying function for shrinkage depends only on material composition, temperature, shape and time at observation and loading. It does not depend on stress-strain conditions. The creep and shrinkage analysis is based on assumption of Stieltjes integral. Some results from ATENA modelling are presented on Fig. 9.

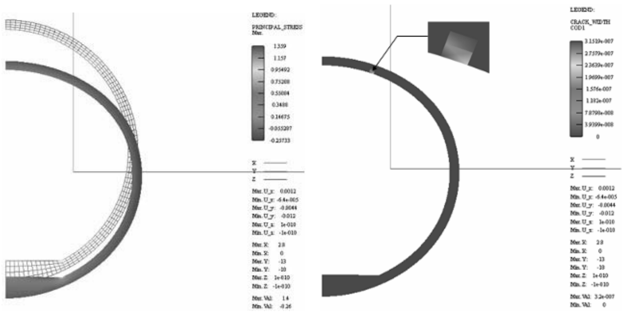

Figure 9: Analysis with worst parameters - principle stresses and crack development in tunnel lining.

7 WIRELESS DATA COLLECTION AND TRANSFER

For monitoring of underground structures this type for long-term monitoring is foreseen for the future. This approach allows connecting different sensors used for monitoring on the wireless network. Once the data are sensed they are sent to the central point of the wireless sensor network and afterwards all measured data from a short period of time are together transferred again wirelessly via internet on the server for further processing. Currently it is necessary to provide power supply for the central point of the network a battery power for every point on the wireless network. Due to these limitations options for renewable energy harvesting that would secure enough energy to maintain the wireless network power independent are sought in the frame of our international research project (Vaníček & Vaníček, 2007).

For wireless data collection we have chosen a wireless technology on the ZigBee platform. Everything is just a question of interconnection of relevant interfaces for data collection with the chip for wireless communication. For our particular needs we used the sensors that monitor basic climate properties in order to be able to determine the influence of those on the behaviour of tunnel lining and this way differentiate them from other influences, mainly from dynamic loading by traffic, long-term influence for rock massive and ageing of the lining material, which is the main goal of the monitoring. In order to study long-term deformation of tunnel lining due to the above mentioned processes further sensors like inclinometers and crackmeters developed at the University of Cambridge were installed.

Data transfer in this sense is transfer of monitored and collected data from wireless network gateway to the server in the office for further processing. Currently is this transfer realized on the mobile phone platform - GSM/GPRS. Transfer of measured data is in our case performed automatically in 30 minutes intervals to the server, where the data are automatically saved into the database and are available for further processing.

8 CONCLUSION

Up to date results made it possible to define some conclusions namely in the basic three levels as is practical level of metro operation, investigation level – verification of new measuring and monitoring methods in real conditions of underground structure and finally in theoretical level, above all from the view of observed changes in internal bonds in structural concrete (reinforced concrete) and from numerical modelling of this phenomena – ageing – creep, deterioration. Therefore partial conclusions for individual levels are further briefly specified.

From the practical point of view it is possible to conclude that so far performed measuring proved that the quality of lining is in very good state. Even in selected measuring profiles, where some problems with deterioration were expected as based on the visual observation. Measuring proved that the deformations in time (even for short period of 2 years) are practically negligible, on the level of the preciseness of the conventional methods. Measured changes are devoted mainly to the temperature changes.

At the same time these small changes in relatively short time interval reflect the significance of initial information about lining state. In the absence of this initial state it is impossible to compare present-day state with the state at the end of construction or with state, which existed before flooding of some metro parts. Therefore we support the creation of such a database of initial (or current state) and we are recommending laser scanning system, which is very quick, cheap and able to record this state for long section (even in kilometres). This approach can be recommended especially for new metro lines in order to be able to evaluate changes at the end of guarantee time and to evaluate the sections, where for defined time period changes are more significant. Preciseness in the range of 1-2 mm we count as adequate. Alternatively this method can be used for parts of metro lines, where new construction activities will start at the surface. Between the two stations where the profile 1 is situated such activities are expected in the near future and all up to date monitoring can serve as very useful and precise basis (Vaníček M et al, 2008).

Each measuring method proved to be very important. As each is focusing on different range (point, profile, section) and hence different precision, their combination seams to be very important.

From the view of safe metro operation the fact that tested methods are based on specific measurement is very important as compared to visual observation during night break. Particularly, certified wireless technology data transfer that can bring measured data on the computer of the person responsible for their evaluation, is a great benefit to the safety of underground structures namely during untypical situation as is terroristic attack. In the measuring profile No 2, close to the station Můstek, it is impossible to eliminate micro seismic effects. The results achieved to-date confirm that the designed dynamic diagnostics is able to make macroscopically unobservable changes in behaviour, caused by the ageing of a structure, but also e.g. by temperature and moisture conditions of the environment, visible. Interpretation of the monitoring results in time makes it possible together with the numerical model simulating creep and shrinkage of concrete to propose the first setting up of the ageing curve and its theoretical prolongation up to the failure phase.

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