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IMPLEMENTATION OF STRUCTURAL HEALTH MONITORING INTO LIFE CYCLE MANAGEMENT OF TUNNELS: CASE STUDY TUNNEL BRAJDICA

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Abstract

This paper presents a case study focused on the Brajdica railway tunnel, which carries the Zagreb-Rijeka railway line into the port of Rijeka in Croatia and thus represents a critical node on the European TEN-T network. The tunnel is undergoing a major reconstruction project to increase its capacity. As part of this work an extensive embedded monitoring system comprising inclinometers, extensometers, micrometers and survey markers were installed to monitor the tunnel response. This data is supplemented with periodical laser scanning of the tunnel interior. Measurement profiles are set along the tunnel bore and the data collected is used for the development of a tunnel performance model. Long-term monitoring data from a neighbouring road tunnel was used to develop models tho predict the long-term response of the Karst bedrock in the area. Combining these models with the settlements measured during the construction phase of the works at Brajdica railway tunnel allow prediction of settlements and the future occurrence of damage in the rail tunnel. Based on different limit states, life cycle management scenarios are developed and used for maintenance planning, with the aim to decrease short and long-term risks. This work has been performed within European H2020 SAFE-10-T project.

Keywords:

1 Introduction

Tunnels are one of the most critical structures on transport infrastructure networks which provide vital links for society, having a large impact on the regional economy and environment. They are designed and built for a long design life (usually for more than 100 years) and therefore regular maintenance interventions are necessary in this period. Poor understanding of tunnel behaviour, in all life cycle phases, has a result that planning the scope and extent of any intervention is challenging and unnecessary and/or ineffective maintenance and repair activities can cause large financial and environmental costs. Calculation of total life time costs for different design alternatives, maintenance options and societal impacts can be used to compare different technical solutions and select the optimal design and maintenance alternative. Within the SAFE-10-T European research project embedded monitoring techniques and data analytics solutions were developed with aim to improve probabilistic analyses tools for major infrastructure objects (bridges, tunnels and earthworks) resulting in safer and more environmentally sustainable infrastructure. A case study of tunnel Brajdica

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presented in this paper demonstrates the implementation of embedded monitoring systems into long-term predictive performance models and finally life cycle planning for tunnels in general [1].

2 Life cycle management of tunnels

The geological and structural characteristics of a tunnel support system will undergo significant changes during the life-time of the asset. Long-term structural assessment of tunnels support elements is one of the key activities in maintaining the reliability and safety of a tunnel during its service life. The lining structure of a tunnel is subjected to both external loading (weight of retained ground and traffic) and environmental effects like leaking or frost damage for example, see Figure 1.

Generally problems related to tunnel degradation can be divided into those caused by external pressure and those caused by the deterioration of materials [2]. These problems change through all life cycle stages of a concrete structure such as a tunnel, therefore decisions about the timing and the type of maintenance should be based on degradation prediction models and monitoring of the structural performance or degradation processes. Uncertainties in the decision making process can be decreased by using structural health monitoring data and structural models, in order to determine triggering thresholds for the structure passing certain performance levels.

Figure 1 Leakage and cracking in tunnels due to the external forces

3 Case study

3.1 Description of the project

The city of Rijeka is the principal seaport and the third-largest city in Croatia. It is located in the northern coast of Adriatic Sea (131 km southwest of the capital Zagreb), in the Rijeka Bay, which is a part of the Kvarner Gulf. The port is part of the Baltic-Adriatic Corridor on the TEN-T network. The current facilities are being significantly enhanced through the development of a multimodal transport hub in the Port of Rijeka including a connection with the Adriatic Gate container terminal [3]. As part of this project, reconstruction of the Rijeka Brajdica railway station is carried out and an intermodal container terminal is built. Works on the reconstruction and expansion of the capacity of the Rijeka Brajdica freight terminal include the complete reconstruction of the existing nine tracks and an expansion of the existing Brajdica railway tunnel (Figure 2).

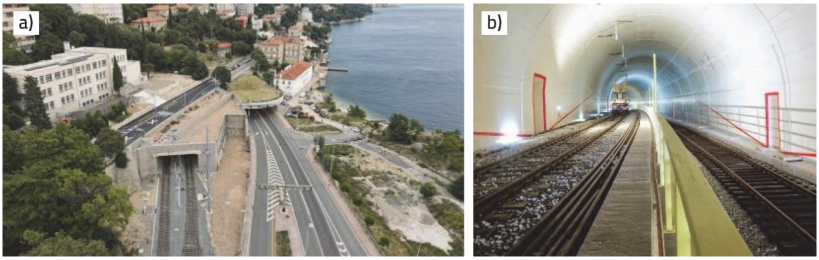

Figure 2 a) Entrance to the renovated and extended railway tunnel Brajdica beside the road tunnel Pećine, b) Finished expanded railway tunnel [3]

One of the unique features of the tunnel Brajdica project is that the railway tunnel is being reconstructed in close proximity to a modern highway tunnel, See Figure 3. The construction of highway tunnel Pećine started in 2005 and the tunnel was opened in 2008. The point at which the tunnels are closest together is at a distance of 11.5 meters between the main structural elements and the rock bolts required for stability of the area where both tunnels are overlapping. It is clear therefore that accurate prediction of the stress-strain response due to reconstruction works is essential for the safety of both tunnels [4 - 6].

3.2 Structural health monitoring of tunnels

Tunnel construction is by its nature an uncertain activity, with the volume of soil and rock being tested even during a comprehensive site investigation being very small in comparison to the volume of excavation. An additional complication in this project is that the rock in this region is formed of cretaceous deposits, breccias, dolomites and limestones, of relatively high permeability. These rocks are highly susceptibility to karstification processes, and phenomena including caverns, voids etc. are commonly encountered during tunnel construction. Recognizing these uncertainties the construction of the Pećine tunnel involved three interlinked phases; (i) ground investigation, (ii) numerical modelling and (iii) instrumentation. The instrumentation phase was seen as vital to confirming the ground model derived from the site investigation and to confirm the constitutive model parameters used in the finite element analyses. The monitoring system installed in Pećine tunnel included inclinometers, extensometers, micrometers and survey markers which supplemented periodical laser scanning of the tunnel interior to monitor ground movement. In addition load cells were placed on some rock bolts, shown in Figure 3 and strain gauges were embedded in the shotcrete lining to monitor bending moments.

The vertical deformation pattern measured directly above the crown of the tunnel Pećine during the 15 year period is shown in Figure 3 [4]. Kovacevic et al. [4] used this data in the development of a model to predict long-term vertical settlement performance of a tunnel in soft rock mass, through the inclusion of a Burger's creep viscous-plastic constitutive law to model post-construction deformations. To overcome issues related to the complex characterization of this constitutive model, a neural network NetRHEO was developed and trained on a dataset obtained using extensive numerical analyses. This model allowed to study the impact of uncertainties on the response of both tunnels to the reconstruction work being undertaken on tunnel Brajdica. This allowed the complex interaction of railway tunnel Brajdica and road tunnel Pećine to be evaluated prior to the reconstruction work on the former [4].

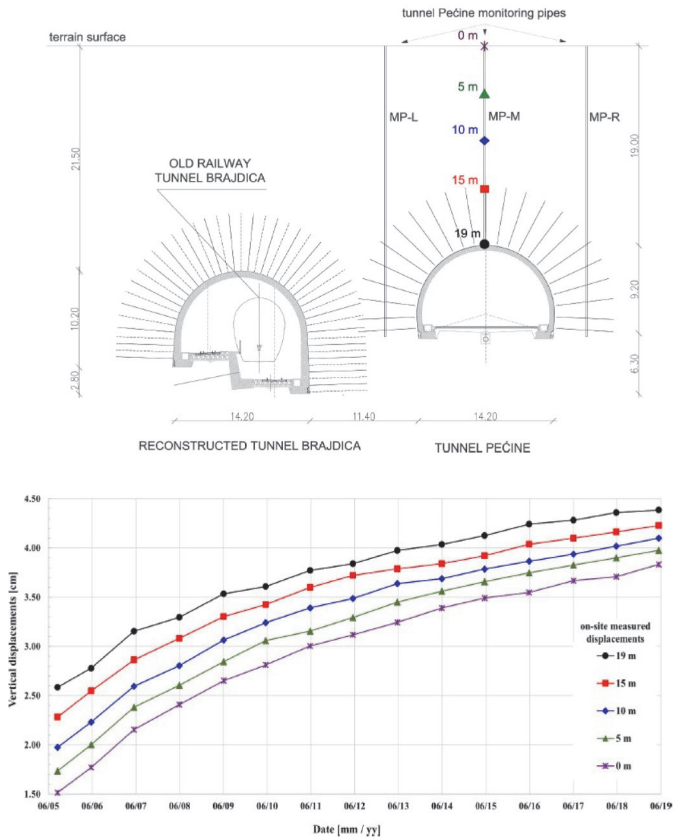

Figure 3 Location of deformation measurements along the vertical shaft and vertical displacement obtained by measurements during construction

3.3 Whole life cycle cost model

Whole life cycle cost (WLCC) analysis aims to support the management of physical assets, promoting informed decisions on the phases of design, construction, operation and end of service life. WLCC methodology gives great importance to the operational period, which includes maintenance, monitoring and inspection activities, with the direct and indirect associated costs they have on the overall economic performance of construction projects [1, 2]. The model developed within our project is integrating monitoring data, previous knowledge and long-term predictions of deformation, which can cause damage of the tunnel and increased risk of the failures. An example of how the impact of gradual deterioration of an ageing structure can be combined with monitoring data to establish threshold values which can then be used for determination of optimal timing for certain measures is shown in Figure 4. The experience gained from previous continuous monitoring systems installed for periods in excess of twenty years in several tunnels bored in the karst bedrock prevalent in Croatia is used for the development of long term performance models [4, 7]. Serviceability limit states (SLS) that can be linked to the continuum response of the tunnel are defined as follows:

- The admissible settlement value at the tunnel crown is exceeded.
- The admissible value of the axial force in anchors is exceeded.
- The compression capacity of the tunnel lining is exceeded due to combined bending moment and axial force.

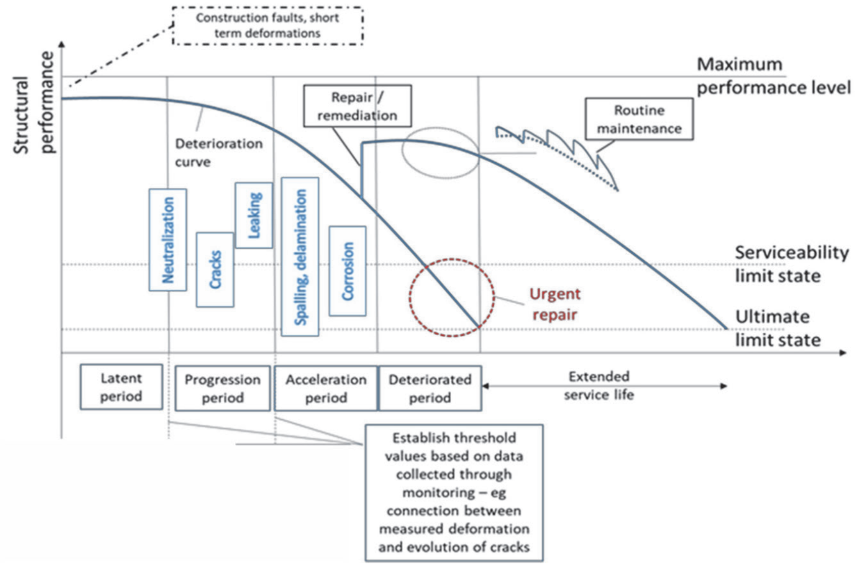

Figure 4 Life cycle model for tunnels using monitoring data and numerical prediction models

Based on the owner's experience with maintenance of similar structures, quantification of direct and indirect costs of certain maintenance activities (related to the SLS thresholds) is performed. Analysis of the whole life cycle cost is aimed for improving decision making process and does not necessarily mean choosing the longest service life or the minimum costs but rather choosing an optimal solution based on reliable data.

In order to determine the value of structural health monitoring, two different life cycle management scenarios are compared, one with the implementation of an embedded monitoring system and the other without. The frequency of maintenance activities is currently based on the expert judgment and previous experience with tunnels in the similar environment. In the future developments the long term deformations model will be used to predict the occurrence of damage and to plan the maintenance activities. The life cycle cost model therefore takes into account the following items:

$$TotalLCC = ICC + \sum_{t=0}^{T} \frac{MC_{t,nom}}{(1+r)^t} + \sum_{t=0}^{T} \frac{TDC_{fr,t,nom}}{(1+r)^t} \qquad (1)$$

Wherein ICC = initial construction costs (€), MCt, nom = maintenance costs for year t (€), t = year in life cycle from 0 until end of life cycle T, r = the discount factor (%), TDCfr,t, nom = nominal freight traffic delay costs in year t (€).

The maintenance costs are calculated based on the quantity of maintenance activities, their accompanying frequencies and their estimated unit costs. The traffic delay costs occur due to the increased time spent on traveling or due to the unavailability of the network caused by the maintenance activities. They are based on the value of time for users, extra travel time, duration of the maintenance activity and average daily traffic [8, 9]. In the case of tunnel Brajdica which serves as a link to the port and containers terminal, freight trains are the only relevant type of users. The traffic delay costs can be then determined by:

$$TDC_t = ETT \times ADT_t \times VOT \times N_t \qquad (2)$$

Wherein TDCt = traffic delay costs for year t (€), calculated separately for freight and for passenger cars, ETT = extra travel time per disruption / maintenance activity (hours), ADTt = average daily traffic in year t passing the analysed tunnel (tonne of freight/day), VOT = is a monetary value for the freight users (€/hour/tonne), Nt = duration of a certain maintenance activity (days).

4 Results

The WLCC model takes into account direct and indirect costs, as presented before for two different management strategies, one based on the historical performance and expert judgment, without embedded structural health monitoring and the other one with embedded structural health monitoring system, which enables data collection periodically during construction and operational stage. Monitoring data is used then for training the neural network model and for the prediction of the future deformations. The aim of the WLCC model is to provide to the infrastructure owner the insights into the impacts of different maintenance strategies and enable optimal decision making. In the model input parameters can be changed according to the decisions made. For the results presented here, we have used the discount rate of 1.5 %, traffic scenarios from [8] and the value of time based on the studies [9, 10]. Traffic regulations and duration of the maintenance activities are used from the current practice of Croatian Railways [11]. The outputs of the costs calculations are presented in Figure 5. The incorporation of SHM reduces both the direct and user delay costs significantly resulting in a 50 % reduction in overall costs over the 100 year-life span considered.

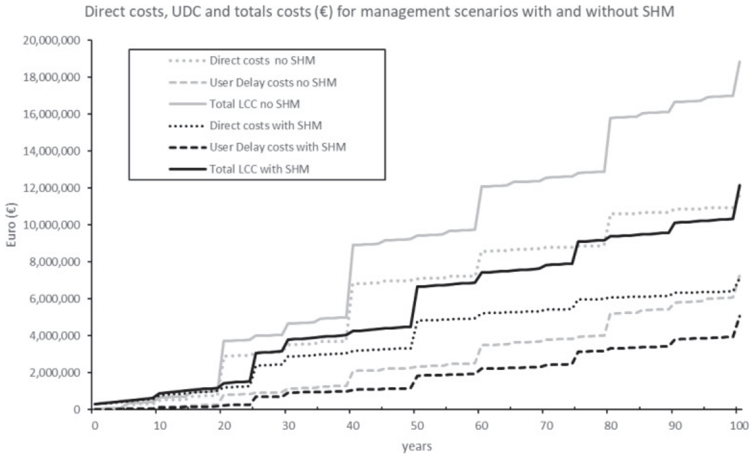

Figure 5 Results of the Life cycle model for two different tunnel maintenance scenarios

5 Conclusions

This paper presents a case study of Brajdica railway tunnel, which carries the Zagreb-Rijeka railway line in Croatia into the multi-modal port of Rijeka and thus represents a critical node on the TEN-T network. The tunnel was a part of a major reconstruction project, during which an extensive embedded monitoring system wasinstalled. The whole life cycle cost analysis model was developed for the management of the tunnel with the aim to support decision making process related to the phases of design, construction, operation and end of service life. The model developed within this project has integrated monitoring data and long-term predictions of deformation into the life cycle performance model. The experience gained from previous continuous monitoring systems installed for periods in excess of twenty years in several tunnels bored in the karst bedrock prevalent in Croatia has been used for the development of the long term performance model, which is capable of predicting forces and stresses in structural elements, thus predicting the occurrence of cracking. The performance model is then integrated into the long term maintenance planning, with the aim of developing optimal management strategies. Within this case study two management strategies were compared, one based on the historical performance and expert judgment without embedded structural health monitoring and the other one with embedded structural health monitoring system. The prediction of costs in the next 100 years clearly shows that the investments into SHM system pays off within first two decades and enables more than fifty percent of saving in the total costs after 100 years.

Acknowledgements

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