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MONITORING OF LONG TERM DEFORMATIONS IN BOBOVA TUNNEL

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Abstract

The 189.50 m long Bobova tunnel constructed in 2005 is located on the D404 state highway and passes under a part of the Vežica – Sušak town area in Rijeka. The overburden above the tunnel pipe is between 2 m to 18 m thick. The rock mass along the tunnel route is made up of karst deposits (transient carbonate breccia, dolomite and limestone interlinked with rudist limestones). Extensive geotechnical instrumentation was installed in the tunnel by researchers at the faculty of Civil Engineering at the University of Zagreb. This consisted of: measurements in the tunnel area from the ground surface using inclinometers for horizontal, and sliding micrometers for vertical soil displacements, measuring displacements around underground openings using sliding micrometers supplemented with scanning of the tunnel interior using laser scanners, and measuring the stress and deformations in elements of support complex by pressure cells and measuring anchors. Data collected during construction and in the twelve years in which the three-lane highway tunnel has been operational, presented in this paper reveal that deformations and stresses in Bobova tunnel have continued to increase with time. The possible role of the shotcrete lining, rock creep and rock-bolt corrosion in the ongoing deformations are discussed. The application of continuous monitoring data from instruments as inputs for numerical model training using a machine learning model, with the objective to improve the predictions of existing probabilistic failure models is considered. The ultimate aim of this work is to develop improved predictive maintenance plans.

Keywords: Bobova tunnel, long-term deformations, karst, monitoring

1 Introduction

The majority of road tunnels in Croatia including tunnel Bobova were constructed using the design procedures, recommendations and philosophy of the New Austrian Tunnel Method (NATM) which aims to optimise the support system by using a design as you go approach based on mobilising the inherent strength through arching of the rock mass and using the observational method to provide supports (rock bolts, wire mesh and steel ribs) as required. In phase one, detailed geotechnical tests and geological mapping were made by assessing results from borings and field and laboratory tests. The second phase consisted of optimising and adjusting tunnel construction and support design through a detailed assessment of the geological and geotechnical conditions made during tunnel construction, between the excavation phase and stabilisation phase. Along with detailed geological mapping and classification following the tunnel excavation, additional rock samples were taken for labora-

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tory testing. This method allows improved insight of the geological model (rock stratigraphy and composition) as the project progresses. The rock in the area consists of late Cretaceous sediments comprising rudist limestones. Quantities of breccia and dolomite rocks were also found in small amounts during execution [1]. The rock mass along the tunnel was classified using the Rock Mass Rating, RMR classification system with a score varying from 19-43. The rock mass was thus classified into categories 3, 4 and 5, for which NATM suggests staged excavation with multiple drifts. It was then decided to construct the tunnel using 2 drifts [2]. Due to the small overburden and proximity of residential buildings, the tunnel excavation was carried out solely using mechanical means (excavation hammer) with treatment of the profile carried out in two phases. Supporting the tunnel excavation was carried out using 30 cm of shotcrete, two steel reinforced Q-257 meshes, steel arch Pantex 130/20/30 supports, 6m and 3m long IBO 32/20 self-drilling rock bolts and a protective roof made from injected steel piping incorporated into the roof zone at an axial interval of 40 cm, at individual lengths of 15 m and with a 3.0 m overlap. Adjustments to the construction method and support design, mentioned previously, were made by combining results from numerical models, empirical approach and the observational method (measurements).

2 Geotechnical monitoring

During the second phase of the project – the construction and monitoring phase – various measurements were conducted in order to ensure the stability and safety of the tunnel and reliability of primary support system which consisted of the pipe-roof, steel-grid-reinforced shotcrete, steel arches and rock bolts. Two types of measurements were conducted during the construction process. The first type the so called “control measurements” consisted of measuring the underground opening deformations from within the tunnel. The second type, the “primary support measurements”, consisted of measuring displacements and deformations of surrounding rock as well as anchor pull-out tests, from within and outside of the tunnel. For the control measurement, 5 geodetic surveying points were placed in each control profile. For the second type, several different monitoring devices were used. This included measurement of horizontal displacements with inclinometers and vertical deformations from the rock surface over the tunnel with sliding micrometer, as well as measurements of axial deformations from within the tunnel in radial directions with deformeters. Pull-out tests were performed to verify whether the ultimate load capacity of rock bolts coincided with at least the minimal value defined with the main project. Fig. 1 shows the arrangement of monitoring instruments in a control profile.

In addition to the instrumentation for the control and primary support measurements, monitoring of the impact of the excavation on buildings in the surrounding area were made using clinometers placed on walls to measure the angle of inclination over time. All the measuring equipment, or parts of it, except for clinometers, were installed in a number of profiles along the tunnel length. More detailed measurements were performed on specifically defined additional profiles, chosen on the basis of geological conditions found during excavation. Since some of the mentioned pieces of equipment give readings dependent on the quality of installation, the first measurements in such cases were used as reference readings. Also, since the readings obtained are relative to the position of the installed measuring tubes embedded in the rock, they cannot measure the change (if any is present) of their own initial position relative to when the previous measurement was made. To overcome this, geodetic surveyal measurements of the test hole openings were made each time before a new measurement was conducted. In the construction phase of the tunnel, measurements were conducted more often (multiple measurements per month), until a time after construction when the deformations ceased. Given that small deformations continue seemingly to this day, annual measurements continue in the tunnel. The short-term (construction) measurements are discussed in Section 3 of this paper, whilst the long-term values are discussed in Section 4.

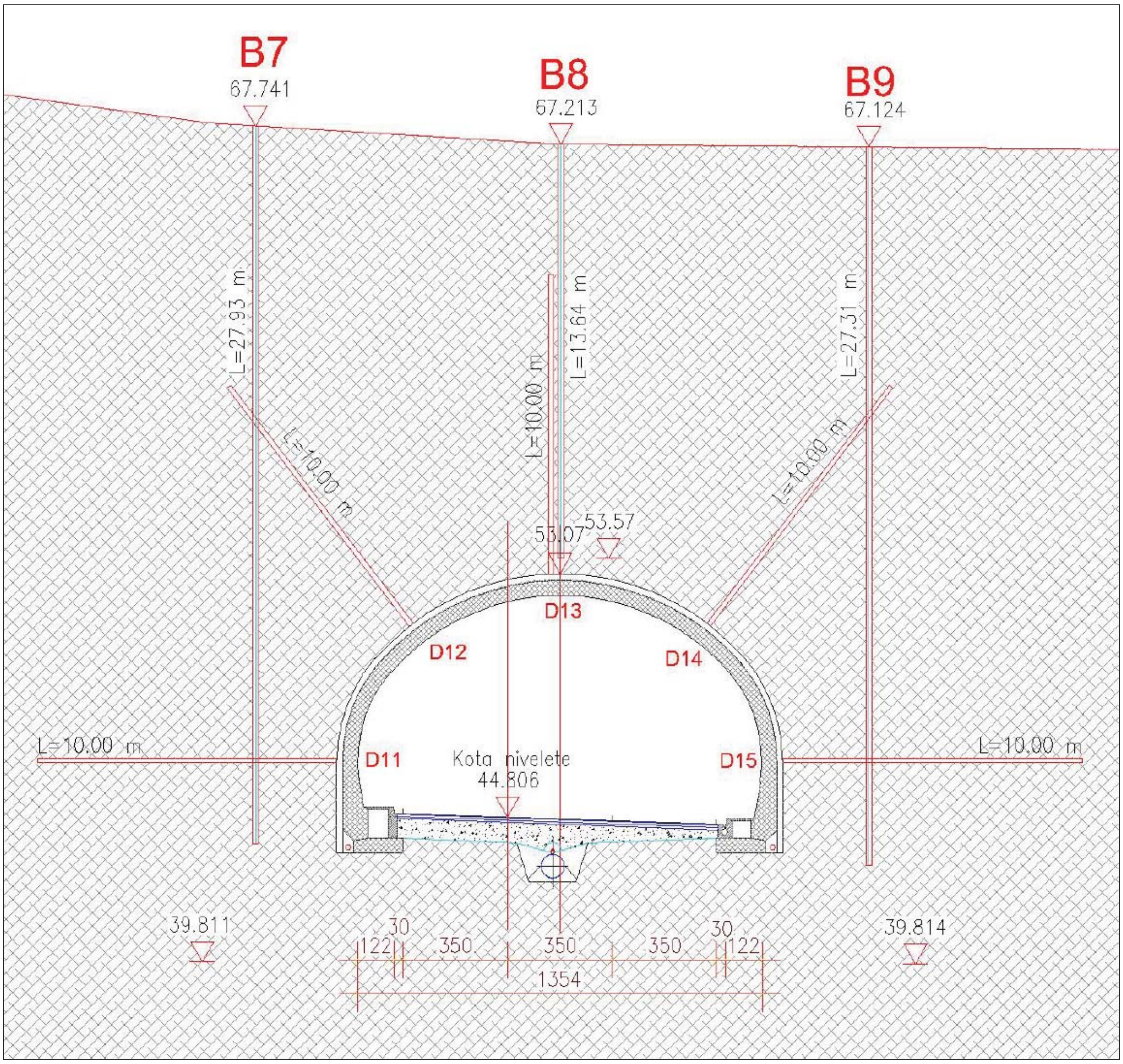

Figure 1 Arrangement of measuring instruments

3 Short-term deformations

Deformations which happen as a direct result from excavation or any other change to the primary stress state and can be achieved over a relatively short period of time following construction compared to the design life of structures, are referred to as "short-term" deformations. A number of methods exist to predict the short-term deformations which depend on the rock mass Young's Modulus, E. The most commonly used approach adopts a single Young modulus value for the whole rock mass. Given the well-known dependence of E on stratigraphy, stress level (depth) and strain level (deformation) choosing a single value to represent the entire rock mass is challenging. A wide range of correlations between Young's modulus with easily obtainable parameters such as rock mass classification, uniaxial compressive strength, disturbance factor etc. exist in the literature. In Croatian practice, deformations calculated with Young moduli obtained from those correlations are known to predict much lower values than measured deformations. The reason for this comes from the fact that all those correlations were obtained from test results on types of rocks very different from those found in Croatian karst. More than half of the surface area covered by Croatian territory is karst. Karst is a type of relief developed by dissolution of soluble rocks such as limestones and dolomites. To address this problem this data measured at the Bobova tunnel was used to calculate the stiffness of Croatian karst [1]. The new approach correlates the Young's modulus with geological strength index (GSI), rock quality index (ID_m) and the dispersion velocity of longitudinal waves through the rock mass (V_p). The correlation was developed using a numerical back analyses technique in which the material parameters were varied to match the results obtained by geotechnical monitoring. The equation by which the stiffness can be calculated is:

$$E_{rm}\left[GPa\right]=ID_m\cdot GSI^2\left[\%\right]\cdot V_p^2\left[km/s\right] \tag{1}$$

V_p is a parameter obtained from geophysical tests and the result is its variation with depth along the whole test profile. Since E_{rm} is proportional to V_p, a profile with varying stiffness can be easily obtained from Eq. (1). Young modulus obtained by Eq. (1) will be used as the initial stiffness of the rock mass for calculations of long-term deformations, discussed in the next section. The short-term deformations used in the development of the approach measured over a two-month period are plotted in Fig. 2. In Fig. 2, the vertical displacement graph shows a displacement of 0 mm at a depth of 24 m. This displacement only serves as an initial value for the beginning of the displacement graph, which means that all the values displayed on the graph are relative to a real value of displacement at a depth of 24 m. Since the values shown are not obtained by direct measurement, rather by integration of relative deformation, they can only serve to analyse the trend of vertical displacements. Thus, for the analysis of long-term rock mass behaviour, vertical relative deformations will be used as it is a directly measured value, along with horizontal displacements derived from inclinometer vertical deflection values.

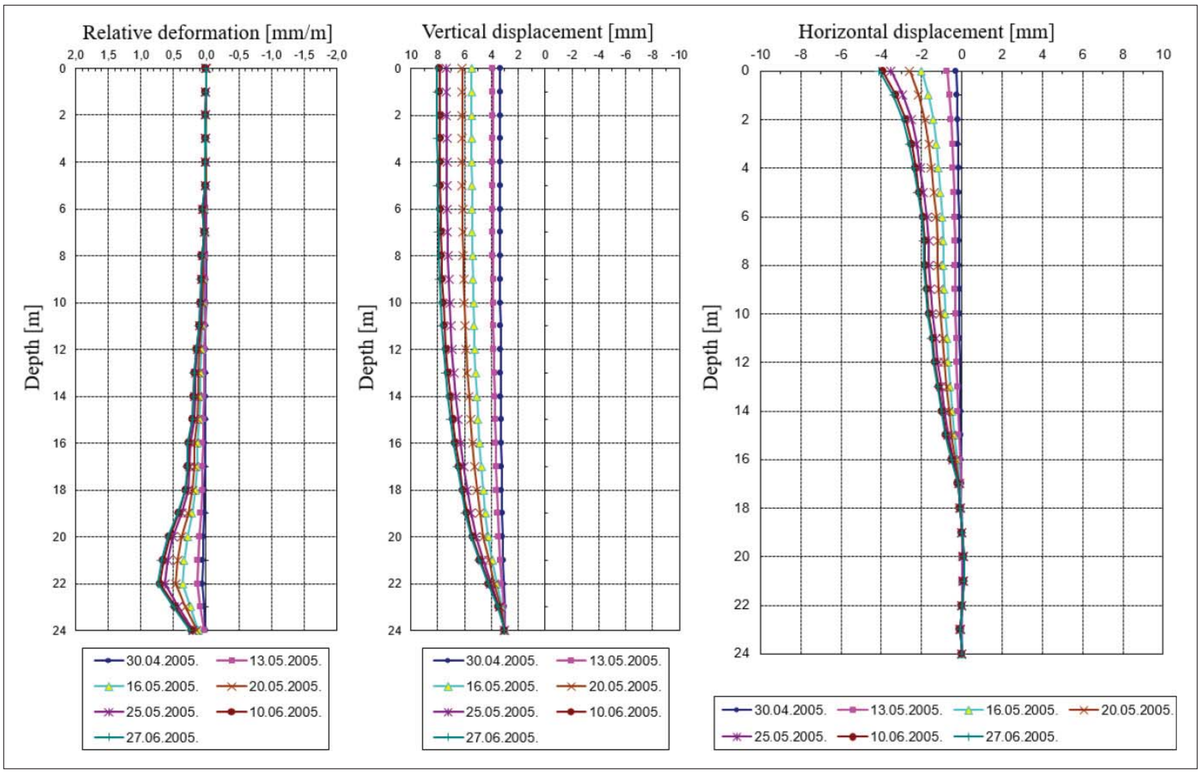

Figure 2 Vertical relative deformation measured by sliding micrometer (left); vertical displacement integrated from relative deformation (middle); horizontal displacements from inclinometer (right)

As can be seen from the Fig. 2, the latter measurements get closer and closer, to the point that the last 2 measurements almost seem to coincide with each other. This shows that some sort of equilibrium state is achieved, and short-term deformations are assumed to be complete. The next section discusses deformations which happen after short-term deformations "ended".

4 Long-term deformations

The measurements of long-term deformations in tunnel Bobova are shown in Fig. 3 and 4. It is clear that deformations and displacements are ongoing even 12 years after construction, albeit at a continuously reduced rate. The cause of these deformations are time dependent processes such as creep, squeezing, swelling, consolidation of clay in any kind of opening etc., meaning that long-term deformations greatly depend on geological field conditions. A preliminary analysis of the measurement data is made by using statistical methods to fit the measured results.

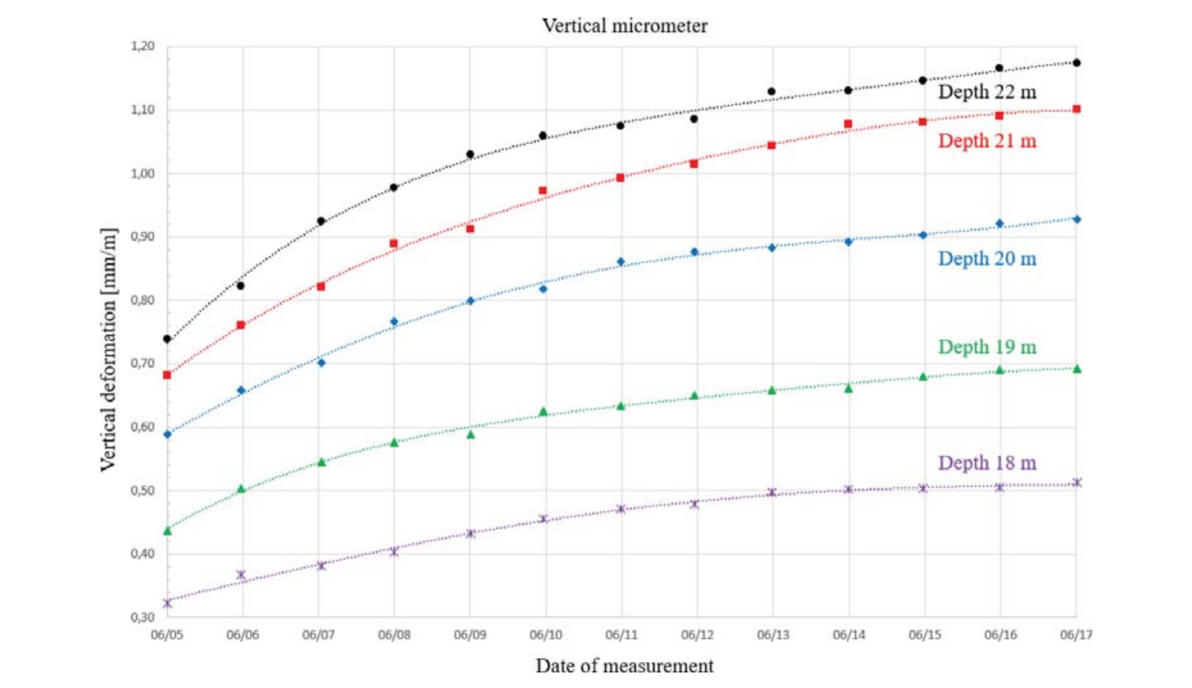

Figure 3 Results from fitting measure data for vertical deformations

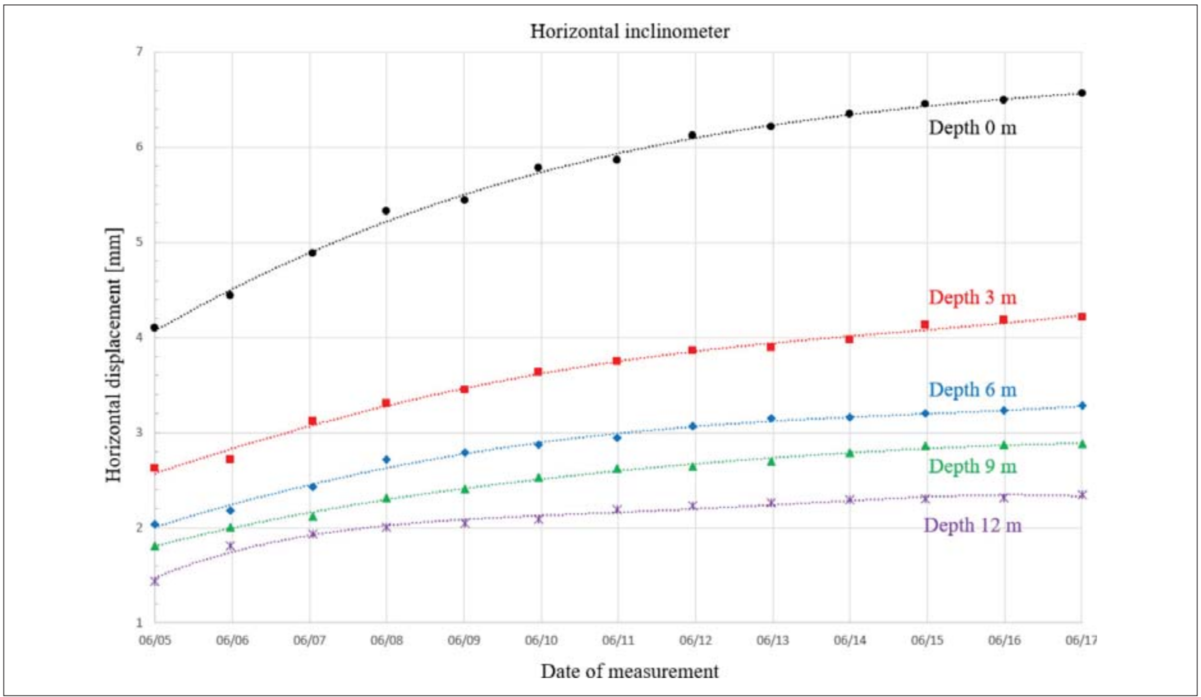

Figure 4 Results from fitting measure data for horizontal displacements

To produce the diagrams shown in Fig. 3 and 4, a few points were chosen along the depth of the micrometer and inclinometer boreholes. For vertical deformations, 5 points with depth values of 22, 21, 20, 19 and 18 m (Fig. 3). For horizontal displacements, 5 points at depths of 0, 3, 6, 9 and 12 m were chosen (Fig. 4). It can be seen from Figures 3 and 4 that deformations have increased by around 60 % of the original values when short-term deformations were assumed to have "ended". This statistical analysis only serves to see the trend of deformations. The measurement data will be used to test a methodology for obtaining creep design parameters from measurement data in Croatian karst, described in Section 4.1.

4.1 Numerical modelling of long-term deformations

According to the principles of NATM, the secondary lining in tunnels should not transfer any load except their own weight. The primary support should help in the load redistribution and take some load on itself, leaving no load to be transferred onto the secondary lining. However, measurements have shown increases of stresses and strains in tunnel secondary linings [3]. As loss of mechanical properties of tunnel primary support has the biggest effect in loading the secondary lining [3], it can then be said that primary support durability can, along with rock creep, contribute to the development of long-term deformations of a tunnel. The loss of mechanical properties can occur due to a combination of rock bolt corrosion and deformations caused by concrete creep. Concrete creep is caused by the increase of primary support pressure caused by long-term rock deformations, as concrete loaded over 50 % of its strength shows notable viscous deformations [3]. Thus, making a constitutive model which would take all these effects into account (rock creep, concrete creep, rock bolt corrosion) would be most appropriate for analysing the real state and predicting long-term deformations. Taking into account rock bolt corrosion and concrete creep would result with higher deformations. However, such a model would be very complicated, and it has been shown that the extreme scenario of complete loss of contact between rock bolts and surrounding rock would have very little effect compared to rock creep deformations [4]. Investigations from ten tunnels constructed over 30 years ago, show that rock bolts as well as primary and secondary lining showed little or no degradation and loss of mechanical properties [5]. From those measurements, it was also noted that little or no stress redistribution happened in the secondary lining, which could mean that either primary support concrete was loaded below 50 % of its strength, or that concrete creep is negligible over such periods of time compared to rock mass creep. Though deformations were not directly measured, it can be concluded that deformations caused by concrete creep can therefore be ignored for the sake of making a simpler constitutive model which predicts long-term deformations based only on rock time dependent properties, with good enough accuracy for engineering purposes. This, however, does not eliminate the need of investigating the contribution of concrete creep to long-term deformations of tunnels. The presented monitoring results will be used to test a methodology for predicting long-term deformations in Croatian karst, which will consist of numerical back analyses along with neural networks and finally genetic algorithms [6]. The first step would be to generate a database as big as possible consisting of input parameters, defined with one of the existing constitutive models, and respective results generated with finite difference method software FLAC. Since numerical models will be complex due to spatial variability of certain parameters and the large number of other parameters which define the time dependent behaviour of rock mass, calculations will take longer to reach equilibrium. Because of this, the generated database achieved by the described method will be used as learning material for neural networks. Neural networks will then produce more similar combinations of parameters and results to form an even bigger database. When this is all done, and a big enough database is available, genetic algorithms will be used to find the best fitting curve which is described by one set of parameters. To control the validity of this methodology, the received set of parameters will then be input again in the numerical model, and the results will then be compared to the actual measurement results. This work will form a part of ongoing research in the EU funded SAFE-10-T project.

5 Conclusion

Measurements in Bobova tunnel have been conducted for 13 years. The monitoring results presented in this paper will be used to test a methodology for estimating rheological parameters for prediction of long-term deformations from monitoring data in the Croatian karst. The initial state will be modelled using the relatively new formulation for Croatian karst rocks stiffness, described in Sec. 3. It is possible that some adjustments will be made to the methodology, regarding the type of neural network and genetic algorithm which will be used. As primary support durability has small contribution to tunnel long-term deformations compared to rock mass deformations, it will not be included in the analysis. So, for the first stage of the research, an existing constitutive model will be used for the numerical modelling of long-term rock mass behaviour, which only accounts for rock mass parameters.

Acknowledgements

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