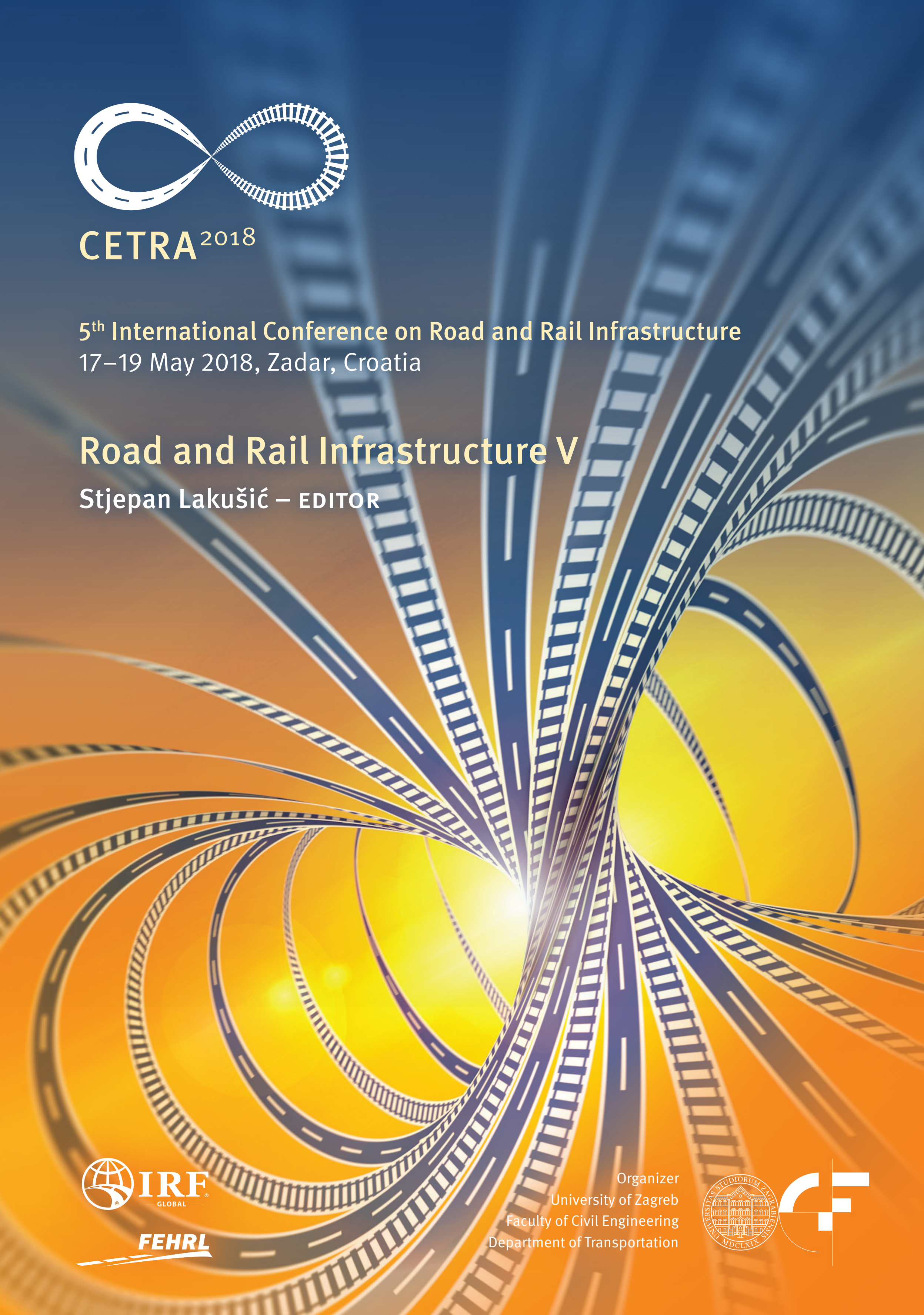

CETRA 2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – **EDITOR**

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CETRA^{2018}

5th International Conference on Road and Rail Infrastructure

17–19 May 2018, Zadar, Croatia

TITLE
Road and Rail Infrastructure V, Proceedings of the Conference CETRA 2018

EDITED BY
Stjepan Lakušić

ISSN
1848-9850

ISBN
978-953-8168-25-3

DOI
10.5592/CO/CETRA.2018

PUBLISHED BY
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE
minimum d.o.o.
Marko Uremović · Matej Korlaet

PRINTED IN ZAGREB, CROATIA BY
“Tiskara Zelina”, May 2018

COPIES
500

Zagreb, May 2018.

Proceedings of the
5th International Conference on Road and Rail Infrastructures – CETRA 2018
17–19 May 2018, Zadar, Croatia

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CETRA2018 17–19 May 2018, Zadar, Croatia
5th International Conference on Road and Rail Infrastructure

MODELLING OF TUNNEL LINING DEGRADATION

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Abstract

Long-term life of tunnel structures within the transport infrastructure is expected to a return of higher investment for construction. Structure of tunnel lining can be exposed to negative influences of ground water etc., which cause degradation of used materials during this long period of time. Reduction of bearing capacity is the result, which in the critical case may cause the collapse of whole structure. Thus, it is advisable to know response of the weakened structure in order to identify the negative trends in its behaviour early and to proceed with remediation. Consequences of lining degradation can be analysed, for example, by FEM (Finite Elements Method) modelling of tunnel. Analysis of utility tunnel in Brno in Czech Republic is presented in this paper as an example. The modelling dealt with the simulation of the construction process for determining the current stress conditions around the tunnel. Further, detailed modelling of sprayed concrete lining using an advanced material model was focused on. The impact on the tunnel stability was investigated by the reduction of bearing capacity of the lining. Possible degradation of the structure was simulated by reducing the thickness of the lining and the material characteristics reduction. Determination of the limit deformations for geotechnical monitoring system can be an example of outcome from the analysis. Unfavourable development of the load bearing capacity can be recognized in early states and collapse can be prevented.

Keywords: tunnel lining, degradation, FEM modelling, shotcrete model

1 Introduction

Tunnel structures are integral part of contemporary infrastructure of both types – railway and road. They represent good solution how to pass through critical places as various terrain barriers, urban areas or sensitive natural sites. Tunnels also allow to improve design parameters of high-speed railways and motorways. Thus, it is expected that number of tunnels will be still increasing due to construction of traffic infrastructure. However, underground structures are more expensive than surface solutions, in general. Therefore, high cost is one of the important factor why the tunnels are designed for long-term life.

Operability can be expected even more than hundred years. Many unfavourable factors can occur during tunnel lifetime, where material degradation of tunnel lining is one of them. The most often structural material is concrete with or without steel reinforcement which is sensitive to the action of some chemical agents. Tunnel lining is often exposed to ground water containing various dissolved compounds. Chemical nature of ground water can vary a lot and it depends on geological environment. Concentration of the chemicals in combination with intensity of ground water flow can create strong attack on concrete lining and consecutive chemical reactions can rapidly decrease original material properties [1]. Concrete degradation rate depends on many factors, e.g. content of particular ions, concentration, water flow, as it

DOI: https://doi.org/10.5592/CO/CETRA.2018.794

was mentioned above, or type of binder, porosity and cracking, temperature, etc. The process of degradation can lead directly to decrease of concrete mechanical properties (strength, Young's modulus) or to reinforcement corrosion. Results of steel corrosion are iron oxides with higher volume than original steel. The noted volume expansion can lead to burst of reinforcement cover, hence resulting in reduction of structure dimensions. Risk and rate of degradation penetration can be estimated by e.g. probabilistic models [2]. Outlined changes of material parameters or even geometry of structure could influence bearing capacity of lining and overall performance of tunnel. Thus, analysis of such effects is reasonable. However, underground structures represent complex system of interaction between tunnel lining and surrounding soil or rock mass. Therefore, application of numerical analysis is necessary, where finite element method (FEM) is the most common. This approach has advantage in possibility of material description by advanced material models for both – ground material and structural material. Using of advanced material models for soils is common in current geotechnical engineering, while using of such models for structural elements description is still in the beginning. Shotcrete (SC) model was developed by Schädlich and Schweiger at Graz University of Technology originally for analysis of shotcrete lining within New Austrian Tunnelling Method, but later case studies showed the SC model is applicable also for other types of geotechnical structures [3]. It is an excellent example of material model which involves features of real behaviour of concrete such as plasticity, tension and compression hardening and softening, etc [4]. Thus, the SC model should be good choice also for application in detailed analysis of concrete lining degradation.

The presented analysis, detailed described in following chapters, attempted to simulate various cases of tunnel lining degradation with using of advanced material models in FEM modelling. By evaluation of obtained results were pointed out most unfavourable cases of degradation and most sensitive parts of analysed structure.

2 Methods

Utility tunnel in Brno in Czech Republic was selected analysis due to availability of data about the structure and exposure of concrete to potential degradation processes. The tunnel was built in late 1980's and because of current water leakages is monitored. Thus, the data about geology, geometry and lining were obtained from recent field works during installation of the monitoring system. The ground profile on the site is formed by 6 layers of various soils described in Table 1. The thickest one is Neogene clay where the tunnel is seated. Ground water level was found at 5.25 m below the surface. The tunnel has circular cross-section with internal diameter of 4.7 m and flat invert. The invert is seated at 28 m below the surface. The tunnel lining was made of shotcrete without any sealing layer. The thickness of 30 cm was determined by core drilling through the lining and two approx. 15 cm layers of sprayed concrete were recognized. Welded mesh reinforcement in depth about 5 cm was found near inner and outer surface of the lining. The concrete invert was constructed with thickness of 60 cm.

Table 1 Description of soil layers and material parameters used in calculation (* $E_{ref} = E_{50}^{ref} = E_{oed}^{ref}$; additional parameters $R_f = 0.9$, $p_{ref} = 100$ kPa)

Soil [-]	Thick. [m]	Model [-]	$\gamma_{unsat/sat}$ [kN/m^3]	E_{ref}/E_{ur} [MPa]	ν [-]	c' [kPa]	φ' [°]	m [-]
Backfill	1	MC	18.0/20.0	11.2/-	0.35	14	25	-
Loam	2	MC	20.0/21.5	10.7/-	0.40	16	24	-
Clay	2.25	MC	18.5/19.5	6.4/-	0.35	14	24	-
Sand I	3.75	MC	18.5/20.5	51.1/-	0.28	0	35	-
Sand II	3.25	MC	18.5/20.5	63.9/-	0.28	0	36	-
Neogene clay	37.75	HS*	18.5/19.0	11.9/36.2	0.20	6	24	0.5

The FEM analysis was carried out by 2D model with using of software Plaxis. Dimensions of the model were defined to 80 m in horizontal and 50 m in vertical direction. Soil layers close to the surface were defined by simpler Mohr-Coulomb (MC) model because of less influence on the tunnel. Neogene clay surrounding the tunnel was described by more advanced Hardening soil (HS) model with parameters taken from previous study published by authors [5]. The lining was modelled by 2D elements with using of SC model. Values of used parameters are listed in Table 2 and they were determined in previous study of the authors [6]. For simplification, the reinforcement was not considered in the lining.

Table 2 Input values used for SC model

E_{28} [GPa]	ν [-]	$f_{c,28}$ [MPa]	$f_{t,28}$ [MPa]	f_{c0n} [MPa]	ε_{cp}^{p} [-]	a [-]	φ_{max} [°]	f_{cfn} [-]	f_{cun} [-]	$G_{c,28}$ [kN/m]
15.5	0.2	35	2.4	0	0.0016	24	39	0.01	0.01	39.8

Stages of construction were implemented into the calculation to find current state of stresses in the lining. This was used as starting point for application of variable potential degradation cases. The construction process was simulated by following 7 stages of calculation: 1) Initial phase – generate the original geostatic pressure; 2) Excavation I – excavation of the tunnel crown; 3) Excavation II – excavation of the tunnel invert; 4) Lining I – installation of the 1st layer of lining; 5) Lining II – installation of the 2nd layer of lining; 6) Lining III – installation of concrete invert; 7) Consolidation – consolidation after construction. The stages above were defined according description of Horák [7].

New stages of simulated hypothetical lining degradation listed in Table 3 were employed after reaching current state. Two main types of possible degradation were analysed: concrete degradation by decreasing of the Young's modulus and reinforcement corrosion causing structural dimension reduction. The first type of degradation was defined by reduction of concrete Young's modulus value from the initial value 15.5 GPa to 80 %, 60 % and 40 % respectively. The mentioned steps were applied in three different cases: (A) whole thickness of the lining; (B) outer layer of the lining; (C) left half of the lining arch. Homogeneous attack of negative agents with partial penetration of degradation was simulated in the case B, while in the case C was only left side of the tunnel exposed to degradation in whole thickness. Thin isolated sandy layers with higher permeability were identified in the Neogene clay. Thus, effect of more intensive water flow can occur on isolated parts of the tunnel lining. Lastly, degradation by reduction of the lining thickness was employed in case (D) with possible burst of 5 cm thick layer from inside or outside the tunnel and from both surfaces. Theoretical surface load was added in order to enhance the effect of degradation in calculated results. Similar approach was used in [8]. The theoretical load with intensity set to 5 kN/m was symmetrically imposed on length of 20 m above the tunnel and it was activated in comparative case without any degradation and in every case of analysed degradation.

Table 3 Analysed cases of the lining degradation (E – Young's modulus of concrete [GPa]; T – reduction of the lining thickness [cm])

case A	**case B**	**case C**	**case D**
A-80: E = 12.4	B-80: E = 12.4	C-80: E = 12.4	D-in: T = -5
A-60: E = 9.3	B-60: E = 9.3	C-60: E = 9.3	D-out: T = -5
A-40: E = 6.2	B-40: E = 6.2	C-40: E = 6.2	D-both: T = -10
whole thickness	outer layer	left half of arch	whole length of arch

3 Results

Values of deformations, principal stresses and plastic points were collected from calculations in characteristic parts of the tunnel lining in order to evaluate impact of each case of degradation. The deformations are listed in Table 4 according the same labelling as stated in Tab. 3. Values were always recorded in millimetres on contour of the lining inside the tunnel. The first row labelled 100 represents comparative case in the same conditions as following but without any degradation.

Table 4 Deformations [mm] (Top – top of the arch, Inv – middle of flat invert span, L/R – left and right side wall in the widest span of tunnel)

case A				**case B**			
E	Top	Inv	L/R	E	Top	Inv	L/R
100	12.67	10.24	11.33	100	12.70	10.29	11.36
80	12.82	10.12	11.35	80	12.76	10.28	11.37
60	13.03	9.98	11.40	60	12.82	10.26	11.37
40	13.29	9.74	11.45	40	12.91	10.24	11.38
case C				**case D**			
E	Top	Inv	L/R	T	Top	Inv	L/R
100	12.70	10.29	11.36	-	12.68	10.24	11.34
80	12.77	10.27	11.37/11.38	in	12.94	9.77	11.21
60	12.86	10.24	11.37/11.39	out	13.53	10.15	11.41
40	13.00	10.20	11.37/11.41	both	13.90	9.70	11.28

Trend of increasing deformation of Top with increasing level of degradation can be seen in every case. The same effect appeared in side walls in cases A and B. Vice-versa, in the invert developed opposite effect with smaller deformations under higher degradation. Case C, where the asymmetric degradation was applied, showed interesting trend of side walls deformation. Left side, exposed to degradation, showed very low deformation sensitivity to degree of degradation and bigger changes appeared in right side. In case D the deformation of each lining part was dependant on changes of lining thickness which generated variable stiffness of arch and invert system. The most significant deformations occurred in cases A-40, T-out and T-both. Small variation of deformation among comparative cases was caused by slightly different mesh generated during analysis in each FEM model branch.

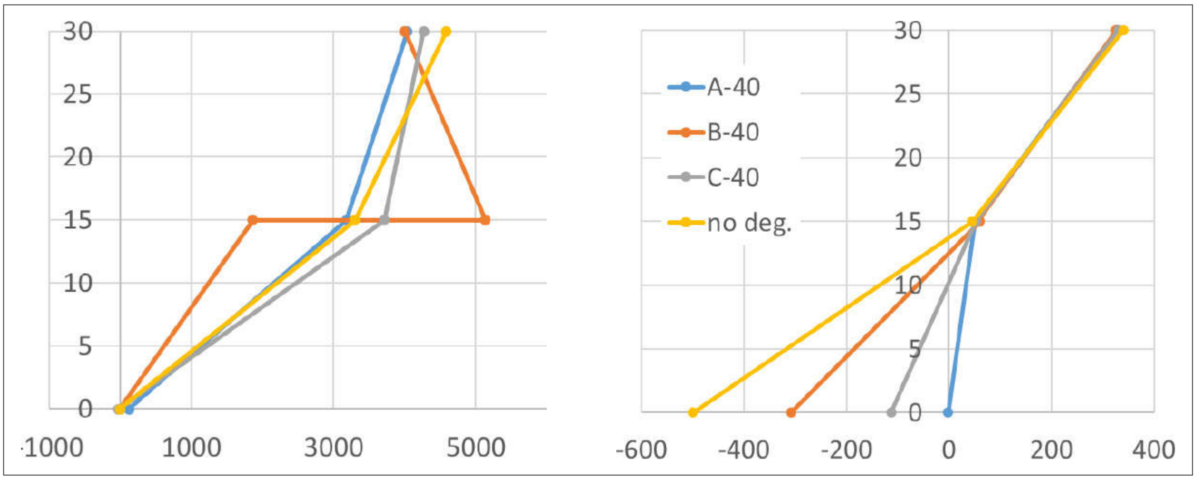

Figure 1 Horizontal axis represents major σ_1 (left) and minor σ_3 (right) principal stresses [kPa] in Top; vertical axis represents depth from lining surface [cm]

Principal stresses in selected sections of the lining are presented in the diagrams (Fig. 1, 2, 3). Horizontal axis shows principal stress in kPa where positive is compression and negative is tension. Vertical axis shows thickness of the lining in cm where 0 represents surface inside the tunnel. Only the most significant cases with the highest degree of degradation are presented.

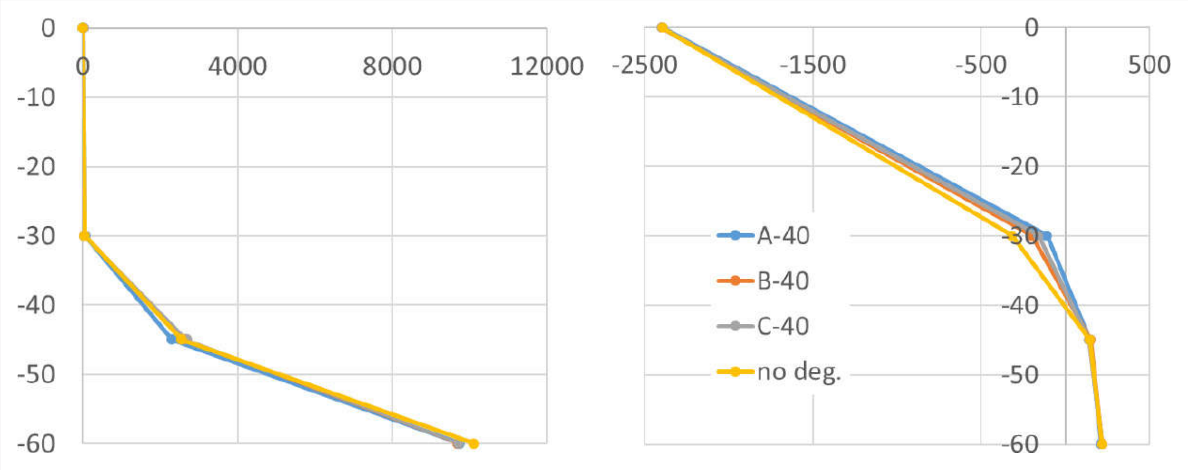

Figure 2 Major σ_1 (left) and minor σ_3 (right) principal stresses [kPa] in Inv

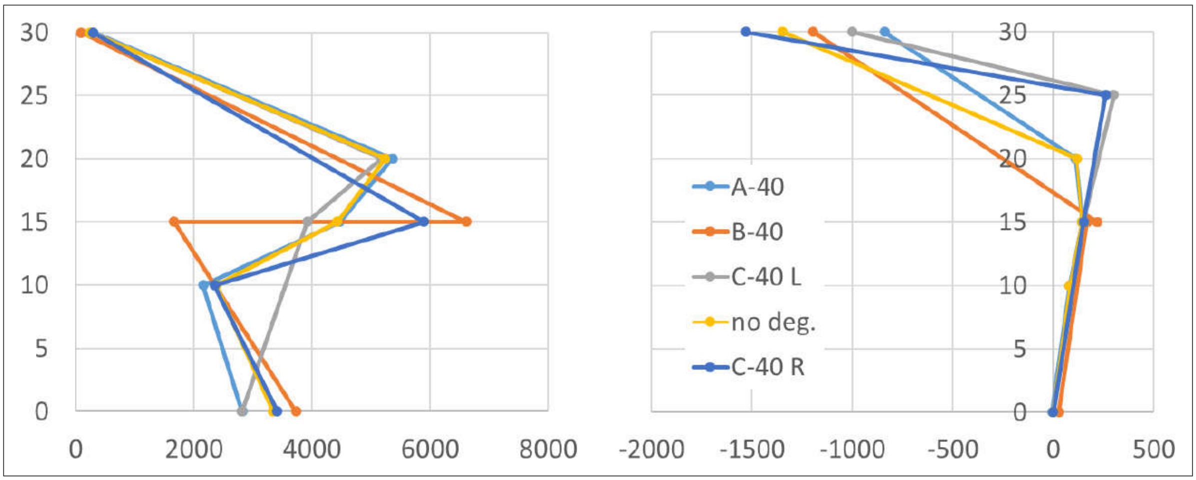

Figure 3 Major σ_1 (left) and minor σ_3 (right) principal stresses [kPa] in side walls

Figure 1 shows variation of principal stresses in Top. Strong influence of different stiffness layers contact is recognized in σ_1 by B-40 curve. Also, variation of σ_3 was found on inside surface, while outside surface values were almost constant. Stresses level in Inv (Fig. 2) was higher than in Top (Fig. 1) but with very low sensitivity to degradation changes. Trend of principal stresses in side walls (Fig. 3) is more variable inside the lining than on surfaces. The difference of σ_1 in C-40 L and C-40 R corresponds with findings in deformations and the same soar of σ_1 occurred in case B-40 as in Top (Fig. 1).

Plastic point distribution was possible to analyse by advanced SC model used for concrete lining. More or less continuous ring of hardening points in outer layer of concrete and tension cut-off points near inside surface of invert were found in every analysed case, what is in compliance with principal stresses findings. Asymmetric stress distribution in case C generated group of hardening points also near right side wall surface, what is clearly visible in Figure 4.

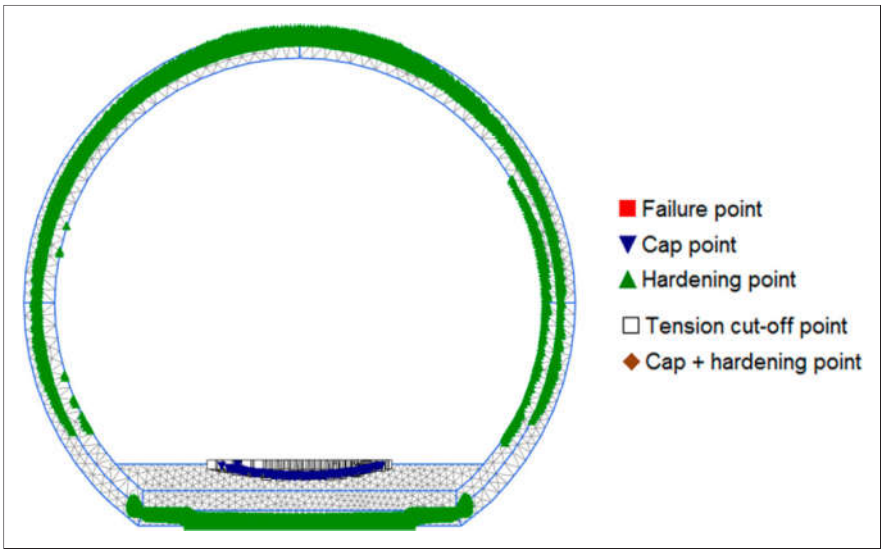

Figure 4 Distribution of plastic points in the lining in case C-40

4 Discussion and conclusion

Negative changes caused by degradation can occur in concrete lining of tunnel during its lifetime, what can affect serviceability or bearing capacity of structure. Different cases of possible lining degradation were analysed by changing Young's modulus of concrete and by lining thickness reduction. FEM analysis combined with advanced material models (HS model for soil, SC model for concrete) was used to determine effects of degradation. Response of the lining was evaluated by analysis of deformations and principal stresses.

Mechanism of the response varied according applied degradation case. The most sensitive part of the lining was identified by deformations in top of the arch. Massive invert was less sensitive to deformations, but the highest compression and tension stresses were found here. The tensile strength of considered concrete was even reached. One of causes of mentioned invert high loading can be explained by squeezing effect of surrounding clay in combination with tunnel geometry (flat invert). The most critical cases of degradation were found during large decrease of Young's modulus in whole lining and during thickness reduction from both surfaces and also outside surface. Attention should be paid on the last mentioned case, because of bad identification of this type degradation in practice.

Sensitivity of structure to the consequences of degradation was found. However, changes in deformations and principal stresses were not such significant as in previous studies [8], [9]. Lower influence of degradation to the results compared to mentioned studies could be caused by usage of different material models for lining and ground in the presented study. Also, the type of analysed lining structure was specific. Analysis of the results divergence among the studies and utilization of other features of SC model, will be the aim of authors further studies.

To summarise, the study is widening field of degradation tunnel lining response analysis. In addition, innovative approach was applied by using of advanced material models in FEM analysis for both – ground environment and lining structure. Attempted type of analysis can be utilized in design of geotechnical monitoring system, determination of critical values of deformations, stresses, etc. Hence, potential application in praxis could be beneficial.

Acknowledgement

This paper has been worked out under the project No. LO1408 “AdMaS UP – Advanced Materials, Structures and Technologies”, supported by Ministry of Education, Youth and Sports under the “National Sustainability Programme I” and under the project No. CZ.01.1.02/0.0/0.0/15_013/0004874 “Vytvoření partnerské kooperace mezi firmou GEOtest a regionálním výzkumným centrem AdMaS” supported by Ministry of Industry and Trade under the “European Regional Development Fund Operational Programme Enterprise and Innovations for Competitiveness.

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