Time - Dependent Processes in Rocks

Časovno odvisni procesi v kamninah

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Received: November 02, 2006 **Accepted**: November 14, 2006

Abstract: Time-dependent transformations in rocks, which occur primarily as a consequence of their natural properties, are a significant factor in the analysis of deformations developing during the construction of underground structures and afterwards. The excavation method used and the method of supporting an underground structure depend to a considerable degree on the intensity of the time development of deformations and their size.
The contribution analyzes the basic rheological models used for computational analyses of time-dependent displacements in the linings of underground structures using the so-called friendly cross sections, and provides a comparison between the measured and calculated displacement values. The exposure of a complex rock structure, which is a frequent occurrence in the construction of underground structures such as, for example, tunnels, is explained using back analyses. These are significant both from the perspective of proper selection of construction technology, and in cases when it is necessary to decide on the basic orientations to be used in the method of supporting a specific underground facility.

Izvleček: Časovno odvisne spremembe v kamninah, ki so posledica predvsem njihovih naravnih lastnosti, so pomemben dejavnik pri analizi deformacij, ki se razvijejo v času gradnje podzemnega prostora in po njej. Od intenzivnosti časovnega poteka razvoja deformacij in njihovih velikosti, je v veliki meri odvisen način izkopa in podpiranja podzemnega prostora.
V prispevku so analizirani osnovni reološki modeli, ki se uporabljajo za računske analize časovno odvisnih pomikov ostenj podzemnih prostorov s t.i. prijaznimi prečnimi profili in narejena primerjava med izmerjenimi in izračunanimi vrednostmi pomikov. Izpostavljenost kompleksne hribinske zgradbe, ki je pogosto primer pri gradnji podzemnih prostorov, kot npr. predorov, je pojasnjena s povratnimi analizami. Te so pomembne tako v pogledu pravilne izbire tehnologije gradnje, kakor tudi takrat, ko se je potrebno odločiti o osnovnih usmeritvah načina podpiranja določenega podzemnega objekta.

Key words: rheological models, time-dependent deformations, viscoelasticity, Permian-Carboniferous rocks

Ključne besede: reološki modeli, časovno odvisne deformacije, viskoelestičnost, permokarbonske kamnine

Scientific paper

Introduction

As is often the case in rock mechanics, a question that frequently arises with rheological models is how far we can go in applying various theories, developed on the basis of the elasticity or elastoplasticity theory, for the evaluation of actual occurrences in complex natural materials. Deformation occurrences in nature, including rocks, are often considerably more complicated than we can actually describe. That is why any progress towards such occurrences is encouraging and will pave the way for the scientific explanation of such processes.

A knowledge of time-dependent processes in rocks is highly significant from the engineering aspect. In our case, we have in mind those processes involving the time development of stress changes and deformations in the vicinity of underground structures. These processes, which are of long duration and may last for several days or even decades, affect the transformation and redistribution of stresses in the vicinity of the underground structures. One of the consequences of this is an increased load on the supporting system and the reduced stability of the structure, which in extreme cases may even lead to collapse.

Analyzing time-dependent processes in rocks and preparing evaluations of possible effects on the stability of an underground structure are of extreme importance in planning the construction schedule, selecting the appropriate supporting method, and ensuring the long-term stability of the structure. To determine or describe these processes, we frequently make use of various rheological models that are linked to individual parameters which can be determined on the basis of various procedures. These parameters may be determined in laboratories or with the help of back analyses, which is shown in this contribution. This paper is divided into an introductory theoretical part presenting basic information on time-dependent processes in rocks, and a practical part in which back analyses are used to determine the parameters of a simple linear, viscoelastic rheological model, which may be used to describe the time development of deformations while taking into account specific assumptions.

Rheological Characteristics of rocks

When calculating deformations in rocks in the vicinity of underground structures, equations are often used in which time does not appear as a variable and we have to content ourselves with so-called final deformations. Such cases are quite frequent and this method of calculating deformations may be completely satisfactory for the needs of standard dimensioning. However, one should be aware that no phenomena in nature is only of a momentary character, and that time is a parameter which can to a great degree influence the final result in rheologically sensitive rocks. In equations uniting the stresses and deformations of a deformable body, the introduction of an independent time variable leads to complicated mutual relations resulting in quite unfriendly mathematical solutions. Yet this method provides us with more detailed insight into the time development of deformations, which is of great significance in the construction of underground facilities with long-term use. There are some known cases in which insufficient attention was devoted to the investigation of such phenomena, neither in the period of designing a specific structure, nor during the course of its construction. The long-term effects of such actions appeared even after ten or more years. The consequences of these influences were numerous rehabilitation works on facilities, in some cases even demolitions.

Today, the systematic investigation of time-dependent phenomena in rocks using numerical procedures and analyses enables better comparative analyses, particularly as regards considering no homogenity and anisotropy, which are frequently present in rocks. The rheology of rocks deals primarily with the following sub areas, which are thematically and conceptually oriented towards:

- searching for and analyzing the causes of the occurrence of time-dependent processes,
- the development and testing of rheological models and influential parameters for describing such processes,
- the method of determining influential parameters,
- searching for mathematical combinations presenting time-dependent processes, etc.

Causes of time changes in stress and deformations

The stresses and deformations occurring in the vicinity of underground facilities may change over time for various reasons. The most frequent among these are changes in loads or rock pressures occurring in and affecting rocks. Such cases occur, e.g. due to flowing strata waters (abundant precipitation, drainage), changes in the geometry of an excavated area (excavation round or gradual, phase construction of a specific type of facility), changes in size and additional loads on an area (construction of new structure in the immediate vicinity), changes in the deformation properties of rocks (weathering), and similar.

A specific example of time-dependent changes in rock stresses and deformations is represented by the viscose properties of rocks. The viscose behavior of rocks causes the material to gradually deform under constant load, depending on the time period, which may last several decades. This phenomenon is also known as creep, whose causes may be explained by two principal factors, i.e. rock mass yielding and the formation of cracks. Some rocks, such as rock salt, tar sands, compact shales, etc. creep at relatively small deviatory stresses, despite their uncracked or undamaged, intact base. In the case of rock salt, the creep process includes movement of dislocations and intercrystalline sliding; in unconsolidated clayey rocks, the creep process includes water migration and movements of clayey particles; bituminous rocks, such as tar sands, are characterized by rock mass yielding, which occurs in particular at higher temperatures. Even solid rocks such as granite and limestone may creep as the result of deviatory stress activity, resulting in the formation and growth of new cracks. A change in deviatory stress may cause changes in the crack network because, after the initial closing of cracks, the old cracks will expand once again and new cracks will appear. A specific example of time-dependent deformations is also rock swelling, which is characteristic of anhydrite, certain types of shales, grey clay, etc... All these factors cause rocks in the phase of additional load to undergo both momentary and delayed deformation, the latter of which is time-dependent. This kind of rock is therefore referred to as viscoelastic or viscoplastic, provided the process occurs in a plastic area. Similar to elasticity, rocks can show different forms of nonlinearity, yet the majority of viscoelasticity theories are based on the treatment of rocks as a linear, viscoelastic material.

Creep, Dilatation and Compression

Two principal factors essentially influence the mode of deformation and, in the final phase, the collapse of the rock mass. One of these is determined by the geotechnical properties of rocks, while the other depends on the size and speed of loading. Both processes are time-dependent, which means that for a realistic definition of rocks, time is a crucial factor to be considered in constitutive equations presenting the association between deformations and stresses.

A typical time-dependent phenomenon found primarily in low-bearing-capacity and soft rocks is creep. Creep is defined as the irreversible deformation of rock mass in the period leading up to its collapse. In general, deformations resulting from creep depend primarily on three main parameters: time, temperature and stress.

The influence of time on the development of time deformations is evident from the creep curve, i.e. as time versus a specific axial deformation, which is schematically shown in Figure 1. As is evident in this figure, the initial elastic deformation is followed by primary creep with a decreasing speed of deformations, then secondary creep, where the change in deformations is constant and tertiary creep, where the speed of deformations increases until final collapse.

Temperature has a negative influence on the development of time deformations, as a rising temperature will increase the speed of creeping. An even greater influence on the development of time deformations is shown by load speed, which is reflected in the following facts:

- comparatively speaking, a higher load speed causes smaller deformations,
- a higher load speed gives a higher peak stress in smaller collapse deformations,
- the yield limit and creep phenomenon already occur at very small loads.

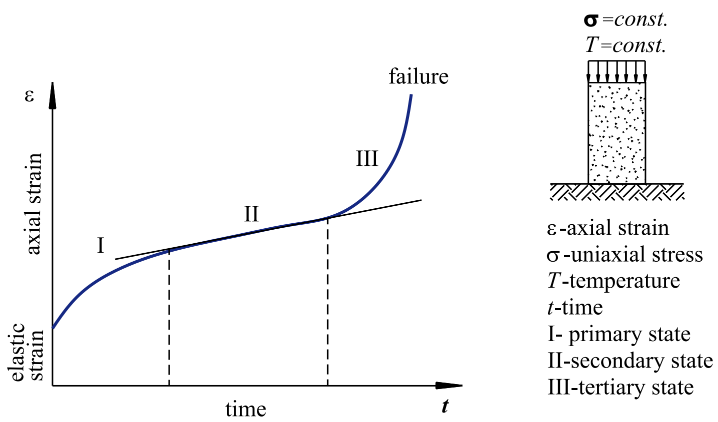

Figure 1. Typical time dependent creep curve
Slika 1. Značilna oblika krivulje lezenja

How the volume of a rock mass will deform in the creep phase depends on the stress state dominating the rock. This is because the volume deformation of a sample may be positive (compression) or negative (dilatation). In an area with smaller stresses, the volume diminishes (contracts) due to the contracting or closing of micro cracks and pores. Areas with higher stresses will witness the irreversible growth of volume, as new micro cracks begin to form and the existing ones begin to expand.

The compressibility and dilatation area obtained using the triaxial test is presented in Figure 2. In this figure, area D_c represents the compression area, and area D_d represents the dilatation area. The boundary between the two areas is called the dilatation limit.

Another interesting figure in addition to the above-mentioned is Figure 3, which shows the development of volume deformations during an unconfined pressure test on a rock sample. The decreasing volume is evident in the first nonlinear part due to the closing of micro cracks and pores. This is followed by the second, almost linear part between stresses *C* and *I*, with a reversible volume deformation. The last, nonlinear part is characterized by the opening and expansion of micro cracks, i.e. dilatation.

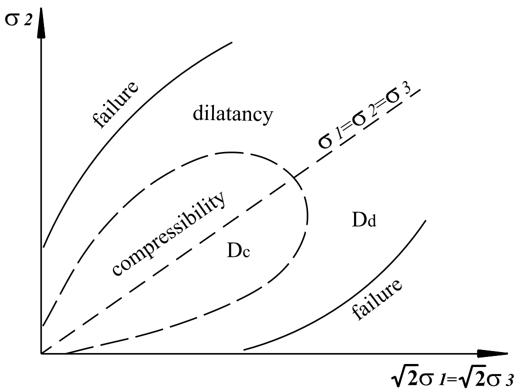

Figure 2. Domains of compressibility and of dilatancy
Slika 2. Območje stiskanja in dilatacije

Creep, Dilatation and Compression in the Vicinity of Tunnels

Knowledge of the dilatation and compression areas in the vicinity of underground structures is of essential importance in their design and construction. Two parameters significantly influence the size and distribution of an individual area. These are: the relation between the horizontal and vertical stress components (σ_h/σ_v), and the effect of the primary supporting system. On the basis of laboratory tests and field measurements, we have arrived at the following conclusions on the behavior of rocks in the vicinity of tunnels and other underground structures:

- a rock is much more unstable when it is $\sigma_h \neq \sigma_v$ than when it is $\sigma_h = \sigma_v$,
- the dilatation area diminishes substantially if the σ_h/σ_v ratio is higher and if the supporting is taken into account,
- creep is more rapid in the direction of the smallest soil pressure component,
- the convergence size depends on the σ_h/σ_v ratio, the height of the overburden, and the functioning of the supporting system.

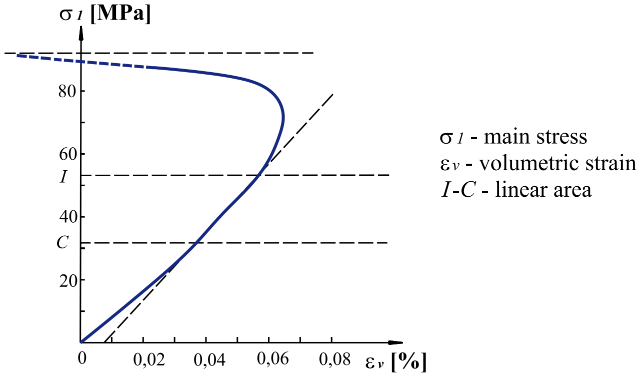

Figure 3. Stress strain curve showing dilatancy
Slika 3. Razvoj volumskih deformacij pri enoosnem tlačnem preiz-

Why is it important to have a knowledge of time-dependent deformations?

In the construction of underground structures, a knowledge of time-dependent deformations will enable the following:

- to select the proper rigidity of supporting,
- to determine the sequence of excavations and supporting,
- to predict a suitable time for incorporating the interior lining,
- to determine the course of increasing load on the supporting,
- to predict the period of eventual rehabilitation of the structure,
- to forecast the long-term stable shape and size of the underground structure,
- to determine the required over profile of the excavation,
- to determine the areas where collapse may occur due to excessive deformations, etc.

All the above-mentioned may be determined with some certainty, if, of course, we are able to correctly assess or forecast the time development of deformations. In doing so we shall have to consider the effect of interactions between the rock mass and supporting, as we are dealing with two materials (rock mass and supporting) that are both time-dependent, but do not behave in the same way in a specific time interval. In this contribution, we shall deal only with time-dependent processes in rocks that can be described using various rheological elements interconnected in various models. Burger's linear viscoelastic rheological model is presented in more detail below.

BURGER'S RHEOLOGICAL MODEL

The dependence of normal specific deformations on time, also referred to as creep curves, which are obtained in laboratory or field investigations, may be described using various rheological models. In this case we shall limit ourselves to linear viscoelastic rheological models comprised of two basic rheological elements. These are Hook's spring and Newton's vessel, which are interconnected in various ways and, through these interconnections, determine various rheological models. Several basic linear viscoelastic rheological models are known, such as Maxwell's, Kelvin's, Generalized Maxwell's, Generalized Kelvin's, and Burger's model. The last mentioned is the most broadly accepted model in rock mechanics, as it best describes and presents the development of rock deformations in dependence of time.

Burger's rheological model is obtained as a consecutive link of Maxwell's and Kelvin's rheological models, as shown in Figure 4. One can see that the model has four rheological elements, whose notation is as follows:

- G_1: shear modulus, which controls the size of delayed elasticity,
- G_2: shear modulus, which defines the size of instantaneous elastic deformation,
- η_1: dynamic viscosity, which determines the stage of delayed elasticity,
- η_2: dynamic viscosity, which describes the stage of viscose yielding,
- γ_1, γ_2, γ_3: shear strains.

The response of time deformations with respect to the instantaneous and constantly active shear load τ, begins with the instantaneous elastic shear strain γ_1, followed by the exponentially diminishing shear strain γ_2, which then approaches the asymptote and continues into the constantly growing shear strain γ_3.

In addition to the shear stress τ, the sample may also be burdened with a normal load σ. By increasing (decreasing) this load, the sample measures the axial specific deformations ε, which is the laboratory procedure for determining the parameters of Burger's model. In this procedure, the cylindrical rock sample is subjected to a uniaxial pressure load by means of an instantaneous load σ_1, during which the time development of specific axial deformations ε_1 are measured. This is observed for as long as the creep curve does not approach the asymptote. The load is then increased and the procedure of strain measurement is repeated. The test is performed in several load stages, and for each stage a characteristic creep curve is obtained, as shown in Figure 5.

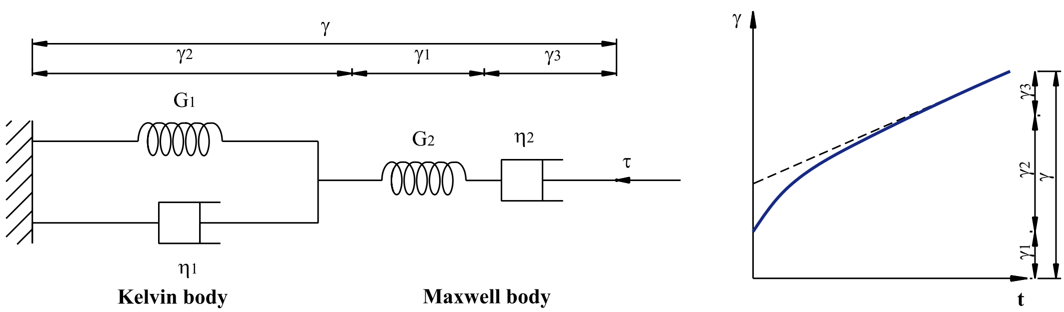

Figure 4. Burger`s rheological model and a diagram of shear strains γ versus time *t*
Slika 4. Burgerjev reološki model in diagram strižnih specifičnih deformacij γ v odvisnosti od časa *t*

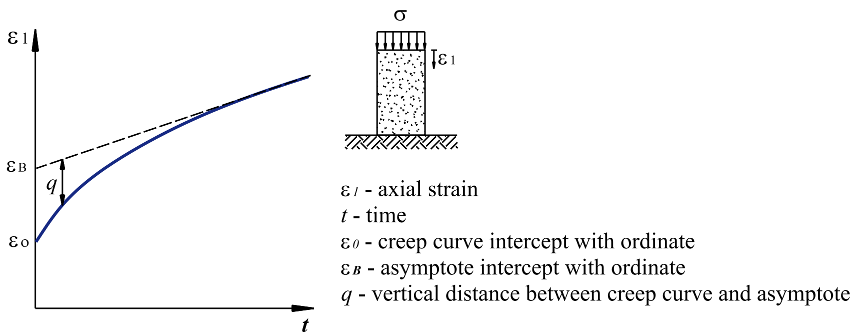

Figure 5. Time dependent curve of the axial strains
Slika 5. Krivulja osnih specifičnih deformacij v odvisnosti od časa *t*

The size of axial specific deformations by time $\varepsilon_1(t)$ for the relevant Burger's model, burdened with constant axial load σ_1, is presented using the equation:

$$\varepsilon_1(t) = \frac{2\sigma_1}{9K} + \frac{\sigma_1}{3G_2} + \frac{\sigma_1}{3G_1} - \frac{\sigma_1}{3G_1} \cdot e^{-(G_1 \cdot t/\eta_1)} + \frac{\sigma_1}{3\eta_2} \cdot t \tag{1}$$

In this equation, the compression module K is independent of time and is calculated using the equation $K = \sigma_1 / 3(\varepsilon_1 + 2\varepsilon_3)$. The sizes of axial ε_1 and transversal ε_3 strains are determined using resistance strain gages. The remaining parameters G_1, G_2, η_1 and η_2 are determined with the help of Figure 5 and the equations presented below. In this diagram, one can see that in time t=0, the curve bisects the ordinate at point ε_0, whereas in time $t \to \infty$ the curve approaches the asymptote, which has a gradient $\sigma_1 / 3\eta_2$ and bisects the ordinate at point ε_B. On the basis of this data, the following three parameters can be calculated:

$$\varepsilon_0 = \sigma_1 \left(\frac{2}{9K} + \frac{1}{3G_2} \right) \quad \Rightarrow \quad G_2 \tag{2}$$

$$\varepsilon_B = \sigma_1 \left(\frac{2}{9K} + \frac{1}{3G_2} + \frac{1}{3G_1} \right) \quad \Rightarrow \quad G_1 \tag{3}$$

$$\frac{\sigma_1}{3\eta_2} \quad \Rightarrow \quad \eta_2 \tag{4}$$

If, in the above diagram, the distance between the curve and the asymptote is designated by q, then at a given moment of time t the semi logarithmic diagram log q may be drawn in dependence of time t. In this diagram (Figure 5) we obtain a straight line, which is presented by the equation:

$$\log q = \log\left(\frac{\sigma_1}{3G_1}\right) - \frac{G_1}{2{,}3\cdot\eta_1}\cdot t \tag{5}$$

The first part of the given equation represents the intersection point of the line and the ordinate, which gives value G_1, and the second part of the equation represents the line gradient, which gives value η_1.

$$\frac{G_1}{2{,}3\cdot\eta_1} \Rightarrow \eta_1 \tag{6}$$

In practice, the rheological model shown above can be satisfactorily used in the majority of cases to describe the curve of so-called secondary creep all the way up to the limit of tertiary creep. If we wish to describe the process of time-dependent creep in rocks, taking into account the plastic deformations, a more complex model will need to be selected, which may also be obtained by connecting additional rheological elements. The deficiency of the linear viscoelastic rheological model is primarily in the fact that it cannot be used to describe the dilatational and compressive specific deformations linked to collapse mechanisms in rocks. In such cases, the elastic viscoplastic rheological model may be used to describe time occurrences in the plastic area as well.

Analysis of time-dependent deformations during tunnel construction in compressive low-bearing-capacity rocks

In the text below, the behaviour of a tunnel during its construction, which took place in rheologically highly sensitive rocks (Figure 6) with varying geotechnical properties, is compared with a computer model of the time development of displacements in the tunnel tube walls. A typical example of such rocks are Permian-Carboniferous layers, which are comprised primarily of

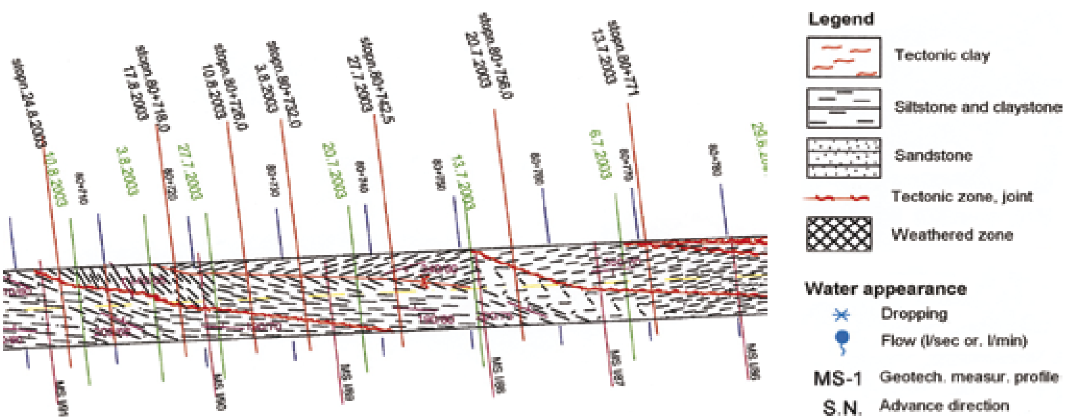

Figure 6. Geological site conditions of the covered area
Slika 6. Geološka sestava analiziranega območja

molded shaley claystones, tectonic clay and siltstones intercalated with various clay minerals, which in reality provide a physical basis for the interpretation of more or less intensive creep.

The description of time deformations is performed using an appropriate rheological model, but one should bear in mind that we are dealing with two time-dependent systems in interaction. These are the rock strata base as the principal medium, and the primary lining comprised of sprayed concrete and other supporting elements, such as rock bolts, steel supports, etc. In the case discussed, only the rheological properties of the rock mass have been taken into account, while the supporting system is treated as an elastic structural element comprised of sprayed concrete or supports.

In the analyzed practical example, equations were used within the scope of a simple analytical method, the so-called closed form solutions[1]. With the help of these equations and measured displacements of the roof measuring point in the tunnel tube, the rheological parameters of surrounding rocks in the analyzed profile were determined by means of a back analysis.

The procedure used in the above-mentioned analysis is based on the use of Burger's model and the Generalized Maxwell's model. Because the parameters of surrounding rocks were not known for the above-mentioned two models, a back analysis was used. Taking into account the actual variability and structural damage of Permian-Carboniferous rocks, and indirectly also the interwoven ness of their individual lithological types, the employed method of determining parameters has, in comparison with classical methods (laboratory, in situ with dilatometer or load plate), several advantages. These are the following:

- problem of acquiring adequate samples for conducting creep tests is eliminated,
- dependence of creep parameters on the structure of tested samples is also excluded, and
- application of laboratory-measured values of creep parameters on the broader rock mass areas is not necessary.
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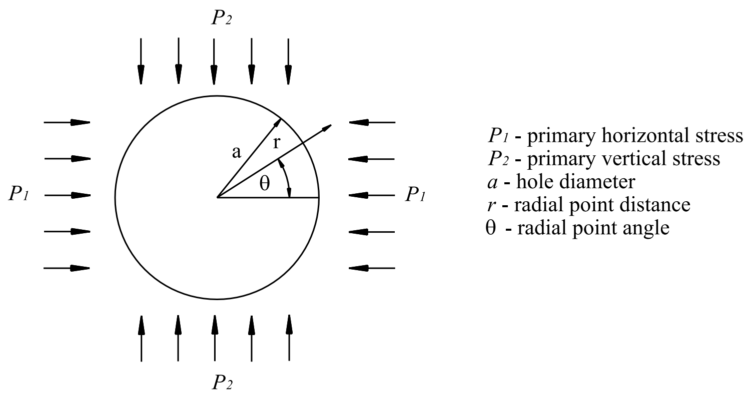

Figure 7. Cross section of an unlined tunnel tube
Slika 7. Shematski prikaz stanja pred vgradnjo primarne obloge v predorsko cev

The back analysis was conducted by dividing the curve of measured displacements in the analyzed profile into three parts, each of which was examined separately. For the entire displacement curve we therefore obtained:

- initial displacements occurring immediately after excavation (using Kirsch's equation for circular opening, Figure 7).
- displacements occurring in the period from the excavation of the calotte until the incorporation of the complete primary lining of the tunnel (using equations for describing the creep of rocks around the unsupported tunnel, Figure 7).
- displacements occurring after the completed incorporation of primary lining along the entire circumference of the tunnel tube (using equations for describing the creep of rocks around the supported tunnel, Figure 8).

For the curve of measured displacements, we took the measured vertical displacements in the left (south) tunnel tube, on the west part of the Trojane tunnel, at cross sections 86, 87, 88 and 89. Relevant data are available in the Report on geological and geotechnical monitoring of the Trojane tunnel excavation no.151[4]. It should be mentioned that an initial displacement u_0 was added to the measured displacements. This displacement is of the same size as the one used in the curve of calculated displacements. However, it is not included in the measured values, as it occurs before the incorporation of measuring points in the analyzed measuring profile. The equations used for the calculation of displacements are presented in[1] and have the following form:

Initial displacement:

$$u_0 = \frac{p\,a}{2G} \tag{7}$$

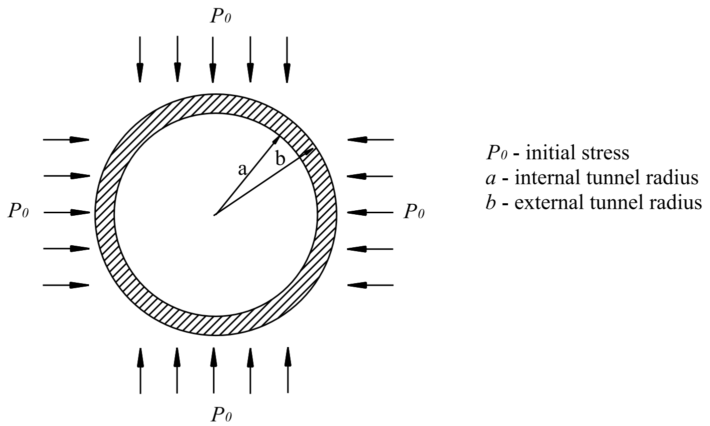

Figure 8. Cross section of a lined tunnel tube
Slika 8. Prikaz predorske cevi z vgrajeno primarno oblogo

An unlined tunnel displacement:

$$u_r(t)=\left[A+B\left(\frac{1}{2}-\frac{a^2}{4r^2}\right)\right]\left(\frac{1}{G_2}+\frac{1}{G_1}-\frac{1}{G_1}\;e^{-(G_1 t/\eta_1)}+\frac{t}{\eta_2}\right) \tag{8}$$

$$A=\frac{p_1+p_2}{4}\frac{a^2}{r} \tag{9}$$

$$B=(p_1-p_2)\frac{a^2}{r}\cos 2\theta \tag{10}$$

A lined tunnel displacement:

$$p_b(t)=p_0\left(1+Ce^{r_1 t}+De^{r_2 t}\right) \tag{11}$$

$$C=\frac{\eta_2}{G_1}r_2\left(\frac{r_1\left(1+\eta_1/\eta_2\right)+G_1/\eta_2}{(r_1-r_2)}\right) \tag{12}$$

$$D=\frac{\eta_2}{G_1}r_1\left(\frac{r_2\left(1+\eta_1/\eta_2\right)+G_1/\eta_2}{(r_2-r_1)}\right) \tag{13}$$

$$\eta_1 Bs^2+\left[G_1B+\left(1+\frac{\eta_1}{\eta_2}\right)\right]s+\frac{G_1}{\eta_2}=0\Rightarrow r_1,r_2 \tag{14}$$

$$B=\frac{1}{G'}\left(\frac{(1-2\nu')b^2+a^2}{b^2-a^2}\right) \tag{15}$$

$$u_r=-\frac{b^2rp_b\left(1-2\nu'+a^2/r^2\right)}{2G'\left(b^2-a^2\right)}\qquad for\quad a\le r\le b \tag{16}$$

$$u_r=-\frac{b^2}{r}p_b\left(\frac{(1-2\nu')b^2+a^2}{2G'\left(b^2-a^2\right)}\right)\qquad for\quad r\ge b \tag{17}$$

With the help of back analyses and the iteration of various parameters, η_1, η_2, G_1 and G_2, we obtained diagrams showing the measured and calculated vertical displacements of roof measuring points in the above-mentioned measuring cross profiles.

On the basis of calculations performed, diagrams shown (Figure 9) and relevant analyses, we may summarize as follows:

- The curve of measured values may be easily followed until approx. day 13, when the primary lining in the tunnel tube was completed. From here on the supported tunnel equation was used, in which we observed a sharp rise in displacements in dependence of time, followed by rapid stabilization.

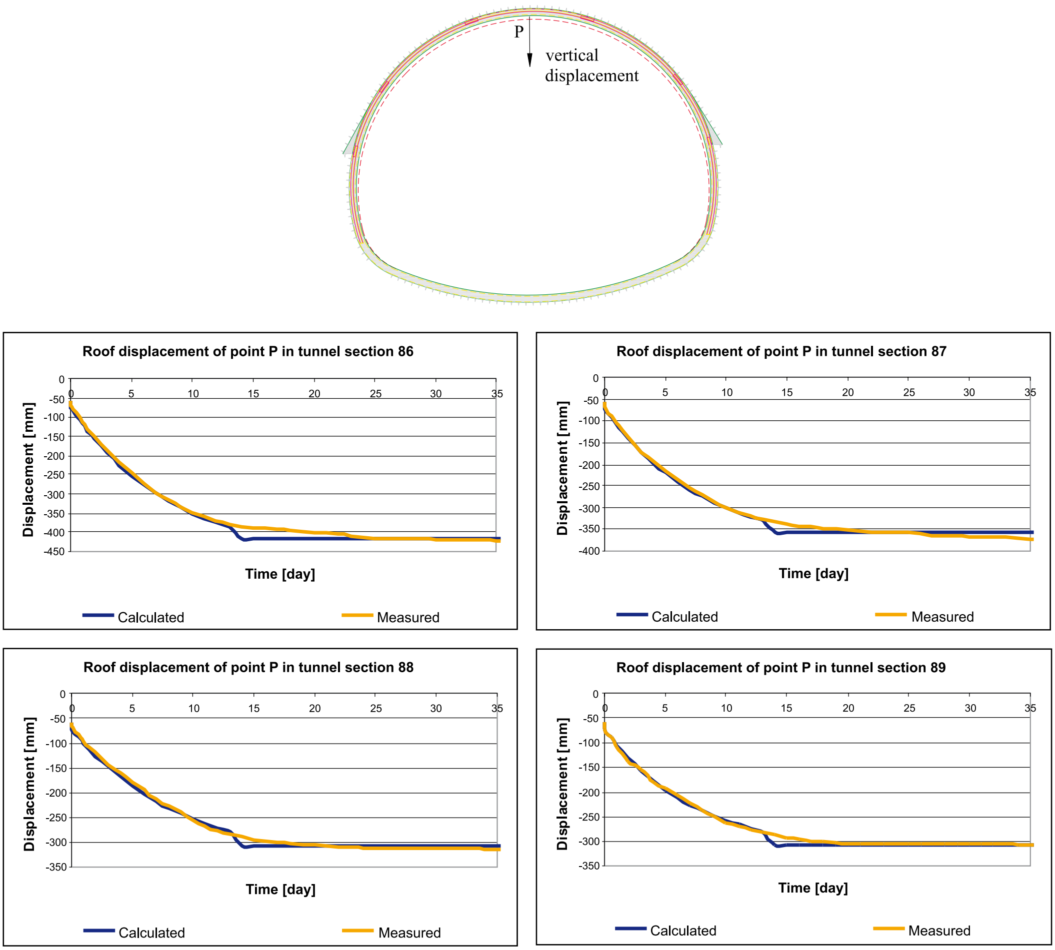

Figure 9. Comparison between measured and calculated vertical displacements of a roof point
Slika 9. Primerjava med izmerjenimi in izračunanimi pomiki stropne točke

- Since the phase of support creeping of primary lining was not taken into account in the supported tunnel equation, which means that its constant solidity and rigidity is assumed from the moment of incorporation, the description of displacements in this phase is not entirely realistic because a certain average value was used. This equation is thus applicable in cases when a tunnel is supported by prefabricated, reinforced concrete segments, which are frequently used in construction works where TBM machines (for cutting the entire tunnel profile) are used.
- The average values of rheological parameters for the above-mentioned profiles are: G_1=5,5MPa, G_2=115MPa, η_1=65000MPa·min, η_2=5,05·10^8MPa·min. It should be mentioned that the average maximum displacements in the analyzed area were approx. 360 mm.
- The established values of rheological parameters were considerably lower than those normally obtained in laboratory tests. It should be taken into account that the excavation of the tunnel tube was performed in a rock mass with low strength and deformability properties, which indirectly called for the immediate incorporation of supporting elements.
- It is evident from the measuring data that the curves of measured time-dependent displacement are of varying shape and size in the observed time period. This is due to the geological composition and structure of surrounding rocks, which are characterized by rapid changes both as regards the content of individual lithological components and the position of rock strata. In the given case, it was thus practically impossible to obtain representational rheological parameters of existing rocks in the laboratory.
- Based on the above-mentioned, we may conclude that describing the time development of deformations in rocks depends on a large number of influential factors which are difficult to include in calculations or whose interrelations are hard to determine. The procedure used in the given case may be suitable for the preparation of preliminary analyses of more simple cases of creep, which by their complexity do not surpass the cross section of an underground structure or the structure of the rock mass. Part of the complexity of a specific problem may be solved by means of numerical methods, which are available within the scope of complex software applications.

CONCLUSIONS

- Time-dependent processes in rocks which, depending on natural conditions, are more or less intensive play a significant role in the construction of underground structures. These processes indirectly influence the design and execution of construction works, including the supporting method, and have a long-term effect on the stability of the structure.
- Typical time-dependent occurrences in rocks often have the character of creeping soft and low-bearing-capacity rocks or rock mass containing soils.

- Typical rock masses with distinctive rheological properties are also Permian-Carboniferous layers, which can be found in several areas throughout Slovenia, such as in the Karavanke mountains, Idrija, Mežica, Trojane, Ljubljana (Golovec hill, Šentvid), and elsewhere.
- The presented practical example of the use of viscoelastic rheological models in the calculation of time-dependent displacements of tunnel tube walls has opened the question of the applicability of such calculations in practice.
- The analyzed comparisons between measured and calculated values of displacements professionally justify the presented calculation methods alongside sufficiently known simplifications and assumptions.
- Quick calculations coupled with practical experience are adequate bases for rough estimates of the method of primary supporting of underground structures being built in rheologically sensitive rocks.
- In describing the creeping of rock masses, it would be necessary to use, for supported underground structures, a more detailed equation that would also take into account the creep of a support system made of sprayed concrete cement or any other time-dependent support system.

Povzetek

Časovno odvisni procesi v kamninah

Poznavanje časovno odvisnih procesov v kamninah, je z inženirskega vidika zelo pomembno. V mislih imamo procese, ki zajemajo časovni razvoj napetosti in deformacij v hribinah in okolici podzemnih objektov. Ti procesi, ki so dolgotrajni in se lahko odvijajo več dni ali celo desetletij, vplivajo na spremembe in prerazporeditve napetosti v hribinah v katerih so zgrajeni podzemni prostori. Posledice tega so med drugim povečanje obremenitev podpornega sistema oz. zmanjšanje stabilnosti objekta, kar v skrajnem primeru lahko privede celo do porušitve.

Dejavnike, ki povzročajo omenjene spremembe napetosti in deformacij v kamninah gre pripisati različnim vzrokom. Med najpogostejše štejemo spremembe obtežb ali hribinskih pritiskov, ki delujejo v kamninah in so lahko posledica pretakanje vode, spremembe geometrije izkopanega prostora, preperevanja in podobno. Drugi pomembni dejavnik, ki prav tako povzroča časovno odvisne procese v kamninah pa je lezenje, čigar vzroke lahko razložimo s tremi glavnimi vplivi. To so plastično tečenje hribinskih mas, širjenje vezanih in nastajanje novih razpok ter nabrekanje. Vsi ti dejavniki povzročajo, da kamnine v fazi dodatne obremenitve, poleg trenutne deformacije, kažejo tudi zakasnelo – časovno odvisno deformacijo, ki je lahko različno velika tako po obsegu kot tudi po času trajanja. Kamnine ali širše gledano hribine, ki imajo te lastnosti, imenujemo viskoelastične oz., v kolikor se ti procesi odvijajo v plastičnem območju, tudi viskoplastične.

Poznavanje časovno odvisnih sprememb deformacijsko napetostnega polja v okolici podzemnih objektov, je z vidika načrtovanja in gradnje podzemnih objektov velikega pomena, saj nam omogoča pravilnejšo izbiro togosti podporja, določitev zaporedja izkopa in podpiranja, napovedovanje primernega časa vgradnje notranje obloge, določiti potek naraščanja obremenitve podporja, določiti potreben nadprofil izkopa prostora, itd.

Eno od pomembnih področij znanstvene vede, ki je se ukvarja s časovno odvisnimi procesi v hribinah, je tudi razvoj in preizkušanje reoloških modelov, s katerimi opisujemo časovno odvisne napetostno deformacijske spremembe v hribinskih sistemih. V pričujočem delu smo se omejili na linearne viskoelastične reološke modele, med katerimi je Burgerjev model dobro uporaben v mehaniki kamnin.

Ta model je določen z zaporedno vezavo Maxwellovega in Kelvinovega reološkega modela. Lastnosti modela podajata dva elastična in dva viskoelastična parametra G_1, G_2, η_1 in η_2, katere določimo s pomočjo krivulje lezenja, dobljene na osnovi laboratorijskih oz. in-situ raziskav. Poznavanje omenjenih parametrov, lahko uporabimo za napovedovanje časovnega razvoja deformacij hribine, izpostavljene določenemu napetostnemu stanju ali spremembi napetosti.

Ker je določitev viskoelastičnih parametrov v laboratoriju oz. in-situ v posameznih primerih lahko vprašljiva, se v ta namen pogostokrat poslužujemo povratne analize, kjer se na osnovi poznanih oz. izmerjenih vrednosti npr. pomikov določenih točk ostenja podzemnega prostora, z iteriranjem poišče iskane realne vrednosti. Ta način dela je prikazan tudi v pričujočem prispevku, kjer smo s pomočjo povratne analize poiskali viskoelastične parametre za Burgerjev in posplošeni Maxwellov model. Navedena reološka modela se uporabljata za napovedovanje časovnega razvoja deformacij nepodprtega in podprtega predora krožnega prereza.

Enačbe omenjenih modelov so podane v[1] in spadajo v kategorijo t.i. preprostih analitičnih enačb zaprte oblike. Ker gre za analitične enačbe, ki opisujejo dogajanje v okolju, ki je izjemno kompleksno in odvisno od številnih parametrov, seveda ni za pričakovati popolnega ujemanja med napovedanimi in izmerjenimi vrednostmi. V pričujočem prispevku je obdelana tematika, ki obravnava v kolikšni meri so omenjene enačbe za napovedovanje časovnega razvoja deformacij nepodprtega in podprtega predora uporabne ter kolikšne so vrednosti viskoelastičnih parametrov analiziranega območja.

Analizirano območje, skozi katero je potekala gradnja predora sestavljajo permokarbonske kamnine, med katerimi prevladujejo pregneteni skrilavi glinavci, tektonska glina in meljevci z različnimi vsebnostmi mineralov glin. Omenjene kamnine imajo izrazite reološke lastnosti in jih lahko srečamo širom Slovenije, kot npr. v Karavankah, Idriji, Mežici, Trojanah, Ljubljani (Golovec, Šentvid) in drugod.
Povratna analiza je potekala tako, da smo s pomočjo iteriranja dosegli ujemanje med krivuljo izračunanih in krivuljo izmerjenih pomikov. Krivuljo izračunanih pomikov smo dobili kot vsoto treh različnih pomikov, katere podajajo tri različne enačbe. To so začetni elastični pomik, viskoelastični pomik nepodprtega predora in viskoelastični pomik podprtega predora. Za krivuljo poz-

nanih vrednosti pa smo privzeli izmerjene vertikalne pomike ostenja predora v štirih zaporednih prečnih profilih na analiziranem odseku predorske cevi.

Na osnovi primerjave rezultatov in oblike krivulj lahko ugotovimo, da enačba časovnih deformacij nepodprtega predora lepo sledi izmerjenim pomikom, dočim pri uporabi enačbe podprtega predora pride do manjšega odstopanja. Vzrok slednjemu je dejstvo, da imamo v našem primeru opravka z dvema časovno odvisnima materialoma, to je hribino in podporjem. Ker v enačbi podprtega predora ni upoštevana faza lezenja podporja oz. primarne obloge, kar pomeni, da je privzeta njegova konstantna trdnost in togost od trenutka vgradnje, opisovanje pomikov za to fazo ni povsem realno, saj upoštevamo določeno povprečno vrednost. Enačba za izračun pomikov podprtega dela predora je zato bolj uporabna v primeru podpiranja predora s prefabriciranimi armirano betonskimi segmenti, kateri se pogosto uporabljajo pri gradnjah z uporabo strojev za rezanje celotnega profila predora (TBM).

Absolutne velikosti viskoelastičnih parametrov imajo precej nižje vrednosti, kot jih dobimo iz laboratorijskih preiskav. Upoštevati je potrebno dejstvo, da je izkop predorske cevi potekal v izjemno heterogeni hribini z nizkimi trdnostnimi in deformabilnostnimi lastnostmi, kar je posredno narekovalo takojšnjo vgradnjo podpornih elementov. Poleg tega je omenjeno dejstvo povezano tudi z geološko sestavo in strukturo okoliških hribin, za katere je značilno hitro spreminjanje tako glede zastopanosti posameznih litoloških členov, kot tudi glede lege hribinskih plasti.

Iz vsega podanega lahko povzamemo, da je opisovanje časovnega razvoja deformacij v hribinah povezano z velikim številom vplivnih dejavnikov, ki jih je v izračunih težko v popolnosti zajeti in poiskati njihove medsebojne povezave. Postopek, ki je bil uporabljen v obravnavanem primeru, je uporaben za izdelavo preliminarnih analiz enostavnejših primerov lezenja, ki po svoji kompleksnosti ne presegajo niti oblike prečnega profila podzemnega prostora niti strukture hribinske zgradbe. Del kompleksnosti določenega problema, ki je prisoten pri analiziranju časovno odvisnih pojavov pri gradnji podzemnih prostorov, je rešljiv z numeričnimi metodami, ki so danes na voljo v sklopu zahtevnih programskih orodij.

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