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# Assessment of time-dependent behaviour of rocks on concrete lining in a large cross-section tunnel

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**Abstract.** Tunneling in rocks having the time-dependent behavior, causes some difficulties like tunnel convergence and, as a result, pressure on concrete lining; and so instability on this structure. In this paper the time-dependent behaviour of squeezing phenomenon in a large cross section tunnel was investigated as a case study: Alborz tunnel. Then, time-dependent behaviour of Alborz tunnel was evaluated using FLAC2D based on the finite difference numerical method. A Burger-creep viscoelastic model was used in numerical analysis. Using numerical analysis, the long-time effect of squeezing on lining stability was simulated.This study is done for primary lining (for 2 years) and permanent lining (for 100 years), under squeezing situations. The response of lining is discussed base on Thrust Force-Bending Moment and Thrust Force-Shear Force diagrams analysing. The results determined the importance of consideration of time-dependent behaviour of tunnel that structural forces in concrete lining will grow in consider with time pass and after 70 years can cause instability in creepy rock masses section of tunnel. To show the importance of time-dependent behavior consideration of rocks, elastic and Mohr-Coulomb models are evaluated at the end.

**Keywords:** creep; burger-creep visco-plastic model (CVISC); numerical; time-dependent; tunnel

## 1. Introduction

One of the most important phenomenon that causes some troubles in tunneling, and greatly affect the result of tunnel convergence is due to squeezing. Deformation of tunnels is usually time-dependent, and the underground space will converge as time passes in some cases, based on squeezing behaviour. Squeezing in rock is communed from the first days of tunneling in Alps mountains and different definitions are offered (Zhu and Zhao 2004, Singh and Goel 2006, Weiqi *et al.* 2020). Some examples of problems caused by squeezing phenomenon in National Road ‹Frejus‹ Lyon-Turin Base tunnels all over the world are reported (Zhang *et al.* 2019). Squeezing of rocks is a time-dependent large deformation, which occurs around the tunnel, and is essentially associated with creep caused by exceeding limiting shear stress. Deformation may terminate construction or continue over a long time period (Zhang and Zhou 2017). The magnitude of tunnel convergence, the rate of deformation and the extent of the yielding and plastic zones around the tunnel depend on the geological and geotechnical conditions, the in-situ state of stress relative to rock mass strength, the groundwater flow, pore pressure, and the rock mass properties. As a result, the high pressures on concrete lining may cause lining failure (Zhang and Zhou 2017, Barla 1995, Feng and Jimenez 2015). The formulations of time-dependent models in the literature can be categorized into three main groups: (a) empirical functions, based on curve fitting of experimental data; (b) rheological models, consisting of mechanical analogues using springs, viscous dashpots, plastic sliders, and brittle yielding elements coupled in series or in parallel; and (c) creep models; since generally rocks are discontinuous and heterogeneous material with inherent defects, creep models with damage and fracture mechanics are introduced (Zhao *et al*. 2018).

In Kali Gandaki and Middle Marsyandgi headrace tunnel in Nepal, squeezing is observed, and the prediction of it is done (Panthi 2013). In Shebli twin tunnels in Iran, the time-dependent behaviour of tunnel and its effect on stability of lining were considered (Sharifzadeh and Moridi 2013, Bo *et al.* 2020, Muhammadi 2020). In Lyon-Turin tunnel in France, an exact and extensive study has been done on squeezing phenomenon. The Lyon–Turin Base Tunnel was excavated through a Carboniferous Formation, a highly heterogeneous overstressed and, in cases, anisotropic rock mass exhibiting a squeezing behaviour, so this phenomenon was studied and predicted by different researchers (Bonini and Barla 2012). In the Laodongshan Tunnel, as a part of Guangtong-Kunming railway in China, a large deformation and failure of primary support occurred in the early tunneling stage as a result of squeezing. In this tunnel, there have been many factors that result in the occurrence of squeezing failure of tunnel during construction, such as high in-situ stresses and weak rocks (Cao *et al.* 2018, Weichang *et al.* 2021). Prediction and estimation the rock mass response due to one excavation

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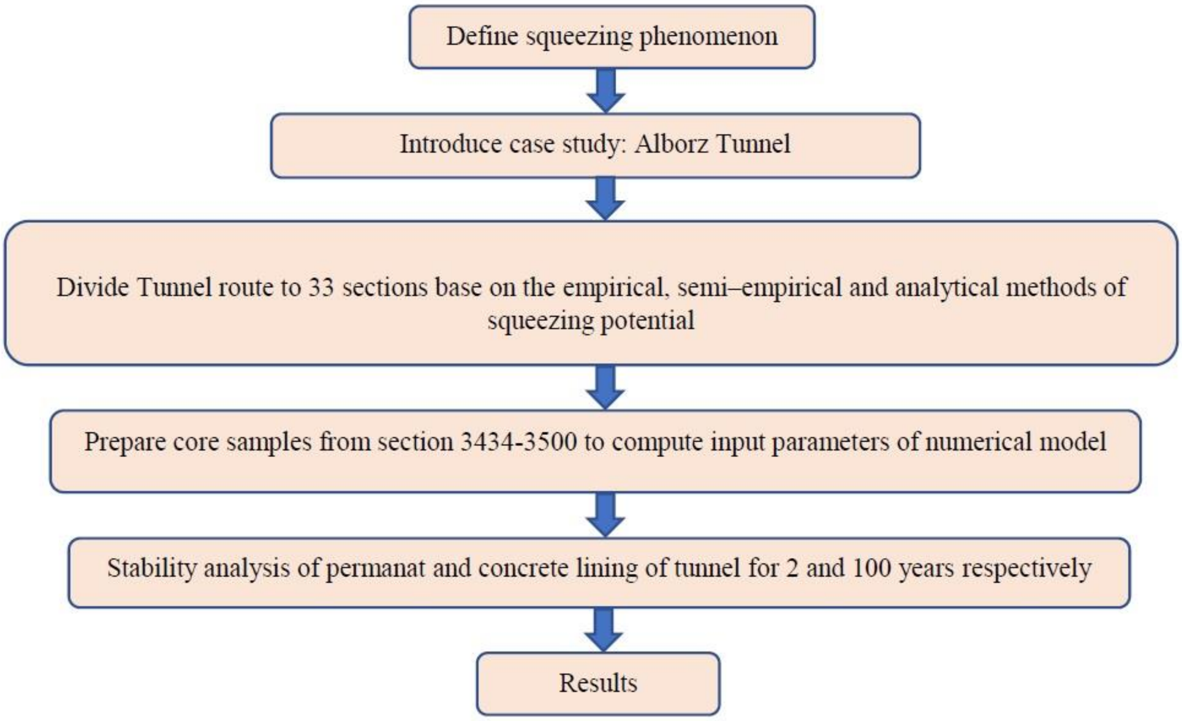


Fig. 1 A schematic structure of this article

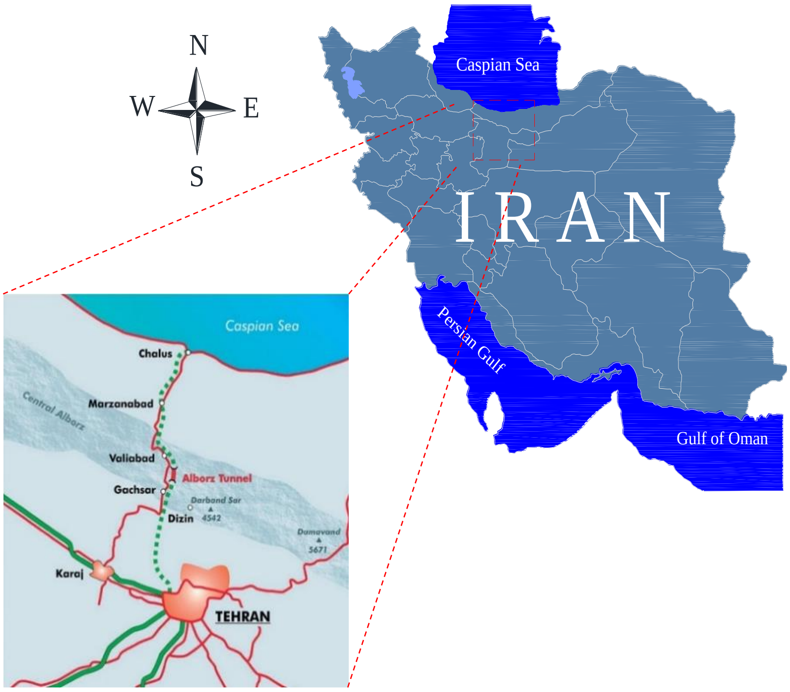


Fig. 2 Project location of the Alborz tunnel

method versus another can lead to project optimization. Optimization of the design usually involves the appropriate selection of the excavation method and the support system. Due to the this optimization, we won’t allow the rock mass to have further deform over limit, that could otherwise lead to support yielding and abrupt rock mass instabilities, safety issues and cost overruns (Paraskevopouloua and Diederichs 2018, Kui *et al.* 2020).

Numerical simulation is an effective means in predicting ground surface and subsurface displacements induced by tunnelling (Wang *et al.* 2021). In this study, since squeezing phenomenon is a time-dependent behavior, the only method that consider time in problem solution is numerical method. On the other hand, there is no special model that define squeezing phenomenon completely in numerical modeling and we have to use Burger-creep visco-plastic model which

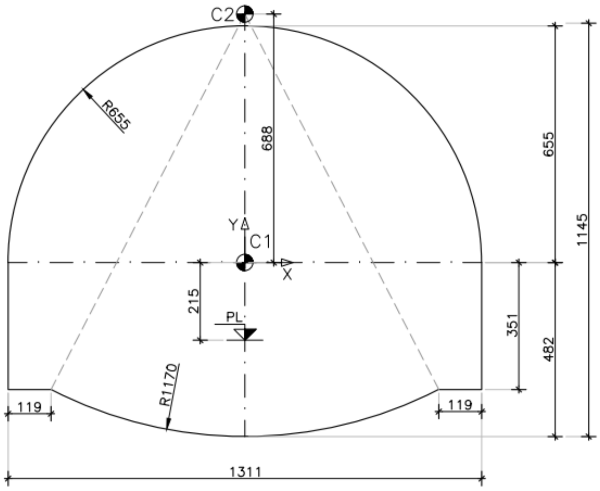


Fig. 3 Tunnel cross section with dimensions and drilling stages

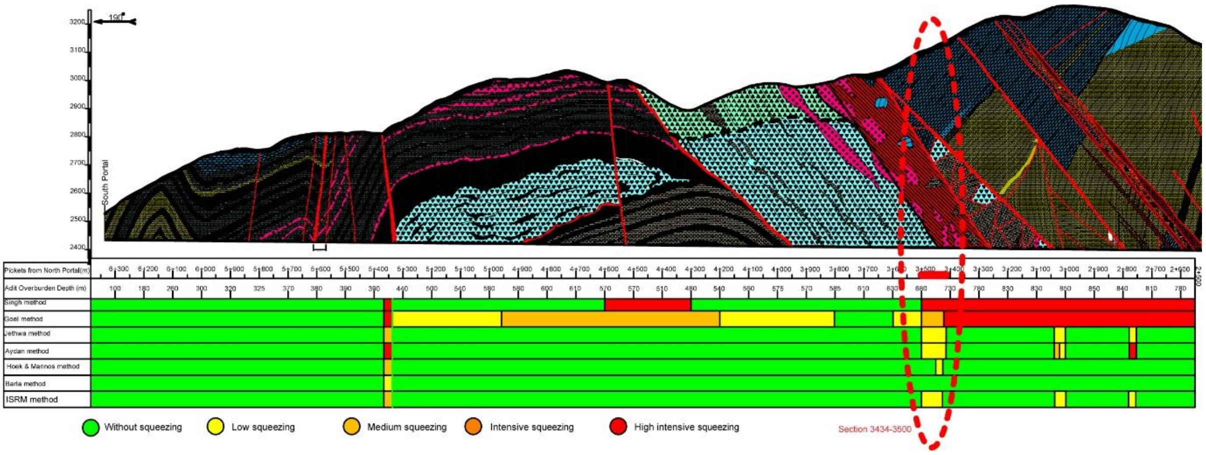
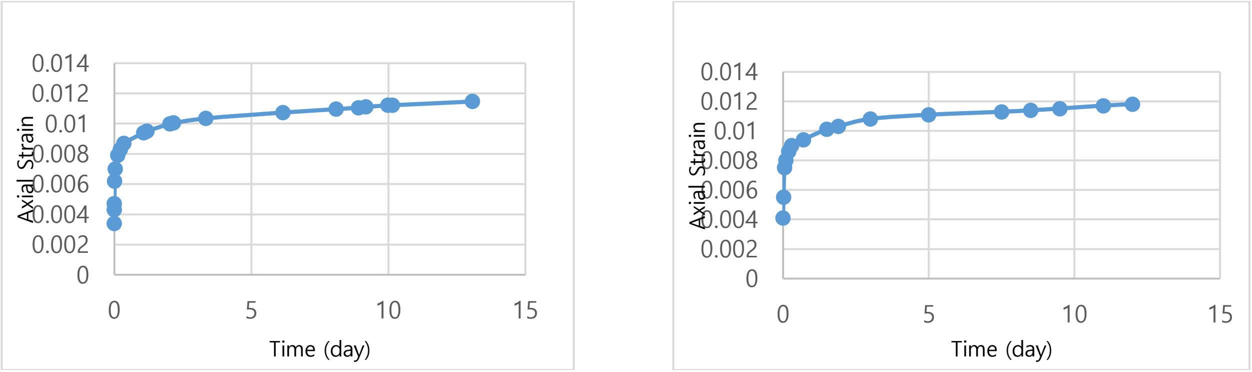


Fig. 4 Longitudinal profile of Alborz tunnel with determination of squeezing tunnel rocks according to empirical, semi-empirical, and analytical methods

is based on creep process model. Design of tunnels in squeezing ground conditions numerical methods involves high degree of complexity particularly for preliminary design (Arora *et al.* 2021). Fig. 1 shows a schematic structure of this article to reproduce a brief of study.

## 3. Evaluation of squeezing potential using empirical, semi – empirical and analytical methods

In order to determine the required parameters in squeezing evaluation methods, at first, rock units in tunnel length are specified, and the qualitative parameters of the tunnel rocks, overburden height of rock masses, width of tunnel, geomechanical properties of intact rock, and rock masses are extracted. Then, quantity of necessary parameters for different methods (empirical, semi-empirical and analytical) is calculated. According to these methods results, sections which are talented in squeezing phenomenon, have been specified. Finally, separated areas, that are specified as squeezing area in more methods, will be modeled by numerical method to clarify more details of squeezing phenomenon in these areas. The length of Alborz tunnel is 6387 meters, and due to the long length of tunnel, tunnel boring was done form two sides that are known as south and north portals. The zero point of tunnel is defined from north portal. For this study, only the data from south portal was available that 3887 meters of tunnel length is included (from 2500 to 6387 meter); for using the methods mentioned above, this 3887 meters is separated to 33 sections which are determined by squeezing methods for potential of squeezing. Based on rock mass parameters and stresses on rock (Basnet 2013), these 33 sections are divided. Therefore, quality of squeezing analysis is dependent on the correct estimation of input parameters. To divide the tunnel length based on rock mass parameters and stresses on rock, a prioritization is done in the segmentation. In this prioritization, at first, rock type of tunnel length, then fault in the tunnel length, and finally level of tunnel overburden are considered. In order to use of the parameters that are used in squeezing evaluation methods (empirical, semi-empirical, and analytical) in correct form, weight ratio of each segmentation is applied. Fig. 4 shows longitudinal profile of tunnel divided based on squeezing phenomenon that are gained by empirical, semi-empirical and analytical methods. To do numerical study due to the operational



(a) Specimen 1 (b) Specimen 2

Fig. 5 Strain-time curves of specimens in creep tests

limitation, the area of 3434-3500 m is selected. Based on 7 (empirical, semi – empirical and analytical methods) methods, the section of 3434-3500 domain, is strong talented for squeezing phenomenon. The most overburden of tunnel is 850 m and, in selected section, is about 700 m that is considerable height, and squeezing phenomenon should be checked.

## 4. Creep laboratory tests

After evaluation and identification of squeezing potential areas, to obtain properties and define them in numerical model, the intact rock samples were taken from squeezing talented area to do creep test in the laboratory. These tests were done to obtain input parameters in time-dependent Burger-model, which is used for rocks with time-dependent behaviour, and it is useful and implementable in numerical software. Fig 5. illustrates the strain-time curves of specimens in creep tests. Based on the Burger model, axial strain with time $\varepsilon_1(t)$ under effect of axial stress $\sigma_1$ is formulated

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

where K is Bulk Modulus, $G_1$ Kelvin shear modulus, $G_2$ Maxwell shear modulus, $\eta_1$ Kelvin viscosity, and $\eta_2$ Maxwell viscosity. To prepare rock sample for laboratory test, from two different positions of 3434-3500 tunnel, with squeezing potential, samples were selected.

The uniaxial compressive strength of the selected rock is 32 MPa based on the compression test. Since the amount of applied load must be in a way that creep occurs in the sample, the selected rock sample was subjected to loading of approximately 64% of the uniaxial compressive strength of the rock, which is equivalent to 20.5 MPa. The test time was approximately 13 days until the rock sample reached the secondary creep stage and the strain-time graph became linear. The parameters of the extracted burger model (Eq. (1)) for the two samples tested are given in Table 1.

Table 2 shows the values of input parameters of the time-dependent behavioural model of CVISC in FLAC numerical software for both samples. The validity of the creep test was performed using FLAC software, which is based on the numerical finite difference method and has been used in this research. In this regard, the amount of strain in the axial direction is calculated by taking the history of displacement from a point in the sample and the

Table 1 Creep burger model parameters for the two samples tested

| parameters | $\eta_1$ (GPa. s) | $G_2$ (GPa) | $G_1$ (GPa) | $K$ (GPa) | $\sigma_{ci}$ (MPa) |
|---|---|---|---|---|---|
| Sample 1 | 2.671e5 | 1.501 | 2.531 | 4.47 | 20.5 |
| Sample 2 | 2.034e5 | 2.220 | 2.741 | 4.47 | 20.5 |

Table 2 Values of input parameters to the CVISC model in FALC for both samples 1 and 2

| specifications | symbol | Sample 2 | Sample 1 | unit |
|---|---|---|---|---|
| Elastic bulk module | k | 4.47 | 4.47 | (GPa) |
| cohesion | C | 5 | 5 | (MPa) |
| Dilation angle | ψ | 9 | 9 | degree |
| Internal friction angle | φ | 50 | 50 | degree |
| Kelvin shear modulus | $G^k$ | 2.741 | 2.531 | (GPa) |
| Kelvin viscosity | $\eta^k$ | $2.034e^5$ | $2.761e^5$ | (GPa. s) |
| Maxwell shear modulus | $G^M$ | 2.22 | 1.501 | (GPa) |
| Tensile limit | $\sigma_t$ | 3.5 | 2.3 | (MPa) |
| Maxwell viscosity | $\eta^M$ | $5.367e^6$ | $7.38e^6$ | (GPa. s) |

Table 3 Comparison of strains resulting from modeling and laboratory results

| parameter | Strain numerical modeling | Laboratory strain | Time (hour) | Relative error ratio % |
|---|---|---|---|---|
| Sample 1 | 0.00745 | 0.0083 | 4.5 | 10.2 |
| | 0.10484 | 0.010732 | 148 | 2.3 |
| | 0.009193 | 0.01146 | 314 | 8.5 |
| Sample 2 | 0.00806 | 0.009 | 7.2 | 10.4 |
| | 0.10484 | 0.00118 | 120 | 5.3 |
| | 0.01129 | 0.00118 | 288 | 4.3 |

Table 4 Arrangement of support system in the tunnel

| specifications | Support type |
|---|---|
| L=4 m, spacing=80 cm | Umbrella arc method |
| advance 1.25 m | drilling |
| 3 cm | Shotcrete (first layer) |
| , 10mm*10mm diameter 6 mm | Steel mesh |
| Type PS 95.2*20+26, H=141 mm | Lattice grader |
| 17 cm | Shotcrete (second layer) |
| , 10mm*10mm diameter 6 mm | Steel mesh |
| length 4.5 m | Bolt |
| 5 cm | Shotcrete (third layer) |
| _ | Waterproof installation |
| 45 cm | Final concrete |

amount of strain is compared with the amount of strain in the experiment, and then the amount of error calculated in Table 3 is shown. According to the table, it can be seen that the relative modeling error is in the acceptable range.

## 5. Numerical modelling

Analytical methods include two main groups, methods based on closed form solutions and numerical methods (Barla 2002).

According to Pent, tunnel convergence has been analyzed for rapid convergence due to tunnel face advance and time-dependent convergence due to the rheological behavior of the rock mass. As the tunnel face advances, if the stress around the tunnel exceeds the strength of the rock mass, the rock mass begins to squeeze instantly; This is called "instantaneous squeezing." If the stored stress does not exceed the strength of the rock mass but is sufficient to cause creep, it will cause convergence into the tunnel; This is called "secondary squeezing". squeezing can therefore occur in one of two stages and depends on the level of tangential stress, the characteristics of the rock mass and the shape of the tunnel (Ingenior 2001). secondary squeezing is time-dependent deformation, which is necessarily accompanied by a creep that is caused by exceeding the shear stress range. It is clear that time has no place in the theory of elasticity; It is assumed that stresses and strains in loading or unloading change instantaneously. It is commonly observed in rock mechanics designs that convergence occurs in tunnels and wells after stress changes. Therefore, to study time-dependent behavior in rock masses, it is necessary to apply the theory of elasticity to the effects of time (Goodman 1989).

Based on the description of the tunnel reaction with severe squeezing conditions, time-dependent continuous models should be used. The behavioral model used in numerical analysis is the CVISC model, which is one of the creep models in FLAC software that is used for squeezing ground (Barla 2002).

Numerical modeling of squeezing phenomenon in the case study of Alborz tunnel has been done using FLAC software. Due to the fact that the tunnel has a large cross section, it is executed in two stages, in which the upper part of the tunnel is drilled in the first stage and the lower part in the second stage. The order of drilling and installation of the support system is shown in Table 4, according to which, after stabilization in the roof area of the tunnel, drilling was done in the upper half of the tunnel, which is semi-circular. The support system designed for the Alborz tunnel in the desired section is divided into two initial and final forms. In the early stages after drilling, 25 cm thick shotcrete with a lattice grader with triangular geometry and 4.5 m restraint shaft was used. The model is implemented for periods of 10 to 100 years, with an interval of 10 years. In other words, the stability of the final concrete lining of the tunnel for a period of 100 years is considered and evaluated by the creep behaviour of the rock mass surrounding the tunnel.

### *5.1 Stability analysis of tunnel after 2 years*

Before pitch the final concrete lining of the tunnel, it is necessary to check the requirements to install a permanent support system lining for the tunnel. For this purpose, the convergence of two points on the roof and floor of the tunnel relative to each other has been evaluated. The measured convergence values for these two points for the creep duration of 10 and 20 years for the rock mass surrounding the tunnel are 38 cm and 71 cm, respectively. Obviously, these displacement values are very high in the tunnel walls. Therefore, it is necessary to design a support lining for the tunnel with long-term stability in mind. Prior to installing the final concrete lining of the tunnel, a stability analysis for a period of 2 years of initial support was reviewed. In order to control the forces and bending moment created in the initial lining section, the permissible stress design has been used. By modeling the desired cross section and applying axial force and bending moment in PCACOLUMN software, the amount of reliability can be calculated for the desired stability period. Next, Eq. (2) has been used to control the shear forces on the lining.

$$V_n = V_c + V_s \tag{2}$$

In this equation, $V_n$ is the nominal shear strength of a reinforced section, $V_c$ is the shear strength provided by the concrete and $V_s$ is the shear strength provided by the lattice grader, which can be calculated from the Eqs. (3) and (4)

$$V_c = 0.45\sqrt{f_c^{'}}b_w d \tag{3}$$

$$V_s = 0.34 f_y A \tag{4}$$

In Eq. (3),$f_c'$ is the compressive strength of concrete.$b_w$ and d are the width and height of the section to be cut, respectively. In Eq. (4), $f_y$and A are the yield strength of the steel and the cross section of cut section, respectively. Figs. 6 and 7 show a diagram of the distribution of axial forces and bending moment on the initial support system.

Considering the maximum values of axial forces and bending moment in the roof and the tunnel aisle, the stability of the initial support system against these forces is

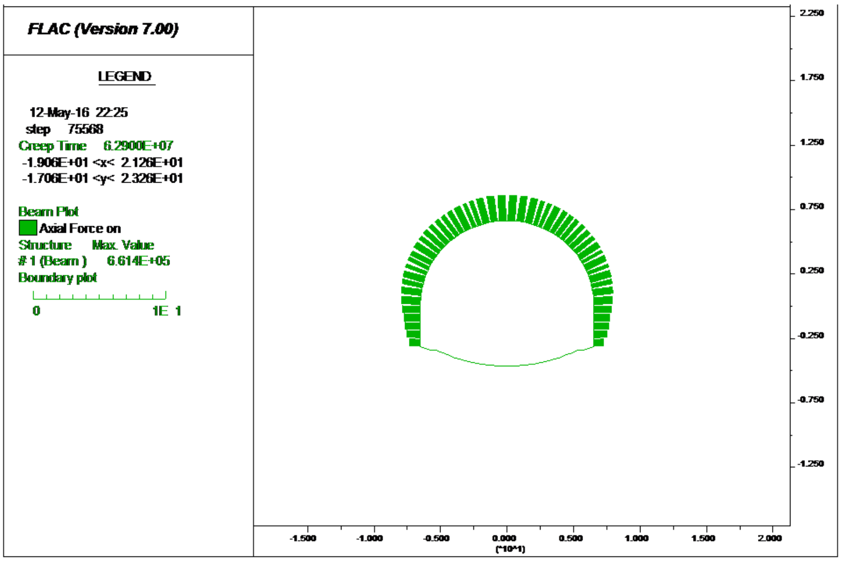


Fig. 6 Axial force distribution of initial support system after 2 years

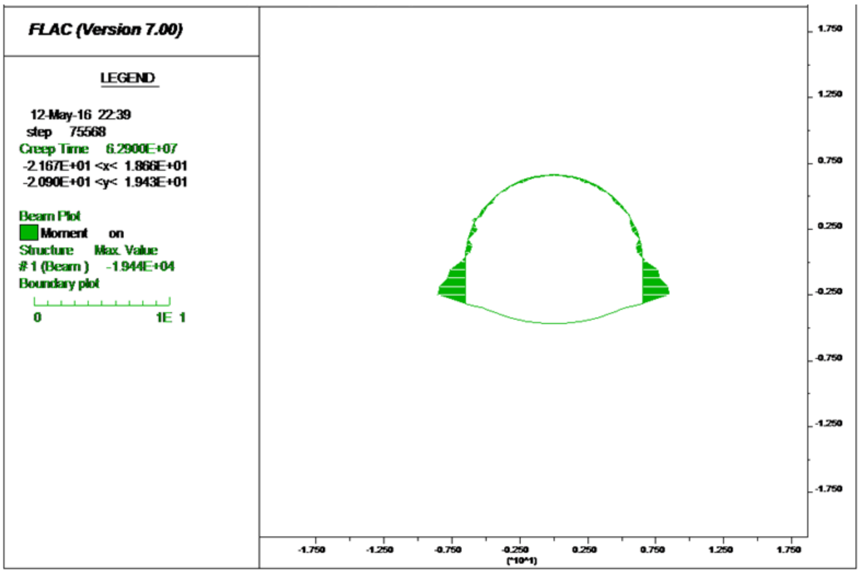


Fig. 7 Bending moment distribution of support system after 2 years

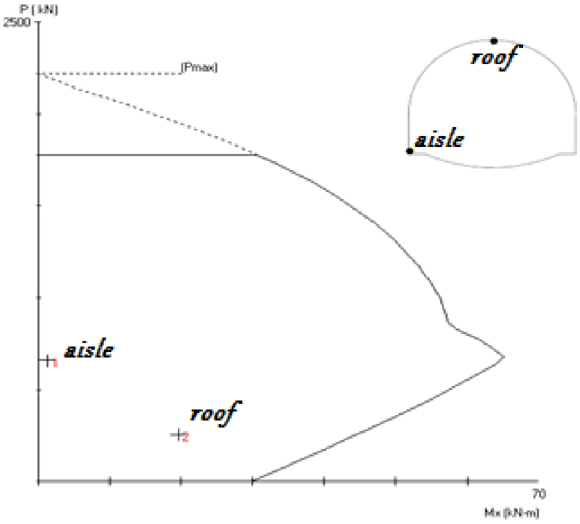


Fig. 8 Stability control based on axial force and bending moment of support system after 2 years

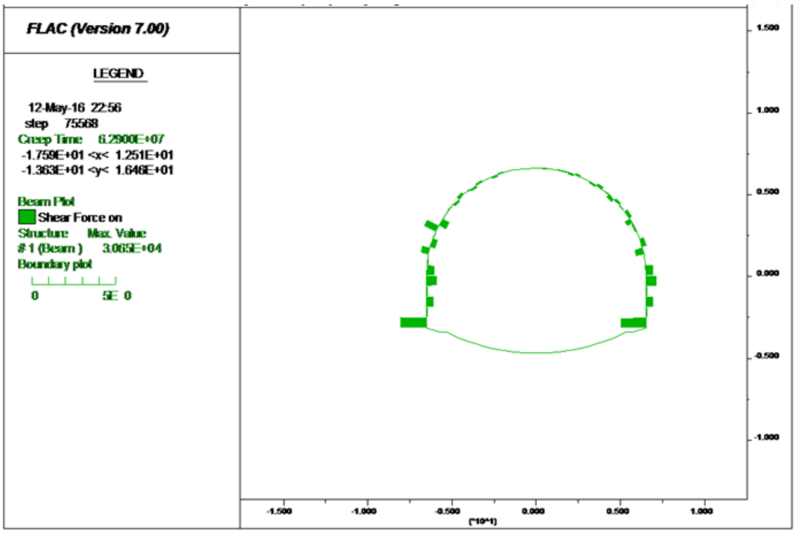


Fig. 9 Shear force distribution of support system for 2 years of rock mass squeezing, around the tunnel

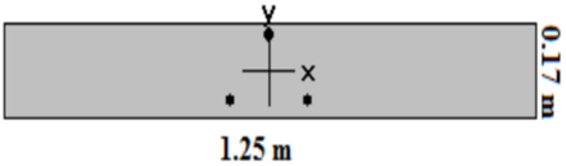


Fig. 10 Equivalent cross-section for lattice grader and shotcrete

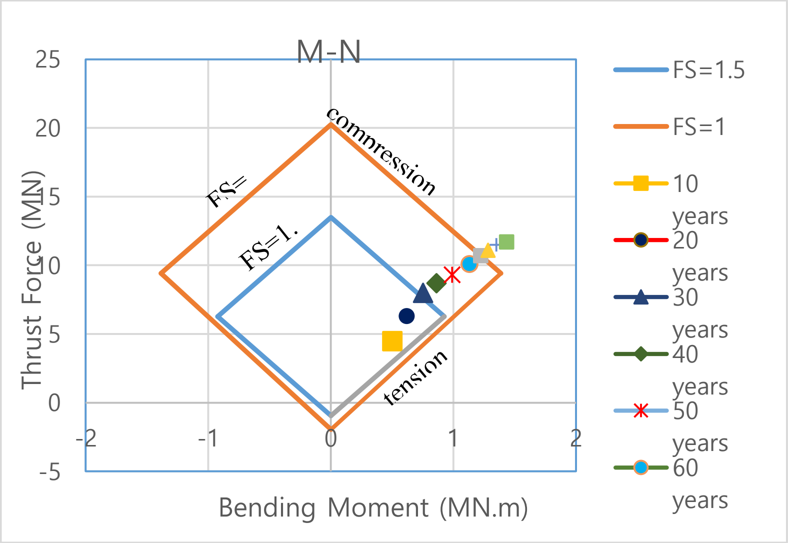


Fig. 11 Axial force-bending moment interaction diagram applied to the final concrete lining during 100 years (tunnel aisle)

investigated using PCACOLUMN software, and the results are shown in Fig. 8. According to Fig. 9, the initial support system is stable against axial forces and the bending moment applied to initial support, for a period of 2 years.

According to Fig. 10, the shear forces of concrete and cross-section rebar are 12.716 KN and 16.992 KN, respectively, so the shear force of reinforced concrete ($V_n=V_c+V_s$) is 29.705 KN. According to the calculations related to the bearing capacity of the shear force, it is observed that the amount of shear force on the initial support system in the aisle area is somewhat less than the allowable shear force of the initial support system, however, due to the small difference, there will not occur a problem for stability of concrete lining.

### *5.2 Stability analysis of tunnel up to 100 years*

Adequate and timely support installation can reduce

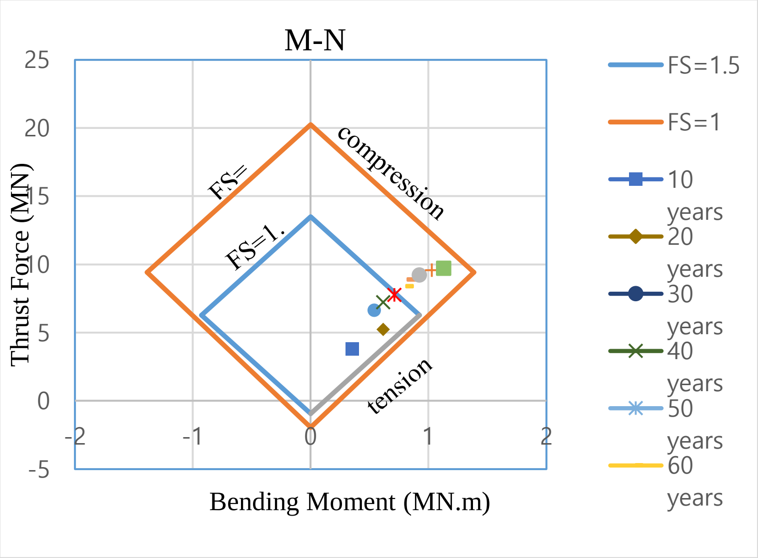


Fig. 12 Axial force-bending moment interaction diagram applied to the final concrete lining during 100 years (tunnel floor)

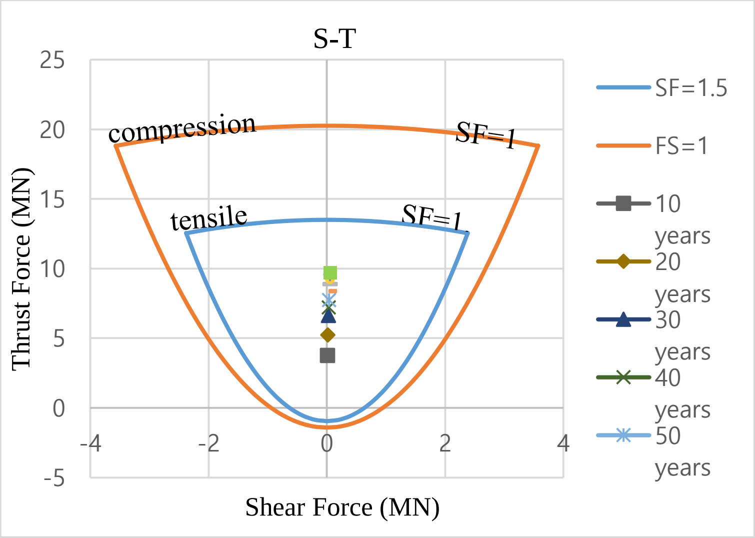


Fig. 13 Shear-axial force interaction diagram for the forces acting on the final concrete lining over a period of 100 years (tunnel aisle)

tunnel deformation. The numerical model made for the studied section is run with a period of 10 years. In this way, the service life of the concrete lining is applied to the model according to the appropriate creep time step. The appropriate creep time step for each time period of the concrete lining life, is obtained by repeated runs of the numerical model for the same time period. Based on the results of numerical modeling, the diagram of axial force-bending moment interaction for the final concrete lining with safety factors 1 and 1.5, for the concrete lining in the aisle and the tunnel floor, are shown in Figs. 11 and 12, respectively.

According to the diagram in Fig. 11, the amount of axial force-bending moment interaction created in the concrete lining exceeds the allowable limit, and its stability in the tunnel aisle in terms of bending moment for 60 years onwards does not satisfy the criterion. On the other hand, in Fig. 12, which shows the diagram of the axial force-bending moment in the tunnel roof, the conditions up to 100 years are acceptable and are in the safe and stable range. Using the allowable bending moment relations and the allowable axial force, the shear stress –axial force diagram has also been evaluated for the concrete lining used, under the forces created during a period of 100 years. In the same way as for drawing and evaluating the axial force-bending moment interaction diagram, for drawing and evaluating the shear force-bending moment interaction diagram of concrete lining, in two parts of the aisle and the tunnel roof, tunnel time-dependent behaviour is analysed in Figs. 13 and 14, for 100-years.

As can be seen, based on the results obtained in the diagrams of Figs. 13 and 14, the forces on concrete lining for the roof and aisle, are within acceptable limits over a period of 100 years. In Figs. 15 and 16, the axial force-

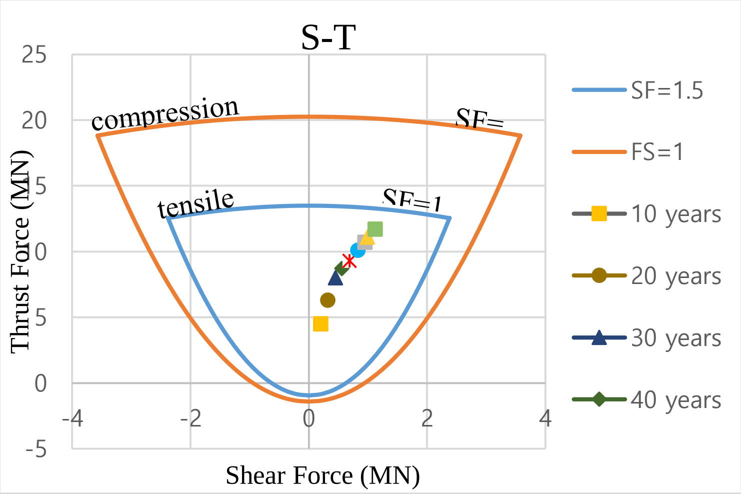


Fig. 14 Shear-axial force interaction diagram for the forces acting on the final concrete lining over a period of 100 years (tunnel roof)

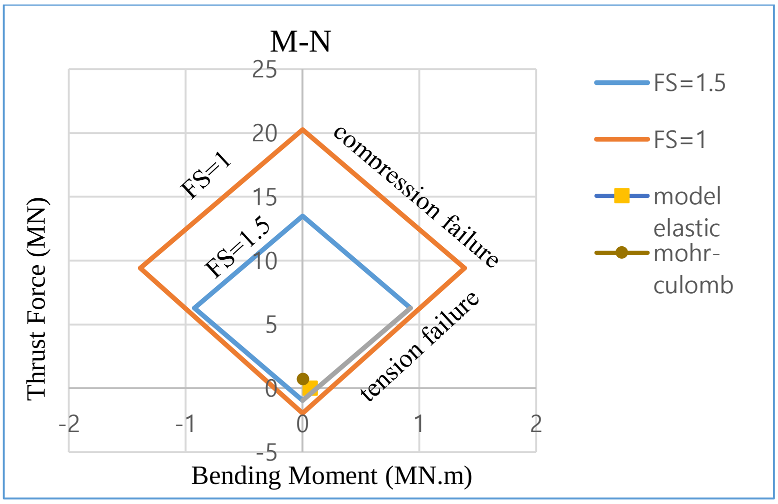


Fig. 15 Axial force-bending moment interaction diagram for forces applied to the final concrete lining for elastic and Mohr coulomb models

bending moment shear force-bending moment interaction diagrams are used for the two elastic behavioural models and elastoplastic Mohr-coulomb. Modeling with these two behavioural models has been done to compare time-dependent behavioural models with time-independent behavioural models.

By applying the elastic model, it is observed that the forces acting on the lining are equivalent to the forces acting on the lining in less than 10 years. But by applying of the Mohr-coulomb model, it was observed that the values of axial forces, shear and bending moment are equal to zero. It can be concluded that time-independent models are unsuitable for time-dependent analysis.

## 6. Discussion

For design of tunnel there are different factors that we must consider; squeezing is an important one. To have safety tunnel boring and stable lining during life of tunnel, we study squeezing potential of ground including tunnel. We tried to identify squeezing rocks along Alborz tunnel route, by using empirical, semi – empirical and analytical methods. Based on rock mass parameters and stresses on rock, we divided study range to 33 sections. These methods have weakness points because we have obtained many sections as squeezing section, while in real we did not see squeezing in these parts. Therefore to choose rock specimens, we chose a section that most of mentioned methods recognized it as a squeezing section; 3434-3500 section. To have more accurate results from laboratory tests, it is necessary to prepare specimens in three directions perpendicular to each other and also from some different locations, but due to the high cost of creep tests, we were not able to do it. After obtaining input parameters of FLAC form laboratory tests, the model of mentioned squeezing section was prepared. Results of numerical modeling demonstrates instability of lining after 70 years, that is shown in Fig. 11.

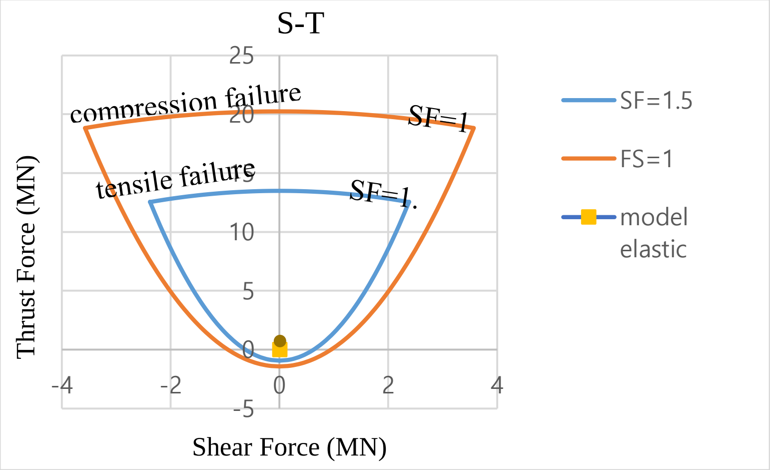


Fig. 16 Shear force-bending moment interaction diagram for forces applied to the final concrete lining for elastic and Mohr coulomb models

## 7. Conclusions

According to the research, the most important results are as follows:

- The results of the analyses have shown that to evaluate the squeezing potential of the rocks in the studied tunnel route, empirical, semi-empirical and analytical methods have been relatively well matched, although the same results are not always obtained. They can be used to select appropriate sections for numerical analysis. Most of mentioned methods show that section 3434-3500 has squeezing potential. Therefore to obtain input parameters of numerical modelling, selected specimens from this section.
- In designing tunnels, time-dependent characteristics in weak rock masses, especially for important tunnels with large cross sections, should be considered.
- The results of the analysis show that the axial force, bending moment and axial stresses in the concrete lining increase over time, as it is shown in Fig. 11–14.
- Analysis of numerical modeling results indicates that the concrete lining after 60 years can suffer from some compressive instability (instability caused by squeezing) due to the increase in bending moment in tunnel aisle part.
- To compare time-dependent behavior and time-independent behavior, in squeezing rocks, modeling has been done with two models; elastic behavioral model and Mohr-Coulomb behavioral model. Which, in the elastic state, forces on the concrete lining are approximately equal to the forces in the time-dependent state, (that is less than 10 years); which it is obtained that for the Mohr-Coulomb model the forces applied to the concrete lining are small and reliable. As a result, due to the limitations of time-independent behavioral models, the importance of time-dependent behavior modeling, is determined.

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