Prediction of Failure-Time for Soft Rock Tunnels based on Monitored Convergences

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Abstract. Predicting the failure-time for soft rock tunnels is an issue of great significance for disaster prevention and mitigation. The inverse-velocity (INV) method, which uses the rates of displacement to predict the failure-time, is often applied to predicting the failure-time of rock slopes. And the slope (SLO) method, which predicts the failure-time based on the slope (gradient), is another method for the same purpose. In this study, the validity of these two methods to predict failure-time of tunnels was evaluated by applying them to predicting the failure-time of the Ayas tunnel. The results show that the failure-time predicted by the INV method is closer to the actual failure-time compared with that predicted by the SLO method.

1. Introduction
Monitoring of tunnel convergences is critical to the design and safe construction of tunnels. The monitored tunnel convergences is one of the most important indicators to assess the stability of tunnels. Pervious research shows that the evolution of convergences in soft rock tunnels might be analogous to that of soft rock specimens subjected to constant loads, which consists of the primary, secondary and tertiary creep stages.

Many methods [1-7] associated with the accelerated (or tertiary) creep have been proposed to predict the failure time of rock slopes. Among them, the inverse-velocity (INV) method [8], which uses the rates of displacement to predict the failure-time, has been widely used in the prediction of failure-time of slopes. Recently, the slope (SLO) method [9], which predicts the failure-time based on the slope (gradient), was proposed to give earlier/safe predicted failure-time. In addition, Yoon et al. [10] tried to predict the failure time of tunnel using the materials failure relation. They believed that material failure relation [11] could be used to describe the acceleration creep of rocks. Based on the monitored deformation (or rate), different curve fitting techniques were used to predict the failure time of the tunnel.

In this study, the INV and SLO methods are employed to predict the failure-time of the Ayas tunnel, with the aim of evaluating the validity of these two method in the context of tunneling.

2. Methods for predicting failure-time
Based on the assumption that the accelerating convergences of soft rock tunnels prior to failure are “analogous to the terminal phase of tertiary creep” [9], the tunnel convergences could be expressed as

\[ u = -B \log(T_f - t) + C \]  

(1)
where \( u \) represents the convergences, \( t \) represents the time, \( T_f \) is the failure time and \( B \) and \( C \) are constants.

Differentiating Eq. (1) with respect to time \( t \) and rearranging terms yield [9]:

\[
\frac{1}{v} = \frac{du}{dt} = \frac{T_f - t}{B} \tag{2}
\]

\[
t \frac{du}{dt} = T_f \frac{du}{dt} - B \tag{3}
\]

where \( v \) is the rates of convergence and \((T_f-t)\) defines the life expectancy. Eq. (2) indicates that the rate of convergence is inversely proportional to the life expectancy, therefore it is called the inverse-velocity (INV) method. Eq. (3) is called the SLO method because \( T_f \) is just the slope of the curve \( t(du/dt)\sim du/dt \).

In general, the convergence curve based on the actual monitoring data is not smooth and it fluctuates with time. In order to smooth these short-term deformation deviations, the data filtering method could be used to compute the convergence rate as:

\[
\left( \frac{du}{dt} \right)_i = \frac{u_i - u_{i-n}}{t_i - t_{i-n}} \quad (i = n+1, n+2, \ldots, m) \tag{4}
\]

where \( (du/dt)_i \) is the \( i \)-th computed rate, \( t_m \) and \( u_m \) are the final time and convergence, respectively [12], and \( n \) is the sampling value, which should be carefully selected so as to determine the appropriate onset of the tertiary creep stage.

3. Prediction of failure-time for Ayas tunnel

The Ayas railway tunnel between Ankara and Istanbul, with a length of 10.064 km, is chosen as an example to show how to use the INV and SLO methods to predict the failure time. The lined inner diameter of the Ayas tunnel is about 9.60 m, with a horseshoe shaped cross section. The New Austrian Tunneling method was used for the main part of the tunnel. Figure 1 shows the evolution of horizontal convergences with time for Section 6+760 in Ayas tunnel [13]. It was reported that “after 88 days, in km 6+760 it was broken”.

![Figure 1. The evolution of horizontal convergences for Section 6+760 in Ayas tunnel [13].](image-url)

The starting point of tertiary creep stage should be first determined because only the monitored convergences of tertiary creep stage could be used to predict the failure time. Figure 1 shows that the convergence curve is generally smooth. Hence, five small sampling values was chosen (i.e., \( n = \))
1, 2, . . . , 5) to determine the onset of the tertiary creep stage. The results show that the \( n = 3 \) is the best choice to determine the appropriate starting point of tertiary creep stage (i.e., \( t = 60 \) days; see Figure 1).

Then, the INV and SLO methods were employed to predict the failure time of the Ayas tunnel, and the results were shown in Figure 2 (Note that only convergence data with \( t > 60 \) days have been used). Figure 2 (a) shows that the predicted failure time with INV method is about 89.9 days, and Figure 2 (b) show that the predicted time with SLO method is about 92.3 days. And the actual failure time was reported as 88 days. It can be concluded that (i) both methods could give reasonable predictions, and (ii) at least in this case, the INV method performs better than the SLO method.

![Figure 2. Predicted failure times for Ayas tunnel using the INV and SLO methods.](image)

In addition, the previous predictions were repeated with different sampling values and the results are shown in Table 1, which suggests that the predicted failure times using both methods are the closest to the actual failure time with \( n \) being equal to 3. And the choice of the sampling value directly affects the prediction results.

| \( n \) | \( T_{fp} \) INV (days) | \( T_{fp} \) SLO (days) |
|-------|----------------------|----------------------|
| 1     | 116.5                | 93.6                 |
| 2     | 120.8                | 94.0                 |
| 3     | 89.9                 | 92.3                 |
| 4     | 93.0                 | 92.8                 |
| 5     | 91.8                 | 92.4                 |

4. Conclusions

This paper employs the INV and SLO methods to anticipate the occurrence of failure at tunnel sections whose convergences have entered the tertiary creep stage. Although these two methods should be further validated using more unstable rock tunnel cases with good-quality convergence data, results show that both methods could give reasonable predictions that are close to the actual failure time, indicating that both methods could be used to predict likely failure-time for soft rock tunnels entering tertiary creep stage. And the INV method performs slightly better than the SLO method (at least in this case).

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