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Displacement prediction of tunnels based on a generalised Kelvin constitutive model and its application in a subsea tunnel

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ABSTRACT

Soft rock has the characteristic of time dependency, namely, creep or rheology. When the tunnel is located in weak surrounding rock, due to the rheology properties of surrounding rock, the load on the tunnel support and the displacement of tunnel lining may continue to increase. If the tunnel does not receive timely reinforcement and repair, these problems may threaten the safe operation of the tunnel. For tunnel repair and maintenance, we want to install some displacement monitoring sections in the appropriate position. However, tunnels are linear underground structures, and it is challenging to determine the location of the monitoring section and the displacement monitoring standards. In this study, based on the state equation of the generalised Kelvin constitutive model, a tunnel lining displacement analytical expression with a time variable was derived. Using actual data obtained during the construction of a subsea tunnel in Xiamen City and the theoretical research results presented in this paper, the final displacement of the subsea tunnel lining was forecasted and analysed. According to the results of the prediction and when considering the geological conditions along the longitudinal axis of the tunnel, the location of monitoring cross sections and monitoring standards was given. In the end, the measured data and the prediction result were compared, which proves that the conclusion is reliable. This study provides a useful reference for the maintenance and repair of tunnels in rheology rock mass.

1. Introduction

There have been great strides in tunnel engineering technology in recent years, including the universal application of the new Austrian tunnelling method (NATM) for tunnel construction and the increased use of mechanisation. Around the world, especially in China, an increasing number of long tunnels and subsea tunnels have been built or are being built. With the increase in the overall scale of tunnel engineering, engineers and researchers have paid more attention to the maintenance and repair of these tunnels (Miyaguchi, 1986; Asakura and Kojima, 2003; Lu et al., 2005; Ikuma, 2005; Konishi et al., 2008). During a tunnel's service life, there may be a series of problems, such as deformation and cracking in the lining or water seepage. For long or subsea tunnels and other key tunnel projects for which any required maintenance and repairs should be undertaken without delay, monitoring should be installed in those parts of the tunnel that traverse complex geological formations. Therefore, tunnel managers can constantly monitor the displacement of those sections and create maintenance plans by analysing the cumulative values of the monitoring data and their change rules. If we can estimate the displacement of the tunnel lining based on data obtained in the field, we can devise appropriate inspection, maintenance, and repair regimes even to the extent of ascertaining why certain problems occur. By implementing effective and timely maintenance, tunnels will remain in a serviceable and reliable state.

In this study, field data obtained from the China Xiamen subsea tunnel project was applied to a generalised Kelvin constitutive model state equation, such that we could derive an analytical solution to the temporal–spatial displacement of the tunnel lining. Then, using crown settlement monitoring data obtained from different sections before the construction of the lining, the final displacement of the tunnel lining can be obtained by applying an analytical formula. Using the predicted results obtained, we can determine the tunnel cross section where we should install monitoring. The results of this research will provide a useful reference for the establishment of measures for implementing the maintenance and repair of tunnels.

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2. Theoretical derivation of final displacement of lining

2.1. Constitutive model for rheology rock mass

The Xiamen subsea tunnel traverses soft rock formations. This rock mass has distinct rheological characteristics such that because of its properties and upon completion of the tunnel excavation, the deformation of the rock mass due to spatial effects did not increase, but the displacement due to temporal effects continued to develop. Under similar conditions, tunnel measurements showed that the rock deformation after the construction of the tunnel lining would increase over a long term (Guan et al., 2008; Boidy et al., 2002). In some cases, the residual deformation after the construction of the tunnel lining constitutes a certain proportion of the total deformation to a point where the pressure caused by the residual deformation cannot be ignored.

During the excavation of the tunnel, the deformation of the rock mass has two components. One component is caused by spatial effects and is correlated to the continuous excavation of the tunnel face, and the other component is caused by temporal effects and is correlated to the rheological properties of the rock mass. Panet and Guenot (1982) proposed a concept of equivalent initial stress, which is a function of time or the amount of tunnel face extension. We can use this concept to analyse the overall rock deformation process. Based on this concept, we are proposing an analytical method that we can use to estimate the deformation of the tunnel lining according to the measured data.

To analyse the deformation law of tunnels along with the time, we need to use surrounding rock rheological models to solve the problem. At present, there are many rheological models, such as Maxwell model, Kelvin model, and Burgers model. However, for a specific tunnel project, we should first perform a triaxial creep test on intact rock specimens and then choose a suitable constitutive model according to the test results. The rheological characteristics of rock mass had been comprehensively studied for the Xiamen undersea tunnel (Qi, 2006). which concluded that the generalised Kelvin model was more suitable for the actual situation, and some parameters of this model were also given in above paper. In view of the above analysis, in this paper, we used the generalised Kelvin constitutive model (Fig. 1) to describe the visco-elastic displacement of the tunnel lining in a rheological rock mass.

In Fig. 1 above, E_1 is the instant elastic modulus of the rock mass, E_2 is the visco-elastic modulus of the rock mass, and η is the viscous coefficient. To overcome the mathematical challenges, the tunnel profile is initially assumed to be a circle, such that if we consider only the axisymmetric tunnel in the initial hydrostatic stress state when using a polar coordinate system, the strain in the normal, tangential, and longitudinal directions will be as follows (Kolymbas, 2005):

$$\varepsilon_r = \frac{\partial u}{\partial r}, \quad \varepsilon_\theta = \frac{u}{r}, \quad \varepsilon_z = 0 \tag{1}$$

where u is the displacement of the tunnel, which can be expressed as a function of the polar coordinates r, angle θ, and position z. When the shape of the rock and soil change due to plastic deformation, the rock volumetric strain is almost zero, that is:

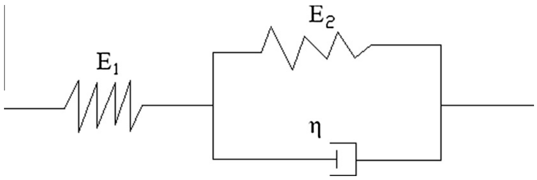

Fig. 1. Generalised Kelvin constitutive model.

$$\varepsilon = \frac{1}{3}(\varepsilon_r + \varepsilon_\theta + \varepsilon_z) = 0 \tag{2}$$

Thus, given Eq. (1), Eq. (2) can be rewritten as follows:

$$\frac{\partial u}{\partial r} + \frac{u}{r} = 0 \tag{3}$$

Solving Eq. (3), the displacement of the tunnel is derived as

$$u = \frac{1}{r}A(t) \tag{4}$$

where $A(t)$ is a dimensionless function of time. As a result, Eq. (1) can be written as follows:

$$\varepsilon_r = \frac{\partial u}{\partial r} = -\frac{1}{r^2}A(t), \quad \varepsilon_\theta = \frac{u}{r} = \frac{1}{r^2}A(t) \tag{5}$$

The three-component model state equation is given as follows (Shunjun, 1999):

$$\overset{\bullet}{\sigma} + (E_1 + E_2)\frac{1}{\eta}\sigma = E_1\overset{\bullet}{\varepsilon} + \frac{E_1E_2}{\eta}\varepsilon \tag{6}$$

where σ is the stress tensor component, $\overset{\bullet}{\sigma}$ is the stress velocity tensor component, ε is the strain tensor component, $\overset{\bullet}{\varepsilon}$ is the strain velocity tensor component, E_1 is the instant elastic modulus of the rock mass, E_2 is the visco-elastic modulus of the rock mass, and η is the viscous coefficient.

Eq. (6) can also be written as follows:

$$\left.\begin{array}{l} \frac{\partial}{\partial t}(\sigma_r - \bar{\sigma}) + (E_1 + E_2)\frac{1}{\eta}(\sigma_r - \bar{\sigma}) = E_1\frac{\partial}{\partial t}(\varepsilon_r - \bar{\varepsilon}) + \frac{E_1E_2}{\eta}(\varepsilon_r - \bar{\varepsilon}) \\ \frac{\partial}{\partial t}(\sigma_\theta - \bar{\sigma}) + (E_1 + E_2)\frac{1}{\eta}(\sigma_\theta - \bar{\sigma}) = E_1\frac{\partial}{\partial t}(\varepsilon_\theta - \bar{\varepsilon}) + \frac{E_1E_2}{\eta}(\varepsilon_\theta - \bar{\varepsilon}) \end{array}\right\} \tag{7}$$

where σ_r is the radial stress, σ_θ is the circumferential stress, $\bar{\sigma}$ is the mean stress, ε_r is the radial strain, ε_θ is the circumferential strain, and $\bar{\varepsilon}$ is the mean strain.

According to the boundary conditions, when $r \to \infty$, $\sigma_r = \sigma_\theta = P$, and $\overline{\sigma} = P$, under axisymmetric conditions using Eqs. (4)–(6), Eq. (7) can be written as follows:

$$\frac{\partial}{\partial t}(\sigma_r - P) + (E_1 + E_2)\frac{1}{\eta}(\sigma_r - P) = -\frac{E_1}{r^2}\frac{\partial A(t)}{\partial t} - \frac{E_1E_2}{r^2\eta}A(t) \tag{8}$$

2.2. Analytical solution for determining displacement of tunnel without lining

To study the spatial effect of the displacement caused by the extension of the tunnel face, the viscosity of the rock mass can be temporarily omitted, such that the rock is regarded as being a purely elastic medium. A theoretical analysis by Panet (1979) showed that in this case, the tunnel peripheral displacement is relative to the distance between the measurement cross section and the tunnel face. This relationship can be expressed as follows:

$$u_m = u_{m\infty}(1 - e^{-\frac{x}{X}}) \tag{9}$$

where $u_{m\infty}$ is the actual final measured displacement after the installation of the measuring points, x is the distance between the tunnel face and the measured cross-section, and X is a constant. The meanings of these symbols are explained in Fig. 2.

In fact, when the tunnel face has just arrived at the measurement cross section, the displacement has already occurred. Therefore, the overall displacement should be expressed as follows:

$$u = u_{m\infty} + u_0 = (u_\infty - u_0)\left(1 - e^{-\frac{x}{X}}\right) + u_0 \tag{10}$$

where u_∞ is the theoretical overall displacement and u_0 is the displacement that occurred before the measurement.