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Research Paper

Time-dependent tunnel deformations in homogeneous and heterogeneous weak rock formations

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ABSTRACT

To investigate long-term, time-dependent tunnel deformations, this study employs a non-linear rheological model capable of considering the tertiary creep behaviour of the rock mass (Okubo and Fukui, 2006). A model parametric study is undertaken with a 3D numerical model encompassing a tunnel. The results show that the tunnel walls start to deform at an accelerating rate after a lapse of ten years. The results offer an explanation to previously reported tunnel instability cases. A 3D numerical model encompassing weak rock formation obliquely intersecting with the tunnel is then constructed. The analysis yields asymmetric wall deformation pattern, suggesting the need for optimizing rock supports.

1. Introduction

Despite recent advances in tunneling technologies, it is still a challenging task to ensure the stability of the tunnel over its planned service life. This is particularly true when a tunnel is driven through weak rock formations. More attention needs to be paid to the behaviour of such weak rock mass to prevent instability from taking place. To date, a number of studies have been undertaken to better understand the effect of weak rock formations such as a fault zone on the stability of a tunnel [1–4]. Nilsen [2] conducted case studies to investigate cave-in and rock fall that occurred in tunnels constructed through weak rock mass in Norway. One of the case studies shows that rock fall took place in an area where a fault zone containing swelling clay intersects with the tunnel. Interestingly, there were no noticeable signs of instability during the construction of the tunnel. Based on the case studies, Nilsen (2011) concluded that the presence of swelling clay plays a key role in causing instability over time. It is also indicated that the time period required for the development of instability varies from several hours to more than 10 years. Huang et al. [5] performed experiments using a physical model that represents a tunnel intersecting with a weak rock layer. The failure pattern observed from the test is then compared with those derived from numerical analysis. Additionally, a model parametrical study was carried out while varying several parameters, such as dip angle of the weak interlayer and the distance between the tunnel and the interlayer. For the numerical analysis, a plastic damage model is used to model the weak interlayer, whereby deformation modulus is decreased with the evolution of plastic strain. Mao and Nilsen [3] performed elasto-plastic analyses to investigate the behaviour of a tunnel intersecting with a weakness zone. A model parametrical study with respect to the width of the weakness zone is conducted. Dong et al. [6] constructed a 3-D model to assess the impact of tunnel excavation in geologically weak zones on surrounding constructions, such as highway.

Thus, it can be said that numerical approaches have been attempted assuming elasto-plastic behaviour of weak rock formations to assess tunnel stability. It should be noted, however, that the time-dependent behaviour of the rock mass is also critical in predicting tunnel stability. Since the last century, significant efforts have been made to clarify the time-dependent behaviour of rock surrounding underground openings in civil and mining engineering projects [7–22]. For instance, Nadimi et al. (2011) carried out laboratory tests to obtain parameters for a power constitutive creep model. Using the estimated parameters, they performed numerical analysis with 3-dimensional discrete element modelling while considering the time-dependent behaviour of the rock mass around a cavern. The results obtained from the numerical simulation coincide well with deformations monitored in the field. Stress hardening elastic viscous plastic model and three-stage creep model were employed in previous case studies [14,15] for a tunnel excavated through extremely weak formations to examine

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severely squeezing ground conditions. In these studies, the numerical modelling of the tunnel cross-sections successfully reproduced the time-dependent deformational behaviour of the tunnel after calibrating material properties with back analysis. Sharifzadeh et al. [13] simulated the long-term deformation of a tunnel excavated in a weak, jointed rock mass with 2-dimensional analysis. It is reported that the instability of the tunnel might happen due to the stress induced by the creep behaviour of the surrounding rock. Weng et al. [17] developed a new constitutive model that combines the generalized Burger model with anisotropic stiffness degradation depending on the level of deviatoric stress, whereby the squeezing behaviour of a tunnel excavated through weak sandstone is simulated with two dimensional analyses. Manh et al. [23] also employed the Burger model, which is combined with the ubiquitous joint model to consider anisotropic behaviour of rock mass.

As can be seen from the above discussion, a variety of constitutive models and numerical analysis methods were previously used to examine tunnel deformations in weak rock formations. It should be noted, however, that most of the analyses were 2-dimensional, plane strain, aiming at simulating tunnel deformation that takes place during a relatively short period of less than several years. It would not be uncommon that weak rock formations are locally present or intersect with the tunnel obliquely in a similar way to a shear or a fault zone, leading to critical tunnel instability caused by the development of tertiary creep after a lapse of several years. In such cases, the plane strain condition is no longer applicable. Thus, 3D analysis with representative numerical models needs to be performed for a better understanding of the effect of the weak rock formations on the deformational behaviour of the tunnel. In addition, the time-dependent degradation of the rock mass over a long period as well as the occurrence of tertiary creep needs to be taken into consideration. As a matter of fact, there are limitations with respect to the constitutive models that were developed and employed in previous studies to simulate the creep behaviour of weak rock mass, especially in terms of the validation of tertiary creep and the determination of model input parameters from field measurements, which are discussed in more detail in a later section. Hence, adequate knowledge of the time-dependent behaviour of a tunnel intersecting with weak rock formations has not yet been fully developed. The present study aims at elucidating and characterizing the evolution of tunnel deformation over a long period of more than ten years with a non-linear rheological model. The deformational behaviour of a tunnel excavated through a weak rock formation is examined. While undertaking a case study based on field measurements obtained from an actual tunnel is admittedly important for the validation of the numerical analysis results, it is indispensable to first understand and characterize the time-dependent deformation of a tunnel intersecting with a weak rock formation prior to the validation stage. It is possible then to determine proper field measurement settings including the duration of monitoring. The present study serves as a first step to achieve such goal.

2. Scope and objective

The present study focuses on two aspects: (1) the influence of the ductility and time-dependency of the rock mass in a tunnel on its time-dependent deformational behaviour, assuming a homogeneous rock mass, and (2) the time-dependent behaviour of the tunnel when the rock mass is heterogeneous, including a weak formation intersecting obliquely with the tunnel. The first aspect aims to elucidate and characterize the fundamental time-dependent deformational behaviour of the tunnel by undertaking a model parametric study with respect to rheological and ductility parameters of the rock mass. The second aspect examines the influence of such a weak rock formation on the time-dependent deformational behaviour of the tunnel. In both the cases, the influence of tertiary creep on the deformation of tunnel walls is particularly examined. The tunnel is assumed to be subjected to relatively high overburden pressure (approximately 8 MPa). Such stress environment is generally experienced when road tunnels are excavated through mountainous terrains. 3-D numerical models are constructed with FLAC3D code [24]. The present study employs the non-linear rheological model developed by Okubo and Fukui [25], which is newly implemented into the FLAC3D code in order to take into consideration the time-dependent behaviour of the rock mass. Although several studies take into account the anisotropic response of rock mass as well as its creep behaviour, the present study assumes isotropic rock mass behaviour, while focusing more on distinctive, time-dependent behaviour leading to tertiary creep and caused by the presence of a weak rock formation.

3. Constitutive models

3.1. Review of creep models developed and applied to tunnel deformations

Various constitutive models have been developed and applied for analyzing the time-dependent mechanical behaviour of the rock mass in a tunnel. Table 1 summarizes the constitutive models. It is found from the literature review that the constitutive models are generally classified into three types. The first one is the Burger-creep visco-plastic model [13,26], which is based on the Kelvin cell in series with the Maxwell component. The Kelvin cell is responsible for the production of primary creep, which is reversible, and the Maxwell component generates visco-plastic strain pertaining to secondary creep, which is irreversible. The conventional Mohr-Coulomb criterion is combined with the model to account for rock

Table 1
Constitutive models previously employed for time-dependent behaviour of a tunnel.

Reference	Constitutive model	Necessary parameters	Tertiary creep simulation
Barla et al. [14]	Stress hardening elastic viscous plastic model (SHELVIP model)	6	No
Sterpi and Gioda [20]	Three-stage creep model	6	Material strength reduction
Causse et al. [19]	Burger-creep visco-plastic model	5	No
Moghadam et al. [18]	Combination of Cristescu's model [29] and Peric's viscoplastic power law [30]	13	No
Weng et al. [17]	Burger's model and stiffness degradation	12	No
Xu et al. [16]	Damage model and time-dependent strength degradation	2	Strength heterogeneity leading to "apparent" tertiary creep
Pellet et al. [21]	Visco-plastic model with damage evolution over time	10	Damage evolution law with a second-order symmetrical tensor
Pellet [26]	CVISC model	8	Cohesive strength reduction