International Journal of Rock Mechanics & Mining Sciences 76 (2015) 112–126

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

# An analytical model considering interaction behavior of grouted rock bolts for convergence–confinement method in tunneling design

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ARTICLE INFO

*Article history:*
Received 16 August 2006
Received in revised form
25 August 2014
Accepted 4 March 2015
Available online 21 March 2015

*Keywords:*
Rock bolt
Reinforcing effect
Quantitative evaluation approach
Tunnelling construction
Underground excavation

ABSTRACT

A new analytical model that represents the behavior of reinforced ground near a circular underground opening in a homogeneous, uniform stress field has been developed by considering the interaction behaviors between the grouted rock bolt and ground. Axial force distribution along the rock bolt has been analyzed at first. The coupling and decoupling behaviors of the interface between the ground and rock bolt are taken into account in the model. Thereafter, the mechanical behaviors of the reinforced mass are also evaluated according to the elasto-plasticity concept and the strain softening characteristic of ground. It highlights the influence of the different bolting patterns on the extent yield zone and tunnel deformation. The derivation of the analytical model and the influence of bolts on the stress and displacement field near an opening are illustrated in this paper. The theoretical predictions are verified with the measurement data in field, e.g. a Shinkansen tunnel named as Tawara Zaga Tunnel, which is planned to be open in 2022. Moreover, the applications of the proposed approach to tunnel design are discussed further according to the rock bolting effects of the standard supporting patterns of Japan Highway Public Corporation (JH) in different ground conditions.



## 1. Introduction

It is well know that any kind of underground supporting system should be able to assist the ground in supporting itself by building a ground structure. The grouted rock bolt becomes an integral part of the ground, thereby restricting its deformability by internal strengthening. The description of interaction behaviors between the rock bolt and ground is very critical to the evaluation of the reinforcing effect. Unfortunately, the interaction mechanism of rock bolt and ground is very complicated, and there is few ways to evaluate the performance of rock bolt quantitatively at present. The rock bolting design is still in an empirical and semi-empirical state. During a tunneling construction, the wall convergence is a readily recordable indicator of overall response of the ground, and the so-called convergence–confinement approach has been widely accepted in tunneling. In the convergence–confinement approach, the rock bolt or shotcrete is expected to adding an equivalent internal pressure to the tunnel wall [1–7]. This equivalent internal pressure is originated from the axial force in case of grouted rock bolt, and it is related with the deformable behavior of rock mass [8]. Obviously, the equivalent internal pressure of grouted rock bolt should be estimated from the interaction behavior because the axial force distributes a non-uniform shear stress along the whole length. In order to obtain the distribution of axial force, field monitoring is a good way and sometimes it is necessary to ensure a rock bolting design. However, the monitoring results could only provide limited information at the design stage, and it is more expensive either to some degree *in-situ*. The rock bolt design in NATM tunneling is based on the classification of the ground in Japan and other countries. The monitoring results are also considered to be necessary especially for the excavation in soft rock. The measured distribution of the axial force along a rock bolt is also considered as an important factor to adjust the rock bolting design during tunneling construction [9].

A lot of field monitoring works were carried out on the rock bolts installed in various rock formations [10–14]. Freeman [10] monitored both the loading process of the bolts and the distribution of the stresses along the bolts, and proposed the concept of “neutral point”, “pick-up length” and “anchor length” first. At the neutral point, the displacement of the ground and the rock bolt is consider as the same, and the induced shear stress at the interface

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http://dx.doi.org/10.1016/j.ijrmms.2015.03.006
1365-1609/

is zero while the induced axial force of the bolt reaches the maximum. The location of neutral point is difficult to determine. Based on some assumptions, Tao and Chen [12] investigated the interaction mechanism of the fully grouted bolts around a circular tunnel and gave the neutral point's position $\rho$ as:

$$\rho = L/(\ln[1+(L/r_a)], \qquad L = 40r_b \sim 60r_b \tag{1}$$

where $L$ is the length of bolt and $r_a$ is the internal radius of the tunnel; $r_b$ is the radius of the rock bolt; $\rho$ is the distance from the center of the circular tunnel to the neutral point. Considering the position of neutral point, there are several analytical models for the rock bolt design according to different constitutive laws [13–16]. However, Eq. (1) is limited and sometimes not right, for example, it is not valid at least when a decoupling phenomenon is initiated on interface [17,18]. According to [19], there may exist not only one but several neutral points along the rock bolt. In fact, the axial force in rock bolt is caused by the deformation or displacement of the ground, and the neutral point is influenced by the interaction behavior of the reinforcement and the ground. In order to predict the axial force in the rock bolt, the relationship between the shear stress on rock bolt surface and the displacement of ground is often interested, and a constitutive equation was assumed as [20],

$$\frac{d^2u_b}{dx^2} = \frac{2\tau_{bx}}{E_b r_b} \tag{2a}$$

where $u_b$, $E_b$, $r_b$ are the displacement, deformation modulus and radius of the rock bolt, respectively; $\tau_{bx}$ is the shear stress on rock bolt surface. In order to obtain the solution, the distribution of the interaction shear stress in the ground is often assumed as [20–22],

$$\frac{d\tau_{br}}{dr} = -\frac{\tau_{br}}{r} \tag{2b}$$

where $\tau_{br}$ is the interaction shear stress in ground; $r$ is the radial distance from the axial of the rock bolt. However, this assumption needs more discussion because it leads the interaction pressure on the ground to be zero, which is not expected in the convergence–confinement approach. Oreste and Peila [8] proposed another model to describe the axial force of the rock bolt for the convergence–confinement concept. The relationship between the relative displacement of the ground and the interaction shear stress on bolt surface is focused on. A boundary condition at the end of the rock bolt was discussed, but the shear stress distribution in the ground was ignored.

Based on the deformation interaction of a reinforcement and ground, the authors have proposed a model to predict the axial force distribution of a reinforcement in a deformed mass [23], and an approach is given to get the solution of a rock bolt around a circular opening considering the coupling and decoupling characteristic on its interface for the rock bolting design in tunneling [24]. Based on the proposed model, this paper is to suggest a theoretical approach to quantify the mechanical characteristic of reinforced ground considering the interaction of reinforcement and ground for NATM tunneling.

## 2. Theory analysis considerations

### 2.1. Interaction behavior and mechanical model of reinforced ground

The grouted rock bolt deforms together with the ground before slipping failure takes place. Modeling the rock bolting system is to take the grouted rock bolts and ground as a whole and analyze its behavior numerically. In order to simplify the analysis, the hydro-pressure and a circular tunnel are considered in this study. The ground is assumed to be homogenous. The relative position of rock bolts around a circular tunnel is shown in Fig. 1, and their arrangement is illustrated in Fig. 2. The mechanical behavior of the equilibrium elements and the coordinate are illustrated in Fig. 3. Correspondingly, the axial force in the rock bolt element $dF_b$ can be written as the following expression,

$$dF_b = 2\pi r_i \tau_i dr \tag{3}$$

where $r_i$ is the potential decoupling radius around the rock bolt; $\tau_i$ is the shear stress at the position of radius $r_i$. According to the balance of the infinitesimal element of the ground with a rock

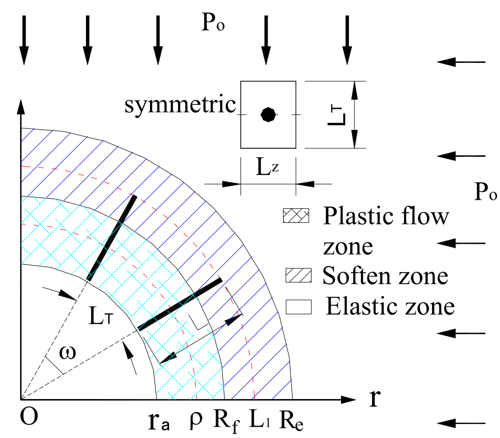


**Fig. 1.** Relative position of the rock bolt around tunnel.

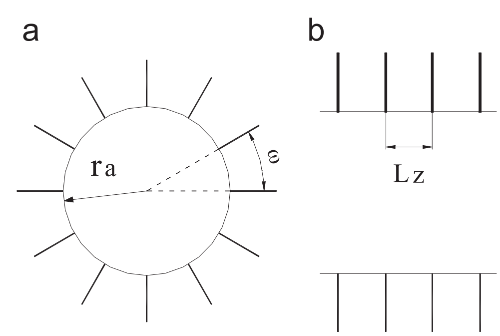


**Fig. 2.** Illustration of the rock bolting arrangement in tunneling.

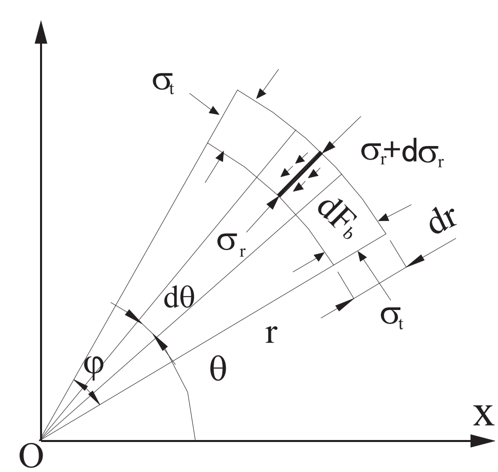


**Fig. 3.** Mechanical behavior of reinforced element.