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Finite element analysis of jointed rock masses reinforced by fully-grouted bolts and shotcrete lining

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ABSTRACT

This paper presents the formulation of an equivalent constitutive model for jointed rock masses reinforced by fully-grouted bolt and shotcrete lining and its implementation in a finite element program. This model takes into consideration the elasto-viscoplastic behavior of the rock masses as well as the contribution of the bolt and lining to both the stiffness and shear resistance of the jointed rock masses. The equivalent model and corresponding software are verified by comparison to conventional numerical models which consider the individual contribution of the reinforcement. The relationship between the constitutive parameter "effective height" and the thickness of the lining is evaluated using the ANN approach. Finally, the interest of the proposed model is illustrated through its application for the analysis of the excavation of an underground cavern in a hydropower project.

1. Introduction

Fully-grouted bolt and shotcrete lining are widely used in tunnel and slope engineering [1–3]. Shotcrete lining is a flexible supporting structure which is about 10–15 cm in thickness, it prevents the rock from loosening and transfers loads to the rock bolts. Rock bolts penetrate into the rock mass to depths of about 4–12 m, and form a reinforced layer of definite thickness around the tunnel or along the slope surface.

Numerical simulation of joints, bolts and lining can be carried out using the explicit (or distinct) method [4–11] or the implicit (or equivalent) method [12–17]. The former describes the individual behavior of the bolt and lining, while the latter uses an equivalent approach which is well adapted for complex engineering problems with a large number of joints and bolts. In the implicit (equivalent) method, it is essential to develop equivalent constitutive equation which takes into account the influence of joint, bolt and shotcrete lining. If the reinforced rock masses behave elastically, the equivalent method would be quite simple and effective. However, if the plasticity starts, the equivalent method will be extremely cumbersome for modeling the exact behavior of the reinforced rock masses. Usually, several assumptions concerning the interactions of different components within the REV (representative element volume) are used for the formulation of an equivalent constitutive equation. Based on this idea, some equivalent constitutive relations have been proposed to simulate the non-linear behavior of the jointed rock masses reinforced by bolts: Pietruszczak and Mroz [12] proposed a smeared joint model, Pande and Gerrard [13], Pande and Sharma [14] proposed an elasto-viscoplastic "multi-laminate" model, Larsson and Olofsson [15] proposed a similar approach. However, these models encounter some difficulties in describing the bolt's behavior at joint. In addition, for shotcrete lining there is so far no reasonable equivalent constitutive model which is able to describe the interaction among lining, bolts and joints.

The first author of this paper proposed a constitutive model for the jointed rock masses reinforced by bolts [16,17] which can describe the bolt's behavior at joint in more detail even with an implicit approach. In this paper, this constitutive relation is extended to modeling jointed rock masses reinforced by both bolt and shotcrete lining. The presentation of this model will be followed by its validation. The key parameter—"effective height" of the lining is evaluated using numerical computations and the artificial neural network (ANN). The interest of the proposed model will be illustrated through its use for the analysis of the excavation of an underground cavern in a hydropower project.

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2. Rheology model and equivalent constitutive relation

2.1. Deformation and reinforcement mechanism

It has been confirmed from tests that there are two hinges formed by bending in the bolt near the joint [18]; between the hinges the bolt undergoes strong localized plastic shear and tensile deformation. With ongoing deformation, the dip angle of the bolt as well as the angle between the bolt and the normal of the joint will be changed (Fig. 1a). This phenomenon, together with the hardening of the steel bar, will enable the bolt to mobilize larger shear resistance along the joint until the plastic deformation reaches a definite criterion depending on the steel quality. Therefore, it is natural to assume that there is an "effective length" L_b (corresponding to the "effective height" h_b) [17] of the bolt which is the same quantity as the length between the hinges within which nearly all deformations will occur (Fig. 1b).

On the analogy of bolt, it is reasonable to regard the shotcrete lining as a thin layer pasted on the rock surface, the main function of which is to protect the joints near the shotcrete from shear and tension. There are also two hinges formed by bending in the lining near the joint; between the hinges the lining undergoes strong localized plastic shear and tensile deformation. With ongoing deformation, the dip angle of the lining as well as the angle between the lining and the normal of the joint will be changed (Fig. 2a). This enables the lining to mobilize larger shear resistance along the joint until the plastic deformation reaches a definite criterion. Therefore, it is also natural to assume that there is an "effective length" L_l (corresponding to the "effective height" h_l) of the lining which is the same quantity as the length between the hinges within which nearly all deformations will occur (Fig. 2b).

2.2. Rheology model and assumptions

The applicability of the equivalent method depends on the following conditions: REV for the mechanics behavior exists and whose size is much smaller than the dimension of the structure concerned. The REV could be defined theoretically as the size beyond which the elastic tensor will be unchanged. In the practice, the REV can be identified when the elastic tensor undergoes small fluctuation when the size of the rock sample increases. Fig. 3 shows four REV types around an excavated cavern: element A contains joints only, element B contains joints and shotcrete lining, element C contains joints and bolts, element D contains joints, shotcrete lining and bolts.

The proposed constitutive relation is illustrated in Fig. 4. It constitutes a generalization of the constitutive model proposed for jointed rock masses reinforced by bolt [17]. It should be noted that the interfaces between the steel and the grout and between the grout and the rock are not included in this model. It also should be noted that the joint persistence is not included in the model, the influence of the joint persistence can be considered indirectly by the average of the deformation and strength parameters between the joint and the "rock bridge".

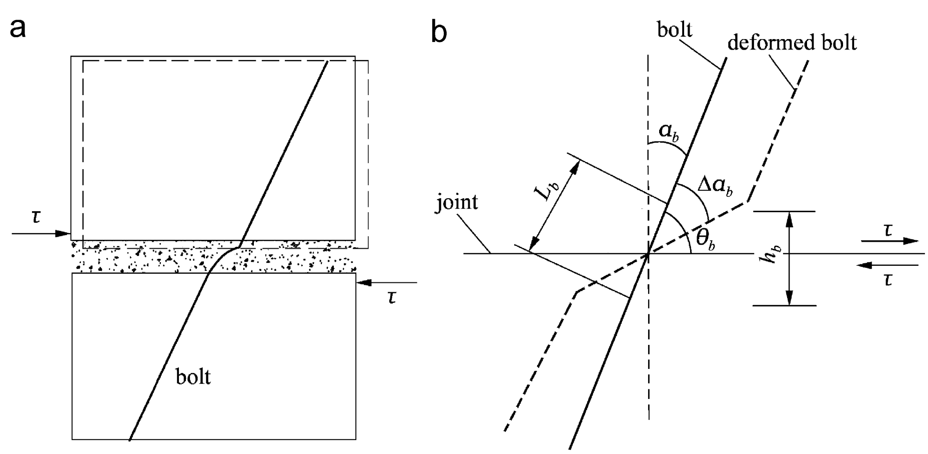

Fig. 1. Deformation of a bolt near the joint.

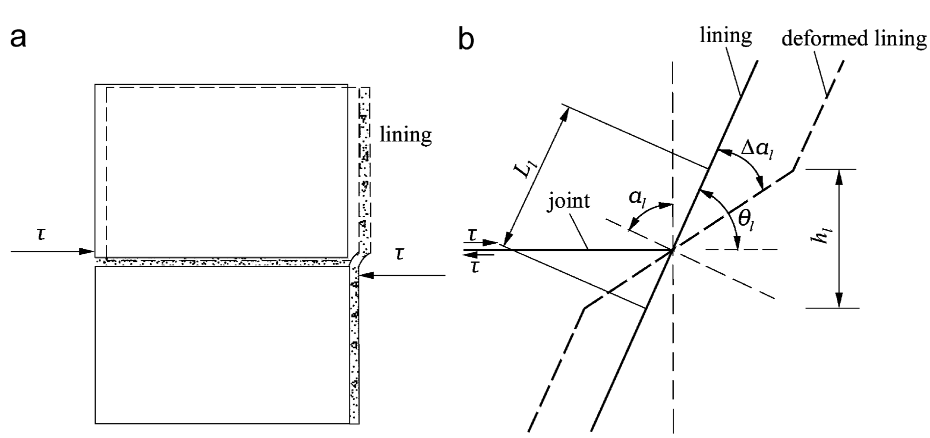

Fig. 2. Deformation of a shotcrete lining near the joint.