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Constitutive representation and damage degree index for the layered rock mass excavation response in underground openings

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ABSTRACT

In this study, a layered rock mass was regarded as a composite material, composed of interlayered intact rocks and bedding planes. Based on this assumption, we developed a transversely isotropic elastic–plastic model to describe the elastic response and post-peak failure behavior based on the Mohr–Coulomb and maximum tensile-stress criteria. Then, we proposed a damage index to estimate the damage degree of layered rock mass during excavation based on the developed model. The numerical simulation of the conventional uniaxial tests indicated that the failure mode and strength predictions of the model were in well agreement with the physical model test results. The index distribution was also shown to be more effective than the plastic zone distribution in identifying layered rock mass failure. The combined application of the mode and the index to assess the stability of the rock mass around the diversion tunnels at the Wudongde hydropower station in China showed that they could accurately estimate the locations and the depth of the potential collapses. Therefore, they are of significant practical value in the stability evaluation of layered rock mass surrounding underground openings.

1. Introduction

Layered rock mass, often encountered in all types of engineering construction, can be found in many parts of the world. As a complicated geological mass, it is in general, composed of interlayered rocks and bedding planes. A typical characteristic of layered rock mass is the transverse isotropy. Some earlier studies (Niandou et al., 1997; Tien and Kuo, 2001; Nasseri et al., 2003; Tien et al., 2006) have shown that the strength and failure mode of layered rock are highly dependent on the bedding plane dip angle, β. Moreover, Amadei et al. (1987) has also reported the differences in elastic properties of layered rock mass in a plane of transverse isotropy compared to that in the direction normal to it. This is due to the poor mechanical property of bedding planes, i.e., the strength and the stiffness in the transversely isotropic plane are different than those in the direction normal to it. This poses a significant challenge to engineering construction in underground openings and slopes because of the instability of layered rock mass.

In order to predict the layered rock mass excavation response by using continuum Modeling, the first step involves the establishment of a complete elastic–plastic model, which includes the stress–strain relation, the strength criterion, and the post-failure behavior under transversely isotropic condition. In order to evaluate the strength criterion of the layered rock mass, three strength criteria have been presented that are related to the bedding plane. First, layered rock mass strength is regarded as a function of the stress state and β. By introducing anisotropic parameters, the isotropic yield criteria are extended to establish the continuous strength criteria (Smith and Cheatham, 1980; Nova, 1980; Cazacu et al., 1999; Pietruszczak and Mróz, 2000, 2001; Mróz and Maciejewski, 2002; Lydzba et al., 2003; Lee and Pietruszczak, 2008). Second, tensors composed of shear strength or tensile strength in dominant orientation are introduced to seek the most probable failure surface under a stress condition (Walsh and Brace, 1964; McLamore and Gray, 1967; Jaeger, 1971; Hoek, 1983; Ramamurthy and Arora, 1994; Nasseri et al., 2003). Third, the failure modes revealed by experimental results have been simplified into sliding failure along discontinuities and fracture across interlayered rocks, and the two modes are described by different criteria to establish the continuous strength criteria (Jaeger, 1960, 1971; Duveau and Shao, 1998; Tien and Kuo, 2001; Tien et al., 2006; Mojtaba and Mohammad, 2015). For the deformation anisotropy of layered rock mass, few researchers introduced the anisotropy of elastic properties to the elastic–plastic model for

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Nomenclature

c_j	cohesion of bedding plane
c_{j0} and c_{jd}	initial and residual cohesions of bedding plane
c_m	cohesion of interlayered rock
c_{m0} and c_{md}	initial and residual cohesions of interlayered rock
D_j	distance between the σ-related reference point and the shear yield surface of bedding plane
D_m	distance between the σ-related reference point and the shear yield surface of interlayered rock
E_1 and E_3	Young's moduli in the directions parallel and normal to the bedding plane
d_j	distance between the stress point and the shear yield surface of bedding plane
d_m	distance between the stress point and the shear yield surface of interlayered rock
FAI	failure approach index
FAI_j	failure approach index for bedding plane
FAI_m	failure approach index for interlayered rock
FD_j	failure degree for bedding plane
FD_m	failure degree for interlayered rock
G_{12} and G_{13}	shear moduli in the directions parallel and normal to the bedding plane
l_j	distance between the stress point and the tensile yield surface of bedding plane
l_m	distance between the stress point and the tensile yield surface of interlayered rock
YAI	yield approach index
YAI_j	yield approach index for bedding plane
YAI_m	yield approach index for interlayered rock

Greek symbols

α	strike angle of bedding plane
β	dip angle of bedding plane
$\bar{\gamma}^{s}_{jp}$ and $\bar{\gamma}^{t}_{jp}$	equivalent plastic shear strain and plastic volumetric tensile strain of bedding plane
$\bar{\gamma}^{sr}_{jp}$ and $\bar{\gamma}^{tr}_{jp}$	equivalent plastic shear strain and plastic volumetric tensile strain limits of bedding plane
$\bar{\gamma}^{s}_{mp}$ and $\bar{\gamma}^{t}_{mp}$	equivalent plastic shear strain and plastic volumetric tensile strain of interlayered rock
$\bar{\gamma}^{sr}_{mp}$ and $\bar{\gamma}^{tr}_{mp}$	equivalent plastic shear strain and plastic volumetric tensile strain limits of interlayered rock
$\bar{\varepsilon}^{p}_{c_j}$ and $\bar{\varepsilon}^{p}_{\phi_j}$	equivalent plastic shear strain components corresponding to the ultimate frictional and cohesive strength components of bedding plane
$\bar{\varepsilon}^{p}_{c_m}$ and $\bar{\varepsilon}^{p}_{\phi_m}$	equivalent plastic shear strain components corresponding to the ultimate frictional and cohesive strength components of interlayered rock
ν_{12} and ν_{13}	Poisson's ratios in the directions parallel and normal to the bedding plane
σ_1 and σ_3	minor and major principal stresses
$\sigma_{1'2'}, \sigma_{2'3'}$ and $\sigma_{3'3'}$	stress components in the local space
σ_c	uniaxial compressive strength
σ^t_j	tensile strength of bedding plane
σ^t_m	tensile strength of interlayered rock
τ_j	shear strength on the bedding plane
τ^p_j	peak shear strength on the bedding plane
ϕ_j	friction angle of bedding plane
ϕ_{j0} and ϕ_{jd}	initial and residual friction angles of bedding plane
ϕ_m	friction angle of interlayered rock
ϕ_{m0} and ϕ_{md}	initial and residual friction angles of interlayered rock
ψ_j	dilation angle of bedding plane
ψ_m	dilation angle of interlayered rock
ω_j	stress risk coefficient for bedding plane
ω_m	stress risk coefficient for interlayered rock

rock mass (Nova, 1986; Niandou et al., 1997). Moreover, for layered rock masses with bedding planes at different dip angles, following remarkable post-failure behaviors have been observed (Niandou et al., 1997; Nasseri et al., 2003; Zhang et al., 2010): the strength drops rapidly along with plastic strains during the post-failure phase under different confined stresses. This indicates that the response of layered rock mass after initial failure is an important factor in many cases of underground opening design. As such, an ideal model for layered rock mass is the one which describes the strength transverse isotropy with the deformation transverse isotropy and the post-failure behavior.

In addition, it is necessary to propose a quantitative index to assess the rock mass damage, and mark the excavation damaged zone when numerical simulation is used to assist the support design in underground opening. The depth and extent of plastic zones are the indices commonly used in continuum modeling to estimate the degree of damage and failure of rock mass. However, it is well-known that rock mass yield does not necessarily indicate failure. For example, for the brittle rock specimens, although strength dropped on the stress–stain curves after the peak, it did not lose the bear capacity immediately until its strain reached a critical value. Thus, it is necessary to subdivide the state of the rock mass after yield in order to provide guidance to the rock mass support design. For this purpose, Zhang et al. (2011) proposed the failure approach index (*FAI*) to assess the degree of damage and subdivide the plastic zone of the rock mass. However, this index was established under isotropic condition. Therefore, it cannot evaluate the effect of bedding plane damage on layered rock mass.

Therefore, the present study focuses on the following objectives:

- Establishment of a transversely isotropic elastic–plastic model to describe the elastic response and post-peak failure behavior based on the Mohr–Coulomb and maximum tensile-stress criteria.
- Proposal of a damage degree index corresponding to the elastic–plastic model by extending *FAI* to the transversely isotropic condition.

Finally, to verify the rationality in engineering application, the model was incorporated into FLAC3D (Itasca Consulting Group Inc., 2005) and applied together with the index to assess the stability of the rock mass around the diversion tunnels of the Wudongde hydropower station.

2. Proposed model

2.1. Coordinate system

In this proposed model, a layered rock mass was regarded as a composite material, composed of interlayered intact rocks and bedding planes. It has been developed in accordance with the coordinate system, as shown in Fig. 1. In this coordinate system, the local space is defined by the dip direction (d), strike direction (s), and normal direction (n) of the bedding plane. The global space