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An enhanced equivalent continuum model for layered rock mass incorporating bedding structure and stress dependence

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ABSTRACT

Layered rock masses exhibit significant anisotropy in both the deformability and strength. Properties of this rock mass are largely affected by its bedding structure and also by the stress state change. For the purpose of characterizing these salient features using the equivalent continuum concept, an enhanced model is proposed in this paper based on the ubiquitous-joint model. In the enhanced model, the intact bedded rock is assumed to behave as a transversely isotropic elastic body. A modified anisotropic strength criterion is adopted to describe the direction dependence of the strength of intact bedded rock. In addition, stress-sensitive parameters are utilized for both the intact rock and bedding plane, among which the dilation angle and strength parameters of intact rock are influenced by confining pressure and loading history, whereas the stiffnesses of bedding planes are closely related to the current normal stress. The effect of layer thickness on the mechanical behavior of rock mass is reflected by continuously updating the global stiffness matrix after failure of bedding plane, and by conditions for conducting bedding plane related calculations determined by the relative scales between element size and layer thickness. Preliminary validation of this model is conducted by comparing with the closed-form solutions and with laboratory tests. Generally good agreements can be achieved between numerical simulations and theoretical/experimental results, which indicate that applicability of the enhanced model on underground engineering issues related to layered rock mass is promising.

1. Introduction

Layered rock mass is one of the rock masses which possess clear and definite bedding structure.[1] Rock layers with different thicknesses and bedding planes, cemented or separated, comprise the whole rock mass. From engineering point of view, the mechanical properties of layered rock mass, such as its stiffness directionality[2] and mixed failure modes,[3] have closer relationship with instability problems encountered in underground excavations. It is well recognized that the relative orientation of rock layers with respect to underground openings has prominent effect on the deformation and stability of surrounding rocks.[4,5] Besides, layer thickness also influences the size of failure zone as well as the equivalent rock mass stiffness.[6,7] In order to better predict the mechanical responses of layered rock mass, a suitable constitutive model which is defined based on laboratory tests and monitoring information[8] is usually needed. Such constitutive model specialized for layered rock mass should reflect fundamental properties of this rock mass, such as the orientation and layer thickness, meanwhile incorporates the essential features exhibited under different stress states, such as the anisotropy in both stiffness and strength, and their evolution with loading history. Engineering tasks involving the analysis of excavation and support design in layered rock mass could thus be more conveniently realized using models of this kind. Dynamic adjustment of excavation sequence and support optimization could also be more scientific-oriented.

The mechanical response of layered rock mass has so far been characterized by various numerical methods. According to the differences among the assumptions and algorithms, layered rock mass is represented either as discrete body or equivalent continuum. The discrete element method (DEM)[9] treats rock mass as an assemblage of blocks or particles. In block-based codes, bedding planes are defined as boundaries of rock layers according to their orientation and layer thickness,[10] while in particle-based codes, bedding planes are defined either as boundaries of particles or as a group of particles within a band.[11] Therefore by using DEM bedding planes should be first explicitly built up, and then assigned independent constitutive relations.[12] The

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advantage of this method is that it can more realistically capture the large deformation and failure mechanism along bedding plane under structurally-controlled conditions. Using particle-based model, the micro-crack initiation process within layers could be simulated[13] simultaneously. Computational efficiency of this method is obviously influenced by the minimum thickness of layers. In fact, thickness less than 10 cm could hardly be handled by DEM when dealing with engineering-scale problems. Another limitation is that acquisition of the microscopic parameters used in particle codes usually needs tedious calibration. Recent development in hybrid continuum-discontinuum (HCD) method[14] provides more insight into the failure mechanism of rock masses. The initiation and propagation of cracks could be reproduced by special element or separation/slip along element boundaries,[15] and governed by fracture mechanics principles, for example, the combined finite-discrete element method (FDEM),[16] the numerical manifold method[17] or extended FEM.[18] Layered rock mass is treated in a similar way by HCD[19] as by DEM, namely independently defining rock layers and bedding planes. Computational cost is still heavy using HCD because the spontaneous fracturing process and the subsequent block movements require more variables and computer memories, despite the fact that failure phenomenon may be more realistic. Besides, parameters describing the fracture process would not be readily available.

Considering the computational expense of large-scale excavation simulation, the equivalent continuum method[20] is still the most suitable way at present. In this method, bedding planes are not necessarily defined explicitly, although there are various joint elements aimed at reproducing the discontinuous distributions of displacement or stress field. The main goal of the equivalent continuum is to render results comparable to DEM results while maintaining relatively high performance in large-scale engineering computations. According to the difference of representing bedding planes, the equivalent continuum method could be further divided into the following three subcategories:

Completely equivalent model: Effects of bedding planes are smeared into the continuum description of rock mass, including the classical elasto-plastic theory,[21] coupled elasto-plastic damage theory,[22] as well as the micropolar theory[23] which introducing additional degrees of freedom and characteristic length.

Explicit joint element: Bedding planes are represented by various joint elements, such as Goodman element,[24] Desai element,[25] or the special interface in FLAC^{3D}[26] commercial code. Strictly speaking, using joint element usually obtains a result analogous to DEM. However, the fundamental ideas behind the two methods are different. Therefore joint element is still regarded as a continuum method.

Between the above two schemes: No bedding planes are explicitly defined, while the effects of bedding planes are equivalently reflected by constitutive equations. This idea first comes from the microplane model[27] widely used in concrete analysis, and another similar model called the multilaminate model.[28] Both models are proposed to describe the equivalent macroscopic behavior of concrete or rock from a microscopic perspective. The contacts among aggregates are abstracted as fictitious planes, or microplanes. Each plane has a unique local stress-strain relation. By integrating over the entire orientation domain, the macroscopic stress-strain relation is acquired. The ubiquitous-joint model and bilinear strain-hardening/softening ubiquitous-joint model developed in FLAC^{3D}[29] is just a simplified version of the microplane model because only one set of planes is considered. However, the ubiquitous-joint model further defines the elasto-plastic calculations for rock and joint independently. Compared with the completely equivalent model, the displacement and stress distributions computed by these implicit models can better reflect the effect of bedding planes. However, if these models are applied to evaluate the mechanical responses of layered rock mass, several deficiencies must be acknowledged. The first limitation is that the layer thickness is not explicitly expressed in the formulation. In fact the layer thickness could substantially affect the magnitude and distribution of both the displacement and failure zone depth. Another drawback is that the anisotropy of stiffness and strength of intact bedded rocks are ignored. In addition, engineering problems require that the appropriate model is capable of predicting reasonable response of rock mass induced by stress state change.

In order to solve engineering problems involving excavations in layered rock mass in a continuum framework and to overcome the above mentioned deficiencies, in this paper we first present a brief summary of the mechanical properties of bedded rock and layered rock mass. On the basis of the ubiquitous-joint model, we propose an enhanced model which takes into account important features of layered rock mass including the stiffness and strength directionality, the stress dependence of mechanical parameters, and the effect of layer thickness. The formulations and numerical implementation are explained in detail. A series of numerical tests are then performed to validate the proposed model by comparing with the laboratory tests and with theoretical solutions.

2. Mechanical properties of bedded rocks and layered rock masses

2.1. Bedded rocks

Several important mechanical properties of bedded rocks have been revealed by various laboratory tests, among which the anisotropy of stiffness and strength has been reported by different researchers.[30,31] It is therefore necessary to consider this anisotropy for single layer comprised by bedded rock even if bedding planes are thought to be the major source of rock mass anisotropy. Besides anisotropy, results of triaxial tests[30] have proved that the apparent moduli of bedded rocks increase with increasing confining pressure, and decrease gradually with damage accumulation.

The typical U-type curve[32] describing the relation between peak strength and inclination angle (Acute angle between the maximum principal stress σ_1 and normal vector of a plane (= 90° - β)) is obviously associated with the transition among various failure modes,[3] including fractures across bedding, sliding along bedding plane, and separation of bedding plane, etc. Each mode usually corresponds to a certain range of inclination angles. In addition, two or more failure patterns may appear simultaneously on a single specimen. For example, cracks nucleating and propagating within the matrix may arrest at the intersection with weak plane or material interface, followed by a new crack along the same plane.

The dilation angle[33] is proposed to describe the development of inelastic volumetric deformation, and is usually employed in a plastic potential function. Experiments reveal that this parameter also varies with the increasing inelastic deformation. It will decrease progressively to a relatively small value at post-peak stage. This trend can be well fitted by exponential or polynomial functions.[34] Besides, the peak dilation angle is believed to be negatively related to confining pressure.[35] This suggests that stress state variation in the rock mass will first influence dilation angle, then all the elasto-plastic calculations that have connection with that angle, if a plastic potential function based on the dilation angle is adopted.

Many experimental studies[36,37] on the indirect tensile strength of anisotropic rocks have shown that this strength and the corresponding failure modes vary more or less with the loading angle, i.e., the angle between intrinsic structure and loading direction. Cracks usually initiate and propagate along internal bedding or schistosity under small angles, leading to relatively low strength. Shear fracture along these structures may happen within a specific angle range. Tensile fractures completely along rock material under large angles represent failure of intact rock. These results support the idea that the apparent tensile strength (obtained by indirect tension test but not always tensile failure) of bedded rocks may be certain functions of loading angle. It should also be noted that this function exhibits considerable discrepancy among different rock types, therefore must be determined by experiments.