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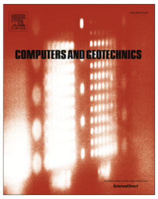

Research Paper

An improved unified constitutive model for rock material and guidelines for its application in numerical modelling

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ABSTRACT

This paper presents the theoretical backgrounds, guidelines for selection of inputs, validation, and limitations/assumptions for a proposed improved unified constitutive model (IUCM). The IUCM is a collection of the most notable and widely accepted work in rock mechanics and is a unified constitutive model that can better and more accurately predict the stress-strain relationships of the rock mass or intact rock samples in continuum numerical models than conventional constitutive models.

The IUCM accounts for important and fundamental mechanisms, such as the transition from brittle to ductile response, confinement-dependent strain-softening, dilatational response, strength anisotropy, and stiffness softening. The IUCM was developed with the intention to provide a unified constitutive model that has the complexities required for application to a wide range of geotechnical applications and conditions, yet is simple enough to be used by most geotechnical practitioners.

1. Introduction

Numerical modelling is increasingly used in the field of applied rock mechanics to predict the response of the rock mass to various engineering activities.

In recent years, increased computational power has helped facilitate the application of more sophisticated discontinuum codes for practical engineering design purposes. These codes can model the rock response to increasing stress levels at a more fundamental level by explicitly representing the discontinuities and the induced fracturing in the rock mass. As a result, these models can replicate complex failure mechanisms much more accurately than conventional continuum or semi-discontinuum models (semi-discontinuum models only include the major rock mass discontinuities explicitly and the remainder of the model is still represented through a continuum representation, in which its behaviour is controlled by a continuum constitutive model). Some recent applications of high-end discontinuum numerical methods were presented by Vyazmensky [71], Vakili and Hebblewhite [69], Hamdi et al. [29], Elmo et al. [26], Vakili et al. [70], Vakili et al. [68], Lisjak et al. [41] and Mahabadi et al. [44]. These studies showed that advanced discontinuum codes can reproduce complex failure mechanisms, such as time-dependent progressive failure, brittle damage, and caving mechanisms more realistically than semi-discontinuum or continuum models.

However, owing to computational limitations, most of the above studies were either conducted in 2D or small-scale 3D. Significantly greater computer power is required for construction and analysis of large-scale 3D discontinuum models. Furthermore, the input parameters required to construct these models are often not available, nor well understood. Consequently, fewer methods have been developed to derive representative inputs for discontinuum models.

In practice, continuum and semi-discontinuum models are quicker to construct and require less computational run time, which has resulted in their wider application amongst practitioners. Consequently, research over the last decade within the field of rock mechanics has largely focused on methods to define input parameters, refine failure criteria, and develop constitutive models for continuum medium.

The main problem associated with continuum models, however, is that they rely heavily on constitutive models. The role of a constitutive model is to implicitly represent the underlying failure mechanisms that are in place without explicitly including the micro-structures, block interactions, or the fracturing process. Therefore, a suitable constitutive model is one that can correctly represent the major controlling mechanisms that occur during the process of rock mass loading and failure.

The Mohr-Coulomb peak strength criterion and associated constitutive models have gained wide acceptance and application in the field of geotechnical engineering. Many analysis methods and software programs still use this criterion as part of their default

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Nomenclature

C	cohesion
ϕ	friction angle
m	Hoek-Brown material constant
mb	Hoek-Brown material constant
a	Hoek-Brown material constant
mi	Hoek-Brown material constant for intact rock
m_{iMax}	Hoek-Brown constant mi for the intact rock matrix
m_{iMin}	Hoek-Brown constant mi for the plane of anisotropy of the intact rock
s	Hoek Brown material constant
UCS	unconfined compressive strength
σ_c	unconfined compressive strength
σ_t	unconfined tensile Strength
GSI	geological strength index (IUCM input)
σ_1	minor principal stress
σ_2	intermediate principal stress
σ_3	minor principal stress
D	disturbance factor
ψ	slope of the failure envelop in the principal stress space
d	equivalent edge length of the model zone
ψ_{peak}	peak dilation angle
σ_{ci}	unconfined compressive strength of the intact rock
σ_{ti}	unconfined tensile Strength of the intact rock
Sigci	unconfined compressive strength of the intact rock (IUCM input)
$\sigma_{c\ min}$	lowest directional unconfined compressive strength of the intact rock (anisotropic rocks)
$\sigma_{c\ max}$	highest directional unconfined compressive strength of the intact rock (anisotropic rocks)
β	the orientation of the anisotropic plane with respect to the specimen loading axis
miMax	Hoek-Brown constant mi for the intact rock matrix (IUCM input)
Ei	elastic Modulus of the intact rock (IUCM input)
E_M	elastic Modulus of the rock mass (IUCM input)
miMin	Hoek-Brown constant mi for the plane of anisotropy of the intact rock (IUCM input)
AnisoFac	anisotropy factor (IUCM input)
AnisoDip	dip angle of the plane of anisotropy (IUCM input)
AnisoDipD	dip direction angle of the plane of anisotropy (IUCM input)
DisFac	disturbance factor (IUCM input)
CRes	residual cohesion of the rock mass (IUCM input)
FricRes	residual friction angle of the rock mass (IUCM input)
TenRes	residual tensile strength of the rock mass (IUCM input)
CritRed	reduction factor for critical strain (IUCM input)
MR	modulus ratio
ν_M	rock mass Poisson's ratio
ε_1	major principal strain
ε_2	Intermediate principal strain
ε_3	minor principal strain
ΔV	change in volume
V_0	initial volume

constitutive model. This criterion is obtained from two key parameters—cohesion (c) and friction angle (ϕ), which became widely accepted parameters for describing soil and rock strength properties. In addition, many of the well-known concepts such as Factor of Safety are still based on Mohr-Coulomb parameters to describe the strength of soil or rock.

Despite its wide application, several research works and studies have questioned its usefulness and accuracy for many rock mechanics applications. This is particularly pronounced when a linear Mohr-Coulomb model is used in an unsuitable modelling software code or when other fundamental failure processes like strain-softening, dilation, confinement dependency, anisotropy, etc. are ignored.

According to Brown [13], the linear Mohr-Coulomb consisting of two independent cohesive and frictional components does not provide a realistic representation of the progressive failure and disintegration of rock under stress. Some recent studies such as Hajiabdolmajid et al. [28], Barton and Pandey [6], and Barton [7] also highlighted the limitations of this model and its application to predict damage in rock material.

At a fundamental level, when dealing with laboratory triaxial test results, Hoek and Brown [30] reviewed several sets of laboratory test results and found that unlike the traditional Mohr-Coulomb criterion, the peak failure envelope at different confinement levels follows a non-linear relationship in major and minor principal stress space. As a result, they proposed an empirical criterion, where material constants m and s and uniaxial compressive strength (UCS) of intact rock represents the curvature and position of the failure envelope. The material constant m represents the characteristics and size of the micro-grains that form the rock sample (and also reflect the ratio between UCS and tensile strength) and s represents the degree of rock jointing or blockiness of the sample. Subsequently Hoek et al. [35] provided some relationships to derive the rock mass properties using the Geological Strength Index (GSI) and the disturbance factor.

Because most modelling software codes (and also the majority of practitioners) still use the Mohr-Coulomb failure criterion, a line-fitting procedure was proposed to find equivalent cohesion and friction angle values based on the Hoek-Brown curves and the maximum confinement pressures. Nonetheless, there remains two fundamental problems associated with applying a linear model which often lead to a considerable mismatch between the Hoek-Brown and the Mohr-Coulomb predicted peak stress values. The first problem is that in many rock mechanics applications, such as mining, a significant variation exists in the level of confinement at different locations within the rock mass. Secondly, even for a particular excavation at a given depth there can be a large variation in confinement levels depending on the position with respect to excavation boundaries. This is mainly caused by the redistribution of stress around excavations and also new phases of confinement that can be induced as result of nearby excavations or yielded material. These two issues can be a lot more pronounced in high stress and high yield environments, or in rock material that exhibits a more curved peak failure envelope (rocks with high Hoek-Brown material constant m values).

It is globally accepted that the Hoek-Brown criterion (and a non-linear failure criterion in general) can forecast the "peak failure" state of rock samples with better accuracy than a linear criterion such as Mohr-Coulomb. However, when speaking of rock damage, "peak failure" is not the main or only controlling mechanism. Other contributing factors including residual strength, strain-softening, confinement-dependency, dilatational response, stiffness softening mechanism, and anisotropic behaviour also have significant influence on how damage initiates and propagates within the rock material. These factors are particularly important when stress elevates to levels that can initiate brittle intact rock failure.

This paper introduces an improved unified constitutive model (IUCM), which is based on widely accepted research cases of rock damage noted in the literature. It also outlines several examples