Engineering Geology 228 (2017) 107–120

Contents lists available at ScienceDirect

Engineering Geology

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

Modelling jointed rock mass as a continuum with an embedded cohesive-frictional model

Linh A. Le[a], Giang D. Nguyen[a,*], Ha H. Bui[b], Abdul H. Sheikh[a], Andrei Kotousov[c], Aditya Khanna[c]

[a] School of Civil, Environmental and Mining Engineering, The University of Adelaide, Adelaide, SA 5005, Australia
[b] Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia
[c] School of Mechanical Engineering, The University of Adelaide, Adelaide, SA 5005, Australia

ARTICLE INFO

Keywords:
Jointed rock mass
Constitutive modelling
Double scale
Coupled damage-plasticity
Cohesive model

ABSTRACT

The mechanical and hydraulic properties of a jointed rock mass are strongly affected by the characteristics of joints within the intact rock mass. In this study, a constitutive model for jointed rock masses is developed by incorporating the contributions of both the joint and its surrounding rock mass. The behaviour of the joint is represented by a new coupled damage-plasticity cohesive-frictional model taking into account its dilation evolution and the reduction of both strength and stiffness, while the surrounding rock behaviour is assumed to behave elastically. The interactions between the joint and the surrounding rock are described by a set of kinematic enhancements and internal equilibrium equations across the interface of the joint. The formulation of the proposed model is presented along with its implementation algorithms and validation with experimental data. The enhanced kinematics facilitates the incorporation of both behaviour and orientation of the joint, together with the size and behaviour of the surrounding rock, allowing capturing key characteristics of jointed rock mass responses under mixed-mode loading conditions at different spatial scales.

1. Introduction

The mechanical and hydraulic properties of a rock mass are strongly affected by the presence of discontinuities such as joints, fractures or faults. The effects of these features, generally referred to as joints, can be very significant in many problems in geology or geophysics, mining or petroleum engineering, hydrogeology and waste management, therefore, it is important to be able to locate and characterise them remotely within a rock mass using geophysical methods (Cook, 1992). In general, the behaviour of a rock mass is discontinuous, anisotropic, inhomogeneous and inelastic (Harrison and Hudson, 2000). There are two approaches which are normally used to model these features. The first approach describes joints or system of joints as aggregate effects within a representative volume element to come up with a practicable continuum model. Some studies following this approach can be listed as Cai and Horii (1992), Lee (1998), Chalhoub and Pouya (2008), Martinez et al. (2012). The other approach treats joints as discrete entities. Studies which incorporated this approach include Plesha (1987), Haberfield and Johnston (1994), Huang et al. (2002), Grasselli and Egger (2003), Mihai and Jefferson (2013), Schreyer and Sulsky (2016). One of the advantages of treating joints as discrete entities is that the mechanical responses of components (i.e. intact rock, joints) and the interactions between them are taken into account in details within a constitutive model. This would be very useful for further developing those constitutive models to continuum models. The current work utilises the second approach as it allows more realistic description of various deformation effects and mechanisms.

It is well recognised that understanding the mechanical behaviour of rock joints plays a very important role in designing rock structures such as underground excavations, rock slopes (Singh and Rao, 2005). As reported in many studies (Bandis et al., 1983; Desai and Fishman, 1991; Jing, 1990), the deformation behaviour of rock joints is complicated. Under shear displacements, rock joints would exhibit dilatant behaviour which is strongly associated with the development of shear and normal stresses across the joints plane. Several models were proposed to simulate the shear stress–displacement relationships of rock joints with combinations of empirically based relations and mechanical formulations. For example, Patton (1966) and Ladanyi and Archambault (1969) were among the first to develop empirical shear strength formulations for rock joints accounting for the effect of its roughness nature. These roughness factors were then generalised as joint roughness coefficient (JRC) in the commonly used empirical shear strength model by Barton and Choubey (1977). This empirical model is capable of predicting the shear strength under the normal compression

* Corresponding author.
E-mail address: g.nguyen@adelaide.edu.au (G.D. Nguyen).

http://dx.doi.org/10.1016/j.enggeo.2017.07.011
Received 14 February 2017; Received in revised form 19 July 2017; Accepted 28 July 2017
Available online 02 August 2017
0013-7952/

but the progressive development of stresses during shearing is missing. To address this shortcoming, Li et al. (1989) proposed an elasto-plastic model to link the normal stress and the shear stress of a contact unit in the rough crack surface. Igcacio et al. (1997) presented a normal/shear cracking model for quasi-brittle materials. Su et al. (2004) developed a continuum-level phenomenological interface constitutive model which accounts for both reversible elastic behaviour, as well as irreversible inelastic separation-sliding deformations prior to failure for rock joints. Although the joint behaviour can be mimicked in these models, the interactions between the joint and the bulk material are totally neglected. This would hinder the model's extension for modelling the rock mass where joints are distributed within and interact with the surrounding rock. Wang et al. (2003) proposed a constitutive model with an ellipse yield function and associated flow rules for the rock joint. In this model, a shape function is used along with the yield function to incorporate the shear anisotropy of the joints. However, this might not be applicable for modelling in situ joints where anisotropy usually is not of interest and hard to characterise. Recently, in 2016, Schreyer and Sulsky (2016) proposed a nonlinear elasticity model where the joint widths are taken into account to enable the modelling of either pre-existing gaps or the formation of new joints. Nonetheless, in this research, three separate yield surfaces and separate softening/hardening rules were used to capture key characteristics of the joints. The discontinuity at apexes where these three yield surfaces intersect might bring difficulties and require treatments in the implementation. In addition, only joints that are parallel to the sides of square finite elements can be taken into account in this approach (Schreyer and Sulsky, 2016).

Glossary

$\boldsymbol{\sigma}$	Average stress vector
$\boldsymbol{\sigma}_o$	Stress vector of the material outside the joint
$\boldsymbol{\sigma}_i$	Stress vector of the material inside the joint
σ_n	Constant normal stress in shear test
σ_c	Compression strength of the material
$\boldsymbol{\varepsilon}$	Average strain vector
$\boldsymbol{\varepsilon}_o$	Strain vector of the material outside the joint
$\boldsymbol{\varepsilon}_i$	Strain vector of the material inside the joint
ε	Tolerance of the traction continuity condition
$\mathbf{a}_o$	Elastic stiffness matrix of the bulk material
$[\![\mathbf{u}]\!]$	Displacement jump vector of the joint in global coordinate system
$[\![\dot{\mathrm{u}}_c]\!]$	Displacement jump vector of the joint in local coordinate system
u_n	Total normal displacement jump of the joint in local coordinate system
u_n^p	Plastic normal displacement jump of the joint in local coordinate system
u_s	Total shear displacement jump of the joint in local coordinate system
u_s^p	Plastic shear displacement jump of the joint in local coordinate system
u_p	Effective plastic factor
h	Width of the joint
H	Characterised length of the joint
Ω_o	Volume of the bulk material outside the joint
Ω_i	Volume of the joint
η	Volume fracture of the joint
Γ_i	Area of the joint
$\mathbf{t}_i$	Traction vector of the joint in global coordinate system
$\mathbf{t}_c$	Traction vector of the joint in local coordinate system
$\mathbf{t}_c^{trial}$	Trial traction vector of the joint in local coordinate system
t_n	Normal traction of the joint in local coordinate system
t_s	Shear traction of the joint in local coordinate system
τ_y	Shear strength in shear test
$\mathbf{K}^t$	Inelastic tangent stiffness matrix of the joint in global coordinate system
$\mathbf{K}_c^E$	Elastic tangent stiffness matrix of the joint in local coordinate system
$\mathbf{K}_c^t$	Inelastic tangent stiffness matrix of the joint in local coordinate system
K_n	Elastic normal stiffness of the joint in local coordinate system
K_s	Elastic shear stiffness of the joint in local coordinate system
D	Damage variable of the joint
f_n	Tension strength of the material
m	Parameter controlling the curvature of the initial yield surface
μ_0	Parameter controlling the inclination of the initial yield surface
μ	Parameter controlling the inclination of the failure yield surface
ϕ	Internal friction angle
λ	Factor of proportionality in flow rule
y	The yield surface of the cohesive model
g	The potential function of cohesive model's non-associated flow rule
δ_0	Displacement corresponding to shear strength
α	Parameter controlling energy dissipation
γ	Parameter controlling the dilation during the shear
E	Young's modulus of the bulk material
G_{comp}	Fracture energy computed from the model
G_f	Fracture energy measured from the experiment
r	Residual stress of the traction continuity
n	Normal vector of the joint face in Voight notation
ν	Poisson's ratio of the bulk material
R	Transformation matrix from global to local coordinate system

One of the difficulties in analysing jointed rock masses is its diversity in natural characteristics. Because rock mass is a natural material, rock joints are formed under different stress states and continuous loadings from dynamic movements of the upper crust of the Earth such as tectonic movements, earthquakes, glaciation cycles. This complex and long history of formation makes the in situ characteristics of rock joints hard to be determined. Experiments on rock joints are mostly based on small specimens corresponding to a certain location within the rock mass. The geometry and roughness of the joints are usually presented by the joint roughness coefficient (JRC) which is often estimated by visibly comparing to standard profiles (Barton and Choubey, 1977; Li and Zhang, 2015). However, it is widely recognised that the mechanical behaviour of rock joints can vary as a function of scale, although the extent is arguable (Tatone and Grasselli, 2013, 2009).

In the past decades, many studies have been carried out to characterise the effects of the scale on the mechanical behaviour of jointed rock masses. A relatively comprehensive review of statistical scale effects on jointed rock behaviour from previous studies is presented in the work done by Bahaaddini et al. (2014). Bahaaddini et al. (2014, 2013) also used the discrete element method (DEM) to investigate the shear behaviour and statistical scale effects of the rock joints. Although such explicit simulations are good for understanding the mechanical mechanisms of the joints, they might need several millions of particles for modelling a rock mass and its joints, and hence are too expensive for practical purposes. Phenomenological approaches could be a good choice to deal with this difficulty by using curve fitting-based techniques to yield similar results by experiments or to obtain empirical equations for a certain experimental data. However, focusing on one particular path with a precise matching to experimental data cannot always warrant a success in light of the uncertainty associated with both the properties of in situ joints and the variety of stress paths