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Review

A review of shear strength models for rock joints subjected to constant normal stiffness

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ABSTRACT

The typical shear behaviour of rough joints has been studied under constant normal load/stress (CNL) boundary conditions, but recent studies have shown that this boundary condition may not replicate true practical situations. Constant normal stiffness (CNS) is more appropriate to describe the stress–strain response of field joints since the CNS boundary condition is more realistic than CNL. The practical implications of CNS are movements of unstable blocks in the roof or walls of an underground excavation, reinforced rock wedges sliding in a rock slope or foundation, and the vertical movement of rock-socketed concrete piles. In this paper, the highlights and limitations of the existing models used to predict the shear strength/behaviour of joints under CNS conditions are discussed in depth.

1. Introduction

An appropriate evaluation of the shear behaviour of rock joints is vital, for instance when analysing the stability of rock slopes, designing excavations in jointed rock, assessing the stability of concrete dam foundations, and designing rock-socked piles. In conventional studies, the shear behaviour of a joint is usually investigated in the laboratory under constant normal load/stress (CNL) boundary conditions where the normal stress remains constant and the surface of the joint dilates freely during shearing. The best example to illustrate a CNL condition is a slope stability problem where the rock block is sliding along the joint without any constraint. However, in engineering practice, the normal stress acting on the joint interface may vary during shearing, and dilation of the joint may be constrained by the confined environment formed across the interface, which often represents a constant normal stiffness (CNS) condition. The practical implications of this are movements of unstable blocks in the roof or walls of an underground excavation, reinforced rock wedges sliding in a rock slope or foundation, and the vertical movement of rock-socketed concrete piles, as illustrated in Figs. 1–3, respectively. Several researchers have insisted that a CNS boundary condition is more appropriate for many field situations (Heuze, 1979; Leichnitz, 1985; Johnston et al., 1987; Ohnishi and Dharmaratne, 1990; Saeb and Amadei, 1990; Skinas et al., 1990; Haberfield and Johnston, 1994; Kodikara and Johnston, 1994; Indraratna and Haque, 1997, 2000; Indraratna et al., 1999, 2010a, 2015; Seidel and Haberfield, 2002; Jiang et al., 2004; Thirukumaran et al., 2015). The CNS boundary condition is usually simulated by a spring with a CNS $K_n = d\sigma_n/d\delta_v$, where $d\sigma_n$ and $d\delta_v$ are the changes in normal stress and normal displacement, respectively. The value of this CNS K_n is externally controlled by applied reinforcement or the adjacent rock mass across the joint interface.

In addition to the boundary normal stiffness imposed by the surrounding rock mass, there are other parameters that may affect the shear behaviour of rock joints such as the joint surface roughness and strength, the level of initial normal stress acting on the joint interface, the presence of infill (gouge) material, and water in the joint interface. A considerable amount of work has been conducted to describe how these factors affect the shear behaviour of joints under CNL conditions, but only a few studies with limited experimental data and analysis on the shear behaviour of joints under CNS conditions are available as yet. Apart from this boundary effect, the shear behaviour of rough rock joints is complex because the stress–strain response is governed by non-uniform asperity damage and gouge material that accumulates on the joint interfaces. To date, only a few studies have been devoted to studying

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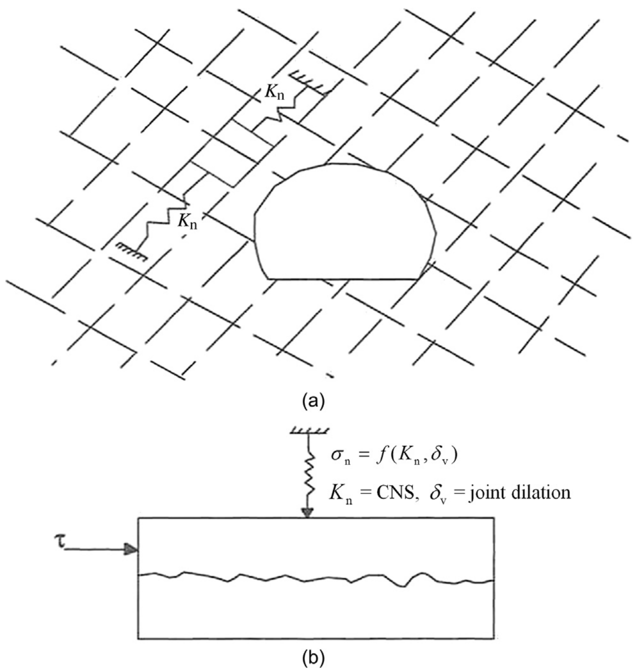

Fig. 1. Joint behaviour in the roof or walls of an underground excavation (after Indraratna et al., 1999). (a) Underground excavation in jointed rock. (b) Equivalent two-dimensional model for joint on the top of roof.

the evolution of asperity damage and production of gouge on the joint surface due to the technical difficulty of experimentally measuring the rate of asperity damage and the production and distribution of gouge material. Some studies have attempted to characterise the asperity deformation directly on the joint surface (Ladanyi and Archambault, 1970; Riss et al., 1997; Roko et al., 1997; Gentier et al., 2000; Homand et al., 2001; Grasselli et al., 2002; Yang et al., 2010; Indraratna et al., 2014; Tatone and Grasselli, 2015). Others indirectly appraised asperity deformation by assessing the joint dilation angle (Plesha, 1987; Hutson and Dowding, 1990; Leong and Randolph, 1992; Lee et al., 2001; Indraratna et al., 2015), or mobilised the friction angle (Barton, 1982), as well as provided insight into asperity deformation on the basis of numerical modelling (Karami and Stead, 2008; Asadi et al., 2012) during shearing. Nevertheless, incorporating the influence of asperity degradation and gouge accumulation to the model for rock joints is still a very challenging task that needs more advanced studies.

Unlike CNL boundary conditions, only a few methods have been proposed to model either the peak shear strength of rock joints or the complete shear behaviour of rough rock joints under CNS conditions (Heuze, 1979; Leichnitz, 1985; Saeb and Amadei, 1990, 1992; Skinas et al., 1990; Seidel and Haberfield, 2002; Indraratna et al., 1999; Indraratna and Haque, 2000; Indraratna et al., 2005, 2010b, 2015; Oliveira and Indraratna, 2010). The objective of this review paper is to study the importance of developed models and also identify the limitations for using these existing models in practical applications.

2. Existing shear strength models

2.1. *Heuze's (1979) analytical model*

Heuze (1979) emphasised that when a joint begins to dilate, it is partially restrained by external normal stiffness applied across the interface and thus the normal stress across the joint increases. Therefore, he used an analytical method to calculate the incremental

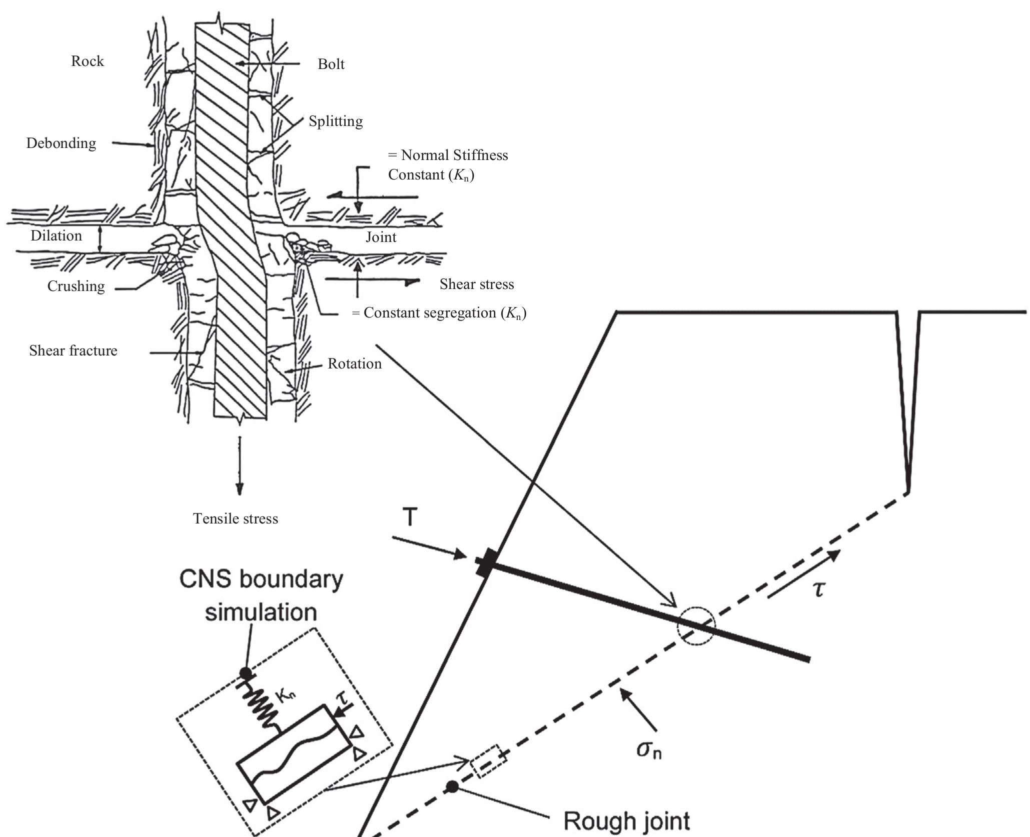

Fig. 2. Behaviour of joints in a reinforced rock slope (inspired after Indraratna and Haque, 2000).