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Distinct element method simulations of rock-concrete interfaces under different boundary conditions

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ABSTRACT

The shear behaviour of concrete-rock interfaces has been the aim of extensive research in geotechnical engineering applications such as rock socketed piles, rock bolts and concrete dam arch bridge foundations. Several experimental studies through direct shear tests have been conducted to evaluate the shear behaviour of rock-concrete interfaces under CNL (Constant Normal Load) and CNS (Constant Normal Stiffness) conditions. In this paper, PFC2D numerical simulations of unbonded rock-concrete planar and saw-tooth triangular joints under CNL and CNS boundary conditions are conducted using the Shear Box Genesis (SBG) approach proposed by Bahaaddini et al. (2013b). The numerical simulation results are compared with experimental data published by Gutiérrez (2013) and Gu et al. (2003). Results indicate that the SBG approach reproduces suitably the shear behaviour, failure mode and asperity damage of unbonded (planar and triangular) rock-concrete interfaces, specially under CNL conditions.

1. Introduction

Modelling the shear behaviour of rock joints and of rock-concrete interfaces is crucial for the success of many geotechnical designs, such as concrete dam and arch bridge foundations (Krounis et al., 2016; Tian et al., 2015), stability of blocks in rock excavations (Poturovic et al., 2015), rock-bolt or anchor design (Tian et al., 2015), and rock-socketed piles (Johnston et al., 1987; Gutierrez-Ch and Melentijevic, 2016).

Traditionally, the topic has been investigated with the aid of tests in the laboratory or in-situ tests (Shrivastava and Rao, 2015; Asadi et al., 2013; Tian et al., 2018) which, together with analytical approaches (Patton, 1966; Barton and Choubey, 1977), have led to the development of models to estimate (i) the shear strength of rock-rock interfaces (Haque and Kodikara, 2012; Indraratna et al., 2015), or of rock-concrete interfaces (Kodikara and Johnston, 1994); and (ii) their complete shear behaviour (Seidel and Haberfield, 2002; Barton and Choubey, 1977).

As a result of such investigations, it is well known that the mechanical behaviour of such interfaces mainly depends on their mechanical properties and on the initial normal stress acting on them (Fan et al., 2015); it also depends on their roughness profiles, and on the presence of infill material (or water) in the interfaces (Thirukumaran and Indraratna, 2016; Nahazanan et al., 2013). The type of boundary conditions is also very important (see e.g. Shrivastava and Rao, 2015 and Bahaaddini et al., 2013b), with two types of boundary conditions being typically employed in direct shear tests of rock-concrete interfaces: constant normal load (CNL), or constant normal stiffness (CNS) boundary conditions (see Fig. 1).

In CNL tests, the normal load is kept (approximately) constant, and the interface can dilate or contract freely during the test; this condition is suitable, for example, for planar and non-reinforced rock slopes. In CNS tests, the loads at the interfaces depend on its shear and normal stiffness (which are kept constant) and on the displacements that the interfaces can accommodate. The CNS condition is therefore more appropriate for situations with high normal stresses and reduced possibilities for interface dilation, such as deep tunnels or rock socketed piles (Shrivastava and Rao, 2015; Thirukumaran and Indraratna, 2016).

However, the analytical and experimental approaches described above have problems due to their mathematical complexity, or to the difficulties and cost associated to experimental efforts. For that reason, numerical methods –such as the Finite Element Method (FEM) or the Distinct Element Method (DEM)– have gained attention in recent years. Among them, the DEM approach, often through its implementation in Particle Flow Code (PFC) (Park and Song, 2009; Bahaaddini et al., 2013a; Asadi et al., 2012) has been shown to be particularly useful to model this problem, as it can naturally reproduce important aspects of joint behaviour such as dilation, the roughness of contacts and breakage of asperities, and the degradation that leads to the development of

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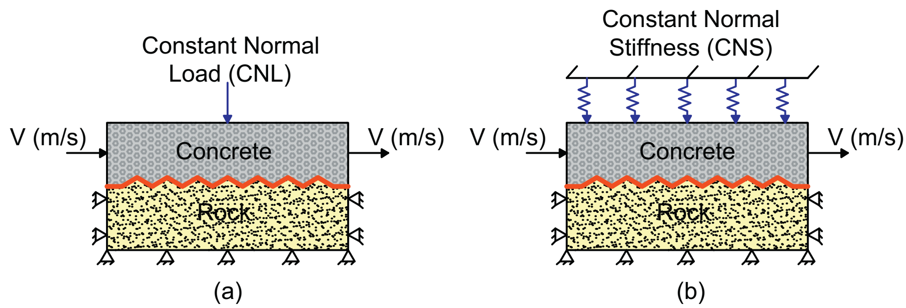

Fig. 1. Idealized sketch of direct shear test: (a) CNL boundary conditions, (b) CNS boundary conditions.

"third-bodies" –the interfacial material coming from the degradation of first-bodies or entering into the contact from the outside– (Mollon, 2015; Royo and Melentijevic, 2014; Bahaaddini, 2017). But, despite its capabilities to characterize the shear behaviour of rock-rock or rock-concrete interfaces more realistically, the DEM-PFC approach still imposes some unresolved modelling challenges. For instance, Lazzari (2013) reported difficulties to reproduce the shear behaviour of rock joints due to an inadequate distribution of normal and shear forces, and to an interlocking problem at the joint plane. (By interlocking we mean an inadequate detection of particles that go across the joint contact, producing numerical difficulties).

Similarly, some attempts have been undertaken to use the Bond-Removal Approach (BRA) –a technique that removes the bonds between particles intersected by the interface plane– to conduct DEM-PFC numerical simulations of direct shear tests of planar or irregular joints (Park and Song, 2009; Asadi et al., 2012; Cundall, 2000); in particular, Bahaaddini et al. (2013b) used the BRA to simulate direct shear tests of planar and saw-tooth triangular joints under CNL conditions. However, results revealed that the BRA methodology is unable to simulate the shear behaviour of rock joints, as unrealistic shear strengths are predicted due to errors associated to the release of stored energy and to an incorrect modelling of energy dissipation (Bahaaddini et al., 2013b).

The other contact model commonly used to characterize the shear behaviour of rock-rock or rock-concrete interfaces in PFC –the Smooth-Joint Contact Model (SJCM) proposed by Ivars et al. (2008) and described in Section 2.3– also has difficulties in some cases. For instance, Bahaaddini et al. (2013b) showed that the SJCM cannot properly simulate direct shear tests of planar or saw-tooth triangular joints under CNL conditions when shear displacements go beyond the diameter D_{min} of the smallest ball employed to simulated the rock or concrete material; and they demonstrated that this deficiency is due to an interlocking problem associated to an inadequate detection of particles that go across the smooth-joint contact during shear tests. Fig. 2 illustrates these difficulties; in particular, it shows the results of our independent simulations for an idealized example in which the results of direct shear tests conducted on sandstone-sandstone planar joints similar to those considered in Tables 1 and 3 are compared with numerical results obtained using PFC2D with the BRA and SJCM approaches described above.

To overcome such shortcomings, Bahaaddini et al. (2013b) proposed the Shear Box Genesis method (or SBG, see Section 3.4) to simulate direct shear tests in PFC, and they employed it to analyze the shear behaviour of rock joints under CNL conditions; later, they have also used the same method to analyze the influence of aspects such as asperity degradation (Bahaaddini et al., 2013a), scale effects (Bahaaddini et al., 2014) or boundary conditions(Bahaaddini, 2017).

However, a more in-depth analysis of this methodology, with additional validation using experimental data, is still lacking in the literature. This paper provides a contribution in that direction, investigating (i) the applicability of the SBG with PFC2D to model direct shear tests of rock-concrete interfaces under CNL and CNS boundary conditions, (ii) the effect of joint roughness on the shear behaviour, and (iii) the validation of results with experimental data previously published in the literature. (Results corresponding to direct shear test conducted on gneiss-concrete (Gutiérrez, 2013) and sandstone-concrete (Gu et al., 2003) interfaces are employed).

2. Fundamentals of DEM modelling with PFC2D

2.1. Introduction

PFC is the commercial program (Itasca Consulting Group Inc, 2014) with an implementation of DEM employed in this work. PFC can simulate the behaviour –interactions, movements, etc.–, of systems

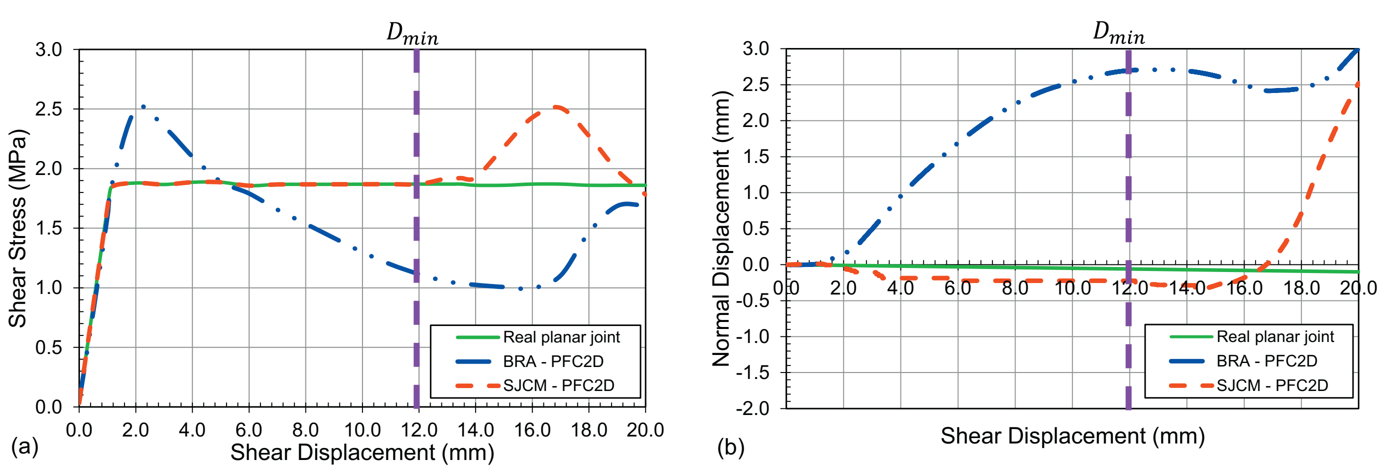

Fig. 2. Comparative curves between real planar joint and numerical models using BRA and SJCM at 2.67 MPa normal stress, (a) shear stress versus shear displacement, (b) normal displacement versus shear displacement.