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A numerical study of rock scratch tests using the particle-based numerical manifold method

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ABSTRACT

A better understanding of the rock-tool interaction is necessary to improve the cutting efficiency. In this paper, we present a numerical study of rock scratching using a newly developed particle-based numerical manifold method (PNMM). The scratching processes with different cutting depths are first simulated, where the failure pattern and cutting force are discussed. The transition of brittle-ductile failure with an increased cutting depth is reproduced. It is validated that when the cutting depth is intermediate, rock scratching presents a transitional mode between ductile and brittle failure. Then, a parametric study is performed by a series of numerical simulations. The effect of cutter operational parameters on the cutting force and energy consumed by the cutter are studied. Three operational parameters of the cutter are considered in this study, including the cutting depth, cutting speed, and cutter rake angle. An estimation of the transitional cutting depth range is given by the result of the mechanical specific energy of the cutter. Besides, some advice is provided to improve the efficiency of rock cutting in engineering practice.

1. Introduction

The interaction between rock and a cutting tool has been at the core of many rock engineering applications, including exploration drilling, mining, tunnelling, sawing, and grinding. With a noticeable trend to mine and drill for reserves at greater depth in recent years, the demand for the continual cutting of rock at high in-situ stress and high-temperature conditions is rapidly increasing in civil engineering industries. Low cutting efficiency and high cutter consumption due to poor cutting conditions has been regarded as one of the main problems encountered in deep ground projects (Gong et al., 2016). A better understanding of the rock-tool interaction is necessary to overcome this problem.

The rock cutting process involves penetrating a cutting tool into the rock and removing a fraction of rock material by moving the cutting tool. There are typically two types of rock cutting in practice: cutting with a cutter and normal indentation with a wedge (Huang et al., 2013). The difference between these two processes is the moving direction of the cutting tool. In the *indentation* process, the cutting tool, usually a wedge indenter, penetrates into and induces fragmentation of rock. The direction of the motion of the cutting tool is normal to the surface of rock. Research on this type of rock cutting process can be found in (Gong et al., 2006a,b, 2005; Li et al., 2016; Liu et al., 2002; Ma et al., 2011; Tkalich et al., 2016; Wang et al., 2011; Xiao et al., 2017). In the other cutting process, the direction of the motion of the cutting tool is parallel to the surface of rock at a certain penetration depth. This type of rock cutting process is also termed as *scratching*.

The scratch test is probably one of the oldest techniques in the characterisation of mechanical material properties, since the Mohs' hardness scale was introduced to quantify the scratch resistance of minerals in 1824 (Akono et al., 2011). Following the effort initiated by Detournay and Defourny (1992), the scratch test has emerged as a promising alternative to determine the strength of various materials ranging from soft to hard, including polymers, metals, ceramics, and rocks (Akono and Ulm, 2011; Rodriguez et al., 2017). Attractively, extensive experiment results have clearly shown a relationship between the energy consumed in a scratch test and the uniaxial compressive strength of rocks, on condition that the cutting depth is shallow (Che et al., 2016; Richard et al., 2012; Schei et al., 2000). Theoretical analysis and experimental observations also indicated a ductile-brittle failure transition of rock when the cutting depth goes from shallow to deep (Huang and Detournay, 2008; Richard, 1999). However, the mechanism of scratch tests remains a challenging problem due to its complexity. In the process of a scratch test, problems of the tool-rock interaction, fracture initiation and propagation in rocks, and the separation of rock fragments are involved. Besides, the setup of a scratch test is also found to influence the testing result (He et al., 2017).

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Nomenclature

d	cutting depth
d_c	critical brittle-ductile transition depth
$\mathbf{d}$, $\mathbf{d}_e$, $\mathbf{d}_i$	vector of DOF for system, manifold element and mathematical cover
F_H	average cutting force parallel to the horizontal direction
$\mathbf{F}$	vector of equivalent loads
$\mathbf{K}$	stiffness matrix
$\mathbf{M}$	mass matrix
$\mathbf{N}_i$, $\mathbf{N}_e$	shape function of physical cover and manifold element
$\mathbf{u}$, $\mathbf{u}_e$	displacement field of particle and manifold element
$\mathbf{u}_i$	cover function
v	cutting speed
x	travel distance of cutter
$\mathbf{x}^c$	coordinates of the centroid of particle
Δ	contact threshold
$\boldsymbol{\varepsilon}$, $\boldsymbol{\varepsilon}_e$	strain of particle and manifold element
σ_c	uniaxial compressive strength
$\boldsymbol{\sigma}$, $\boldsymbol{\sigma}_e$	stress of particle and manifold element
θ	rake angle of the cutter
ϕ	weight function

By considering the limited applicability of analytical solutions, numerical simulations have been widely performed on this topic. Kou et al. (1999) utilised the Realistic Failure Process Analysis (RFPA) to simulate the scratch test of inhomogeneous rocks and successfully predicted the damage under and ahead of the cutter and variously shaped chips ahead of the cutter. However, due to the limitation of their model, they failed to simulate the complete process of scratch tests but only predicted the initiation of fractures. Huang and Detournay (2008) showed an intrinsic length scale of rock material could influence its behaviour in scratch tests using the Distinct Element Method (DEM). The effect of the intrinsic length scale on the critical depth of the ductile-brittle failure mode transition is further studied in (Huang et al., 2013). However, their simulation results were found to considerably overestimate the effect of the length scale when comparing to experimental results, due to the sensitivity of particle distributions and micro parameters in DEM. He and Xu (2015) attempted to overcome this sensitivity and obtain a more realistic ratio between compressive and tensile strength by proposing a cluster DEM. Zhou and Lin (2014) revisited this length scale in the Finite Element Method (FEM). Similarly, Jaime et al. (2015) utilised an explicit FEM to simulate the fragmentation of rock and the force applied on the cutter during a complete scratch test. However, due to the limitation of FEM, failed elements were immediately eliminated from the model, leading to a so-called zero cutting force phenomenon and considerable low energy consumed by the cutter in their simulation. A fine enough mesh must be adopted in FEM to overcome this shortcoming.

In this paper, we apply a newly developed Particle-based Numerical Manifold Method (PNMM) (Li et al., 2017) to study the rock scratch test. PNMM, as an inherently continuum-discontinuum model, is capable of simulating the interaction between the cutter and rock, the initiation and propagation of fractures, the separation and post-failure motion of fragments, and the rate-dependent behaviour of rock materials, which makes it suitable for the simulation of a scratch test. This work will first simulate the complete scratching process of rock. Then, the transition of ductile and brittle failure is presented. Last, parametric studies are performed to investigate the effect of cutting setup on the energy consumed by the cutter.

2. Particle-based numerical manifold method (PNMM)

PNMM is an extension of the Numerical Manifold Method (NMM) by incorporating the particle concept, to simplify geometrical Boolean operations and contact operations in NMM. The method is coupled with the Johnson-Holmquist-Beissel (JHB) model to reproduce the dynamic behaviour of rock. The determination process of JHB parameters for rock materials can be found in (Li et al., 2017; Ma and An, 2008). PNMM provides a unified analysis framework for both pre- and post-failure behaviours of rock. Comparing with NMM, it is flexible in considering the heterogeneity of rock materials and simulating the initiation, propagation, and coalescence of fractures.

PNMM inherits the cover system of NMM, i.e. the mathematical cover and physical cover, to form the manifold element as the first discretisation. The displacement field of a manifold element is given by pasting several related physical covers as

$$\mathbf{u}_e(\mathbf{x}) = \sum_{i=1}^{m} \varphi_i(\mathbf{x})\mathbf{u}_i(\mathbf{x}) = \sum_{i=1}^{m} \mathbf{N}_i(\mathbf{x})\mathbf{d}_i = \mathbf{N}_e\mathbf{d}_e \tag{1}$$

where $\mathbf{u}_e(\mathbf{x})$ is the displacement field, m is the number of physical covers, φ_i is the weight function on the ith mathematical cover, $\mathbf{u}_i$ is the cover function on the ith physical cover, $\mathbf{N}_i$ and $\mathbf{N}_e$ are the shape functions on the ith physical cover and manifold element respectively, and $\mathbf{d}_i$ and $\mathbf{d}_e$ are the vectors of degree of freedom (DOF) on the ith physical cover and manifold element respectively. The definition of the weight function and cover function could be found in the references of NMM, e.g. in (Ma et al., 2010). The vector of DOF $\mathbf{d_e}$ is obtained by solving the global equation in matrix form. For dynamic analysis, the global equation is

$$\mathbf{K}\mathbf{d} + \mathbf{M}\ddot{\mathbf{d}} = \mathbf{F} \tag{2}$$

where $\mathbf{K}$ is the global stiffness matrix, $\mathbf{d}$ is the global vector of DOFs/unknowns, $\mathbf{M}$ is the global mass matrix, and $\mathbf{F}$ is the global vector of equivalent loads.

A group of particles are allocated within each manifold element (see Fig. 1), representing the second level of discretisation in PNMM. Particles in this discretisation do not mean to bring in additional DOFs, but to carry varying material properties, boundary conditions, and body forces. A particle integration scheme is developed to generate element

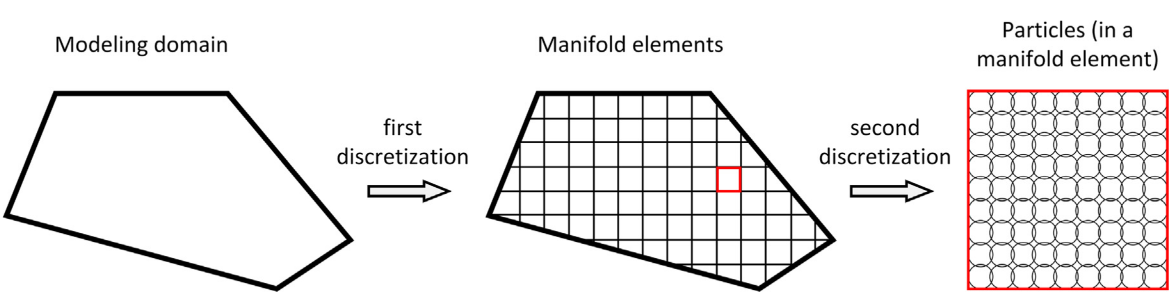

Fig. 1. The dual-level discretization of PNMM.