Technical Memorandum

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To: PFC Development Files and Itasca Website

From: Sacha Emam and David Potyondy

Re: PFC2D Rock-Cutting Procedures

Ref: ICG7156-L

The PFC[1] codes are used to simulate rock cutting to learn more about drilling mechanics (Itasca, 2007). PFC models allow one to define a cutter (as a set of walls), and move this cutter at a specified velocity and depth of cut across a synthetic rock, while monitoring forces on the cutter and damage in the rock. In a real borehole, drilling mud produces a pressure that acts on the rock surface, and this pressure greatly increases the energy requirements of drilling, effectively strengthening the rock. A pressure-application algorithm was developed for PFC2D that simulates the effect of the mud by continually identifying a connected chain of particles on the rock surface, and applying a pressure to those particles as the cutting process proceeds. This pressure inhibits chip formation and leads to a more plastic-like zone of damage that remains near the cutter. The PFC2D rock-cutting procedures are described in this memo. The procedures are provided in PFC Fishtank 1-97, which is included with PFC2D 4.0-162 and above.[2]

1.0 PFC2D ROCK-CUTTING ENVIRONMENT

A parameterized cutting environment for PFC2D is described in this section. This environment supports creation of a bonded-particle model of the rock (Potyondy and Cundall, 2004), specification of a cutter (represented as PFC walls), specification of the pressure to be applied to the rock surface and movement of the cutter at a fixed depth of cut. All of the rock is represented by PFC2D particles. The particle-size refinement procedure in the PFC Fishtank can be used to construct graded particle assemblies with smaller particles in the cutting region and larger particles in the far-field region. The models described here did not use the particle-size refinement procedure.

The PFC2D cutting environment is shown in Figure 1, and the parameters are listed in Table 1. The specimen is rectangular (H,W) and confined by three frictionless walls on the bottom, left and right sides. The cutter is represented by a single wall of two segments (both of length l) that are perpendicular to one another with a back-rake angle of θ. The confining pressure is P. The cutter is moved horizontally across the rock at a velocity V and at a depth of cut D.

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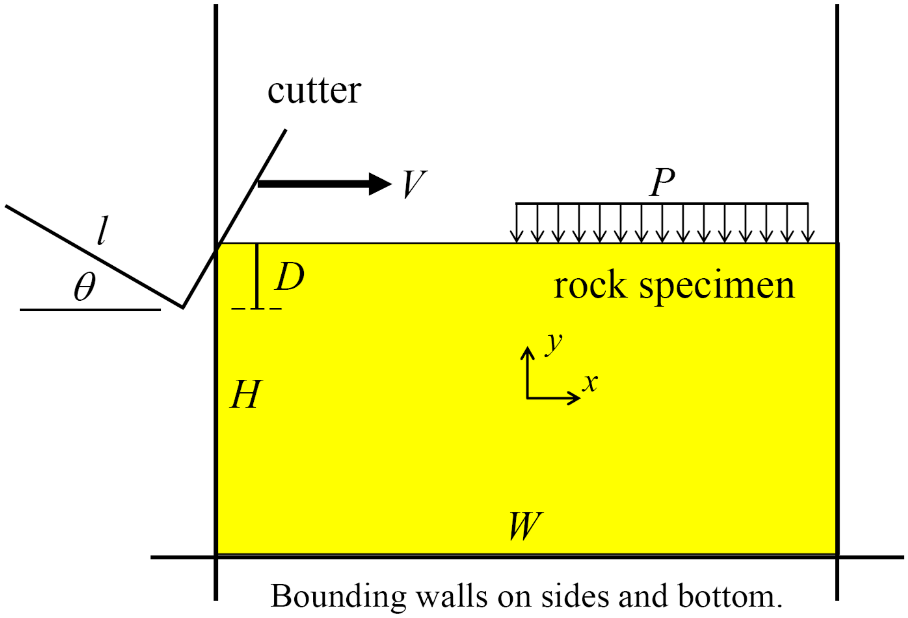
[1] The term PFC refers to both PFC2D and PFC3D (Itasca, 2008a and 2008b).

[2] FISH is a programming language embedded within PFC2D. The PFC Fishtank is a consistent set of FISH functions that extend the range of modeling that can be done with PFC2D. The latest PFC2D 4.0 executable can be obtained from http://www/itascacg.com/software/downloads.php. The PFC2D 4.0 manual (Itasca, 2008) describes PFC2D and the PFC Fishtank.



Bounding walls on sides and bottom.
Pressure is applied to top rock surface.

Figure 1 **PFC2D** ***cutting environment***

Table 1 ***Parameters of the*** **PFC2D** ***cutting environment***

Symbol	**FISH Symbol**	**FISH Type**	**Default**	**Name**
H	`mv_H`	FLT	NA	specimen height
W	`mv_W`	FLT	NA	specimen width
l	`ct_length`	FLT	NA	cutter length
θ	`ct_rake`	FLT	NA	cutter back-rake angle $\left(0 \le \theta < 90^{\circ}\right)$
V	`ct_speed`	FLT	NA	cutter velocity
P	`ct_press`	FLT	NA	confining pressure
D	`ct_depth`	FLT	NA	depth of cut ($D \ge 0$)
G_f	`cs_usegap`	BOOL	0	use-gap flag; if set, then specify $\{G_a, G\}$
G_a	`cs_gapabs`	BOOL	0	use absolute magnitude flag
G	`cs_gap`	FLT	0.0	gap value

We desire a robust and automatic procedure for applying a pressure boundary condition to the rock surface during the cutting process. An ideal procedure would mimic the real process by which drilling mud loads a rock surface during cutting. We envision the process to occur as discussed below.

Drilling mud is a viscous liquid that cannot sustain shear stress; thus, the load it provides to the rock surface can be characterized by a pressure. How does this pressure load the rock? The mud coalesces into a membrane structure that lies on top of the rock surface and bridges across pores in the rock (and across crushed rock particles that form in front of a cutter). The membrane structure defines a surface that transmits normal load to the rock material[3]. This surface evolves during the cutting process. Envision a magic membrane initially lying on the rock surface with pressurized fluid on the non-rock side. The membrane transmits the fluid pressure to the rock, and stays in contact with the rock material (conforming to and thereby defining the surface) as it is broken and deformed by the cutter. The cutter is assumed to interact with the rock, but not with the membrane. The membrane can be thought of as a magic blanket that remains in intimate contact with the evolving rock surface, serving to both define and confine the rock surface. The rock surface is loaded by both the membrane and the cutter.

The PFC2D pressure-application procedure is implemented in the files `fist\2d\ch.fis` and `fist\2d\ct.fis`. The procedure identifies connected chains of particles spanning from the cutter face to the right-hand wall, and from the cutter face to the left-hand wall. The right-spanning chain starts with the highest particle in contact with the cutter, and tests the remaining contacts of this particle (ordered in a clockwise fashion) for chain inclusion. The criterion defining the eligibility of a contact for chain inclusion is specified by parameters $\left\{G_f, G_a, G\right\}$ in the FISH function `cs_contact`; the first eligible contact is used to identify the next particle in the chain. Each chain defines a surface used to compute the force and direction of the applied external force assigned to each chain particle, based on the confining pressure. The chains formed during the application of a 10-MPa confining pressure are shown in Figure 2. These results used a gap-based eligibility criterion such that a contact is used in the chain if the gap between the two chain particles is less than the radius of the smaller particle.

The PFC2D pressure-application procedure mimics the process envisioned above by identifying connected chains of particles that are in contact with, and loaded by, a membrane structure that lies along their centers. The spanning chains define both the rock surface and the membrane structure. The spanning chains can be constructed unambiguously for two-dimensional particle assemblies lying in a plane, because given a particle in the chain, all contacts of that particle can be ordered and the next contact in a specified direction defines the next particle in the chain. As all information is topological, there is no need to perform geometric queries; thus, the topological data structure provided by PFC2D (which provides ball and wall adjacencies via ball-ball and ball-wall contacts) allows one to implement this algorithm in a robust fashion (i.e., the algorithm will never fail, no matter how complex the surface shape).

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[3] The membrane-rock interface is assumed to be frictionless; thus, only normal load is transferred across the interface.

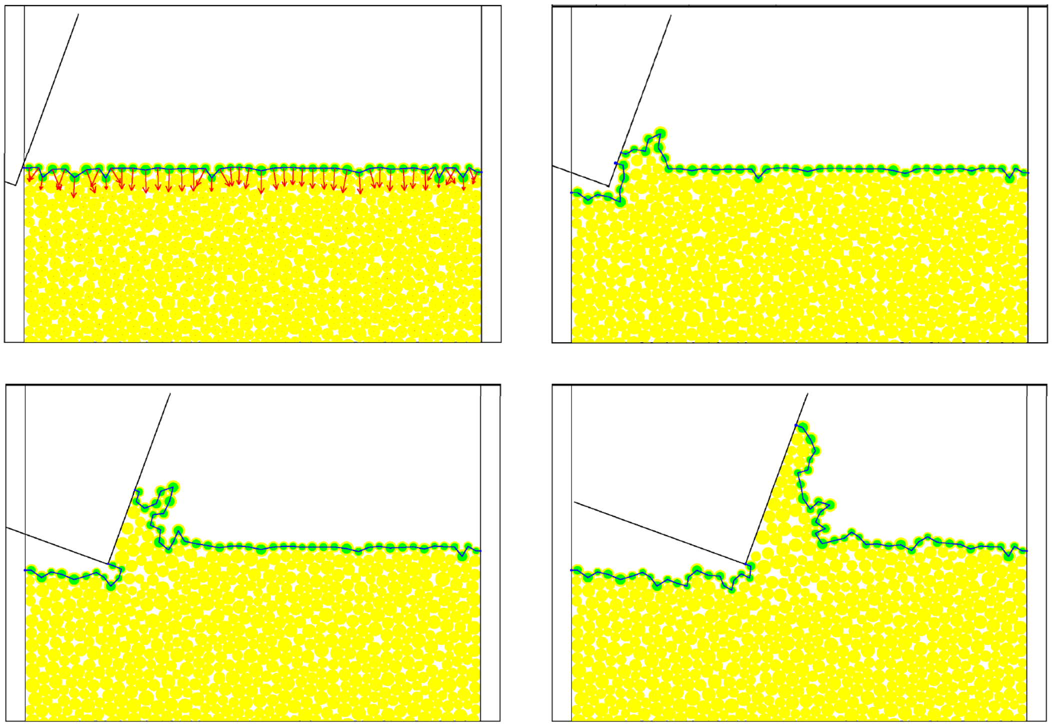

Figure 2 Particles and spanning chains with 10-MPa confining pressure for cutter displacements of 0, 10, 20 and 40 mm (applied external forces shown in upper-left image)

For three-dimensional particle assemblies lying in three-dimensional space, the concept of a spanning chain becomes a spanning surface. Such a surface cannot be constructed by relying on topological information alone, because the ordering of contacts about a surface particle is ambiguous. The adjacent particles on the surface cannot be found by relying solely on contact ordering; instead, they require information about the outside of the body to ensure that each adjacent particle lies on the body surface. However, the body surface is not known in advance, as it is defined by the spanning surface. It may be possible to develop a relatively robust 3D spanning-surface algorithm, but this has not been done. Instead, an alternative procedure was developed that is guaranteed to be robust and does not rely upon topological adjacency information. (For information about this 3D pressure-application procedure, please contact Itasca.)

2.0 EXAMPLE APPLICATION

A model of Carthage limestone is constructed to serve as an example of the material-creation and calibration processes, and to be used in subsequent rock-cutting tests. The corresponding driver files are given in the template directory `fist\templates\RockCut-2d`. The text file `RockCut-2d.txt`, located at the root of this directory, provides details about its layout. The entire suite of simulations described below can be executed by calling the file `RockCut-2d\dodirs.dvr` from the PFC2D command line.

A bonded-particle model consisting of a dense packing of non-uniform-sized circular particles joined at their contact points by parallel bonds is created using the procedures described in Potyondy and Cundall (2004), and implemented in the PFC Fishtank (Itasca, 2008a and 2008b, PFC Fishtank chapter). The microproperties (see Table 2 — parameters are defined in the PFC Fishtank chapter and specified in the file `RockCut-2d\D-param.dat`) are chosen to match Young's modulus, Poisson's ratio and peak strength of Carthage limestone obtained from an unconfined compression (UCS) test (see Table 3).

The driver files used to perform the calibration test are located in the directory `RockCut-2d\MakeTest\100x50mm\Dough20`. In this directory, the driver file `D-spc.dvr` generates a 100-mm x 50-mm specimen with 20-particle resolution[4] and the microproperties listed in Table 2. The driver file `D_ucs-tw.dvr` is used to perform the UCS test.

The driver files used to perform the cutting simulation are located in the directory `RockCut-2d\MakeCut\50x100mm\Dough20`. In this directory, the driver file `D-spc.dvr` generates a 50-mm x100-mm specimen with 20-particle resolution and the microproperties listed in Table 2. The driver file `D_ct-ct.dvr` is used to perform the cutting simulation with the parameters listed in Table 4. The chains formed at different times of the cutting simulation are shown in Figure 2. Note that these results used a gap-based eligibility criterion such that a contact is used in the chain if the gap between the two chain particles is less than the radius of the smaller particle. Additionally, the following driver file repeats the cutting simulation with no applied pressure: `RockCut-2d\MakeCut\50x100mm\Dough20\NoPressure\D_ct-ct.dvr.`

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[4] Resolution is defined as the number of particles across the relevant model dimension. For UCS tests, this is the specimen width. For cutting tests, this is the specimen height (distance from cut surface to bottom surface). Note that because the PFC macroproperties depend on particle size, both the calibration and subsequent cutting simulations should be performed on a synthetic material with the same resolution.

Table 2 **PFC2D** ***model microproperties for Carthage limestone***

Property	Value
$\sigma_0^t\ [\mathrm{MPa}]$	-0.1
N_f	3
n_f/N_b	0
$R_{\min}\ [\mathrm{mm}]$	varies
$R_{\max}/R_{\min}$	1.66
$\rho_{bulk}\ [\mathrm{kg/m^3}]$	2620.
$E_c\ [\mathrm{GPa}]$	83.0
k_n/k_s	3.8
μ	0.5
$\bar{\lambda}$	1.0
$\bar{E}_c\ [\mathrm{GPa}]$	83.0
$\bar{k}^n/\bar{k}^s$	3.8
$\bar{\sigma}_c$ (mean, s.d.) $[\mathrm{MPa}]$	$(91.0, 20.0)$
$\bar{\tau}_c$ (mean, s.d.) $[\mathrm{MPa}]$	$(91.0, 20.0)$

Table 3 Macroproperties obtained from UCS test

Property	Carthage limestone	PFC2D model (specimen based, resolution = 20)
$E\ [\mathrm{GPa}]$	76	75
ν	0.29	0.26
$q_u\ [\mathrm{MPa}]$	100	104

Table 4 Parameters used for the cutting simulation

Symbol	Value
l [mm]	40
θ [°]	20
V [m/s]	0.5
P [MPa]	10
D [mm]	5
G_f	1
G_a	0
G	1.0

3.0 REFERENCES

Itasca Consulting Group, Inc. (2007) Software: PFC2D: ***Examples, Rock Cutting***, http://www.itascacg.com/pfc2d/ex_rockcut.php.

Itasca Consulting Group, Inc. (2008a) **PFC2D *(Particle Flow Code in 2 Dimensions)***, Version 4.0. Minneapolis, MN: ICG.

Itasca Consulting Group, Inc. (2008b) **PFC3D *(Particle Flow Code in 3 Dimensions)***, Version 4.0. Minneapolis, MN: ICG.

Potyondy, D.O., and P.A. Cundall. (2004) "A Bonded-Particle Model for Rock," *Int. J. Rock Mech. & Min. Sci.*, ***41***(8), 1329–1364.