5 Cement Grouting Simulation

5.1 Problem Statement

The Bingham fluid model is widely accepted as an appropriate model for cement-based grouts (see, for example, Littlejohn 1982, Hassler et al. 1987 and Lombardi 1985). This simulation demonstrates use of the Bingham fluid model in *UDEC*.

The problem geometry represents a horizontal section in a regularly jointed rock mass in which a cylindrical hole (1.2 m diameter) has been made. The rock mass is assumed to be subject to an initial biaxial in-situ stress (σ_{xx} = 0.2 MPa and σ_{yy} = 0.1 MPa). Grout injection is simulated by maintaining specified pressures within the hole. The pressure is increased in 2000 Pa increments, and flow conditions are examined at each stage. The hypothetical properties used for the rock, discontinuities and grout are shown below.

Intact Rock		
	bulk modulus	10 GPa
	shear modulus	3 GPa
	density	3000 kg/m^3
Joints		
	normal stiffness	10 GPa/m
	shear stiffness	10 GPa/m
	friction angle	45°
	joint permeability constant	1×10^8 Pa^{-1} sec^{-1}
	aperture at zero normal stress	0.1 mm
	residual aperture at high stress	0.05 mm
Grout		
	cohesion	0.1 Pa
	density	1000 kg/m^3

5.2 *UDEC* Analysis

The *UDEC* model and initial stress state are illustrated in Figure 5.1. The threshold pressure gradient for flow is defined for the Bingham fluid model by specifying a yield strength limit with the **block fluid property cohesion** command.

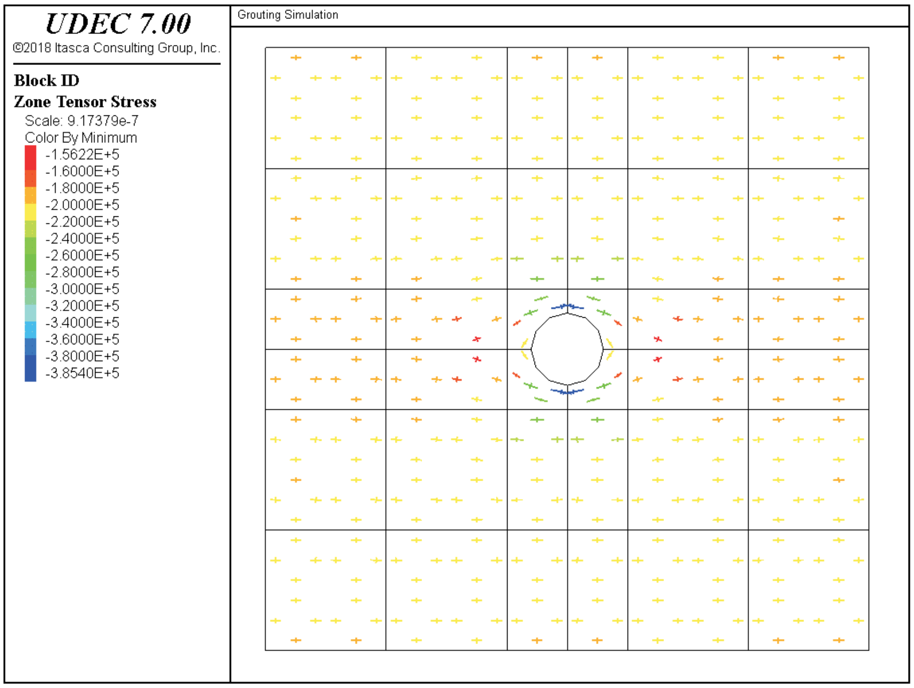

Figure 5.1 UDEC model and initial stress state for grouting simulation

No steady state flow occurs until the pressure in the hole exceeds 8000 Pa. This is indicated in the plot of flow-rate histories at different contact locations versus hole pressure in Figure 5.2.

The flow plots for hole pressures of 10,000 Pa, 12,000 Pa and 16,000 Pa are shown in Figures 5.3, 5.4 and 5.5. The corresponding changes in grout pressure in joints are shown in Figures 5.6 through 5.8.

5.3 References

Hassler, L., H. Stille and U. Hakansson. "Simulation of Grouting in Jointed Rock," in ***Proceedings of the 6th International Congress on Rock Mechanics (Montréal, Canada, 1987)***, Vol. 2, pp. 943-946. G. Herget and S. Vongpaisal, eds. Rotterdam: A. A. Balkema (1987).

Littlejohn, G. S. "Design of Cement Based Grouts," in ***Proceedings of the Conference on Grouting in Geotechnical Engineering (New Orleans, Louisiana, February 1982)***, pp. 35-49. Wallace Hayward Baker, ed. New York: ASCE (1982).

Lombardi, G. "The Role of Cohesion in Cement Grouting of Rock," in ***Proceedings of the 15th International Congress on Large Dams (Lausanne, Switzerland, 1985)***, pp. 235-261 (1985).

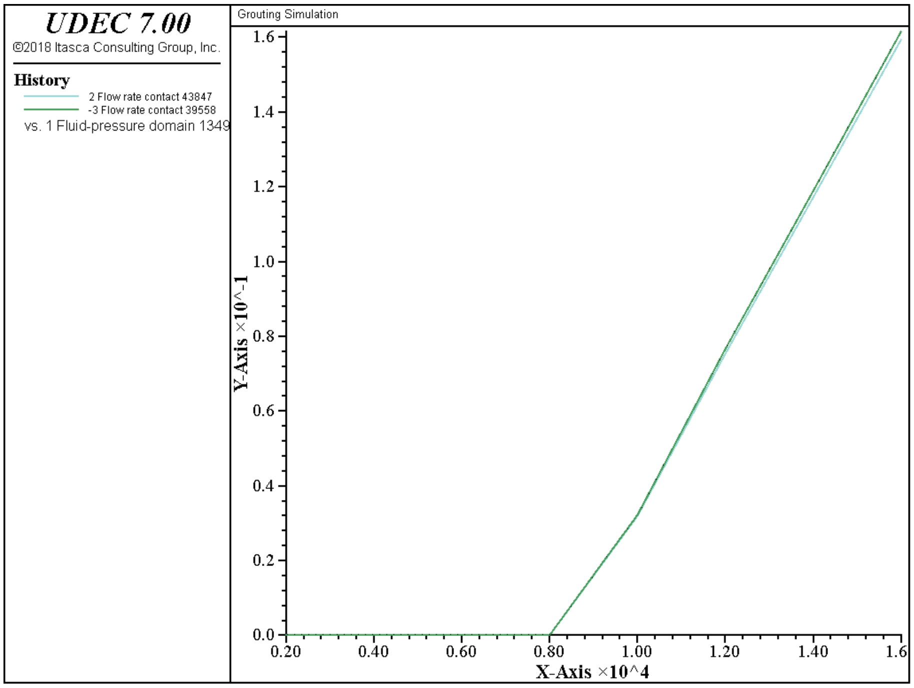

Figure 5.2 Flow rates versus hole pressure

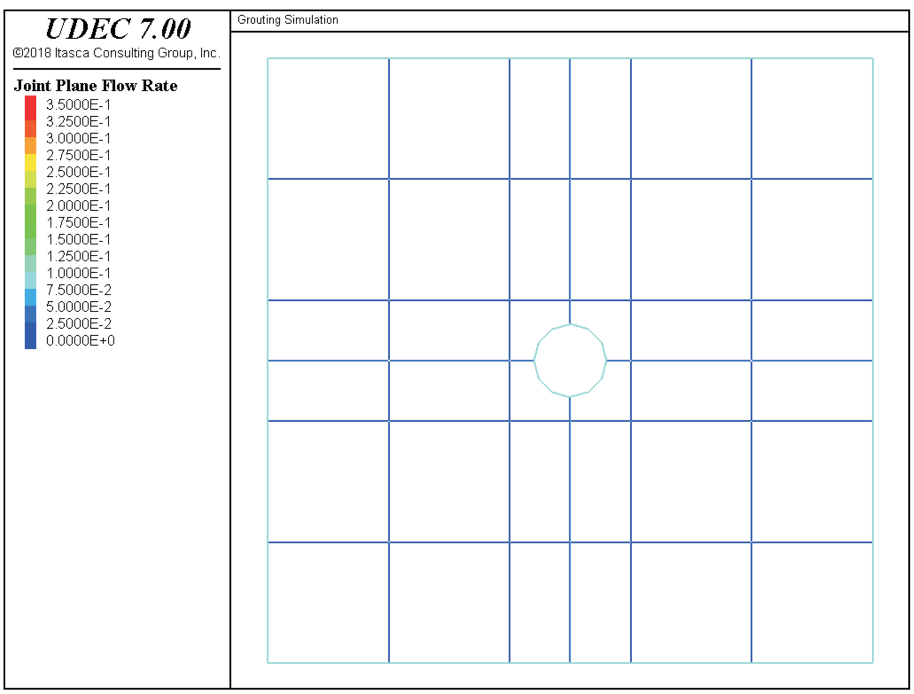

Figure 5.3 Flow rates for grouting simulation at 10,000 Pa

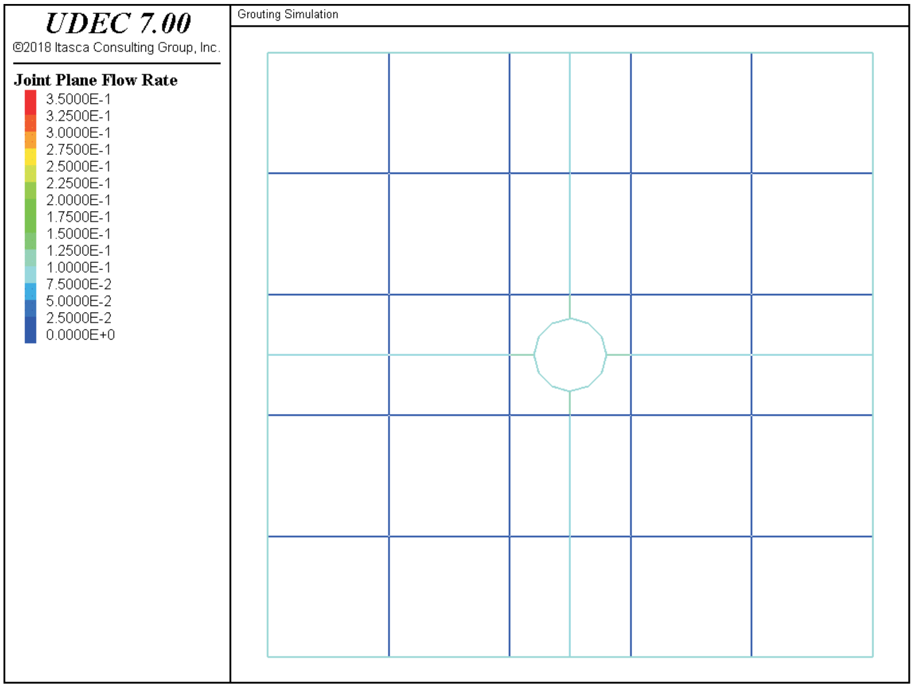

Figure 5.4 Flow rates for grouting simulation at 12,000 Pa

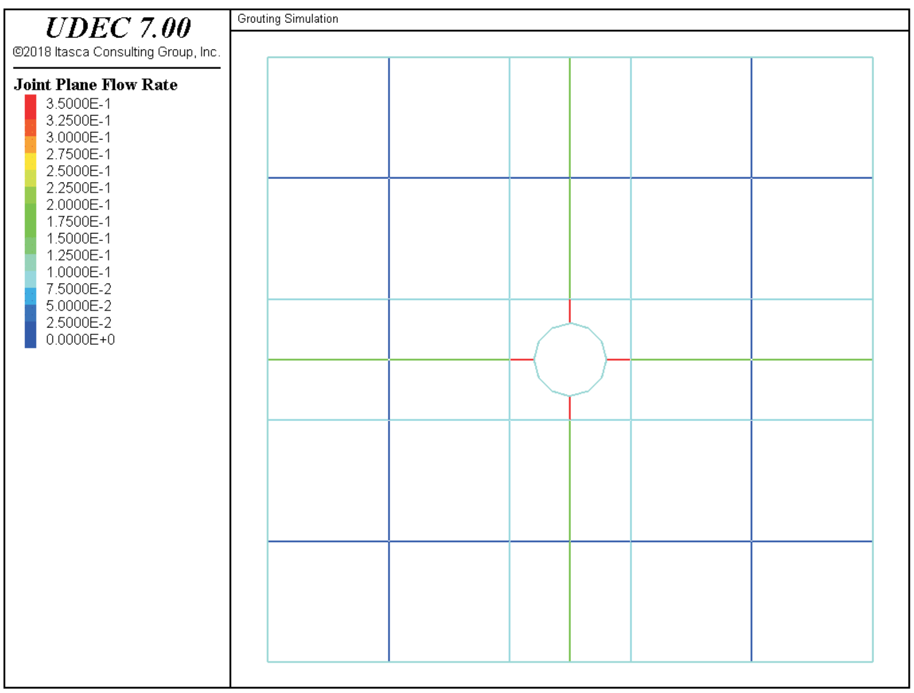

Figure 5.5 Flow rates for grouting simulation at 16,000 Pa

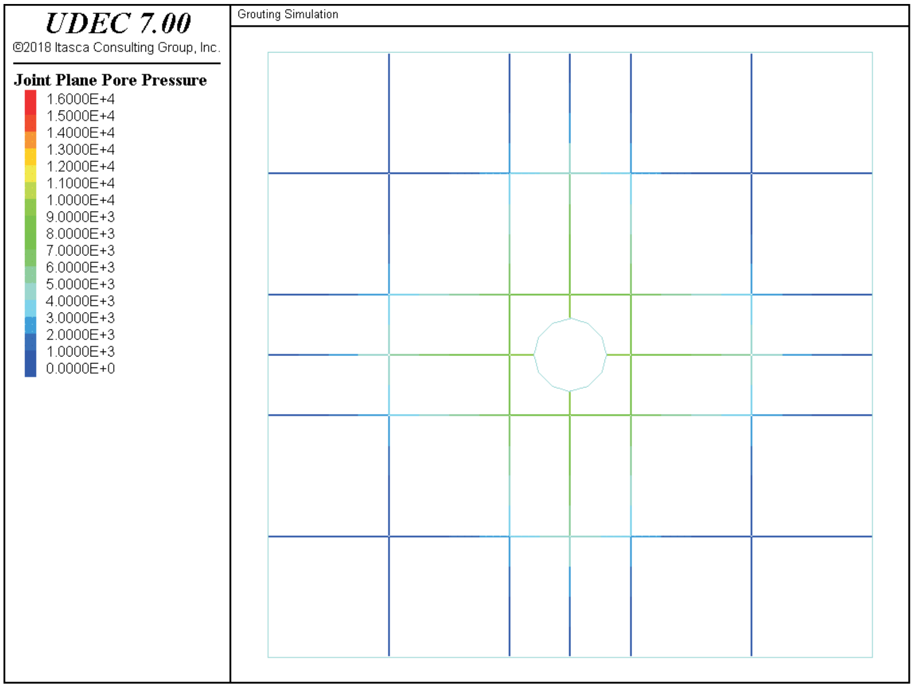

Figure 5.6 Grout pressures in joints for grouting simulation at 10,000 Pa

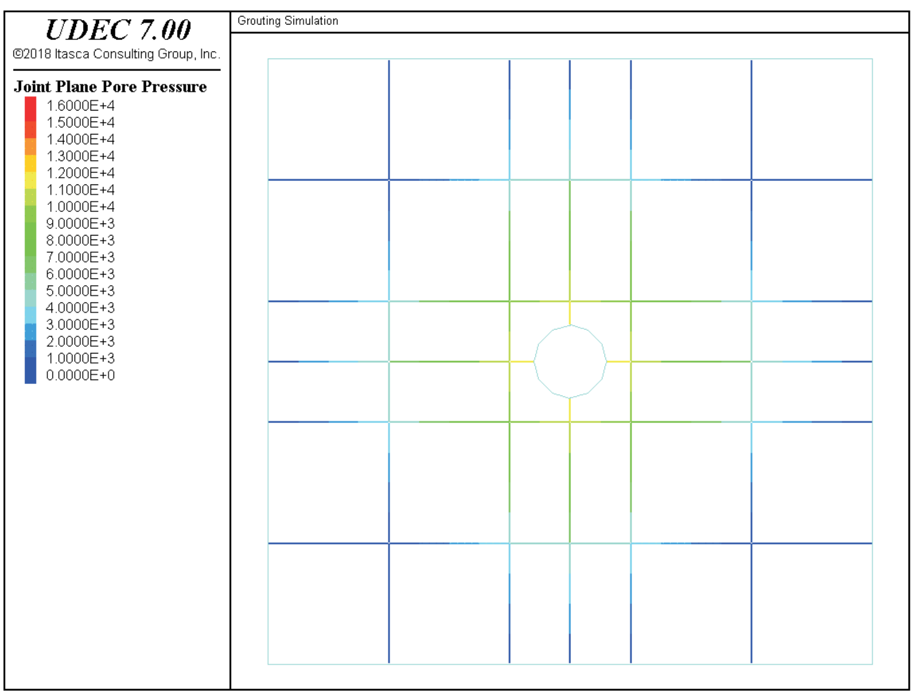

Figure 5.7 Grout pressures in joints for grouting simulation at 12,000 Pa

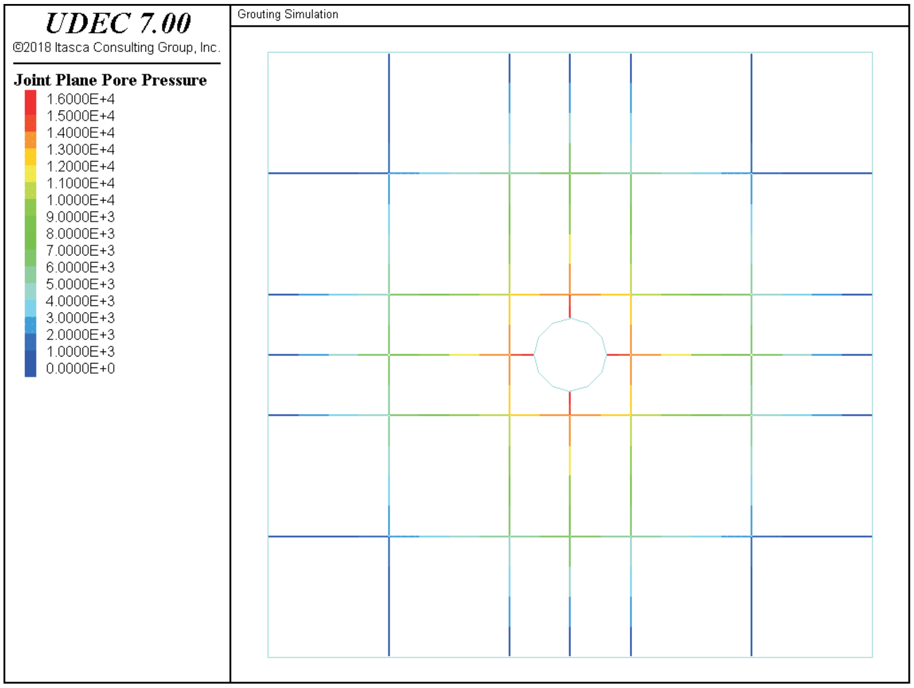

Figure 5.8 Grout pressures in joints for grouting simulation at 16,000 Pa

5.4 Listing of Data File

Example 5.1 GROUT.DAT

```
model new
mode title 'Grouting Simulation'

;File:GROUT.dat
;
; grouting simulation with
; bingham fluid flow logic
;
block config fluid
block tolerance corner-round-length 0.01
block create polygon 0 0 0 10 10 10 10 0
block cut crack 0 5 10 5
block cut crack 5 0 5 10
block cut arc 5 5 5.6 5 360 12
block cut joint-set angle 0 trace 10 spacing 2 origin 0 0
block cut joint-set angle 90 trace 10 spacing 2 origin 0 0
block zone gen edge 1.25
;
;  material properties
;  intact rock
block zone group 'User:mat1'
block zone cmodel assign elastic density 3E3 bulk 1E10 shear 3E9 ...
  range group 'User:mat1'
;  discontinuities
block contact group 'User:jmat1'
block contact cmodel assign area stiffness-shear 1E10 ...
  stiffness-normal 1E10 friction 45 permeability-factor 1E8 ...
  aperture-residual 0.00005 aperture-zero-load 0.0001 ...
  range group 'User:jmat1'
; new contact default
block contact cmodel default area stiffness-shear 1E10 ...
  stiffness-normal 1E10 friction 45 permeability-factor 1E8 ...
  aperture-residual 0.00005 aperture-zero-load 0.0001
; insitu stress and boundary conditons
block insitu  stress -200000.0 0.0 -100000.0 nodis
block edge apply stress -200000.0 0.0 -100000.0
;
; conditions during solution
; create hole
block delete range pos-x 4.5 5.5 pos-y 4.5 5.5
block mechanical history unbalanced-maximum
; cycle to equilibrium
```

```
block solve ratio 1.0E-5
model save 'gr0.sav'
;
; use steady state fluid logic
block fluid steady-state on
hist reset
hist interval =1000
bl domain history pore-pressure 5.0 5.0
block contact history flow-rate 9.0 5.0
block contact history flow-rate 5.0 9.0
;
; grout properties (density - cohesion)
block fluid  property density 1000.0
block fluid  property cohesion 0.1

bl domain fix range pos-x 4.9 5.1 pos-y 4.9 5.1
bl domain initialize pore-pressure 2e3 range pos-x 4.9 5.1 pos-y 4.9 5.1

block cycle 1000
model save 'gro1.sav'
;
;
bl domain fix range pos-x 4.9 5.1 pos-y 4.9 5.1
bl domain initialize pore-pressure 4e3 range pos-x 4.9 5.1 pos-y 4.9 5.1
block cycle 1000
model save 'gro2.sav'
;
;
bl domain fix range pos-x 4.9 5.1 pos-y 4.9 5.1
bl domain initialize pore-pressure 6e3 range pos-x 4.9 5.1 pos-y 4.9 5.1
block cycle 1000
model save 'gro3.sav'
;
;
bl domain fix range pos-x 4.9 5.1 pos-y 4.9 5.1
bl domain initialize pore-pressure 8e3 range pos-x 4.9 5.1 pos-y 4.9 5.1
block cycle 1000
model save 'gro4.sav'
;
;
bl domain fix range pos-x 4.9 5.1 pos-y 4.9 5.1
bl domain initialize pore-pressure 1e4 range pos-x 4.9 5.1 pos-y 4.9 5.1
block cycle 1000
model save 'gro5.sav'
;
;
```

```
bl domain fix range pos-x 4.9 5.1 pos-y 4.9 5.1
bl domain initialize pore-pressure 1.2e4 range pos-x 4.9 5.1 pos-y 4.9 5.1
block cycle 1000
model save 'gro6.sav'
;
;
bl domain fix range pos-x 4.9 5.1 pos-y 4.9 5.1
bl domain initialize pore-pressure 1.4e4 range pos-x 4.9 5.1 pos-y 4.9 5.1
block cycle 1000
model save 'gro7.sav'
;
;
bl domain fix range pos-x 4.9 5.1 pos-y 4.9 5.1
bl domain initialize pore-pressure 1.6e4 range pos-x 4.9 5.1 pos-y 4.9 5.1
block cycle 1000
model save 'gro8.sav'
```