7 Inflow into a Tunnel

7.1 Problem Statement

Solid deformation and groundwater flow are interdependent in many situations in soil and rock mechanics engineering practice: (1) groundwater exerts pressure on the solid portion of the rock mass, while (2) deformation of the rock mass controls conditions of groundwater flow (i.e., changes hydraulic apertures of joints through which groundwater moves). Ignoring coupling between two processes (solid deformation and groundwater flow) may sometimes lead to incorrect predictions of the response of the rock mass to mechanical perturbations (e.g., tunnel excavation, pumping from a well and construction of a dam).

A simple problem of excavation of a tunnel below the water table in a jointed rock mass is analyzed in this example (see Figure 7.1). Material properties (e.g., initial joint hydraulic aperture, joint stiffness and stiffness of the whole assemblage of blocks) and perturbation to the system (e.g., change of total stress and pore pressure due to excavation of the tunnel) are chosen such that full, two-way coupling must be taken into consideration.

The drainage of groundwater into the excavated tunnel causes significant drawdown of the groundwater table and formation of a phreatic surface at a distance above the tunnel comparable to the radius of the tunnel. Therefore, the logic for unsaturated flow (see Section 2 in **Special Features**) is used in this example to provide accurate modeling of unconfined flow.

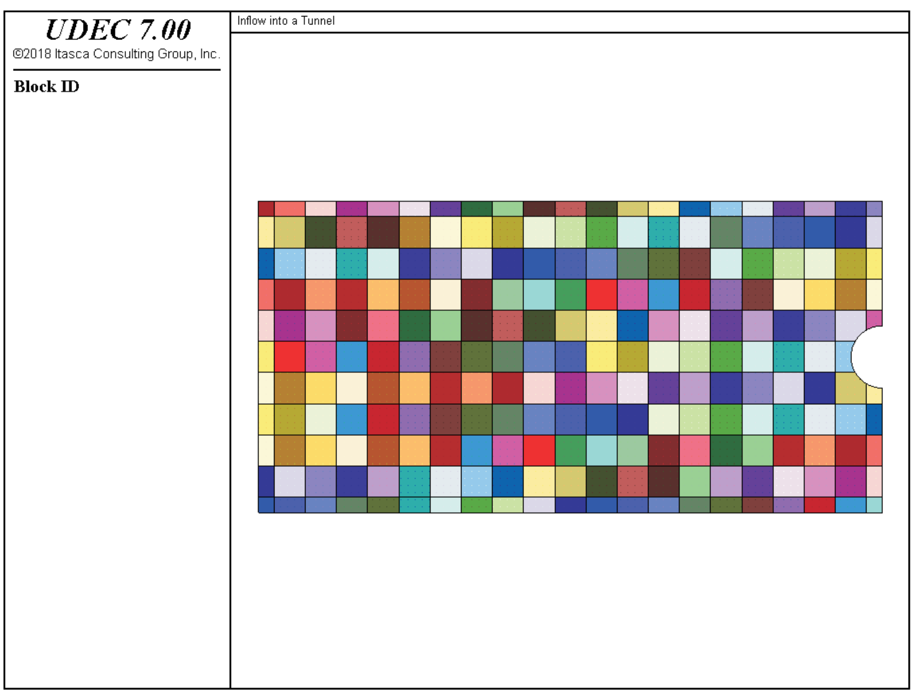

Figure 7.1 UDEC model for inflow into a tunnel

7.2 *UDEC* Analysis

The model is two-dimensional. Two continuous, orthogonal (horizontal and vertical) sets of joints form the blocks of the rock mass (as shown in Figure 7.1). Joint spacing is 10 m in both directions. Several material properties are assumed in the example:

shear modulus of rock (G)	= 15 GPa
bulk modulus of rock (K)	= 20 GPa
density of rock (ρ)	= 2700 kg/m^3
joint normal stiffness (k_n)	= 10 GPa/m
joint shear stiffness (k_s)	= 10 GPa/m
zero stress hydraulic aperture (a_o)	= 10^{-3} m
residual hydraulic aperture (a_r)	= 5×10^{-4} m
joint permeability factor ($k_j = \frac{1}{12\mu}$) (μ is the groundwater viscosity)	= 5×10^8 MPa^{-1}s^{-1}
bulk modulus of groundwater (K_w)	= 0.2 GPa
density of groundwater (ρ_w)	= 1000 kg/m^3

Note that the bulk modulus of water is 2.0 GPa. We used a lower value (0.2 GPa) for two reasons: (1) there are gasses dissolved in the groundwater that increase the compressibility of the groundwater; and (2) a lower value of bulk modulus speeds convergence to steady state of the numerical calculation when using the compressible flow option.

The initial total stresses are isotropic, and increase from the top to the bottom of the model as a function of the density of the rock mass and gravity. The initial hydrostatic pore pressures are defined by the groundwater surface, which is also at the top of the model. The far-field boundary conditions for both the solid and the groundwater models are at equilibrium with the initial conditions. The effective stresses in the joints are initialized as the difference between the normal component of the initial, total block-stress vector in the joint plane and the initial pore pressure in the joints. Accordingly, deformation and hydraulic apertures of the joints are calculated as a function of the initial effective stresses and the normal stiffness of the joints. (Initial joint deformation can be inhibited, and in that case the zero stress hydraulic aperture, a_o, becomes the initial stress state hydraulic aperture.) The initial state of stress in the model is shown in Figure 7.2, while the initial pore pressure distribution is shown in Figure 7.3. Some calculational stepping is necessary due to the irregular geometry.

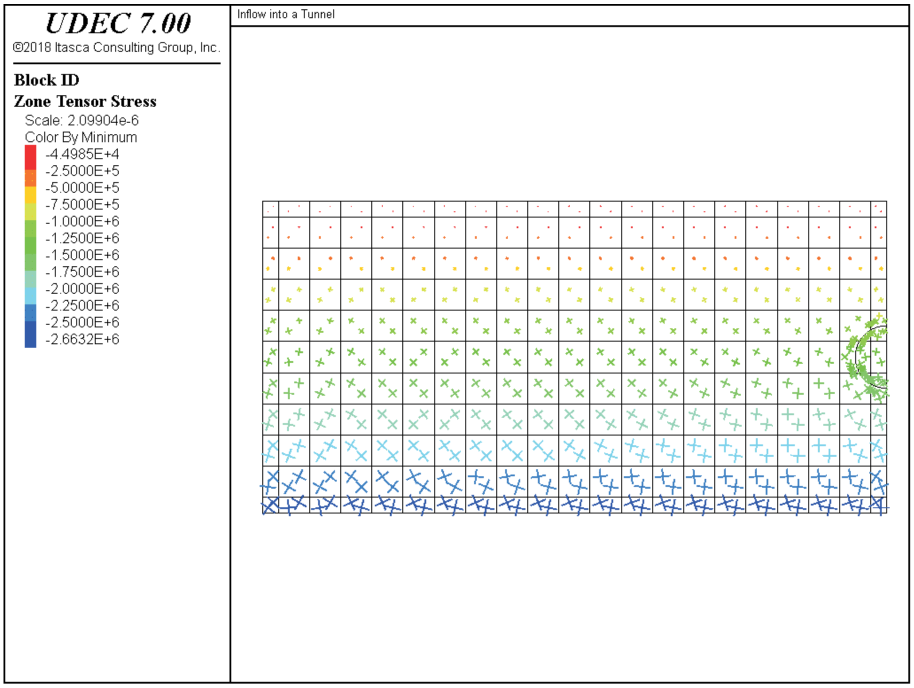

Figure 7.2 Initial total stresses in UDEC model

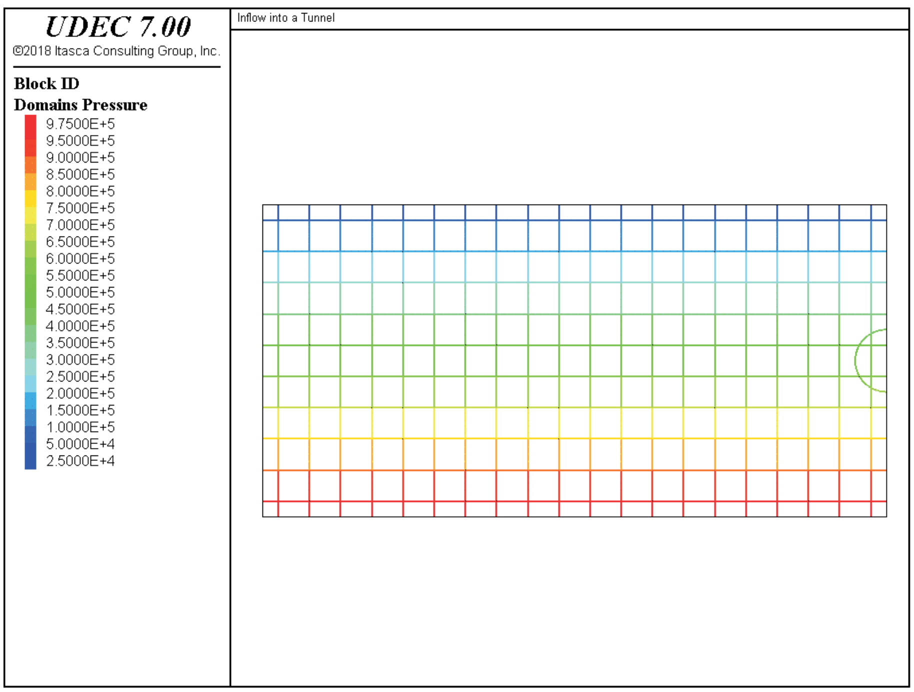

Figure 7.3 Initial pore pressures in UDEC model

After establishing an initial stress state in both the solid and groundwater models, the tunnel is excavated. Excavation of the tunnel introduces a perturbation in both the solid model (the total radial stress at the boundary of the tunnel is reduced to zero) and the groundwater model (the pore pressure at the boundary of the tunnel is reduced to zero). However, the time scales of the mechanical process in the rock mass and the fluid flow process in the joints are of different orders of magnitude. The response of the solid model is at a much shorter time scale; in this example, the response is instantaneous. Therefore, the first stage of the response of the model to the tunnel excavation is undrained deformation: the solid model deforms, while pore pressure in the joints changes as a function of deformation of the solid model and the bulk modulus, K_w, of the groundwater only – there is no flow. Pore pressures and deformation of the model after undrained deformation are shown in Figures 7.4 and 7.5.

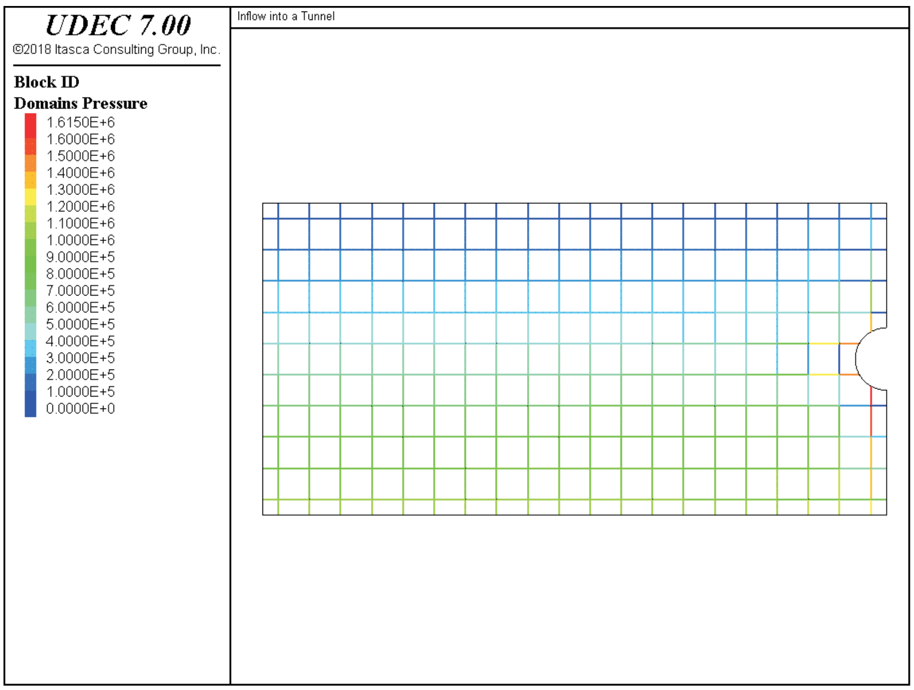

Figure 7.4 Pore pressures after undrained deformation

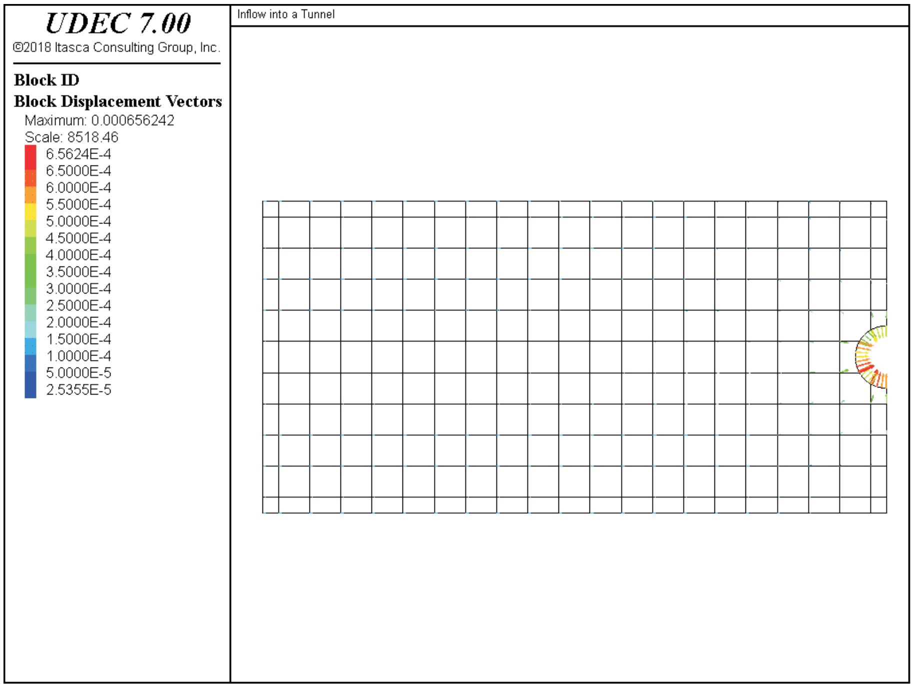

Figure 7.5 Undrained deformation of the model

After reaching mechanical equilibrium in the first, undrained stage of the simulation, the second stage is simulated: deformation due to drainage of the groundwater into the tunnel (i.e., consolidation). This process is time-dependent, controlled by dissipation of the groundwater. This stage is simulated in real (flow) time until steady-state flow is reached and the solid model is at an equilibrium state.

Consolidation (time-dependent deformation due to drainage of the groundwater into the tunnel) is simulated using three different options in *UDEC* for calculation of coupled flow: (1) transient compressible flow (**block fluid compressible**); (2) steady flow (**block fluid steady-state**); and (3) transient incompressible flow (fast-flow) (**block fluid incompressible**). If the steady-state solution is path-independent (e.g., a linear model), these three options should yield the same results in the steady-state condition. The steady-flow option does not consider unsaturated flow: the groundwater table is determined from pore pressures only. However, in this problem, infiltration from the unsaturated zone above the water table must become zero in the limit. Thus, the three models should converge in the limit. It can be verified from Figures 7.7, 7.8 and 7.9 that the results obtained from the compressible and fast-flow options approach those obtained using the steady-flow option. (Locations of the history points are indicated in Figure 7.6.) Note that the calculation times for the steady-flow and the fast-flow options are an order of magnitude faster than for the compressible-flow option. The compressible-flow simulation is only run for a flow time of approximately 20 sec. The results of the fast-flow simulation indicate that almost 200 sec. are required to reach steady state.

It appears that the fast-flow logic is the best method for the solution of this problem, since calculation time is almost the same as for the steady-flow option, while it simulates complete transient response of the model. (The steady-flow calculation is only correct at the steady state.)

Pore pressures at steady-state flow are shown in Figure 7.10. The phreatic surface at steady state is indicated by the limit of the pore-pressure distribution in this plot. Flow rates in joints are shown in Figure 7.11.

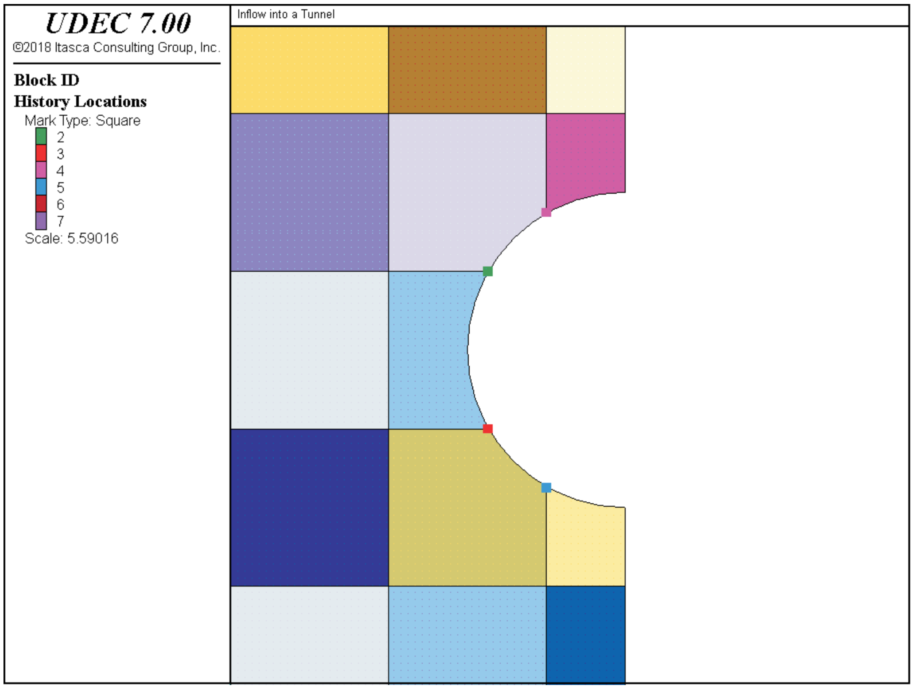

Figure 7.6 Locations of the history points

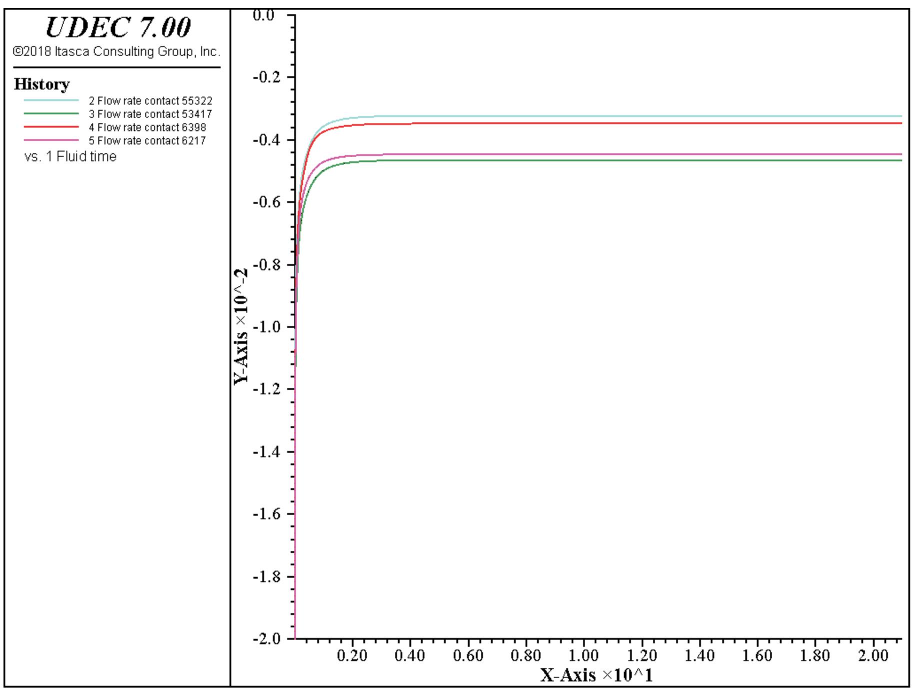

*Figure 7.7 Histories of flow rates during consolidation (***block fluid compressible***)*

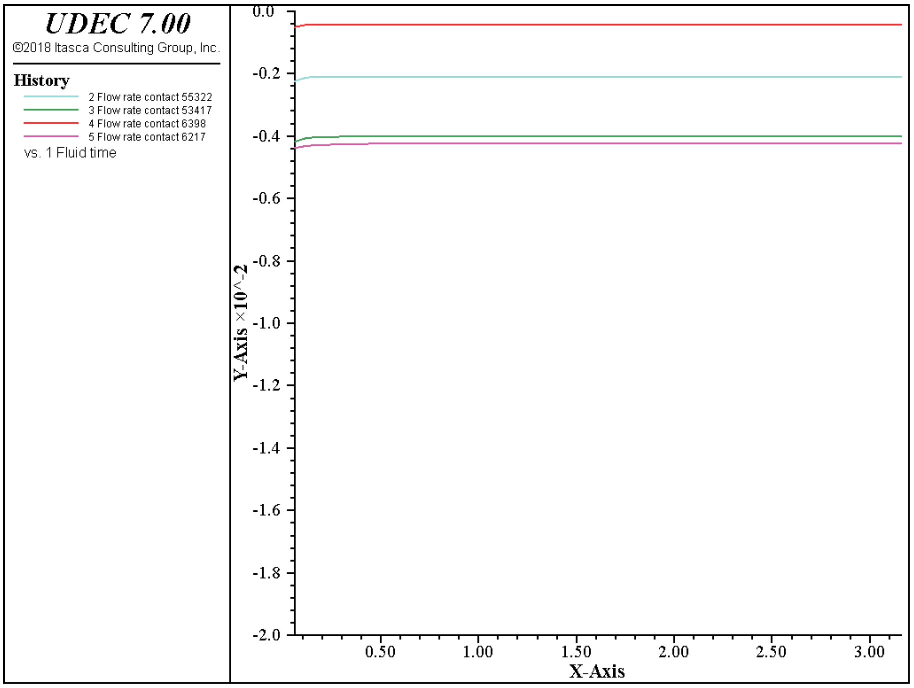

*Figure 7.8 Histories of flow rates during the steady-flow calculation (***block fluid steady-state***)*

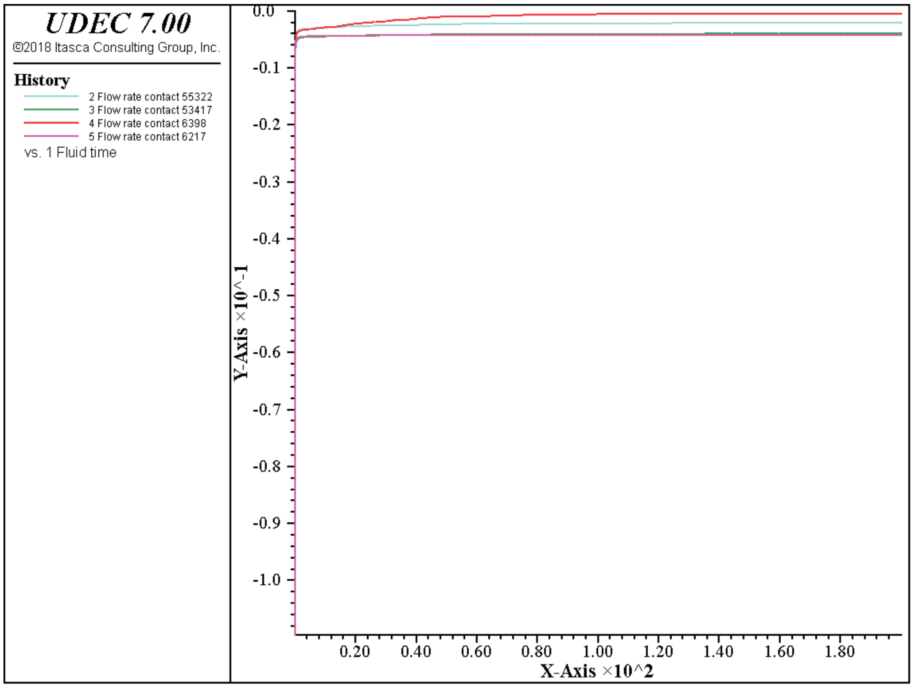

*Figure 7.9 Histories of flow rates during consolidation (***block fluid incompressible***)*

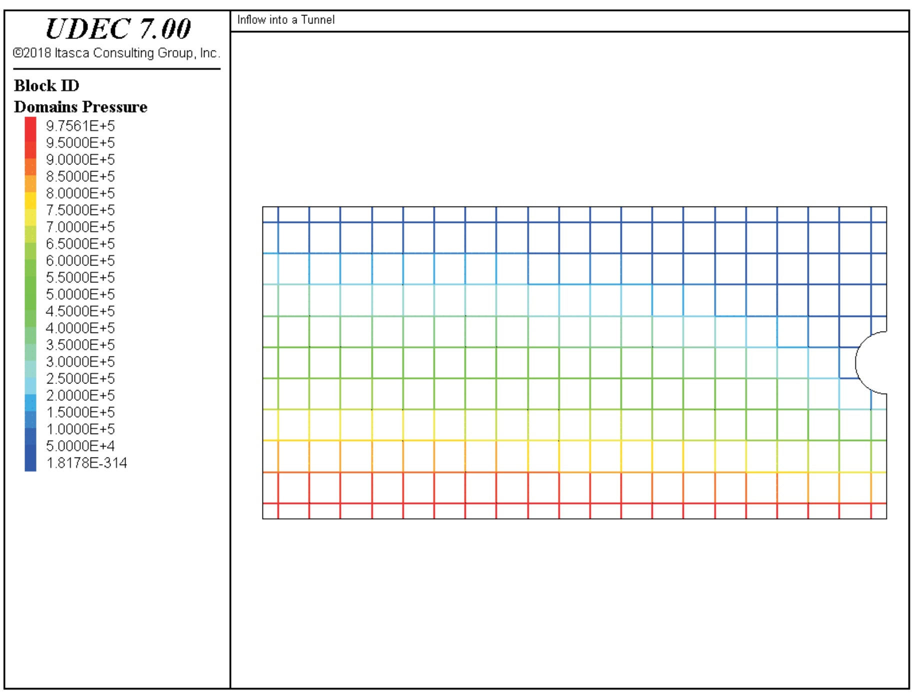

Figure 7.10 Pore pressures at steady-state flow

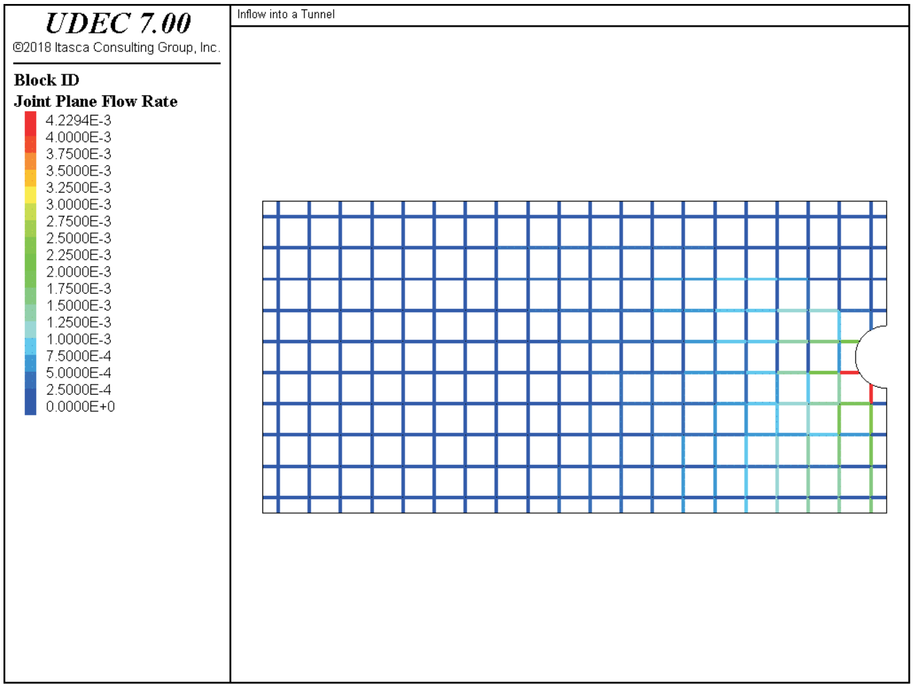

Figure 7.11 Flow rates in the joints at steady-state flow

7.3 Listing of Data File

Example 7.1 INFLOW.DAT

```
model new
;File:inflow.dat
model Title 'Inflow into a Tunnel'
block config fluid
block fluid steady-state off
block tolerance corner-round-length 0.1
block create polygon 0 100 0 200 200 200 200 100
;
; add tunnel
block cut arc (200,150) (210,150) 360 40
;
; two orthogonal joint sets
block cut joint-set angle 90 trace 200 spacing 10 origin 5,0
block cut joint-set angle 0 trace 200 spacing 10 origin 0,5
block zone gen edge 20.0
;
; material properties
block zone group 'tunnel:rock'
```

```
block zone cmodel assign elastic density 2.7E3 bulk 2E10 shear 1.5E10 ...
  range group 'tunnel:rock'
block contact group 'tunnel:joint'
block contact cmodel assign area stiffness-shear 1E10 ...
  stiffness-normal 1E10 friction 30 permeability-factor 300 ...
  aperture-residual 0.0005 aperture-zero-load 0.001 ...
  range group 'tunnel:joint'
block contact cmodel default material 1
block contact property material 1 stiffness-shear 1E10 ...
  stiffness-normal 1E10 friction 30 permeability-factor 300 ...
  aperture-residual 0.0005 aperture-zero-load 0.001
block fluid  property density 1000.0
;
; boundary conditions
block edge apply stress -5400000.0 0.0 0.0 ...
  gradient-x 0.0 0.0 0.0 gradient-y 27000.0 0.0 0.0 ...
  range pos-x -0.1 0.1 pos-y 99.9 200.1
block gridpoint apply velocity-y 0 range pos-x -0.1 200.1 pos-y 99.9 100.1
block gridpoint apply velocity-x 0 range pos-x 199.9 200.1 pos-y 99.9 200.1
block edge apply impermeable range pos-x 199.9 200.1 pos-y 99.9 200.1
block edge apply impermeable range pos-x -0.1 200.1 pos-y 199.9 200.1
block edge apply pore-pressure 2000000.0 pressure-gradient-y -10000.0 ...
  range pos-x -0.1 0.1 pos-y 99.9 200.1
block edge apply pore-pressure 1000000.0 ...
  range pos-x -0.1 200.1 pos-y 99.9 100.1
;
; initial conditions
model gravity 0 -10
block insitu  stress -5400000.0 0.0 -5400000.0 ...
  gradient-x 0.0 0.0 0.0 gradient-y 27000.0 0.0 27000.0 water-table 200
;
; mechanical / steady state flow
; -----------------------------
block gridpoint history displacement-y 100.0 200.0
block mechanical history unbalanced-maximum
block solve ratio 1.0E-5
model save 'inflow1.sav'
model restore 'inflow1.sav'
;
; compressible fluid / no flow
; ---------------------------
block delete range annulus center 200 150 radius 0 10
block fluid compressible
block fluid  property bulk 2.0E8
block contact reset displacement
block gridpoint init displacement-x 0
```

```
block gridpoint init displacement-y 0
block fluid flow off
block solve ratio 1.0E-5
model save 'inflow2.sav'
model restore 'inflow2.sav'
;
; compressible transient flow
; --------------------------
block contact reset displacement
block gridpoint init displacement-x 0
block gridpoint init displacement-y 0
hist reset
block mechanical time 0
block fluid time 0
history interval 100
block fluid history time-total
block contact history flow-rate 191.0 155.0
block contact history flow-rate 191.0 145.0
block contact history flow-rate 196.0 158.0
block contact history flow-rate 196.0 142.0
block domain history pore-pressure 150.0 150.0
block gridpoint history displacement-y 200.0 200.0
block fluid flow on
block fluid substep-mechanical 10
model save 'tempflow.sav'
block cycle time 31.0
model save 'inflow3.sav'
block fluid substep-mechanical 1
block cycle time 110.0
model save 'inflow3.sav'
;
; steady state flow
; -----------------
model restore 'inflow2.sav'
block contact reset displacement
block gridpoint init displacement-x 0
block gridpoint init displacement-y 0
hist reset
block mechanical time 0
block fluid time 0
history interval 100
block fluid history time-total
block contact history flow-rate 191.0 155.0
block contact history flow-rate 191.0 145.0
block contact history flow-rate 196.0 158.0
block contact history flow-rate 196.0 142.0
```

```
block domain history pore-pressure 150.0 150.0
block gridpoint history displacement-y 200.0 200.0
block fluid steady-state
block fluid flow on
block cycle 5000
model save 'inflow4.sav'
;
; incompressible transient flow
; -----------------------------
model restore 'inflow2.sav'
block contact reset displacement
block gridpoint init displacement-x 0
block gridpoint init displacement-y 0
hist reset
block mechanical time 0
block fluid time 0
history interval 1
block fluid history time-total
block contact history flow-rate 191.0 155.0
block contact history flow-rate 191.0 145.0
block contact history flow-rate 196.0 158.0
block contact history flow-rate 196.0 142.0
block domain history pore-pressure 150.0 150.0
block gridpoint history displacement-y 200.0 200.0
block fluid incompressible
block fluid flow on
block fluid incompressible substep-mechanical 1000
block fluid incompressible tolerance-volume 1.0E-4
block fluid incompressible timestep 0.01
block cycle 20000
model save 'inflow5.sav'
ret
```