4 Gravity Dam: Fluid Flow and Dynamic Loading

4.1 Problem Statement

This demonstration problem involves analysis of a 100 m-high concrete gravity dam on a jointed rock foundation. The average joint spacing is 50 m, with joints oriented at 20° and −70°. Two loading conditions are studied. First, the effects of filling the reservoir are studied, including an analysis of fluid flow through the rock joints. Second, a dynamic wave is applied to the base of the model to study potential effects of an earthquake-type loading.

4.2 *UDEC* Analysis

The *UDEC* model for this problem is illustrated in Figure 4.1. The model is an idealized representation of a gravity dam on a jointed rock foundation, and is intended to demonstrate the recommended solution procedure for this type of problem. The data file is listed in Section 4.3. The analysis is performed in the following sequence.

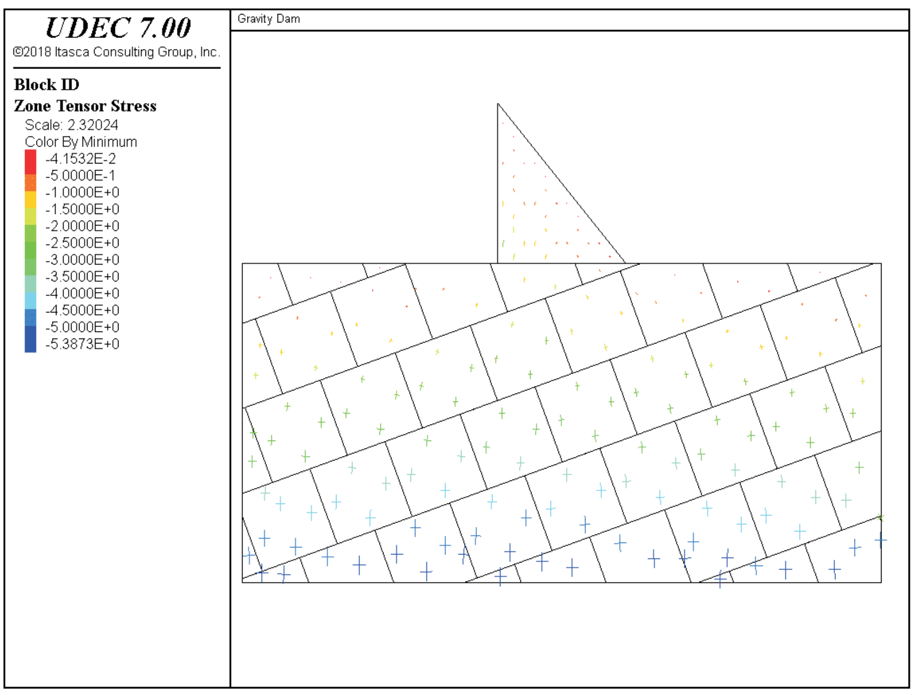

***Figure 4.1** UDEC model of gravity dam with principal stresses plotted at Stage 1*

Stage 1: Gravity Loads – Empty Reservoir

An in-situ state of stress with an effective stress ratio σ_H/σ_V = 0.69 is assumed in the rock mass. The water table is assumed at y = 0. The initial stress state resulting from the weight of the dam, and with the reservoir empty, is shown in Figure 4.1. Note that stresses specified with the **block insitu** command are total stresses. These are assigned to the blocks. For the joints, *UDEC* calculates effective stresses, and sets the domain pressures to the hydrostatic stresses.

Stage 2: Full Reservoir

During this stage, the water table is assumed to be at the top of the dam, exerting hydrostatic pressure on the upstream side of the dam and rock foundation. The horizontal reaction due to the load applied on the dam is taken by the rollers on the lateral boundaries.

Several conditions are assumed with respect to fluid flow:

1. Joint contacts along the bottom and sides of the model are assumed to have zero permeability.
2. On the rock surface upstream of the dam, the head is fixed at 100 m (0.98 MPa) by using the **block edge apply pore-pressure** command. Downstream, the head is set to zero.
3. The interface between the dam and rock foundation is assumed to have low permeability.
4. The algorithm for steady flow (**block fluid steady-state**) is used.

Selected results for Stage 2 are shown in Figures 4.2 through 4.6. The displacements resulting from reservoir filling are shown in Figure 4.2, and the histories of the x- and y-displacements at the crest of the dam are shown in Figure 4.3. The latter figure indicates that the model is in equilibrium with the reservoir full. The plot of flow rates in Figure 4.4 shows that most of the flow is concentrated in the joint directly beneath the dam foundation. Figure 4.5 shows the shear and normal displacements along this joint (at $x = -33.42$, $y = -30.37$). The positive normal displacement indicates that the joint opens during this stage. The fluid pressure history at location $x = -22.1$, $y = -26.3$ along this joint is plotted in Figure 4.6.

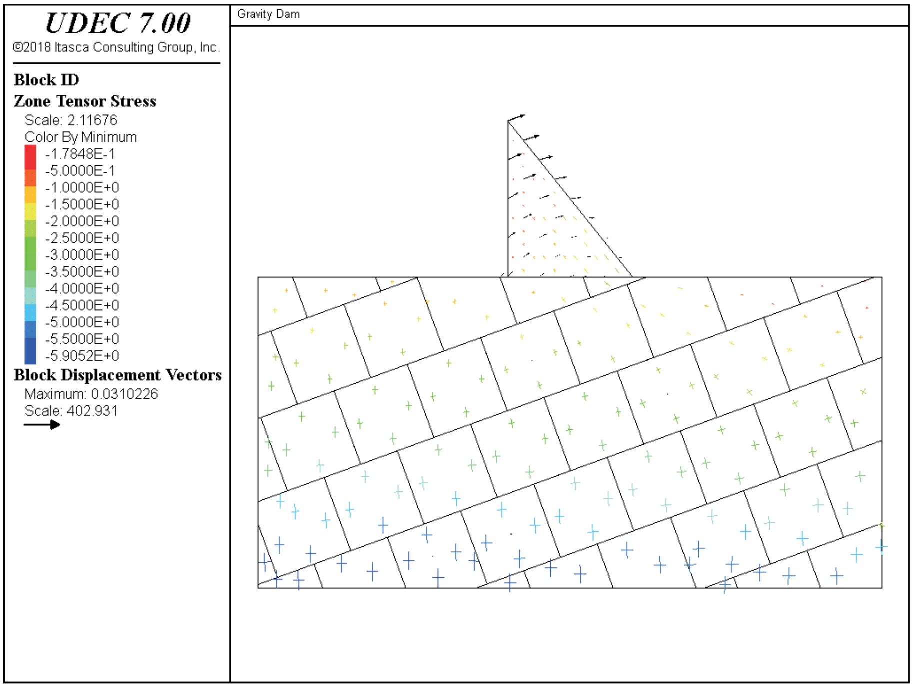

Figure 4.2 Principal stress state and displacements at Stage 2

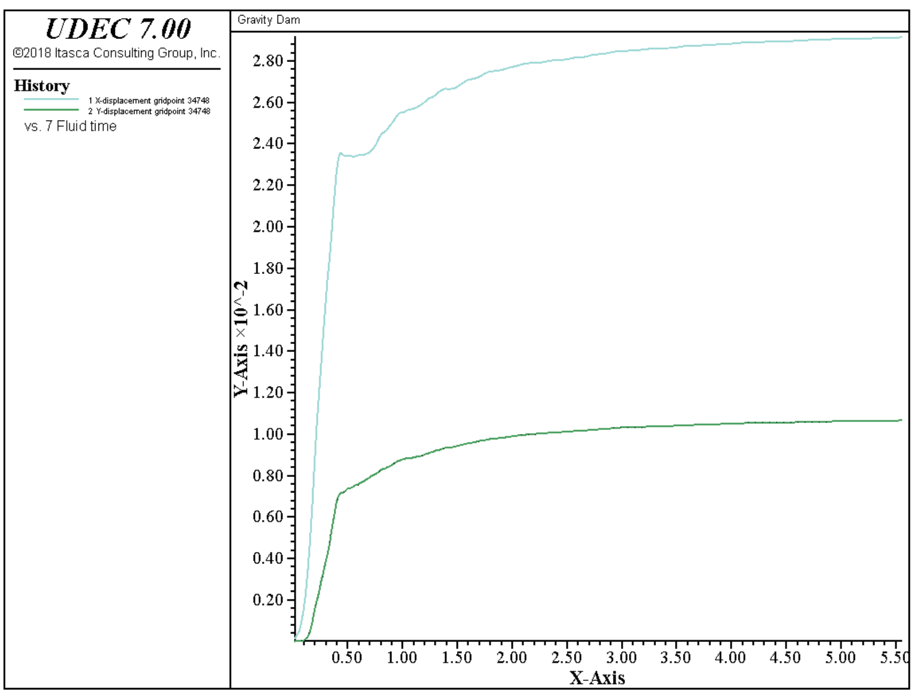

Figure 4.3 x- and y-components of displacement at crest of dam during Stage 2 reservoir filling

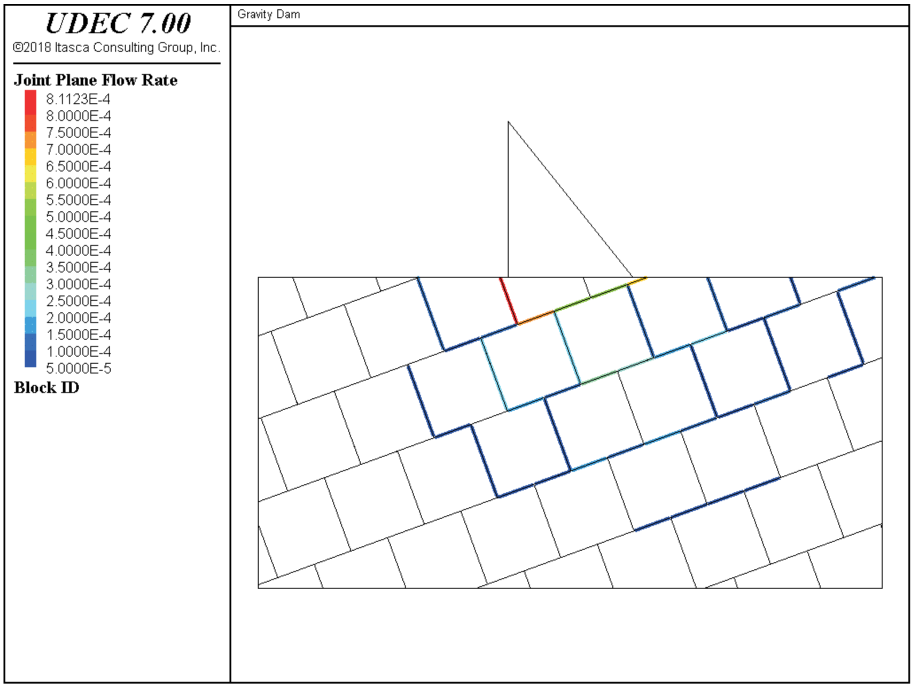

Figure 4.4 Flow rates at Stage 2

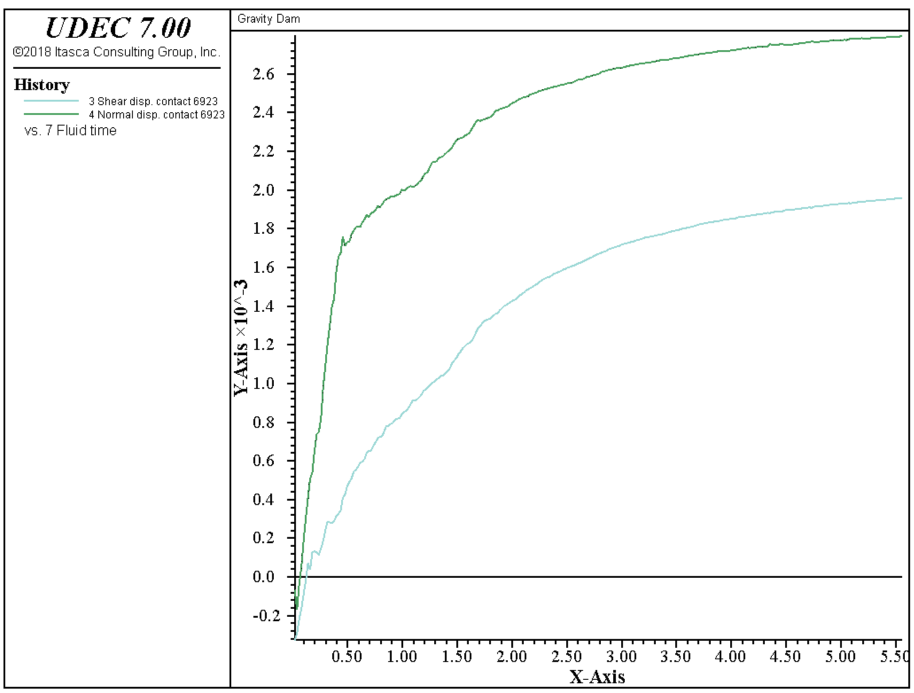

Figure 4.5 Shear and normal displacements along joint at x = −33.42, y = −30.37

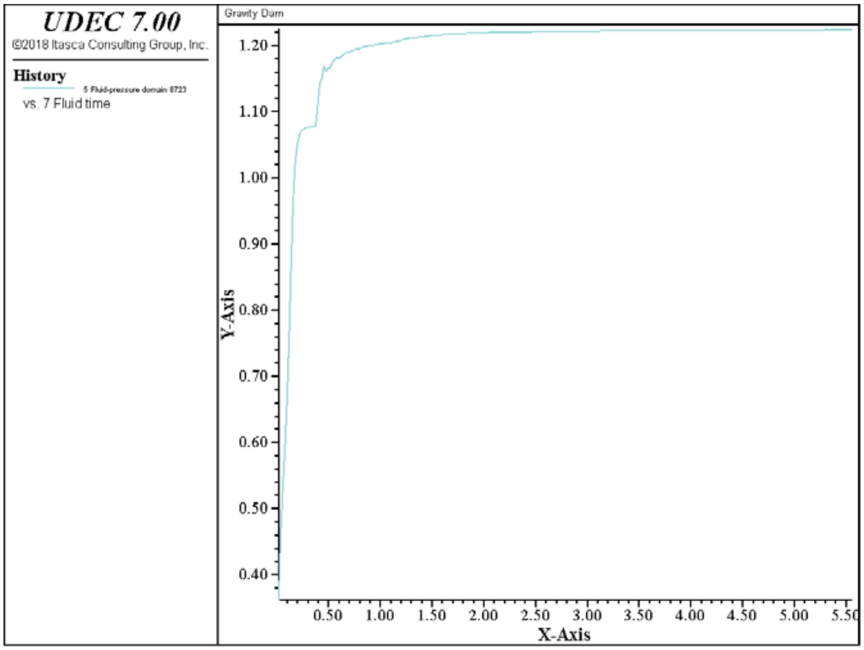

Figure 4.6 Fluid pressure in domain at location x = −22.1, y = −26.3

Stage 3: Dynamic Loading

In this stage, a vertical, propagating, sinusoidal shear wave (frequency = 5 Hz) is applied to the base of the model for 10 seconds. The following boundary conditions are used.

1. The bottom boundary is assumed to be a nonreflecting boundary in the shear direction, and is fixed in the vertical direction. The dynamic input is applied in the form of a shear stress history.
2. A free-field boundary condition is applied to the sides of the model (using **block edge apply dynamic-free-field**). The free field is automatically prescribed the same material behavior as the adjacent blocks along the side boundaries.
3. The static reactions resulting from the flow stage are still applied to the blocks during the dynamic stage, so that the blocks will be in equilibrium in the absence of dynamic loads.

Rayleigh damping is applied to simulate the hysteretic response of the jointed rock foundation. A damping value of 5% of critical damping at a center frequency of 5 Hz is assumed. A shear modulus reduction factor was not applied for this simple demonstration example.

The fluid flow calculation is switched off during this stage (**block fluid flow off**). This is analogous to assuming that no flow occurs during the 10-second dynamic loading.

Figures 4.7 through 4.10 show the results of the Stage 3 analysis after 1.5 seconds of the dynamic loading. The x-velocity histories at the dam crest and model base are plotted in Figure 4.7, and illustrate the amplification of the wave at the surface. The displacement histories at the dam crest (given in Figure 4.8) show an accumulation of horizontal displacement with each load cycle. The joint shear and normal displacements at the joint beneath the dam (in Figure 4.9) show an accumulation of shear displacement. In Figure 4.10, note the large amount of slip that occurs along the first joint beneath the dam foundation; the joint upstream at 70° is open (i.e., no effective stress).

The dynamic phase is repeated to evaluate the influence of hydrodynamic pressure on the response of the dam. Hydrodynamic pressure is simulated by using the Westergaard procedure described in Section 4.3.1.6 in **Special Features**. The *FISH* function **`wester`** is called to apply the hydrodynamic pressure along the upstream face of the dam. Figures 4.11 through 4.14 show the results after 1.5 seconds when hydrodynamic pressures are included.

A substantial increase in displacement is shown. The large displacement of the wedge beneath the dam, along with the accumulation of displacements shown in Figures 4.12 and 4.14, indicate the probable failure of the dam.

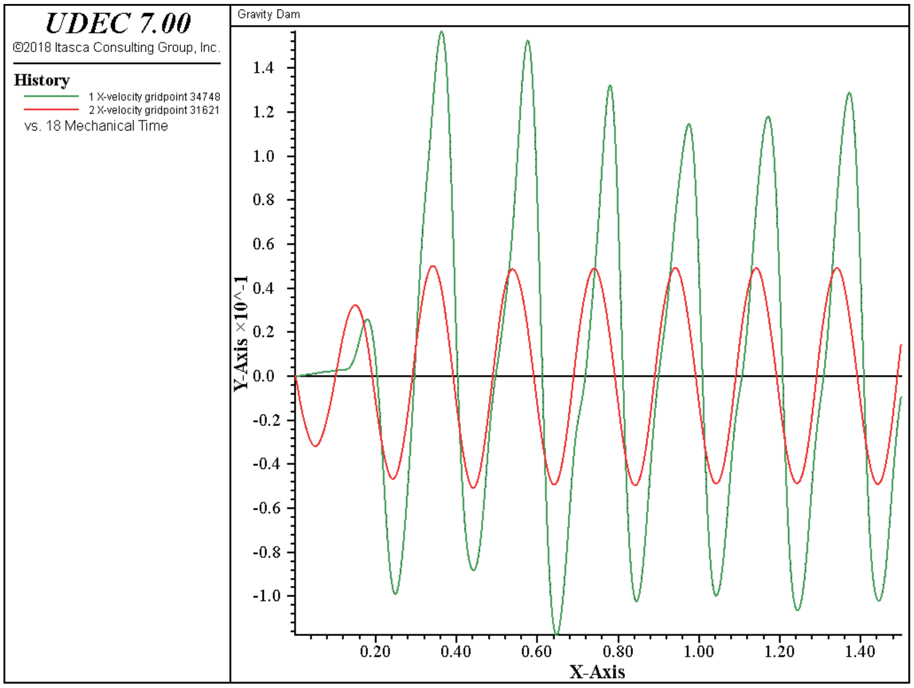

Figure 4.7 x-velocity histories at dam crest and model base at Stage 3

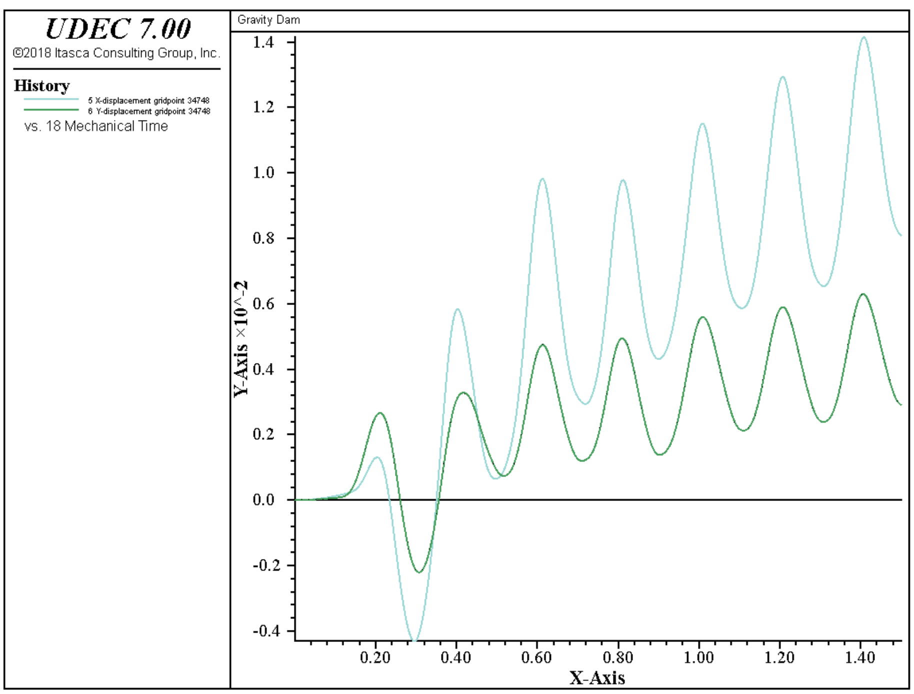

Figure 4.8 x- and y-displacements at dam crest at Stage 3

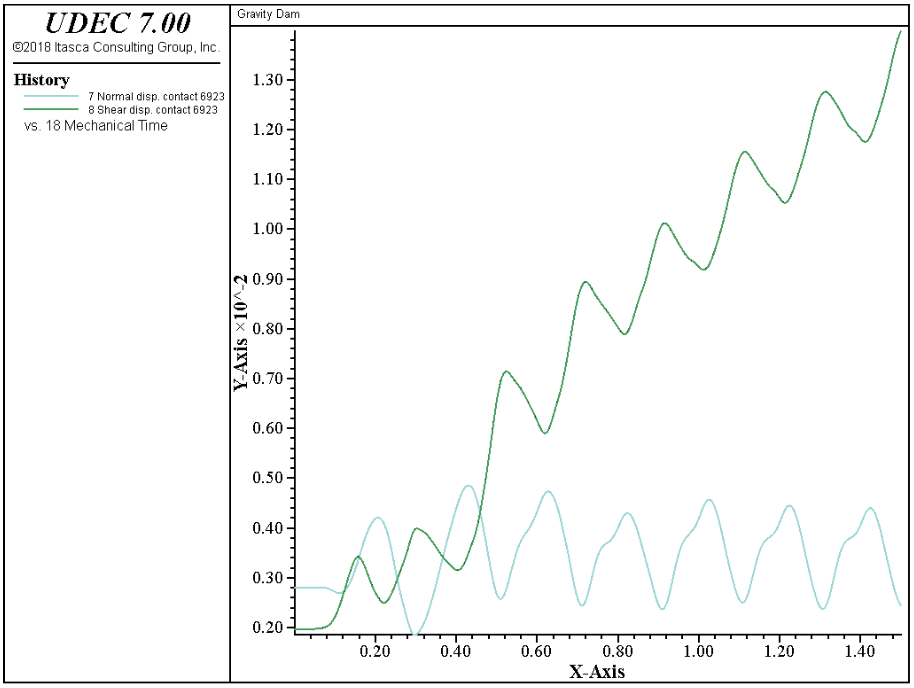

Figure 4.9   Joint shear and normal displacement histories at joint beneath dam foundation at Stage 3

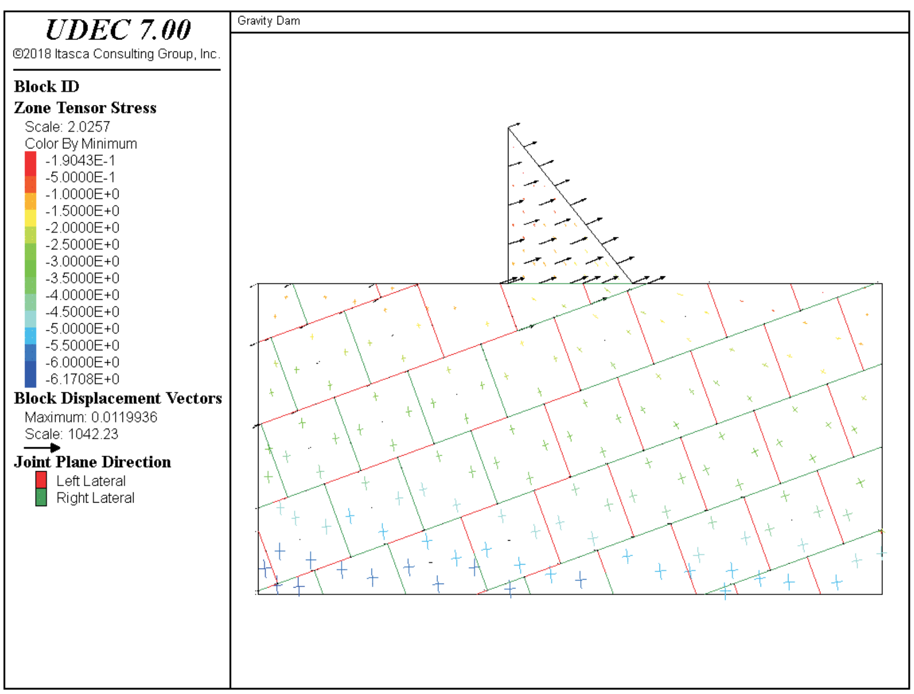

Figure 4.10   Displacements, principal stresses and joint shear displacement at Stage 3

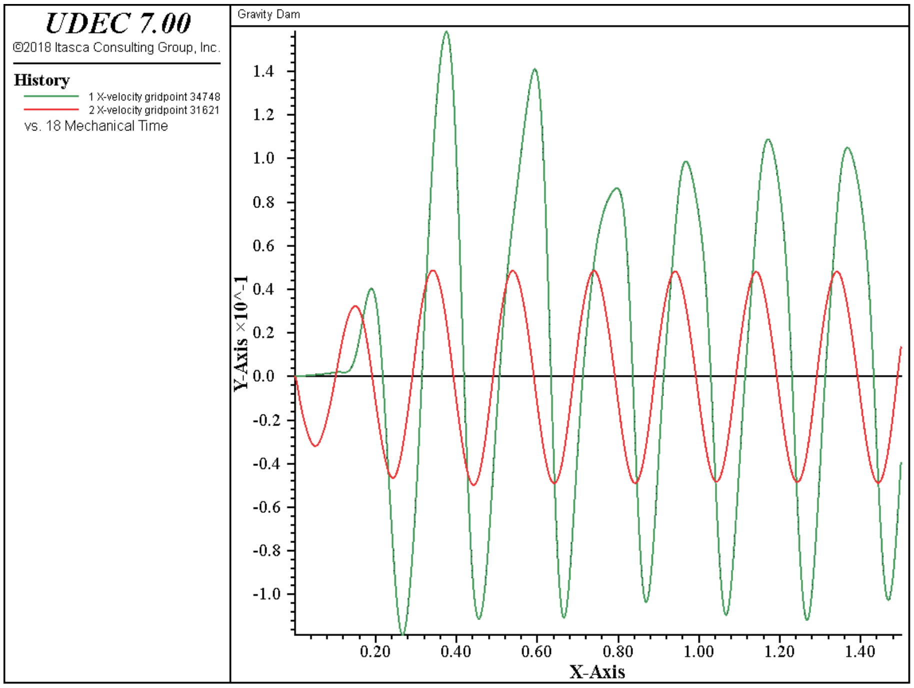

Figure 4.11 x-velocity histories at dam crest and model base at Stage 3

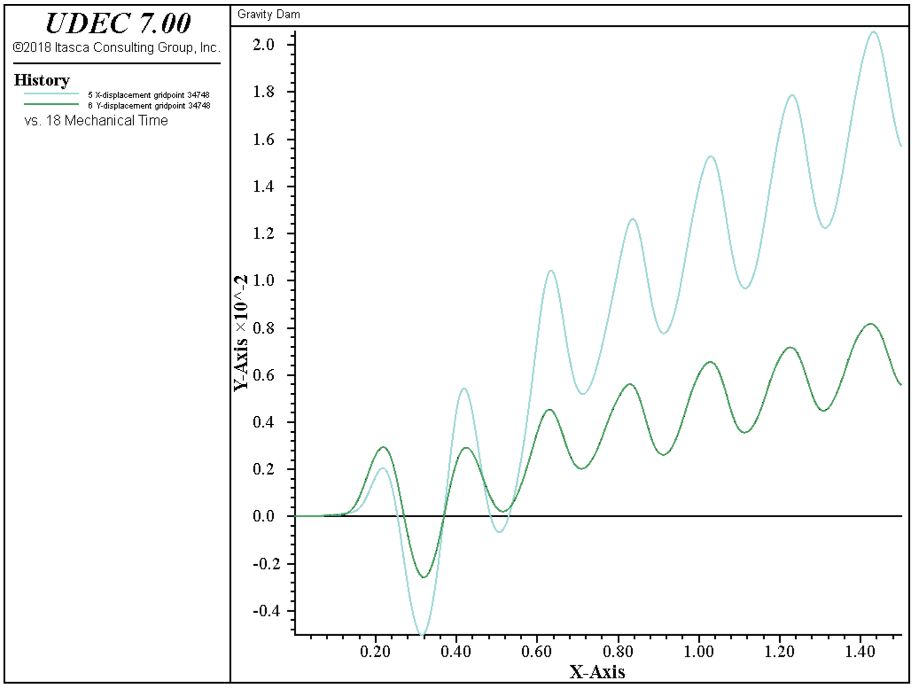

Figure 4.12 x- and y-displacements at dam crest at Stage 3

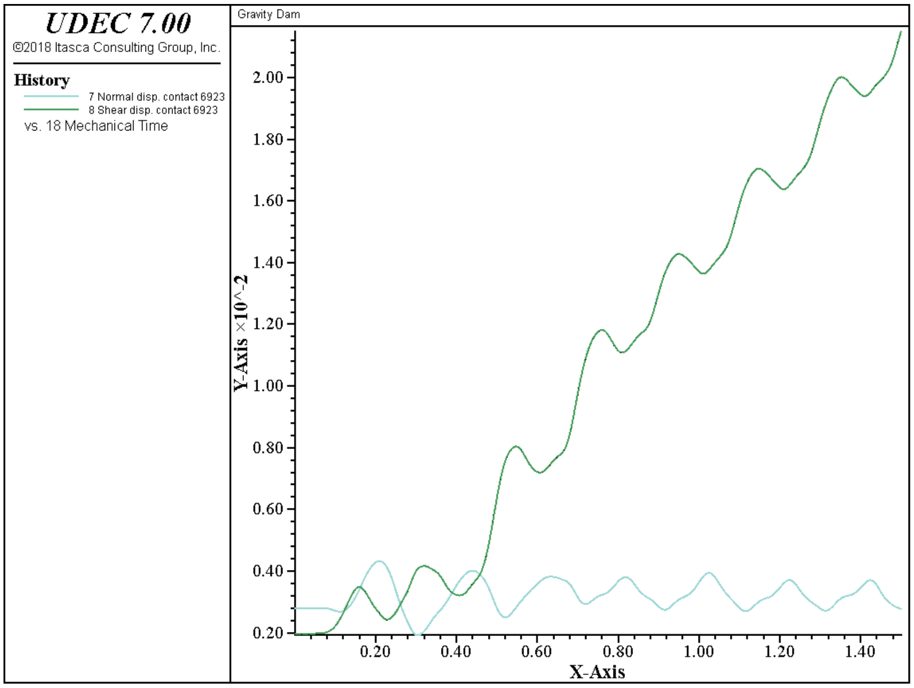

Figure 4.13 Joint shear and normal displacement histories at joint beneath dam foundation at Stage 3

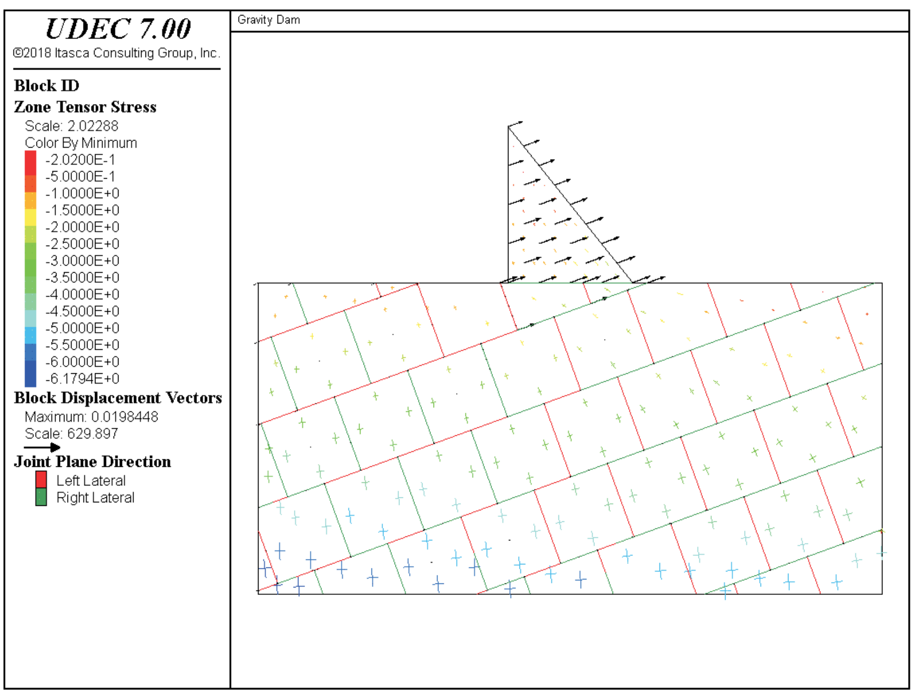

Figure 4.14 Displacements, principal stresses and joint shear displacement at Stage 3

4.3 Listing of Data File

Example 4.1 DAM.DAT

```
model new
;File:dam.dat
model title 'Gravity Dam'
;
; --- dam --- discontinuous joints : 20 and -70 deg.
; --- insitu stresses (k=0.5)
; --- free-field (20 nodes) --- applied only in phase 3
;
; --- phase 1 --- gravity loading; x-fixed boundaries
;
config fluid
bl fluid clear steady-state off
bl tolerance corner-round-length 0.5
bl create polygon -200 -200 -200 100 200 100 200 -200
bl cut crack (-200,0) (200,0)
bl cut crack (-40,0) (-40,100)
bl cut crack (40,0) (-40,100)
bl delete range pos-x -200,-40 pos-y 0,100
bl delete range pos-x 40,200 pos-y 0,100
bl joint-region id 1 -200.0 -200.0 -200.0 0.0 200.0 0.0 200.0 -200.0
bl cut joint-set angle 20 spacing 50 origin 50,0 range jregion 1
bl cut joint-set angle 290 trace 50 gap 50 spacing 50 ...
  origin -50.99,16.45 range jregion 1
bl cut joint-set angle 290 trace 50 gap 50 spacing 50 ...
  origin -10.4,-21.98 range jregion 1
bl zone gen edge 60.0 range pos-x -200,200 pos-y -200,0
bl zone gen edge 30.0 range pos-x -40,40 pos-y 0,100
;
; bl and joint properties
bl zone group 'dam:rock bl' range pos-x -200 200 pos-y -200 0
bl zone group 'dam:dam bl' range pos-x -40 40 pos-y 0 100
bl zone cmodel assign elastic density 2.65E-3 bulk 3.333E4 shear 2E4 ...
  range group 'dam:rock bl'
bl zone cmodel assign elastic density 2.4E-3 bulk 1.667E4 shear 1.25E4 ...
  range group 'dam:dam bl'
bl contact group 'dam:rock joint' range pos-x -200 200 pos-y -200 1
bl contact group 'dam:cohesive joint' range pos-x -200 200 pos-y -200 -150
bl contact group 'dam:foundation joint' range pos-x -40 40 pos-y -1 1
bl contact group 'dam:rock joint - zero perm' ...
  range pos-x -201 -199 pos-y -150 1
bl contact group 'dam:rock joint - zero perm' ...
  range pos-x 199 201 pos-y -150 1
```

```
bl contact group 'dam:cohesive joint - zero perm' ...
  range pos-x -201 -199 pos-y -200 -150
bl contact group 'dam:cohesive joint - zero perm' ...
  range pos-x 199 201 pos-y -200 -150
bl contact group 'dam:cohesive joint - zero perm' ...
  range pos-x -200 200 pos-y -201 -199
bl contact cmodel assign area st-s 1E3 st-n 1E3 friction 30 ...
  permeability-factor 3E8 aperture-residual 5E-4 ...
  aperture-zero-load 1E-3 ...
  range group 'dam:rock joint'
bl contact cmodel assign area st-s 1E3 st-n 1E3 friction 30 ...
  cohesion 2 tension 2 permeability-factor 2E8 ...
  aperture-residual 1E-4 aperture-zero-load 2E-4 ...
  range group 'dam:foundation joint'
bl contact cmodel assign area st-s 1E3 st-n 1E3 friction 30 cohesion 2 ...
  permeability-factor 1E8 ...
  aperture-residual 5E-4 aperture-zero-load 1E-3 ...
  range group 'dam:cohesive joint'
bl contact cmodel assign area st-s 1E3 st-n 1E3 friction 30 ...
  permeability-factor 0 aperture-residual 5E-4 aperture-zero-load 1E-3 ...
  range group 'dam:rock joint - zero perm'
bl contact cmodel assign area st-s 1E3 st-n 1E3 friction 30 cohesion 2 ...
  permeability-factor 0 aperture-residual 5E-4 aperture-zero-load 1E-3 ...
  range group 'dam:cohesive joint - zero perm'
bl fluid  property density 0.0010
;
; boundary conditions : lateral : x-fixed ; bottom : y-fixed
bl gridpoint apply velocity-x 0 range pos-x -201 -199 pos-y -201 1
bl gridpoint apply velocity-x 0 range pos-x 199 201 pos-y -201 1
bl gridpoint apply velocity-y 0 range pos-x -201 201 pos-y -201 -199
;
; set gravity ; set in-situ stresses (total)
model gravity 0.0 -9.81
bl insitu  stress 0.0 0.0 0.0 gradient-x 0.0 0.0 0.0 ...
  gradient-y 0.017885 0.0 0.02597 stress-ZZ 0.0 ...
  gradient-z 0.0 0.017885 water-table 0.0 range pos-x -200 200 pos-y -200 0
bl gridpoint history displacement-x -40.0 100.0
bl gridpoint history displacement-y -40.0 100.0

bl solve ratio 1.0E-5 elastic
model save 'dam1.sav'
;
;
; ---------------------------------------------------------------------
;
; --- phase 2 --- water loads and flow
```

```
;
model restore 'dam1.sav'
bl edge apply pore-pressure 0.981 range pos-x -201 -39 pos-y -1 1
bl edge apply stress 0.0 0.0 -0.981 range pos-x -201 -39 pos-y -1 1
bl edge apply stress -0.981 0.0 0.0 gradient-x 0.0 0.0 0.0 ...
  gradient-y 0.00981 0.0 0.0 range pos-x -40.1 -39 pos-y -0.1 100.1
bl gridpoint apply velocity-x 0 range pos-x -201 -199 pos-y -1 1
bl contact reset displacement-normal
bl gridpoint init displacement-x 0
bl gridpoint init displacement-y 0
hist reset
bl mechanical time 0
bl fluid time 0
bl gridpoint history displacement-x -40.0 100.0
bl gridpoint history displacement-y -40.0 100.0
bl contact history displacement-shear -33.42 -30.37
bl contact history displacement-normal -33.42 -30.37
bl domain history pore-pressure -22.1 -26.3
bl contact history flow-rate -33.42 -30.37
bl fluid history time-total
;
bl fluid flow on
bl solve ratio 1.0E-5
model save 'dam2.sav'
; ----------------------------------------------------------------------
;
; --- phase 3 --- dynamic loading: shear wave at base of model
;  free-field lateral boundaries
;  with constant domain pressures ; no fluid flow by setting flow off
;
bl fluid flow off
bl mechanical damping 0.05 5.0
bl edge apply dynamic-free-field
bl gridpoint apply viscous-x bulk 33333.0 shear 20000.0 density 0.00265 ...
  range pos-x -201 201 pos-y -201 -199
bl edge apply property bulk 33333.0 shear 20000.0 density 0.00265 ...
  range pos-x -201 201 pos-y -201 -199
bl edge apply stress 0.0 0.4 0.0 history sine 5 10 ...
  range pos-x -201 201 pos-y -201 -199
bl gridpoint apply velocity-y 0 range pos-x -201 201 pos-y -201 -199
bl gridpoint init displacement-x 0
bl gridpoint init displacement-y 0
bl gridpoint init velocity-x 0
bl gridpoint init velocity-y 0
hist reset
bl mechanical time 0
```

```
bl gridpoint history velocity-x -40.0 100.0
bl gridpoint history velocity-x 0.0 -200.0
bl gridpoint history velocity-x 0.0 100.0
bl gridpoint history velocity-y -40.0 100.0
bl gridpoint history displacement-x -40.0 100.0
bl gridpoint history displacement-y -40.0 100.0
bl contact history displacement-normal -33.42 -30.37
bl contact history displacement-shear -33.42 -30.37
bl contact history stress-shear -33.42 -30.37
bl dynamic free-field history velocity-x 0 1
bl dynamic free-field history velocity-x 0 2
bl gridpoint history displacement-x -31.765602 -29.082699
bl gridpoint history displacement-x -41.061577 100.286316
bl gridpoint history displacement-x -39.51225 75.49704
bl gridpoint history displacement-x -41.061577 52.25709
bl gridpoint history displacement-x -38.737583 23.594501
bl gridpoint history displacement-x -38.737583 1.9038887
bl mechanical history time-total
model save 'dam3.sav'
bl cycle time 1.5
model save 'dam4.sav'
;
;  repeat dynamic analysis including hydrodynamic pressure
;  using wester.fis FISH function
;
model restore 'dam2.sav'
bl fluid flow off
bl mechanical damping 0.05 5.0
bl edge apply dynamic-free-field
call 'wester.fis'
fish set @dx=-1 @dy=0
fish set @height=100
fish set @yb=0
fish set @c_m=0.743
fish set @den_w=0.001
@westergaard
bl gridpoint apply viscous-x bulk 33333.0 shear 20000.0 density 0.00265 ...
  range pos-x -201 201 pos-y -201 -199
bl edge apply property bulk 33333.0 shear 20000.0 density 0.00265 ...
  range pos-x -201 201 pos-y -201 -199
bl edge apply stress 0.0 0.4 0.0 history sine 5 10 ...
  range pos-x -201 201 pos-y -201 -199
bl gridpoint apply velocity-y 0 range pos-x -201 201 pos-y -201 -199
bl gridpoint init displacement-x 0
bl gridpoint init displacement-y 0
bl gridpoint init velocity-x 0
```

```
bl gridpoint init velocity-y 0
hist reset
bl mechanical time 0
bl gridpoint history velocity-x -40.0 100.0
bl gridpoint history velocity-x 0.0 -200.0
bl gridpoint history velocity-x 0.0 100.0
bl gridpoint history velocity-y -40.0 100.0
bl gridpoint history displacement-x -40.0 100.0
bl gridpoint history displacement-y -40.0 100.0
bl contact history displacement-normal -33.42 -30.37
bl contact history displacement-shear -33.42 -30.37
bl contact history stress-shear -33.42 -30.37
bl dynamic free-field history velocity-x 0 1
bl dynamic free-field history velocity-x 0 2
bl gridpoint history displacement-x -31.765602 -29.082699
bl gridpoint history displacement-x -41.061577 100.286316
bl gridpoint history displacement-x -39.51225 75.49704
bl gridpoint history displacement-x -41.061577 52.25709
bl gridpoint history displacement-x -38.737583 23.594501
bl gridpoint history displacement-x -38.737583 1.9038887
bl mechanical history time-total
model save 'dam5.sav'
bl cycle time 1.5
model save 'dam6.sav'
```