1.6 Example Application of a Seismic Analysis

An example application of a nonlinear seismic analysis is presented in this section. The example illustrates several of the topics discussed in this volume. The data files for this example are contained in the "ITASCA\FLAC800\Datafiles\Dynamic\Earthdam" directory.

1.6.1 Seismic Analysis of an Embankment Dam

1.6.1.1 Problem Statement

An analysis of the seismic performance of an embankment dam should consider static-equilibrium and coupled groundwater conditions, as well as fully dynamic processes. This includes calculations for (1) the state of stress prior to seismic loading, (2) the reservoir elevation and groundwater conditions, (3) the mechanical behavior of the foundation and embankment soils including the potential for liquefaction, and (4) the site-specific ground motion response. This example presents a *FLAC* model for an embankment dam that demonstrates a procedure to incorporate these processes and calculations in the seismic analysis.

The example is a simplified representation of a typical embankment dam geometry. The dam is 130 ft high and 1120 ft long, and is constructed above a layered foundation of sandstone and shale materials. The crest of the dam is at elevation 680 ft when the seismic loading is applied. The embankment materials consist of a low-permeability, clayey-sand core zone with upstream and downstream shells of gravelly, clayey sands. These soils are considered to be susceptible to liquefaction during a seismic event. The materials in this analysis are defined as foundation soils 1 and 2 and embankment soils 1 and 2, as depicted in Figure 1.89.

The earth dam is subjected to seismic loading representative of the 1987 Loma Prieta earthquake in California. The earthquake target motion for this model is taken from that recorded at the left abutment of the Lexington Dam during the Loma Prieta earthquake and, for this analysis, the input is magnified somewhat and assumed to correspond to the acceleration at the surface of the foundation soils at elevation 550 ft. The target record is provided in the file named "ACC_TARGET.HIS." The estimated peak acceleration is approximately 12 ft/sec^2 (or 0.37 g), and the duration is approximately 40 sec. The record is shown in Figure 1.90:

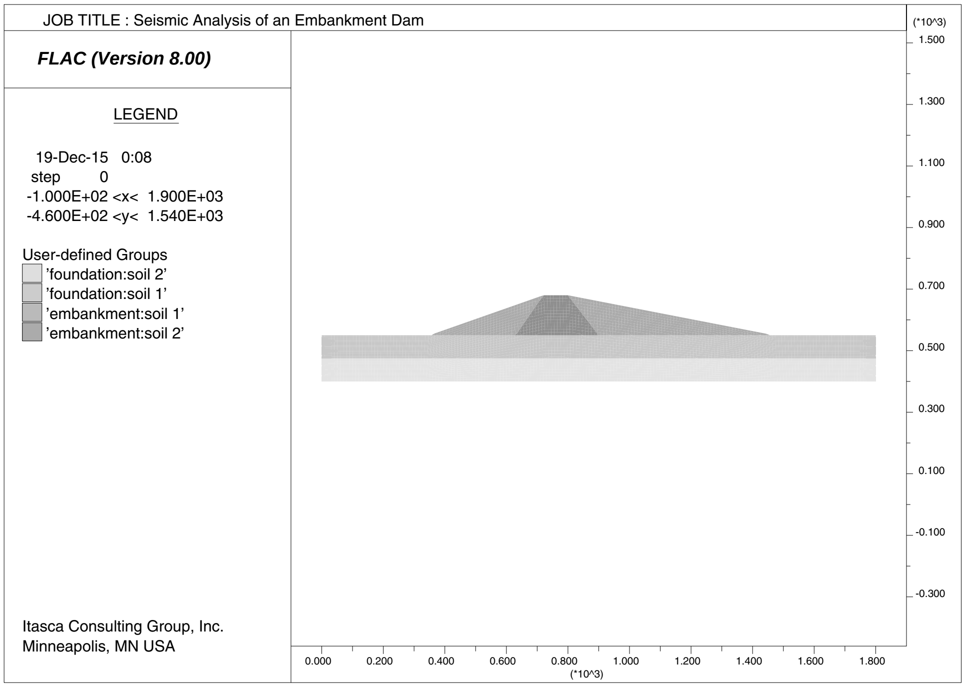

Figure 1.89 Embankment dam

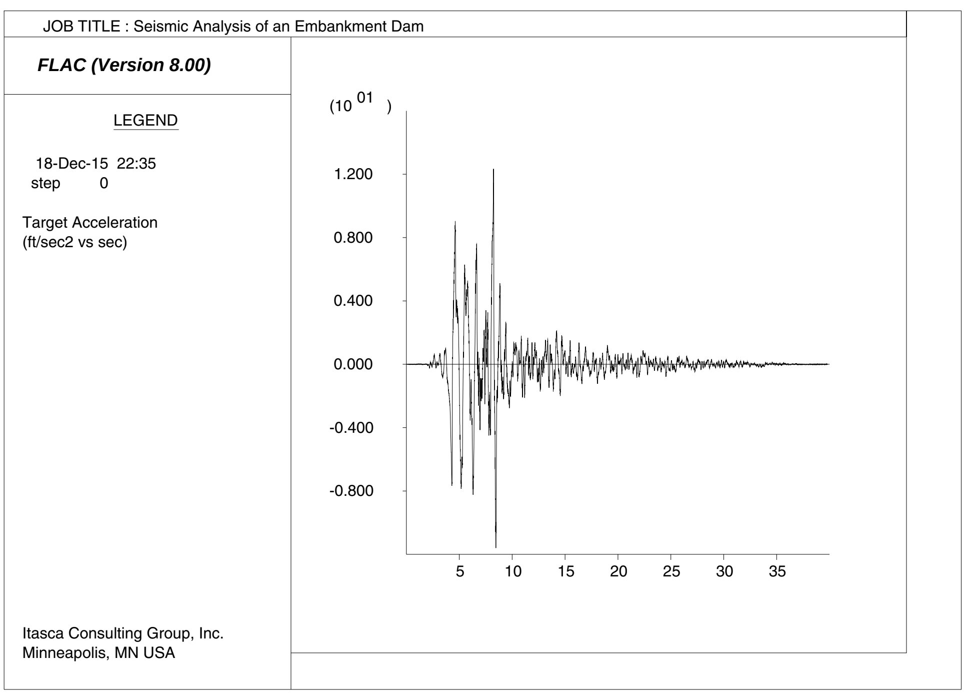

Figure 1.90 Horizontal acceleration time history at elevation 550 ft – target motion

1.6.1.2 Modeling Procedure

This example illustrates a recommended procedure to simulate seismic loading of an embankment dam with *FLAC*. A coupled effective-stress analysis is performed using a "simple" material model to simulate the behavior of the soils, including liquefaction. The soil behavior is based upon the Mohr-Coulomb plasticity model with material damping added to account for cyclic dissipation during the elastic part of the response and during wave propagation through the site. Liquefaction is simulated by using the Finn-Byrne model, which incorporates the Byrne (1991) relation between irrecoverable volume change and cyclic shear-strain amplitude (see Eq. (1.93)) into the Mohr-Coulomb model.

The modeling procedure is divided into eight steps:

1. Determine representative static and dynamic material characteristics of the soils, and estimate representative material properties. This includes an estimate for material damping parameters to represent the inelastic cyclic behavior of the materials.
2. Calculate the deconvoluted dynamic loading for the base of the model, derived from the target seismic record for the site, and evaluate the seismic motion characteristics.
3. Adjust input motion for accurate wave propagation, and create an appropriate model grid.
4. Calculate the static equilibrium state for the site including the steady-state groundwater conditions with the reservoir at full pool.
5. Apply the dynamic loading conditions.
6. Perform preliminary undamped simulations to check model conditions and estimate the dominant frequencies of the site resonance and the maximum cyclic shear strains for the given site conditions.
7. Run a series of simulations with actual strength properties and representative damping, assuming the soils do not liquefy in order to evaluate the model response.
8. Perform the seismic calculation assuming the soils can liquefy.

These steps are described separately in the sections below.

1.6.1.3 Estimate Representative Material Properties

The foundation and embankment soils are modeled as elastic-perfectly plastic Mohr-Coulomb materials. Drained properties are required because this is an effective-stress analysis. The properties for the different soil types are listed in Table 1.3:

Table 1.3 Drained properties for foundation and embankment soils

	Foundation		Embankment	
	Soil 1	Soil 2	Soil 1	Soil 2
Unit weight (pcf)	125	125	113	120
Young's modulus (ksf)	12,757	12,757	6,838	6,838
Poisson's ratio	0.3	0.3	0.3	0.3
Bulk modulus (ksf)	10,631	10,631	5,698	5,698
Shear modulus (ksf)	4,906	4,906	2,630	2,630
Cohesion (psf)	83.5	160	120	120
Friction angle (degrees)	40	40	35	35
Dilation angle (degrees)	0	0	0	0
Porosity	0.3	0.3	0.3	0.3
Hydraulic conductivity (ft/sec)	3.3×10^{-6}	3.3×10^{-7}	3.3×10^{-6}	3.3×10^{-8}

The dynamic characteristics of all of the soils in this model are assumed to be governed by the modulus reduction factor (G/G_{max}) and damping ratio (λ) curves, as shown in Figures 1.91 and 1.92, and denoted by the "SHAKE91" legend. These curves are considered to be representative of clayey soils with an average unit weight of 125 pcf and an average shear modulus of 6270 ksf; the data are derived from the input file supplied with *SHAKE-91* (for more information see http://nisee.berkeley.edu/software/).

The dynamic characteristics of the soils are simulated in the *FLAC* model in two different ways, for comparison. Simulations are made with either Rayleigh damping (Section 1.4.3.1) or hysteretic damping (Section 1.4.3.4) included with the Mohr-Coulomb model and with the Finn-Byrne model, to evaluate and compare their representation of the inelastic cyclic response of the soils during dynamic loading.

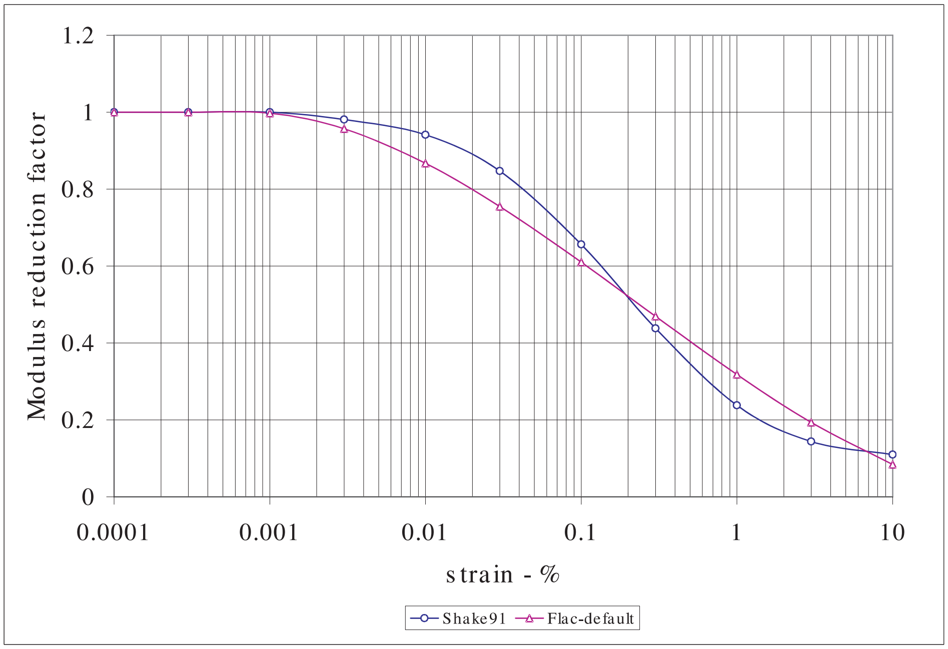

Figure 1.91 Modulus reduction curve for clayey soils (from SHAKE-91 data) FLAC default hysteretic damping with $L_1 = -3.156$ and $L_2 = 1.904$

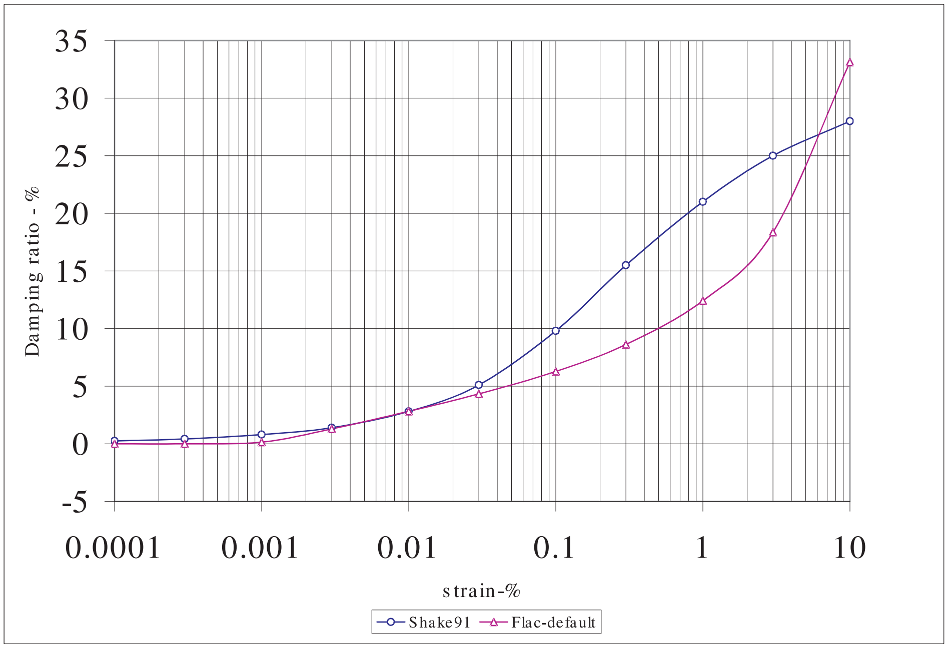

Figure 1.92 Damping ratio curve for clayey soils (from SHAKE-91 data) FLAC default hysteretic damping with $L_1 = -3.156$ and $L_2 = 1.904$

Rayleigh Damping Parameters – The equivalent linear program *SHAKE-91* is run to estimate the Rayleigh damping parameters to represent the inelastic cyclic behavior of the soils in the *FLAC* model, based upon the curves in Figures 1.91 and 1.92. A *SHAKE-91* free-field column model is created for the foundation soils. The *SHAKE* analysis is performed using the shear wave speeds, densities, and modulus-reduction and damping-ratio curves for the two foundation soils, and the target earthquake motion specified for the site. Strain-compatible values for the shear-modulus reduction factors and damping ratios throughout the soil column are determined from the analysis.

Average modulus-reduction factors and damping ratios are then estimated for the foundations soils based upon the values calculated by *SHAKE-91*. The selected damping ratio and modulus-reduction parameters correspond to the equivalent uniform strain (which is taken as 50% of the maximum strain) for each layer. In this exercise, one value is selected as representative for all materials. The maximum equivalent uniform strain for the foundation soils is calculated to be 0.08%, the average damping ratio is 0.063 and the average modulus reduction factor is 0.8. The values for damping ratio and modulus-reduction factor will be input for the Rayleigh damping runs in the embankment dam model.

Hysteretic Damping Parameters – The default hysteretic damping function (**default** see Eq. (1.48)) is used to best-fit the modulus-reduction factor and damping-ratio curves. The parameter values $L_1 = -3.156$ and $L_2 = 1.904$ for the default model provide a reasonable fit to both curves over the range of 0.08% strain, as shown in Figures 1.91 and 1.92. Note that the parameters for the default model may need to be adjusted after the maximum shear strains are calculated from an undamped elastic *FLAC* model of the entire site (see Section 1.6.1.9).

Water Bulk Modulus – The dynamic simulations in this example are fully coupled effective-stress calculations, which require that the water bulk modulus be specified explicitly. For the properties listed in Table 1.3, and assuming the water bulk modulus $K_w = 4.18 \times 10^6$ psf for the site, the value of R_k (see Eq. (1.123)) for the foundation soils is approximately 0.8, and for the embankment soils it is approximately 1.5. In this example, a uniform value of $K_w = 4.18 \times 10^6$ psf is selected as representative of the actual condition. (For further discussion on water bulk modulus, see Section 1.8.5.2 in **Fluid-Mechanical Interaction**.)

Liquefaction Properties – The liquefaction condition is estimated for embankment soils in terms of standard penetration test results. A normalized standard penetration test value, $(N_1)_{60}$, of 10 is selected as representative for these soils. This value is used to determine the parameters C_1 and C_2 in the liquefaction model in *FLAC* (selected by setting the property `ff_switch` = 1 for the Finn model – Byrne formulation). For a normalized SPT blow count of 10, the Finn-Byrne model parameters are $C_1 = 0.2452$ and $C_2 = 0.8156$. See Section 1.4.4.2 for a description of the formulation, and see Byrne (1991) for a discussion on the derivation of these parameters.

1.6.1.4 Perform Deconvolution Analysis and Estimate Seismic Motion Characteristics

The target motion provided for this example, Figure 1.90, is assumed to correspond to the motion at the ground surface of the foundation soils near the site.* It is necessary to modify this motion to apply the appropriate seismic input at the base of the model (in this case at elevation 400 ft). The appropriate input motion at depth is computed by performing a deconvolution analysis using the equivalent-linear program *SHAKE*. This approach is reasonable, provided the model exhibits a low level of nonlinearity. A check on the approach is made in Section 1.6.1.9.

SHAKE-91 is used in this example to estimate the appropriate motion at depth corresponding to the target (surface) motion. This deconvoluted motion should then produce the target motion at the surface. In this example, the upward-propagating motion calculated from *SHAKE-91* is used with a compliant-base boundary. (See Figure 1.88.) Note that *SHAKE-91* accelerations are in g's versus seconds, and need to be converted into ft/sec^2 versus seconds when applied in *FLAC*. The input record (i.e., the upward-propagating motion from the deconvolution analysis and converted to ft/sec^2) is in the file named "ACC_DECONV.HIS," and is shown in Figure 1.93.

The signal is processed using *FLAC* SEISMIC tool (see Section 1.8). Alternatively, *FISH* can be used to filter and baseline correct the signals. In the following, the *FISH* approach is presented. (Both methods produce the same results shown for baseline corrected displacement, in Figure 1.103, and for filtered and baseline corrected velocities, in Figure 1.96.) A fast Fourier transform (FFT) analysis of the input acceleration record (using "FFT.FIS" in Section 3 in the ***FISH* volume**) results in a power spectrum as shown in Figure 1.94. This figure indicates that the dominant frequency is approximately 1 Hz, the highest frequency component is less than 10 Hz, and the majority of the frequencies are less than 5 Hz. The dominant frequencies of the input velocity are also checked by first converting the acceleration record into a velocity record (using the *FISH* function "INT.FIS," described in Section 3 in the ***FISH* volume**, to integrate the acceleration record), and then performing an FFT analysis to determine the power spectrum. Figure 1.95 shows the resulting power spectrum for the velocity record. The dominant frequency is seen to be less than 1 Hz.

The input record is also checked for baseline drift. The *FISH* function "INT.FIS" is used to integrate the velocity record again to produce the displacement waveform related to the input acceleration. The resulting residual displacement is found to be approximately 0.3 ft. A baseline correction is performed by adding a low frequency sine wave to the velocity record; the sine wave parameters are adjusted so that the final displacement is zero. (See "BASELINE.FIS" in Example 1.25.) The uncorrected and corrected resultant displacement histories are shown in Figure 1.96.

---

* This target motion is used for illustrating the principles of deconvolution analysis, and may not be the typical case encountered in many practical situations. It is more common that the outcrop motion, recorded at the top of bedrock underlying the soil layers, is the target motion. Deconvolution in this case is described in Mejia and Dawson (2006), and is summarized in Section 1.4.1.7.

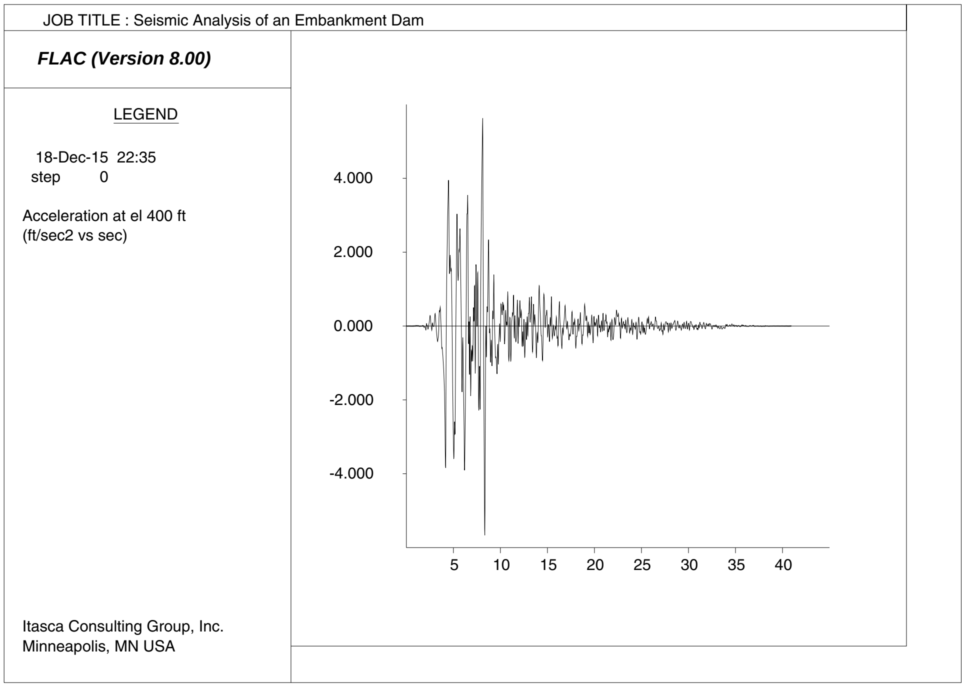

Figure 1.93 Horizontal acceleration time history at elevation 400 ft (upward-propagating motion from deconvolution analysis)

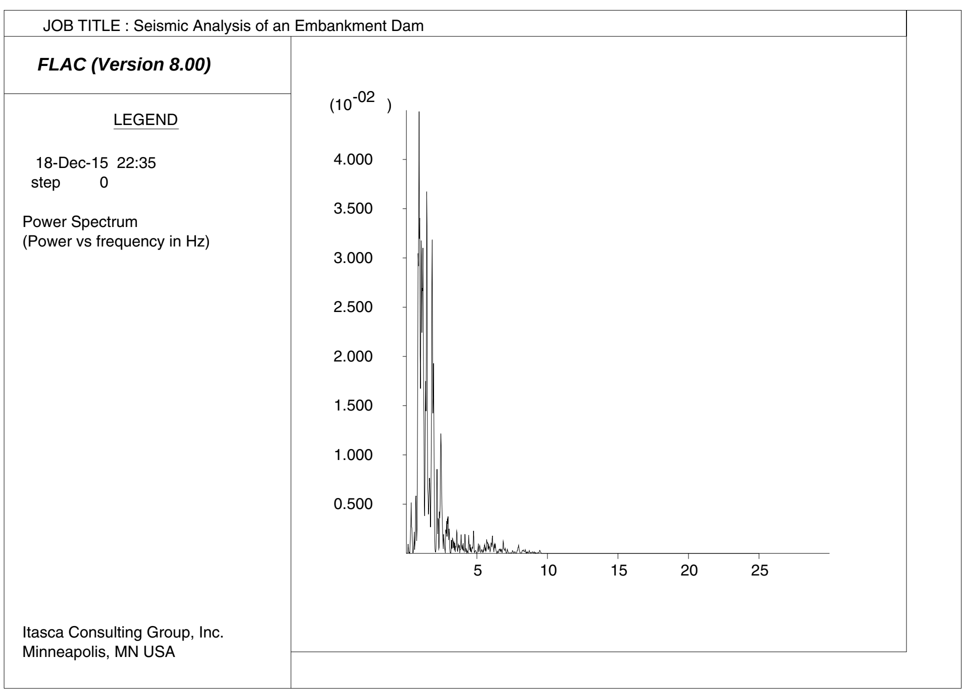

Figure 1.94 Power spectrum of input acceleration

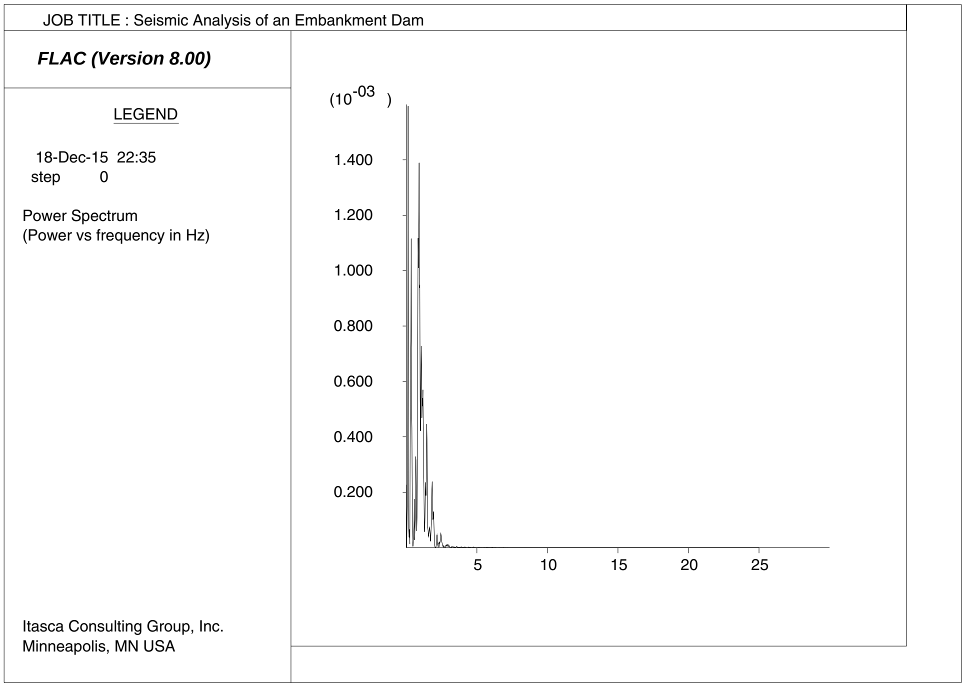

Figure 1.95 Power spectrum of input velocity

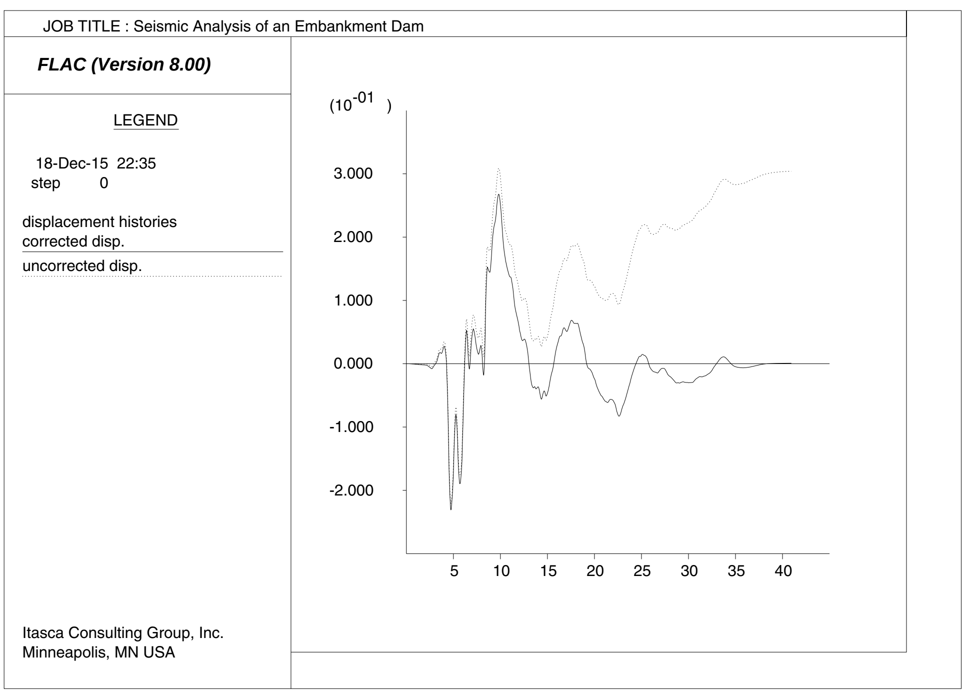

Figure 1.96 Uncorrected and corrected displacement histories

Example 1.25 "BASELINE.FIS" – Baseline drift correction

```
;Name:baseline
;Input:itab_unc/int/102/uncorrected motion table
;Input:itab_corr/int/120/low frequency sine wave correction
;Input:drift/float/0.3/residual value at end of record
;Input:ttime/float/40.0/total time of record
;Input:itab_cmot/int/105/baseline corrected motion
;Note:Perform baseline correction with low frequency sine wave
def baseline
   npnts = table_size(itab_unc)
;
   loop ii (1,npnts)
      tt = float(ii-1) * ttime / float(npnts)
      vv = pi * tt / ttime
      cor_d = drift * pi / (2.0 * ttime)
      ytable(itab_corr,ii) = -(cor_d*sin(vv))
      xtable(itab_corr,ii) = tt
      ytable(itab_cmot,ii) = ytable(itab_corr,ii) + ytable(itab_unc,ii)
      xtable(itab_cmot,ii) = xtable(itab_unc,ii)
    endloop
end
```

1.6.1.5 Adjust Input Motion and Mesh Size for Accurate Wave Propagation

The mesh size for the *FLAC* model is selected to ensure accurate wave transmission (see Section 1.4.2). Based upon the elastic properties listed in Table 1.3, embankment soil 2 has the lowest shear wave speed (781 ft/sec, for a shear modulus of 2630 ksf and a saturated density of 4.31 slugs/ft^3). If the largest zone size in the *FLAC* model is selected to be 10 ft in order to provide reasonable runtimes for this example, then the maximum frequency that can be modeled accurately is

$$f = \frac{C_s}{10\ \Delta l} \approx\ 7.8\ \text{Hz} \tag{1.126}$$

Before applying the acceleration input record, it is filtered to remove frequencies above 5 Hz (by using the *FISH* function "FILTER.FIS" described in Section 3 in the ***FISH* volume**). This filtering value is selected to account for the reduction in shear wave speed that may occur in some of the materials during the dynamic loading stage, as indicated in Figure 1.91. The acceleration history filtered at 5 Hz is shown in Figure 1.97, the power spectrum for the filtered acceleration wave is shown in Figure 1.98, and the power spectrum for the corresponding velocity wave is shown in Figure 1.99. Note that the difference between the frequency content of the unfiltered and filtered acceleration and velocity waves is minor (compare Figures 1.94 and 1.95 to Figures 1.98 and 1.99).

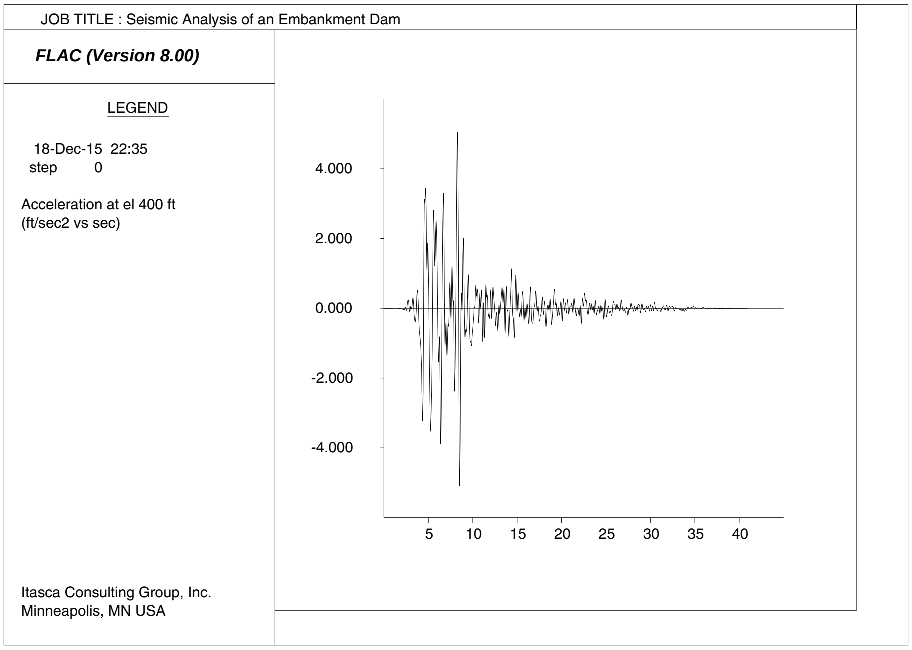

Figure 1.97 Horizontal acceleration time history at elevation 400 ft (upward-propagating motion from deconvolution analysis) with 5 Hz filter and baseline corrected

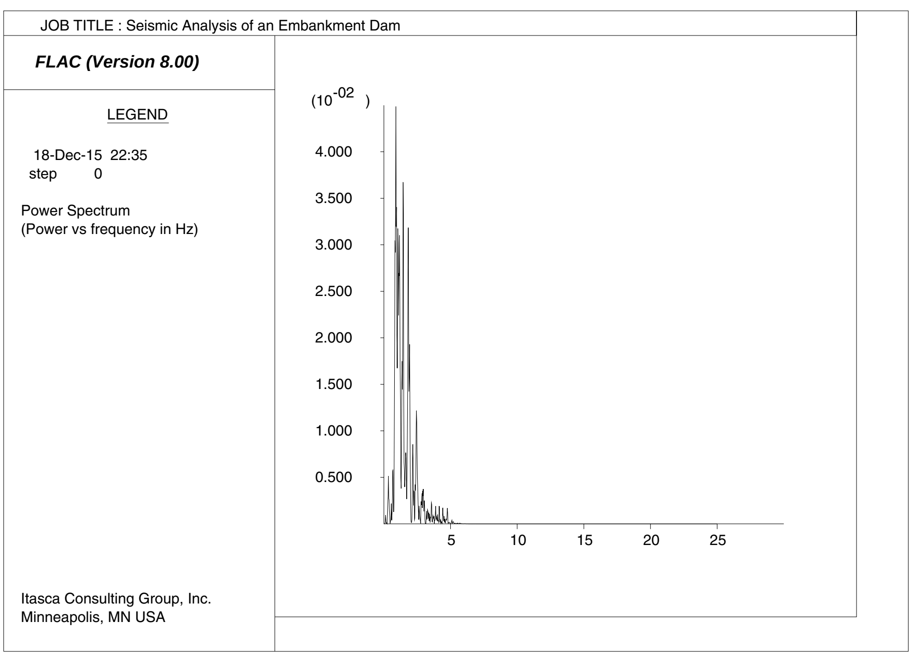

Figure 1.98 Power spectrum of horizontal acceleration time history with 5 Hz filter

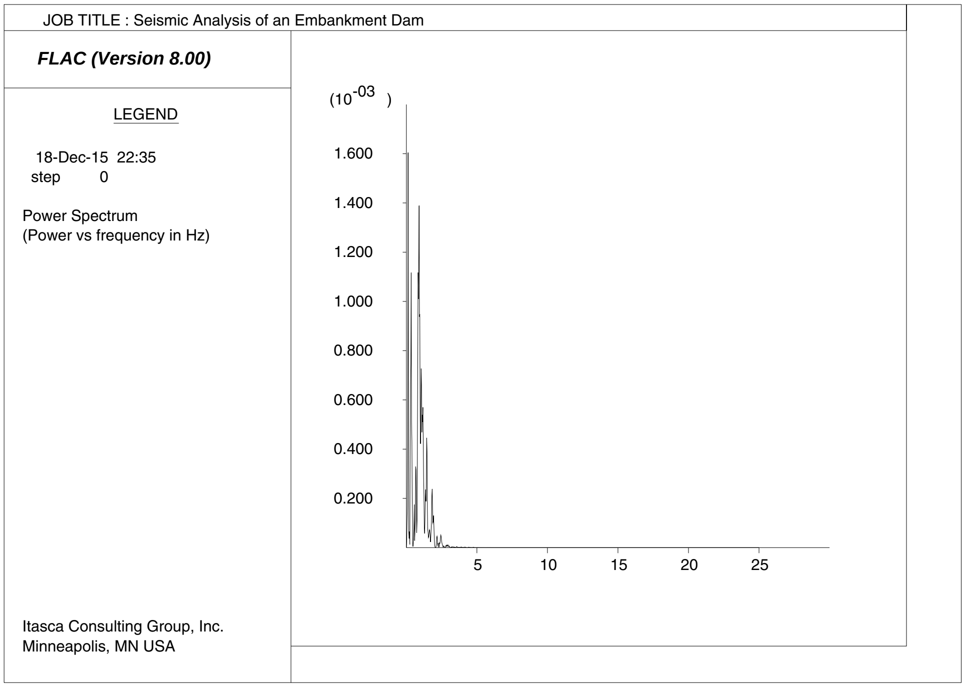

Figure 1.99 Power spectrum of horizontal velocity time history with 5 Hz filter of acceleration history

The data file "INPUT.DAT," listed in Example 1.26, includes the different steps performed in filtering the input acceleration record, integrating this record to produce velocity and displacement histories, and correcting for baseline drift if *FISH* is used for signal processing. The resultant, corrected velocity record, stored in table 104 in this data file, is the input motion for the embankment dam analysis.

Example 1.26 "INPUT.DAT" – Input wave characterization

```
hist 99 read acc_target.his
hist write 99 table 99
hist 100 read acc_deconv.his
hist write 100  table 100
save inp1.sav
set echo off
call fft_tables.fis
set fft_inp1=100 fft_inp2=110
fft_tables
set echo off
call Fft.fis
fftransform
set echo off
call INT.FIS
```

```
set int_in=100 int_out=201
integrate
set echo off
set fft_inp1=201 fft_inp2=210
fft_tables
set echo off
fftransform
save inp2.sav
restore inp1.sav
set echo off
call Filter.fis
set filter_in=100 filter_out=101 Fc=5
filter
set echo off
call fft_tables.fis
set fft_inp1=101 fft_inp2=110
fft_tables
set echo off
call Fft.fis
fftransform
save inp3.sav
set echo off
call INT.FIS
set int_in=101 int_out=102
integrate
set echo off
call INT.FIS
set int_in=102 int_out=103
integrate
save inp4.sav
restore inp3.sav
set echo off
call INT.FIS
set int_in=101 int_out=102
integrate
set echo off
call baseline.fis
set itab_unc=102 itab_corr=120 drift=0.296 ttime=40.0
set itab_cmot=104
baseline
set echo off
call INT.FIS
set int_in=104 int_out=103
integrate
set echo off
call INT.FIS
```

```
set int_in=102 int_out=105
integrate
set echo off
set fft_inp1=104 fft_inp2=210
fft_tables
set echo off
fftransform
save inp5.sav
;
;*** plot commands ****
;plot name: input acc
plot hold table  100 line
;plot name: acc - fft
plot hold table 110 line
;plot name: vel - fft
plot hold table 210 line
;plot name: input disp
plot hold table 103 line
;plot name: input vel
plot hold table 102 line
;plot name: corr. vel
plot hold table  104 line
```

The input motion can be generated for this example by using the GUI. The procedure to create the filtered and baseline-corrected input motion and save it as table 104 is as follows. The acceleration history ("ACC_DECONV.HIS") is read into *FLAC* via the READ button in the UTILITY/HISTORY tool. The EXECUTE button should be pressed to execute the command. The history is then converted into a table by pressing the HISTORY -> TABLE button in the UTILITY/HISTORY tool. The dialog shown in Figure 1.100 appears, and the acceleration history (previously assigned ID number 100) is converted into a table (designated by ID number 100).

The power spectrum is calculated in a two-step procedure. First, the *FISH* function named "FFT_TABLES.FIS" (accessed from the TABLES menu item in the UTILITY/FISHLIB tool) is used to assign tables for inputting the acceleration history and storing the calculated power spectrum. And then "FFT.FIS" is executed from the same location to create the power spectrum.

The acceleration record in table 100 is converted into a velocity record, using *FISH* function "INT.FIS" accessed from the TABLES menu item in the UTILITY/FISHLIB tool, and stored in table 201. A power spectrum is calculated for the velocity record using the same procedure as for the acceleration record.

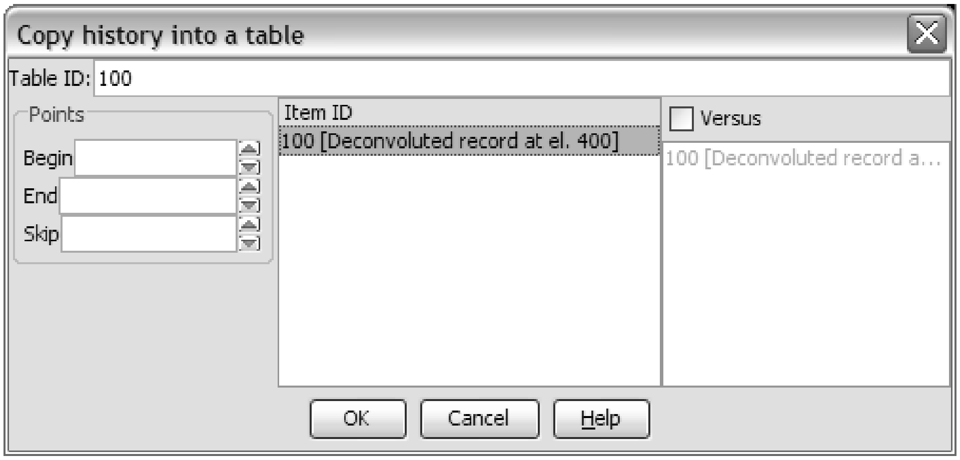

Figure 1.100 Copy history into a table

The *FISH* function “FILTER.FIS” is accessed from the TABLES menu item in the UTILITY/FISHLIB tool to filter the acceleration at 5 Hz. The filtered table is given the ID number 101, and the cutoff frequency is set to 5 Hz, as shown in the dialog in Figure 1.101. OK is pressed to execute this *FISH* function and create the filtered record.

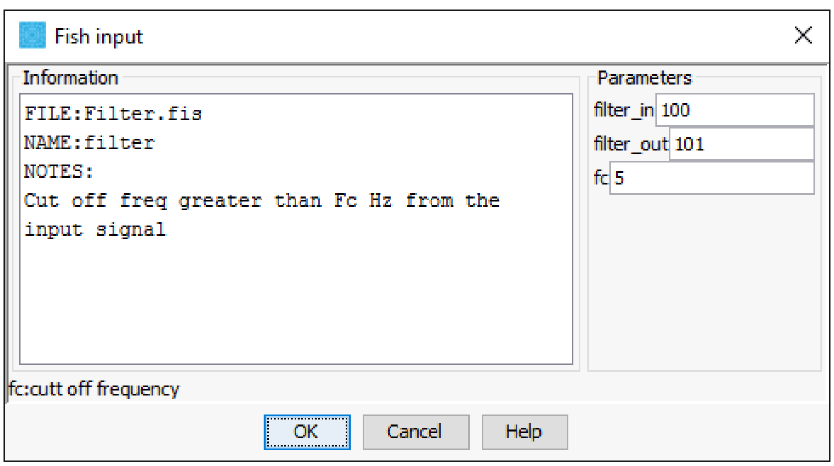

Figure 1.101 Input for **`filter`** *FISH function*

In order to perform the baseline correction, the filtered acceleration in table 101 is integrated (with “INT.FIS”) to produce a velocity record and stored in table 102. Then, a low frequency sine wave is added to this velocity record to produce a final displacement of zero. The sine wave is given in “BASELINE.FIS” in Example 1.25. This *FISH* function is accessed from the *Fish editor* resource pane. The input dialog for this *FISH* function is shown in Figure 1.102.

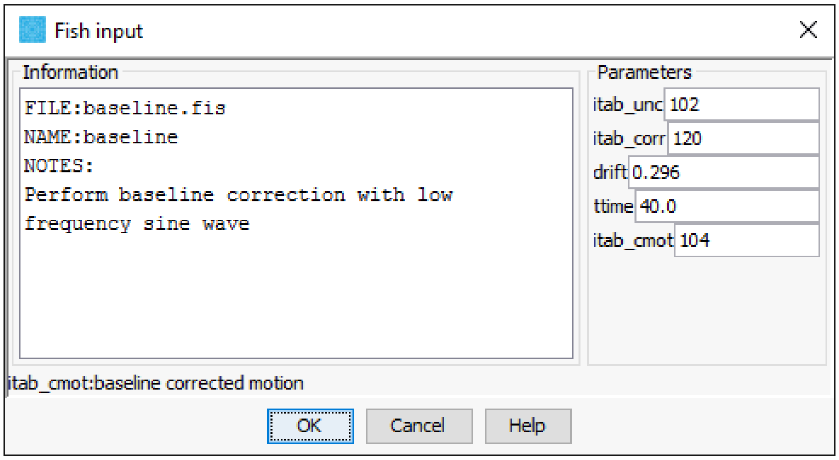

Figure 1.102 Input for **`baseline`** *FISH function*

The corrected velocity wave is written to table 104. Table 104 is written to a file named "TABLE104.DAT" by selecting SAVE in the UTILITY/TABLE tool. The input velocity is plotted in Figure 1.103:

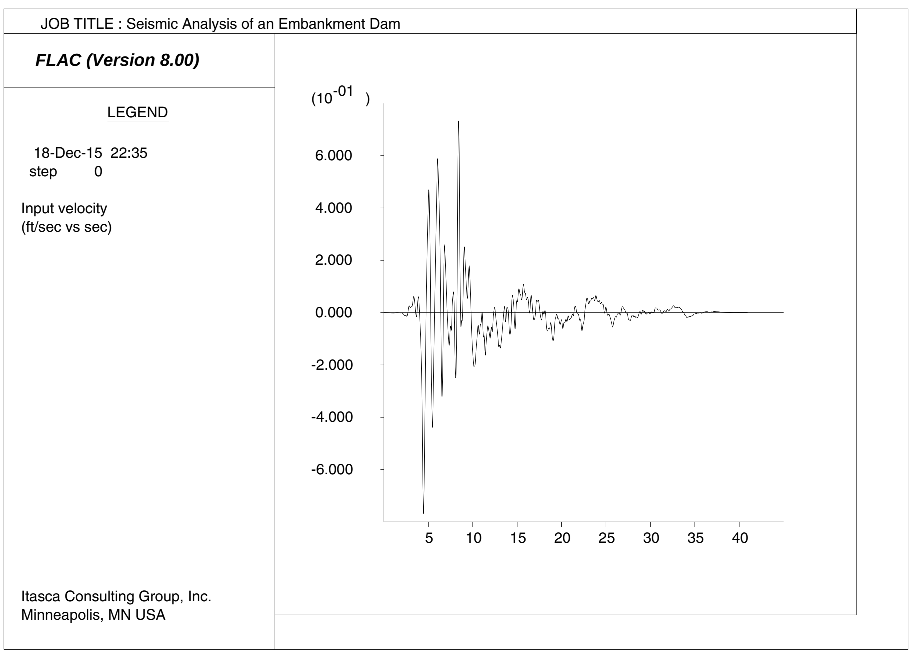

Figure 1.103 Input velocity (in ft/sec versus seconds) with 5 Hz filter and baseline corrected

1.6.1.6 FLAC Model Project Setup and Grid Creation

The *FLAC* model options selected for this analysis are shown activated in the *Model options* dialog displayed in Figure 1.104. The dynamic analysis and groundwater flow options are selected. Advanced constitutive models are also included in order to access the Finn model, which will be used for the liquefaction calculation phase. Twenty extra grid variables are set aside to save user-defined variables, such as excess pore pressures, during the analysis. The Imperial system of units is specified for this analysis. Finally, the factor-of-safety calculation mode is activated in order to check the stability condition of the dam before the earthquake loading is applied.

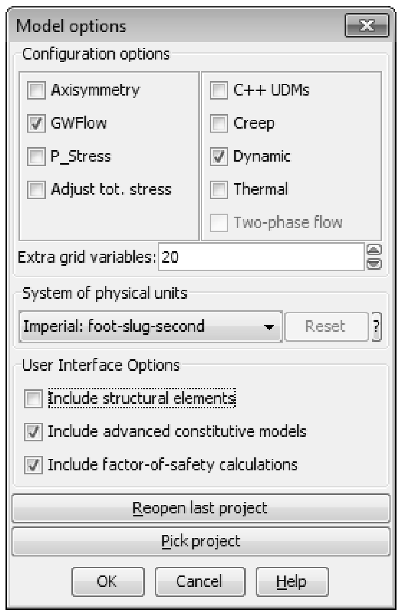

Figure 1.104 Model options selected for the embankment dam example

The embankment dam model is now created. (The commands that will be generated for this model are listed in “EARTHDAM.DAT” in Example 1.30.)

The dynamic calculation phase is performed using the large-strain mode in *FLAC*. When significant deformation and distortion of the grid is anticipated, as in this example, it is important to minimize the number of triangular-shaped zones in the mesh and, in particular, those along slope faces, as discussed in Section 1.5.3, Step 4. A recommended procedure to provide a grid with uniform spacing of quadrilateral zones and a minimum number of triangular zones is described below.

First, the problem geometry is created in the SKETCH tool. The embankment dam geometry is shown in Figure 1.105. The geometry is then copied to the GEOMETRY BUILDER. (See Figure 1.106.) The (3) BLOCKS *Edit* stage is selected to check that one block is created for zoning, and the BUILD button is pressed to extract the block for editing in the VIRTUAL/EDIT tool.

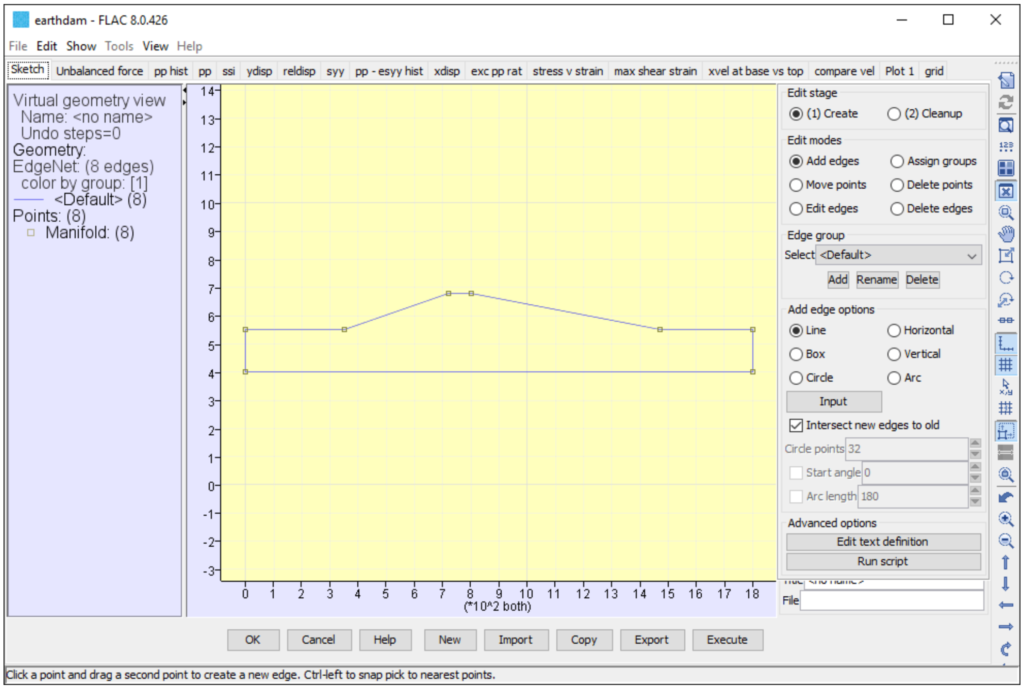

Figure 1.105 Create embankment dam geometry in SKETCH *tool*

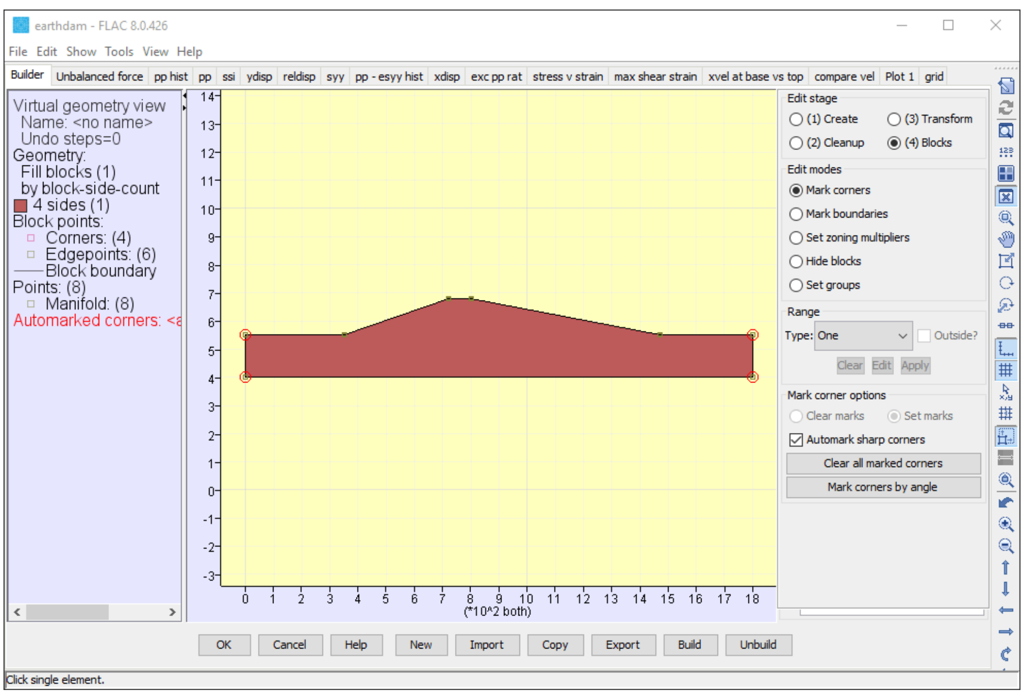

Figure 1.106 Create one zoning block in the GEOMETRY BUILDER *tool by pressing* BUILD

Roller boundaries are assigned along the sides of the model, and a fixed boundary along the base, in the VIRTUAL/EDIT tool. Note that if a roller boundary is specified along the bottom boundary, then the foundation is free to slide along the base, which may cause unrealistic failure modes.

A 180 × 28 quadrilateral-zone mesh is also selected in the tool. The maximum zone size is approximately 10 ft. The tool is shown in Figure 1.107. The virtual grid is executed to create the *FLAC* model by pressing the VIRTUAL/EXECUTE button.

The foundation soil layers and the embankment core and shell regions are delineated by lines generated using the ALTER/SHAPE tool. Then the different materials and properties, listed in Table 1.3, are specified, corresponding to Mohr-Coulomb materials, and assigned using the MATERIAL/ASSIGN and MATERIAL/GWPROP tools. The material properties are also stored in a separate database file, named "EARTHDAM.GMT," which can be accessed at any time in subsequent analyses.

The resulting model is shown in Figure 1.108. Note that some triangular zones are created within the mesh when the different soil regions are defined (see Figure 1.109). Triangular zones are also created at the slope toe and crest. It is difficult to eliminate triangular zones completely in this model. However, there are only a small number of these zones along the slope face, and the strengths of these zones can be readily adjusted if there is a distortion problem.

The model state, after the geometry shaping is complete and materials are assigned, is saved in the *GUI Project Tree* with the name "EDAM1.SAV." The model is now ready to begin the analysis stage.

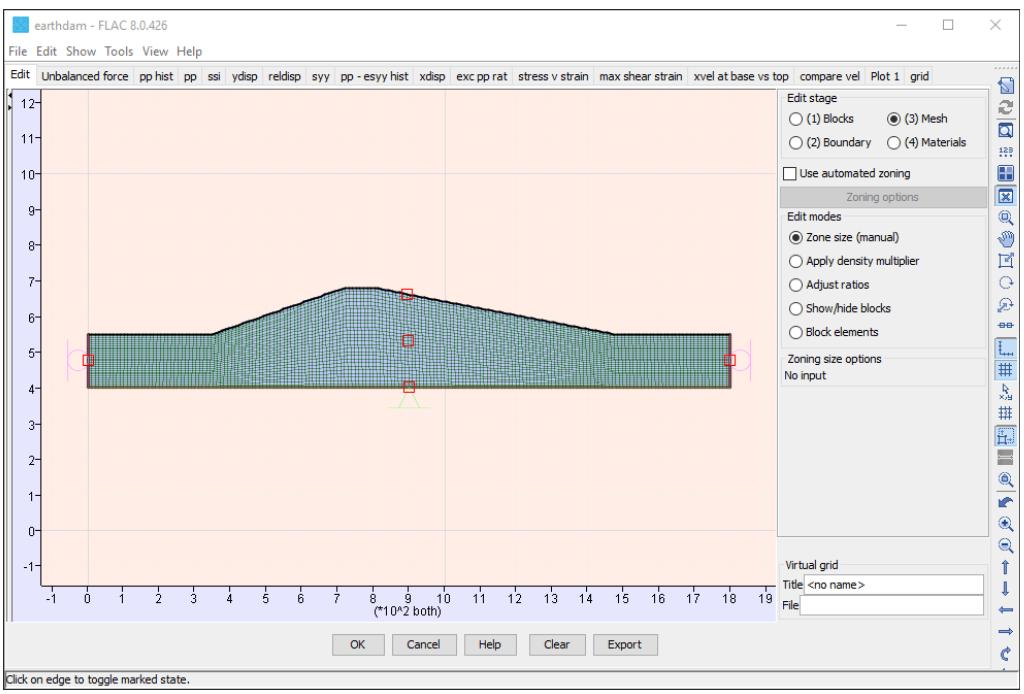

Figure 1.107 Boundary conditions are assigned using the (2) BOUNDARY stage and the mesh size is chosen using the (3) MESH stage in the VIRTUAL/EDIT tool

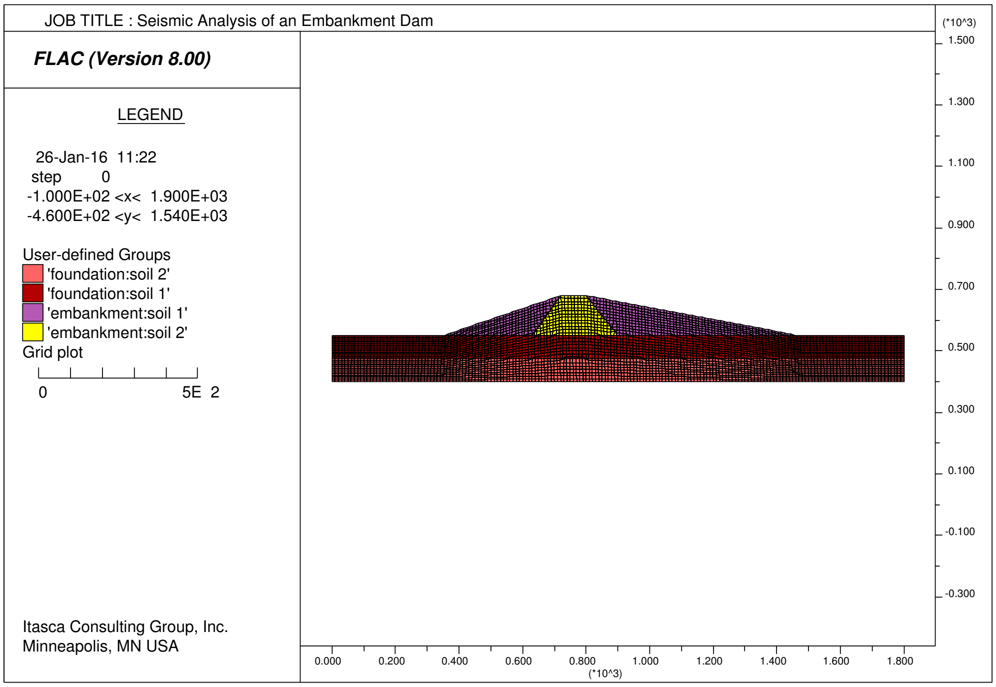

Figure 1.108 Embankment dam model with foundation and embankment soils assigned

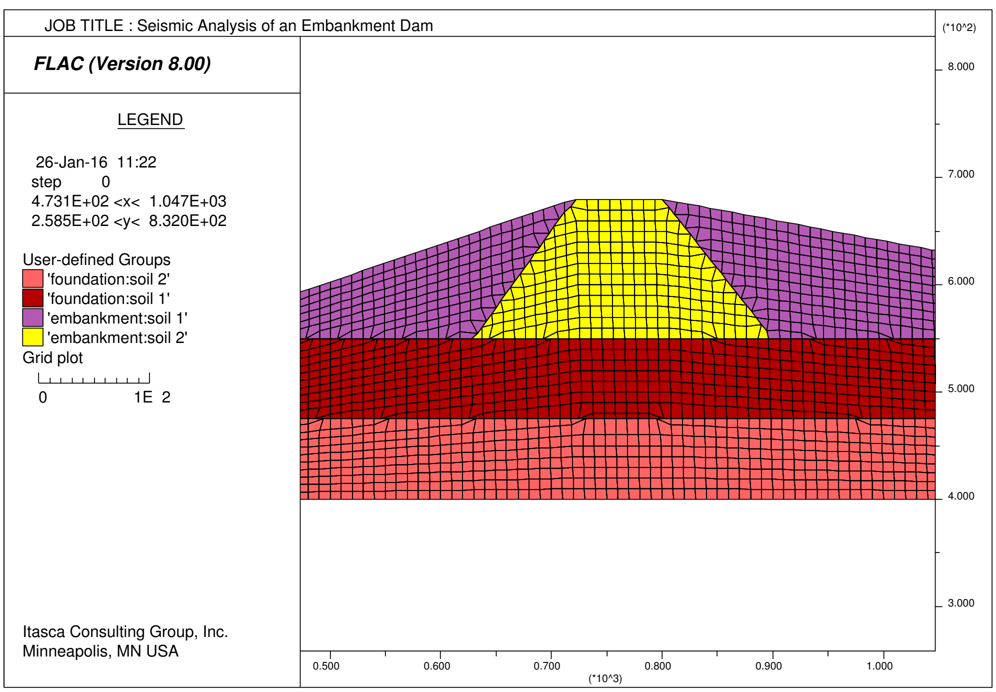

Figure 1.109 Close-up view of embankment dam model

1.6.1.7 Establish Initial State of Stress

State of Stress before Raising Reservoir Level

The analysis is started from the state before the embankment is constructed. The construction process may affect the stress state, particularly if excess pore pressures develop in the soils and do not dissipate completely during the construction stages. The embankment can be constructed in stages, with a consolidation time specified in the *FLAC* model, if pore-pressure dissipation is a concern. In this example, the excess pore pressures are assumed to dissipate before a new lift of embankment material is placed.

It should be noted that staged modeling of the embankment lift construction also provides a better representation of the initial, static shear stresses in the embankment. This is important, particularly in a liquefaction analysis, because the initial, static shear stresses can affect the triggering of liquefaction. In this simplified example, the embankment is placed in one stage. However, it is recommended that the lift construction stages be simulated as closely as is practical, in order to provide a realistic representation of the initial stress state.

The embankment materials are temporarily removed from the model by using the MATERIAL/CUT&FILL tool. These materials will be added back after the calculation for the initial equilibrium state of the foundation.

The water density of 1.94 slugs/ft^3 and gravitational magnitude of 32.2 ft/sec^2 are assigned, and fluid-flow and dynamic-analysis modes are turned off in the global SETTINGS tools.

The most efficient way to achieve an equilibrium stress state in a saturated, horizontally layered soil is to use the special *FISH* tool **ininv**, provided in the UTILITY/FISHLIB library. This function calculates the pore pressures and stresses automatically for a model containing a phreatic surface. The function requires the phreatic surface height (**wth** = 550 in this example) and the ratios of horizontal to vertical effective stresses (assumed to be **k0x** = **k0z** = 0.5 in this example). The pore pressure, total stress and effective stress distributions are then calculated automatically, accounting for the different soil unit weights, and the position of the water table. The equilibrium state is checked (using the **SOLVE elastic** option in the RUN/SOLVE tool). Figure 1.110 shows the initial pore-pressure distribution in the foundation soils. This state is saved in the *Project Tree* as “EDAM2.SAV.”

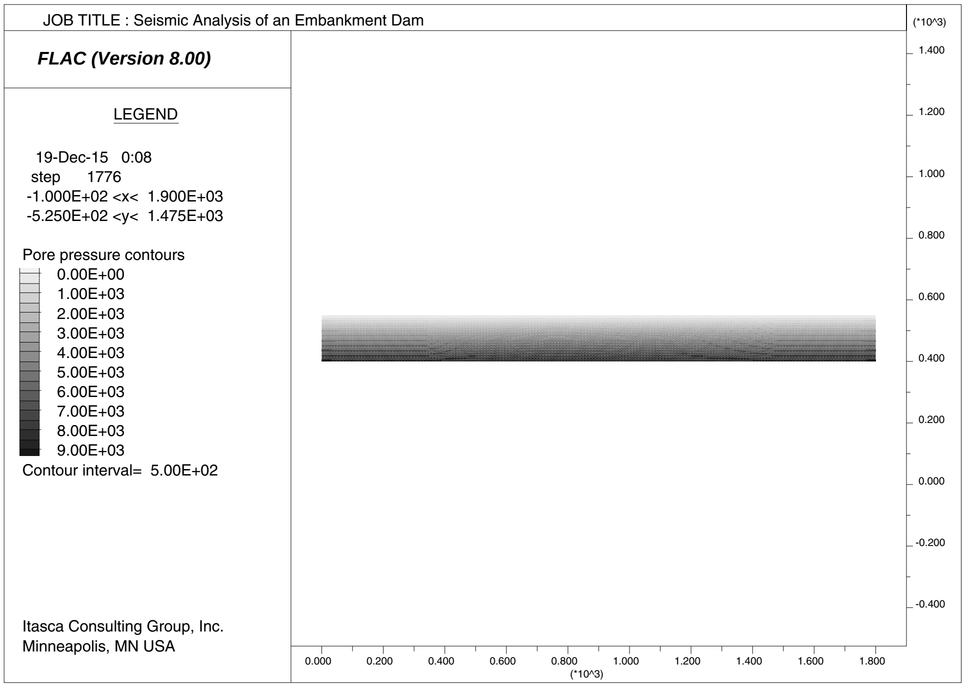

Figure 1.110 Pore pressure distribution in foundation soils

The embankment materials can be added to the model in stages, to simulate the construction process, by using the MATERIAL/CUT&FILL tool. In this example, both embankment soils 1 and 2 are added simultaneously, and pore pressures are assumed not to change. The displacements resulting from adding the embankment in one step are shown in Figure 1.111. This "construction step" is done to simplify the example; a more rigorous analysis should follow the construction sequence as closely as possible, in order to produce a more realistic displacement pattern and initial stress state. The saved state at this stage in named "EDAM3.SAV."

The model is run in small-strain mode up to this stage and, consequently, the gridpoint positions are not changed. This is done so that the embankment crest elevation (680 ft) does not change. If significant deformation occurs during embankment construction, making it necessary to perform this stage in large-strain mode, then the initial embankment crest elevation for the embankment zones (prior to construction) would need to be raised in order to obtain a specified elevation after construction.

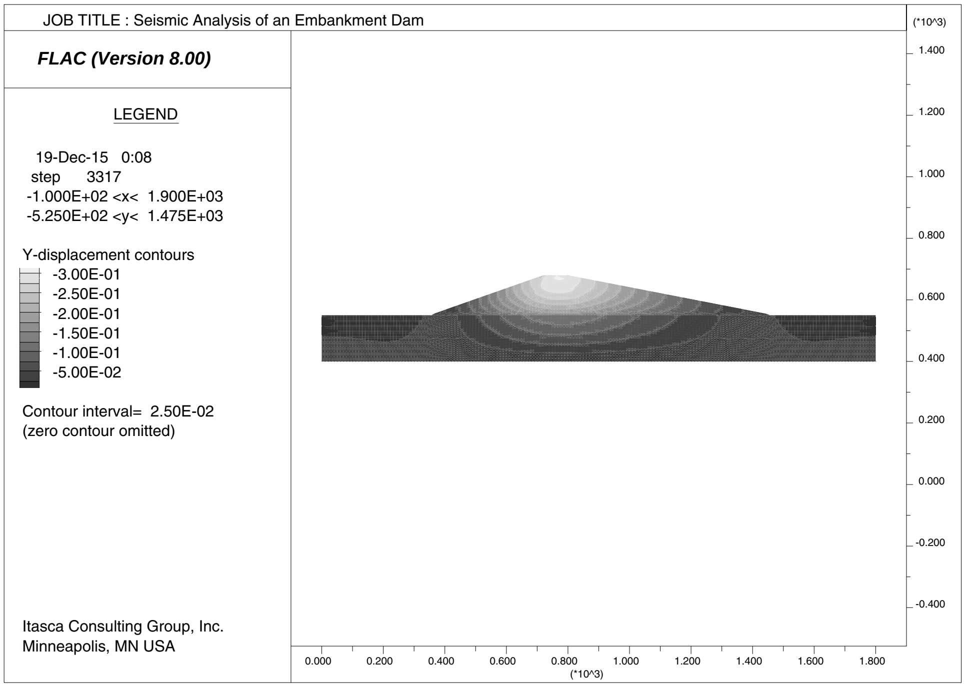

Figure 1.111 Displacements induced by embankment construction in one step

State of Stress with the Reservoir Level Raised

The earthquake motion is considered to occur when the reservoir level is at full pool (i.e., at its full height at elevation 670 ft). For this stage of the analysis, the pore-pressure distribution through the embankment and foundation soils is calculated for the reservoir raised to this height. The IN SITU/APPLY tool is used to set the pore-pressure distribution on the upstream side of the embankment, corresponding to the reservoir elevation at 670 ft. The mouse is dragged in this tool along the upstream boundary starting from the 670 elevation (at gridpoint i = 71, j = 29) and ending at the 400 elevation at the bottom-left corner of the model (at gridpoint i = 1, j = 1). The distribution parameters, shown in the *Apply value* dialog in Figure 1.112, produce a pore-pressure distribution along this boundary that ranges from zero at elevation 670 ft to 16,866.36 psf at elevation 400 ft.

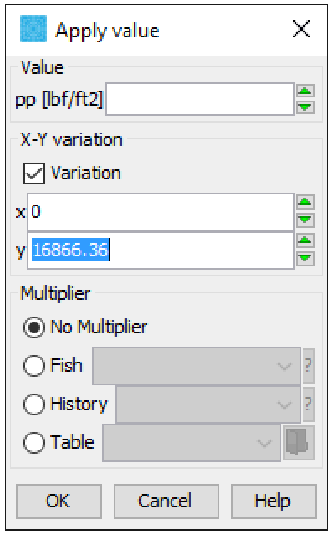

Figure 1.112 Pore-pressure distribution parameters corresponding to a reservoir elevation of 670 ft on the upstream side of the embankment

This calculation is first run in flow-only mode. The groundwater-flow calculation is turned on, and a water bulk modulus of 4.1×10^3 psf is assigned, in the Settings/GW tool. The low value of water modulus will speed the calculation to steady-state flow. There is a two-order magnitude difference between permeability of the embankment core and shell materials. Therefore, the fast-flow scheme **SET fastwb on** is also used to speed the calculation to steady state. In this scheme, the water bulk is scaled with permeability and porosity to speed the calculation. The mechanical calculation mode is turned off in the Settings/Mech tool. In the In Situ/Fix tool, the pore pressures are fixed at gridpoints along the downstream slope to allow flow across this surface. The porosity and permeability values are also specified for the embankment materials, in the Material/GwProp tool.

Figure 1.113 plots pore-pressure histories at different locations in the model, indicating that constant values are reached for the steady-state flow ratio limit. Figure 1.114 displays the pore-pressure distribution through the embankment and foundation at steady state. The saved state at steady-state flow is named “EDAM4.SAV.”

The static equilibrium state is now calculated for the new pore-pressure distribution. A pressure distribution is applied along the upstream slope to represent the weight of the reservoir water. This time a *mechanical* pressure is assigned in the In Situ/Apply tool. The pressure ranges from zero at elevation 670 ft (at gridpoint $\boldsymbol{i}$ = 71, $\boldsymbol{j}$ = 29) to 7496.2 psf at elevation 550 ft at the toe of the slope (at gridpoint $\boldsymbol{i}$ = 1, $\boldsymbol{j}$ = 29); the dialog is displayed in Figure 1.115. The groundwater-flow calculation is turned off, and the water bulk modulus is set to zero (in the Settings/GW tool). The mechanical calculation is turned on (in the Settings/Mech tool). The model is now solved for this applied condition, and the resulting total vertical-stress contour plot for the model at this stage is shown in Figure 1.116. We also note that the shear stresses at this stage are quite low (less than 10% of the total vertical stresses throughout most of the model) and should not adversely affect the application of hysteretic damping during the dynamic loading phase. (See Step 5 in Section 1.5.3.) The saved state at this stage is named “EDAM5.SAV.”

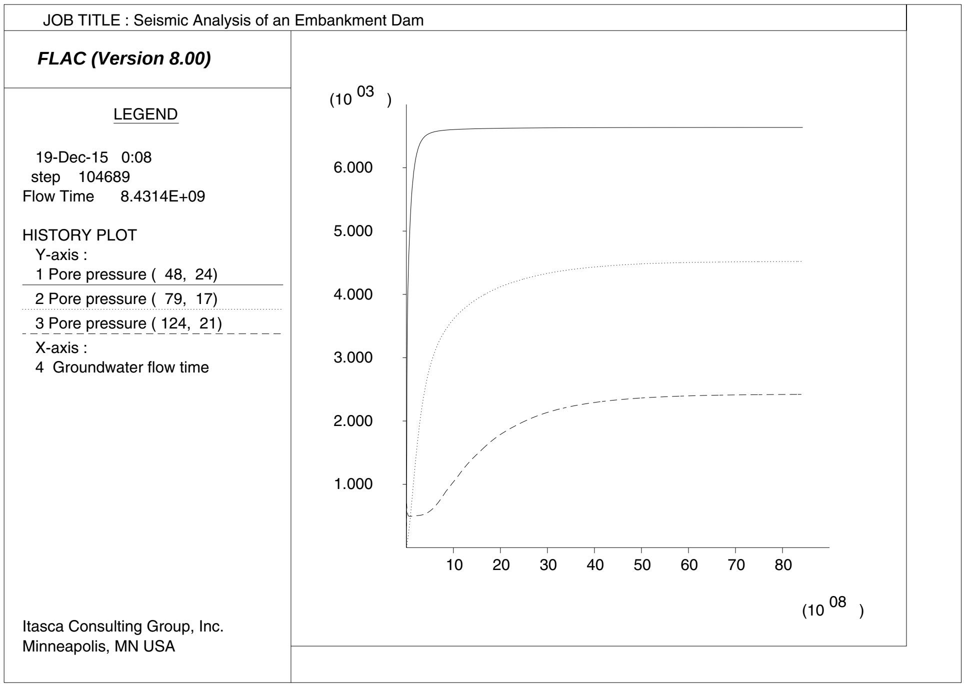

Figure 1.113 Pore-pressure histories

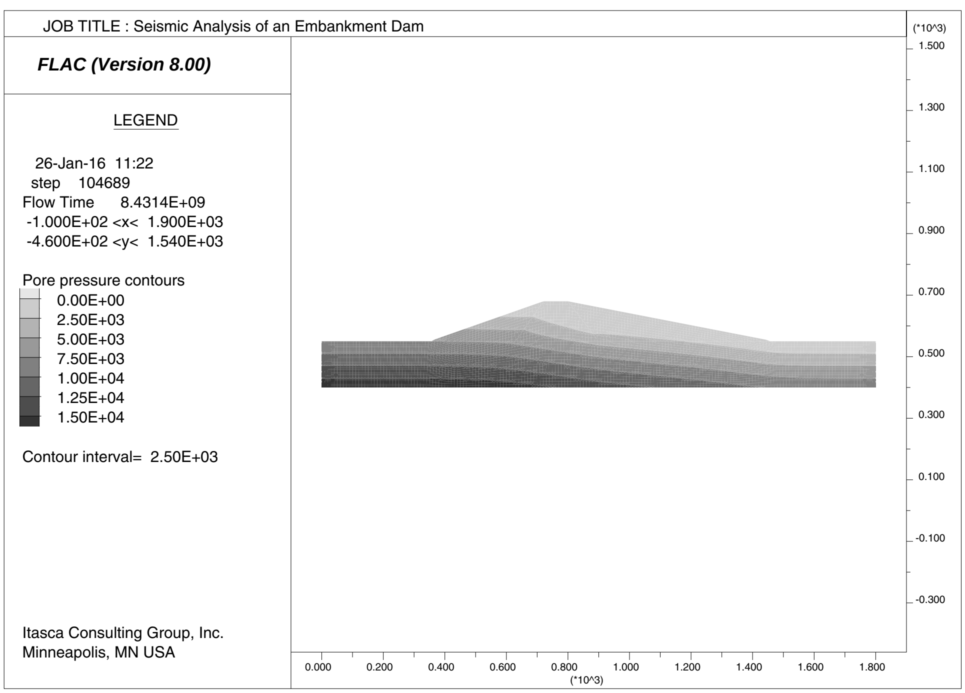

Figure 1.114 Pore-pressure distribution at steady state flow for reservoir raised to 670 ft

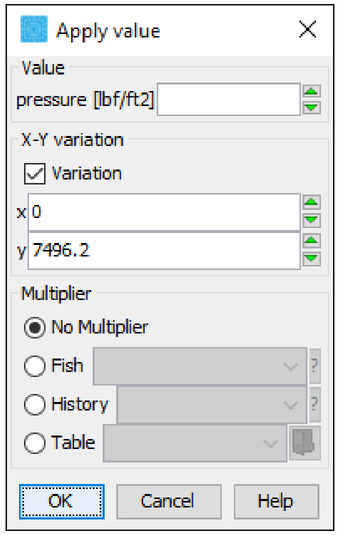

Figure 1.115 Mechanical pressure distribution parameters corresponding to a reservoir elevation of 670 ft on the upstream side of the embankment

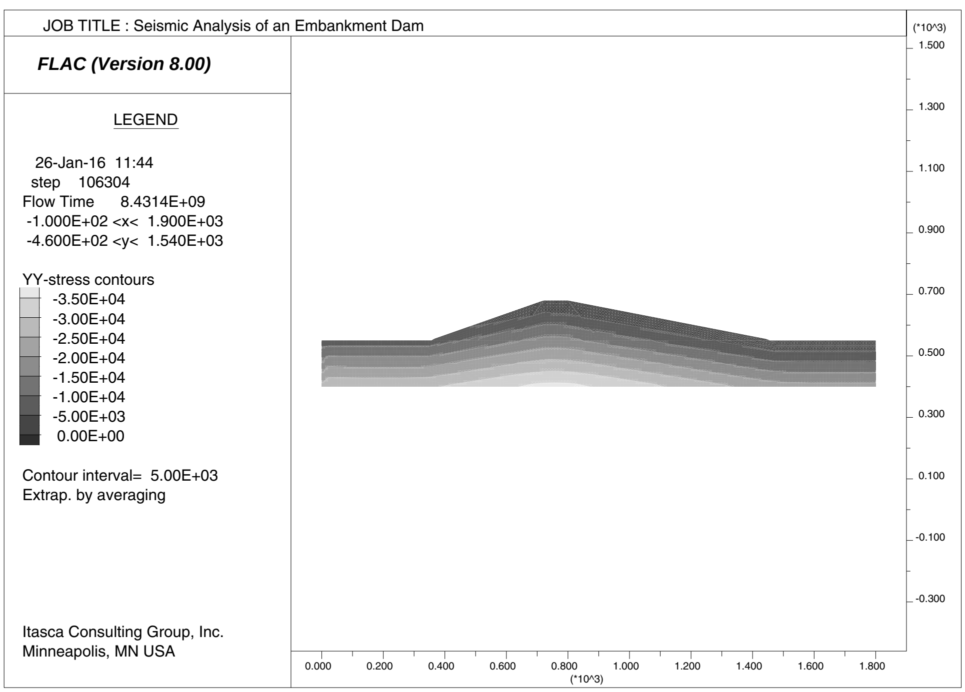

Figure 1.116 Total vertical-stress distribution at steady state flow for reservoir raised to 670 ft

Factor of Safety for Embankment Dam

This is considered to be the state of the embankment dam at the time of the earthquake event. A factor-of-safety calculation (**SOLVE fos**) is done as a check on the stability condition at this state. The result, plotted in Figure 1.117, shows that the safety factor is 2.35 and the weakest failure surface develops along the upstream slope.

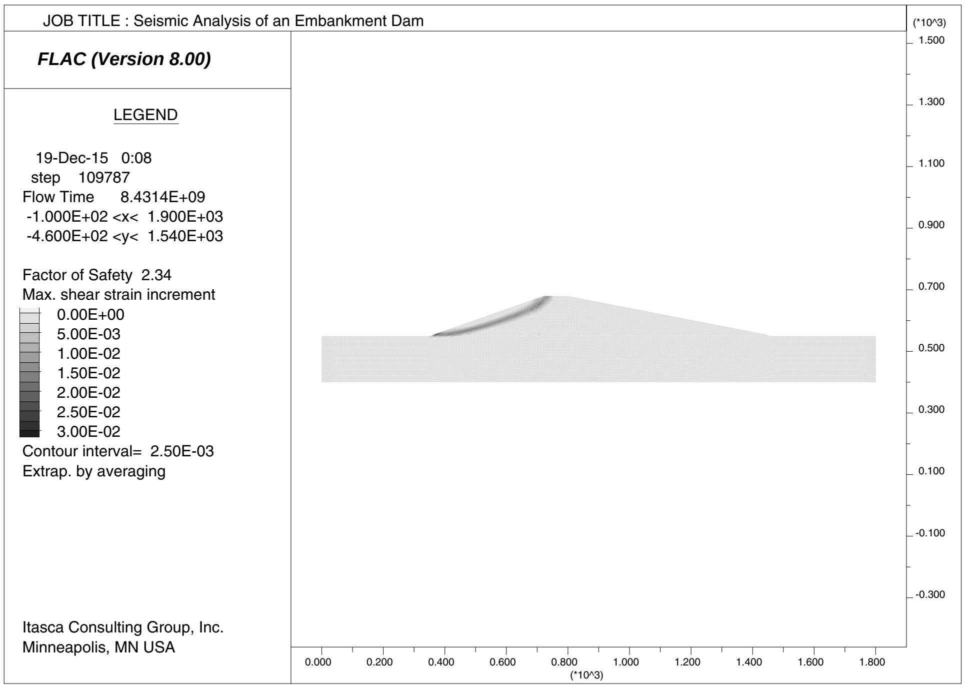

Figure 1.117 Factor-of-safety plot for embankment dam at full pool

1.6.1.8 Apply Dynamic Loading Conditions

For the dynamic loading stage, pore pressures can change in the materials due to dynamic volume changes induced by the seismic excitation. In order for pore pressures to change as a result of volume change, the actual value of water bulk modulus must be prescribed. The value of 4.18×10^6 psf is specified for the water bulk modulus. Note that the groundwater-flow mode is not active, because it is assumed that the dynamic excitation occurs over a much smaller time frame than required for pore pressures to dissipate. (*FLAC* can carry out the groundwater flow calculation in parallel with the dynamic calculation if dissipation is considered important. See Section 1.5.2.3.)

The following dynamic conditions are set in this first dynamic simulation, following the steps listed in Step 6 of Section 1.5.3. The dynamic calculation mode is turned on, using the [SETTINGS/DNYA] tool, and the large-strain mode is selected in the [SETTINGS/MECH] tool.

The filtered and baseline-corrected input velocity created previously and stored in table 104 is called into *FLAC* using the [UTILITY/CALL] tool and selecting the "TABLE104.DAT" file.

The displacements and velocities in the model are initialized by pressing the [DISPLMT & VELOCITY] button in the [IN SITU/INITIAL] tool. In this way, only seismic induced motions and deformations are shown in the model results. Damping is *not* prescribed for the preliminary dynamic simulations. Acceleration and velocity histories are recorded at several gridpoints throughout the model. Also, special *FISH* functions are implemented to monitor the shear strain and excess pore pressure at selected locations, and relative displacements along the upstream slope near the crest.* Examples of these functions are listed in Example 1.27. The velocity and shear strain histories are used to evaluate the dominant natural frequencies and maximum cyclic shear strains in the model, when no additional damping is prescribed. The *FISH* function **mon_ex** monitors shear strains throughout the model and stores the maximum shear strain calculated during the dynamic loading.

The dynamic boundary conditions are now applied in the [IN SITU/APPLY] tool. First, the free-field boundary is set for the side boundaries by selecting the [FREE-FIELD] button.

Next, the dynamic input is assigned to the bottom boundary. In this model, a compliant boundary condition is assumed for the base (i.e., the foundation materials are assumed to extend to a significant depth beneath the dam). Therefore, it is necessary to apply a quiet (viscous) boundary along the bottom of the model to minimize the effect of reflected waves at the bottom.

Quiet boundary conditions are assigned in both the x- and y-directions by first selecting the [XQUIET] button and dragging the mouse along the bottom boundary, and then selecting the [YQUIET] button and repeating the procedure.

---

* Note that relative displacement is referenced to the base of the model. See **reldispx** in Example 1.27.

Example 1.27 FISH functions to monitor variables during seismic loading

```
def reldispx
   reldispx = xdisp(62,29) - xdisp(62,1)
   reldispy = ydisp(62,29) - ydisp(62,1)
end
;
def strain_hist
   array arr1(4)
   while_stepping
   dum1 = fsr(77,20,arr1)
   str_77_20=str_77_20 + 2.0 * arr1(4)
end
;
def inipp
   ppini   = pp(49,23)
end
;
def excpp
   excpp = pp(49,23) - ppini
end
;
def mon_ex
   array arr(4)
   while_stepping
   loop i (1,izones)
     loop j (1,jzones)
       if model(i,j) # 1
         dum = fsr(i,j,arr)
         ex_9(i,j)=ex_9(i,j) + 2.0 * arr(4)
         ex_10(i,j)= max(ex_10(i,j),abs(ex_9(i,j)))
       endif
     endloop
   endloop
end
```

The dynamic wave is applied as a shear-stress boundary condition along the base in the following manner. The STRESS/SXY boundary-condition type is selected in the IN SITU/APPLY tool, and the mouse is dragged from the bottom-left corner of the model (gridpoint $i = 1, j = 1$) to the bottom-right corner ($i = 181, j = 1$). The ASSIGN button is pressed, which opens the *Apply value* dialog. The velocity record, in table 104, is considered a multiplier, v_s, for the applied value. The velocity record is applied by checking the TABLE radio button, and selecting table number 104 as the multiplier.

The applied value for sxy in the *Apply value* dialog is initially set to $-2\rho\, C_s$ (from Eq. (1.125)), in which ρ is the saturated density (4.462 slug/ft^3) and C_s is the shear wave speed (1048.6 ft/sec) for foundation soil 2. The input selections for the *Apply value* dialog are shown in Figure 1.118.

The model state is saved at this point and named “EDAM7E.SAV.”

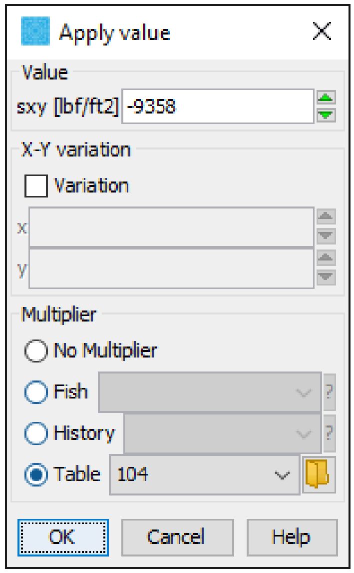

Figure 1.118 Apply shear stress boundary condition in Apply value dialog

1.6.1.9 Run Undamped Dynamic Simulations

Before running a dynamic model with actual material strength and damping properties, preliminary runs are performed to assess the effect of model boundary locations, and to estimate the maximum levels of cyclic strain and natural frequency ranges of the model system. These runs also help to evaluate the necessity for additional material damping in the model.

The input velocity applied at the base of the model is checked first to ensure that the calculated velocity corresponds to the input velocity given in Figure 1.103. The bottom boundary is deep enough so that velocity doubling, as illustrated in Example 1.2, has only a small effect on the calculated velocity at the model base. The comparison of calculated velocity to input velocity is shown in Figure 1.119. There is a slight difference between the input and calculated velocity. The conversion factor relating velocity to shear stress can be adjusted if a closer fit is desired.

The effect of velocity doubling is evident by comparing the velocity at the model base to that at the crest of the dam. As shown in Figure 1.120, there is a significant increase in the velocity amplitude at the free surface compared to the velocity at the base.

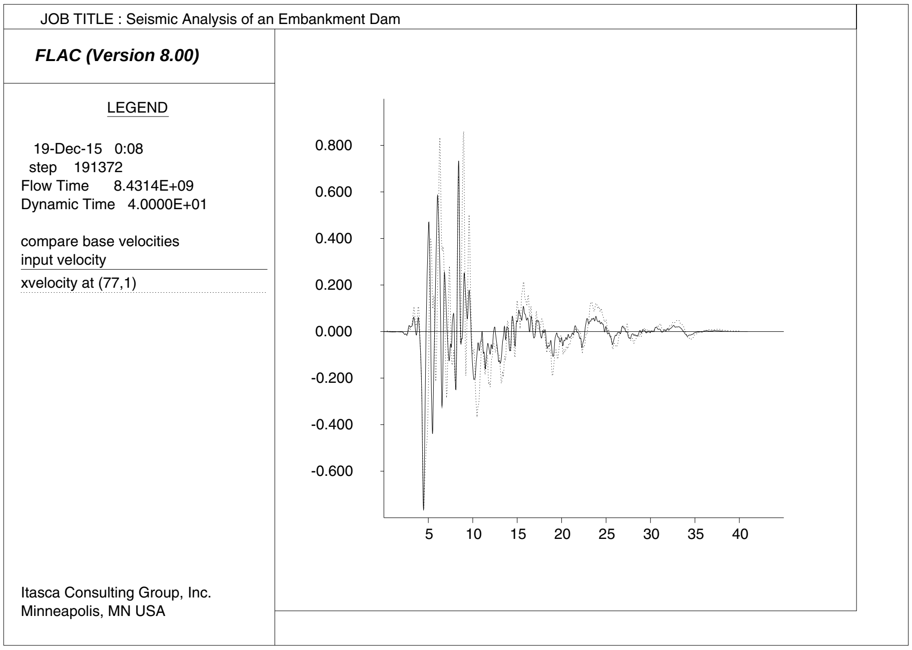

Figure 1.119 Comparison of input velocity to x-velocity monitored at model base, applied shear stress: $\sigma_{xy} = -2\rho\ C_s$ ***– undamped, elastic material***

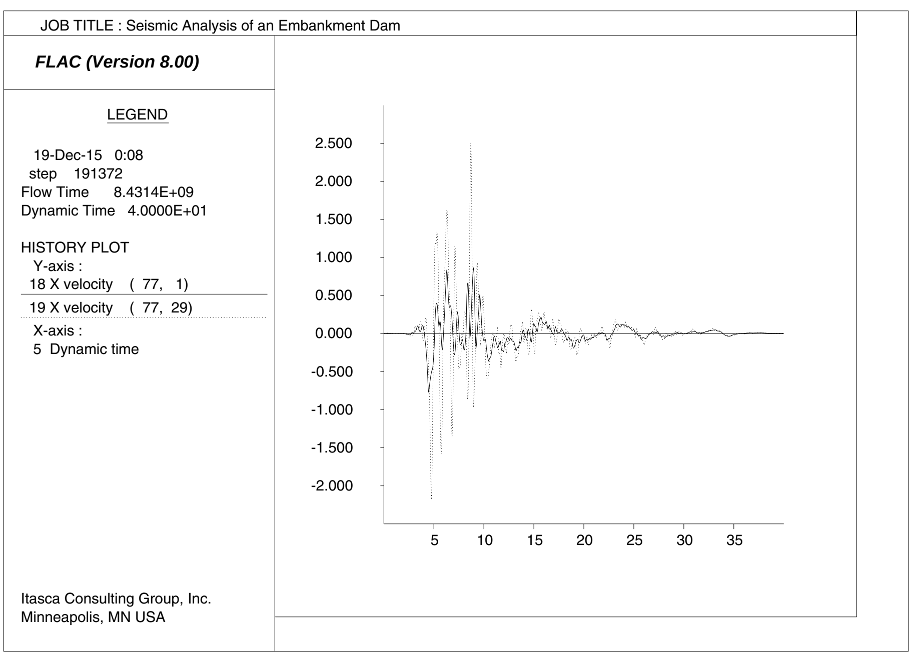

Figure 1.120 Comparison of velocity histories at the base and top of model – undamped, elastic material

Elastic simulations are made without damping, to estimate the maximum levels of cyclic strain and natural frequency ranges. Velocity and shear stress/strain histories are recorded at different locations in the *FLAC* model to calculate frequencies and strain levels.

Figure 1.121 plots shear stress versus shear strain in zone (77,20) located in embankment soil 2. Maximum shear strain contours throughout the model are plotted in Figure 1.122. Maximum shear strains of approximately 0.15% were observed. These strains are not considered to be sufficient to cause excessive reductions in shear modulus. The shear-modulus reduction factor is roughly 0.6 for this strain level, as shown in Figure 1.91.

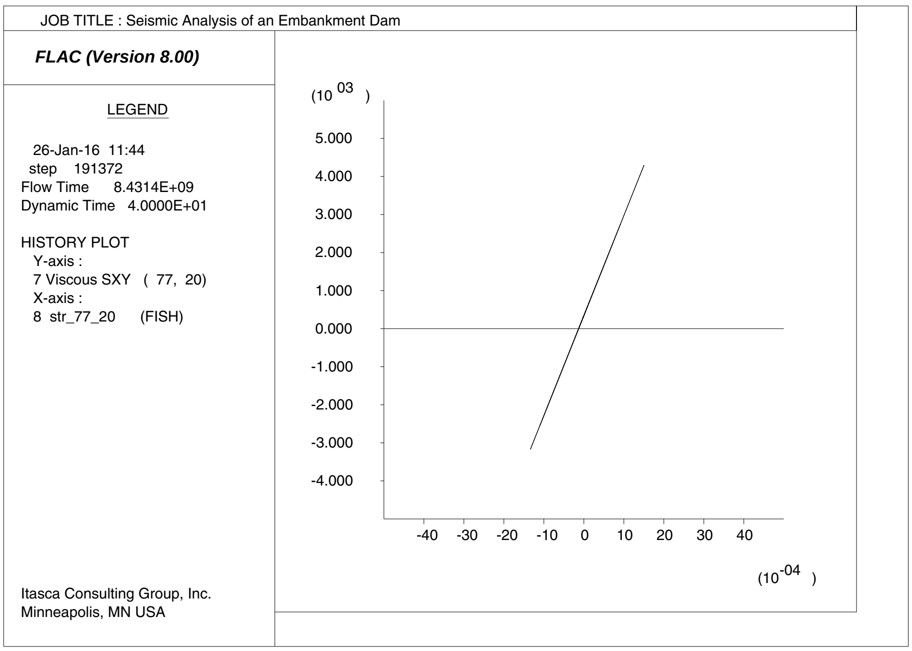

Figure 1.121 Shear stress versus shear strain in embankment soil 2 at zone (77,20) – undamped, elastic material

The frequency range for the natural response of the system is observed to be relatively uniform throughout the model. Figure 1.123 displays a typical power spectrum for this simulation; the predominant frequency was found to be approximately 1.0 Hz.

In this simulation, the dynamic input produces x-accelerations at the surface of the foundation soils that are very similar to the target motion (“ACC_TARGET.HIS”), as shown in Figure 1.124. The peak acceleration is approximately 11 ft/sec^2.

The undamped, elastic calculation is saved as “EDAM8E.SAV.” The fast Fourier analysis results are saved in “EDAM9E.SAV.”

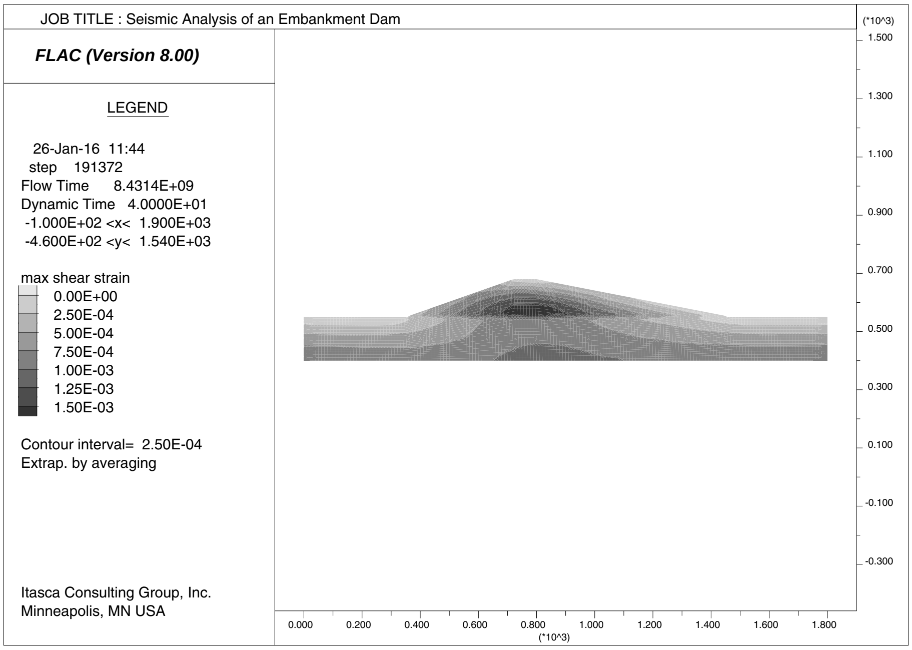

Figure 1.122 Maximum shear strain contours – undamped, elastic material

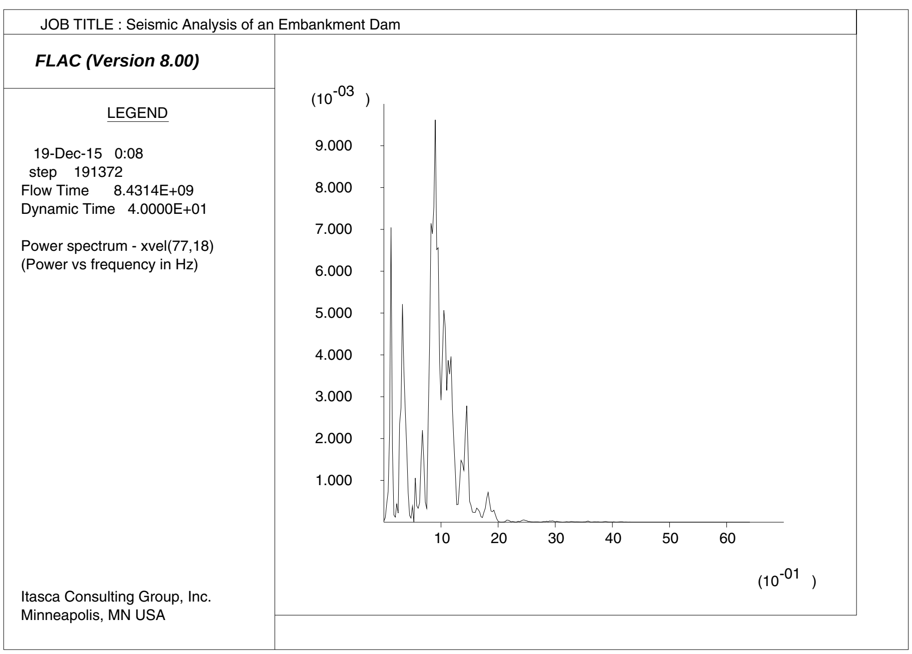

Figure 1.123 Power spectrum of x-velocity time history in embankment soil 2 at gridpoint (77,18) – undamped, elastic material

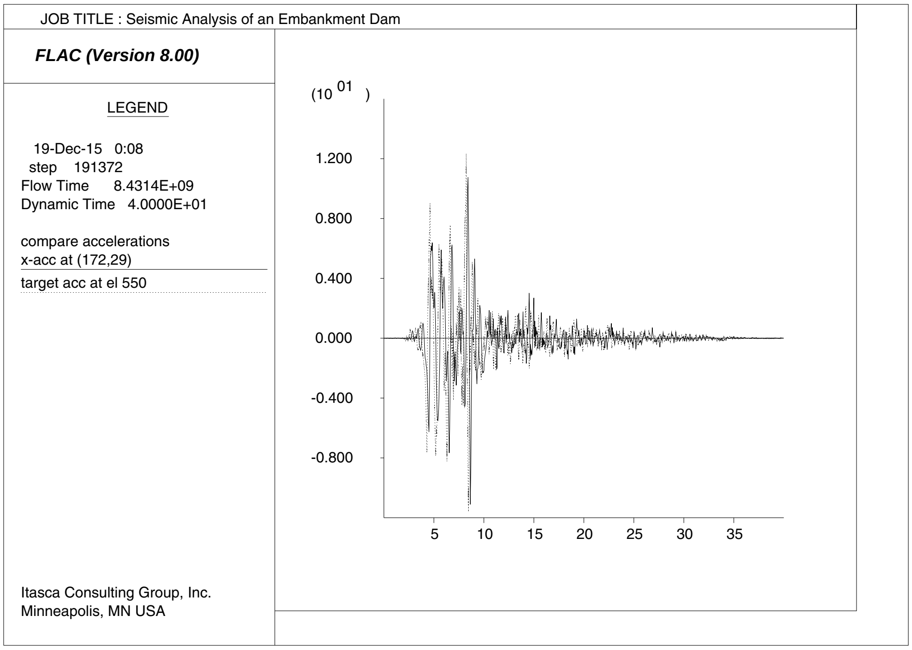

Figure 1.124 Comparison of target acceleration to x-acceleration monitored at surface of foundation soil 1 – undamped, elastic material

1.6.1.10 Run Damped Simulations with Actual Mohr-Coulomb Strength Properties

Simulation with Hysteretic Damping

Hysteretic damping is applied to correspond to the dynamic characteristics represented by the (G/G_{max}) and (λ) curves shown in Figures 1.91 and 1.92. These figures also show a comparison of the (G/G_{max}) and (λ) variations to those computed using the default hysteretic model in *FLAC*. The selected parameters ($L_1 = -3.156$ and $L_2 = 1.904$) for the default model produce curves that provide a reasonable match to the data up to approximately 0.1%, as shown in these figures. This is considered appropriate for the peak strain levels as identified from the undamped run.

A new branch is created with the same histories as the undamped, elastic case, and is saved as model state "EDAM6MH.SAV." Hysteretic damping is now assigned in the In Situ/Initial tool. The dialog shown in Figure 1.125 is opened by selecting the Zones type, checking the Hysteretic Damping menu item, and then Assign, to assign the same values for all zones in the model.

Hysteretic damping does not completely damp high-frequency components, so a small amount of stiffness-proportional Rayleigh damping is also applied. A value of 0.2% at the dominant frequency (1.0 Hz) is assigned in the *Dynamic damping parameters* dialog shown in Figure 1.126. Note that Rayleigh damping is applied by selecting the GPs type, and then Dynamic Damping in the In Situ/Initial tool.

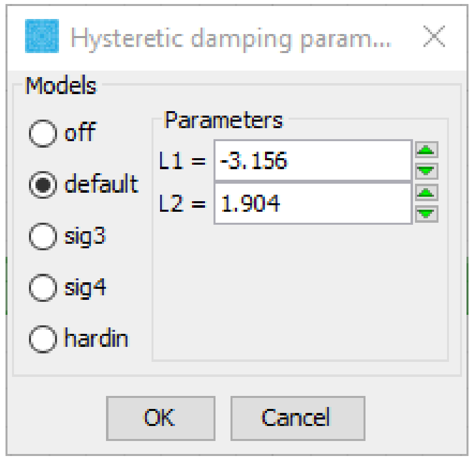

Figure 1.125 Hysteretic damping parameters

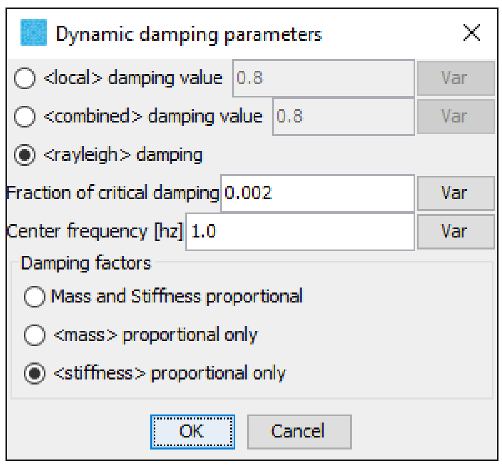

Figure 1.126 Rayleigh damping parameters used with hysteretic damping

The dynamic boundary conditions must be applied again from the In Situ/Apply tool. The free-field is applied on the side boundaries, and *sxy* stress history and quiet boundaries are applied at the base, in the same way as for the undamped simulation. The model state is saved at this stage as "EDAM7MH.SAV."

A new simulation is now made for a dynamic time of 40 seconds. Note that the dynamic timestep used for this calculation is approximately 3.6×10^{-4} seconds.

Movement of the embankment after 40 seconds is primarily concentrated along the upstream slope. This is shown in the x-displacement contour plot (in Figure 1.127) and the shear-strain increment contour plot (in Figure 1.128). The movement of gridpoint (62,29) along the upstream slope is shown in Figure 1.129. The effect of material failure and hysteresis damping is evident in the cyclic shear strain response; compare Figure 1.130 to Figure 1.121.

The pore pressure and effective vertical stress histories in Figure 1.131, recorded at ($\boldsymbol{i}$ = 49, $\boldsymbol{j}$ = 23) near the upstream face, illustrate the minor pore-pressure change in the embankment materials during the seismic loading.

The model state is saved at this stage as "EDAM8MH.SAV."

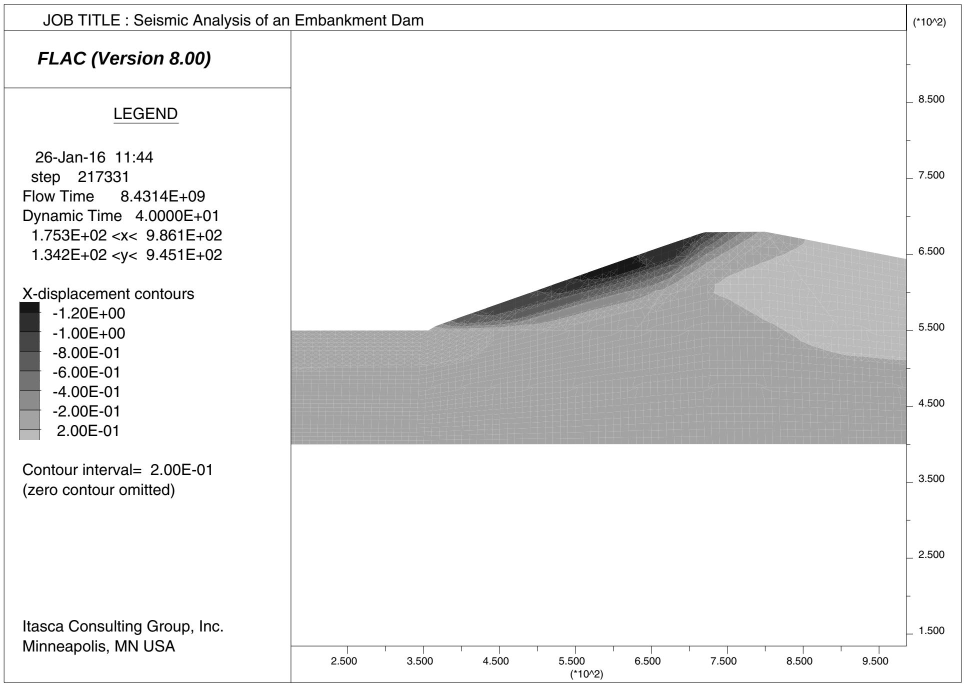

Figure 1.127 x-displacement contours at 40 seconds – Mohr-Coulomb material and hysteretic damping

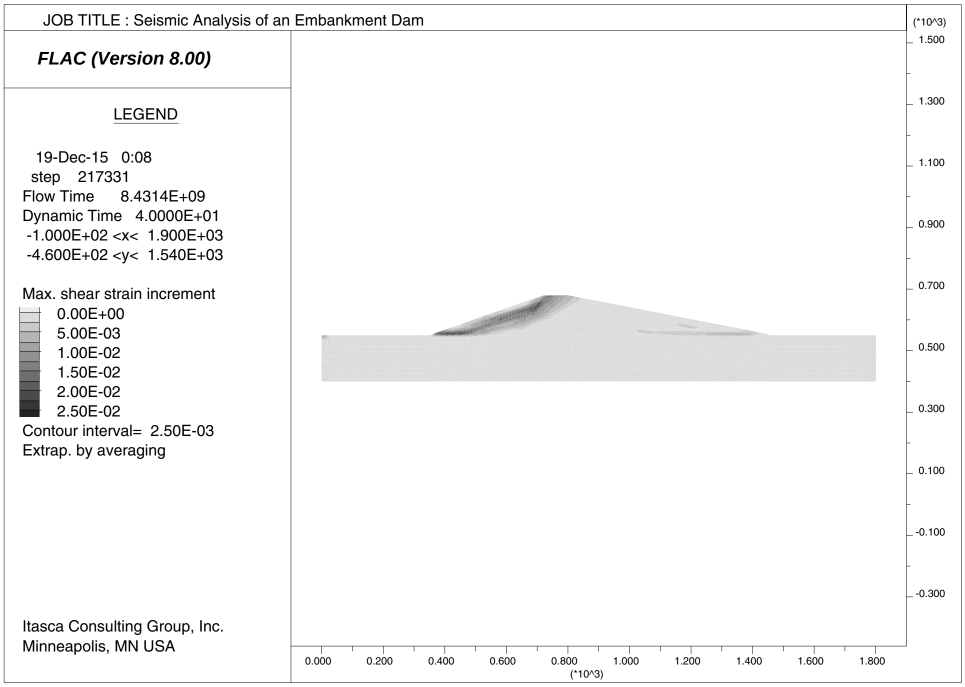

Figure 1.128 Shear-strain increment contours at 40 seconds – Mohr-Coulomb material and hysteretic damping

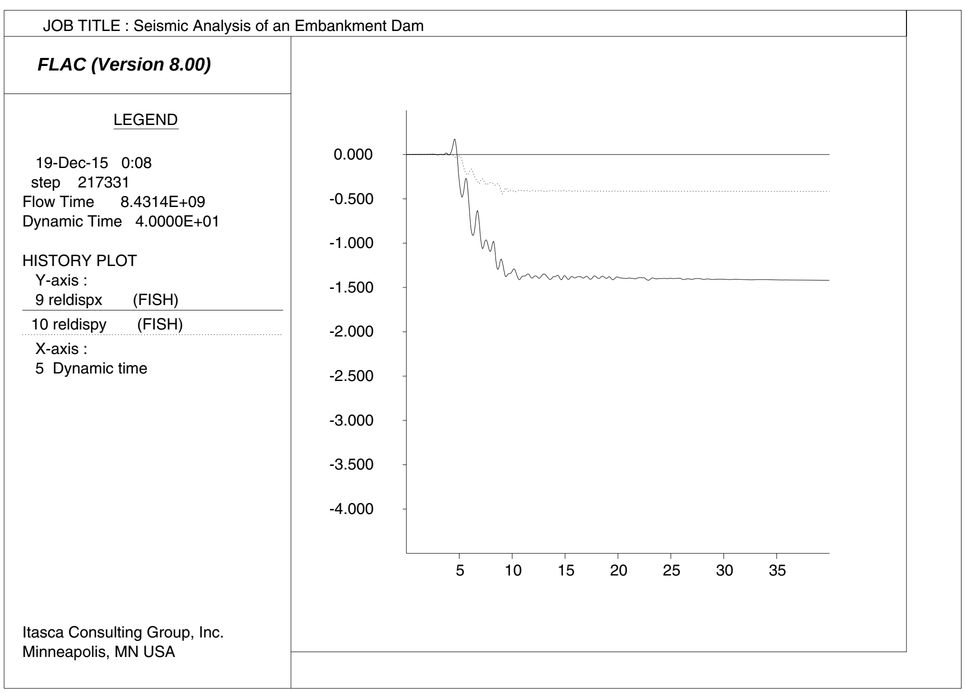

Figure 1.129 Relative displacements at gridpoint (62,29) along upstream slope – Mohr-Coulomb material and hysteretic damping

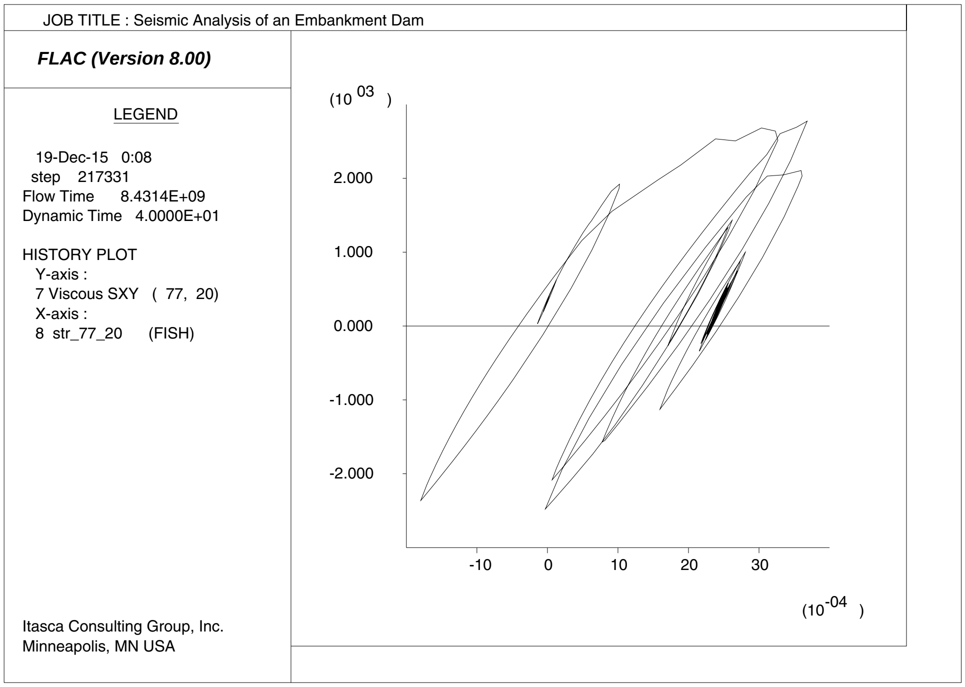

Figure 1.130 Shear stress versus shear strain in embankment soil 2 at zone (77,20) – Mohr-Coulomb material and hysteretic damping

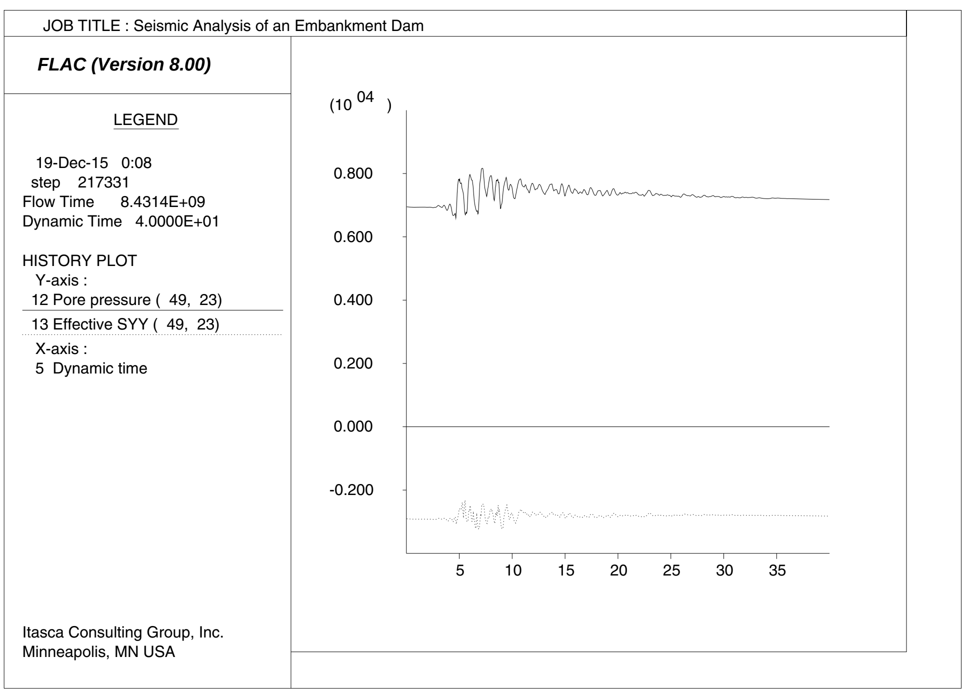

Figure 1.131 Pore-pressure and effective vertical stress near upstream slope – Mohr-Coulomb material and hysteretic damping

Simulation with Rayleigh Damping

The dynamic simulation stage is now repeated using only Rayleigh damping. The parameters for the Rayleigh damping model are initially selected based upon the *SHAKE* analysis described in Section 1.6.1.3. It is assumed that the parameters correspond to an equivalent uniform strain of approximately 0.08%. The initial shear modulus is reduced by a factor of 0.8, and the damping ratio is selected as 0.063. The center frequency for Rayleigh damping is 1.0 Hz, as determined from the input wave (see Figure 1.98) and the undamped analysis (for example, see Figure 1.124). The Rayleigh damping parameters are specified as shown by the dialog in Figure 1.132. The *FISH* function "GREDUCE.FIS" is executed to reduce the elastic moduli by a factor of 0.8 (see Example 1.28).

Note that one set of Rayleigh damping parameters is assumed for all of the soils in this model. In general, different damping parameters may be needed to represent the different damping behavior of the different materials and positions within the foundation and embankment. The spatial variation in damping can be prescribed with the **INITIAL dy_damp** command.

Also note that, for this case, with mass- and stiffness-proportional Rayleigh damping of 6.3% at the natural frequency of 1.0 Hz, the limiting timestep is approximately 3.1×10^{-5} seconds. This timestep is roughly eleven times smaller than that for hysteretic damping. The model state is saved at this stage as "EDAM7MR.SAV." The Rayleigh damping run at 40 seconds is saved as "EDAM8MR.SAV."

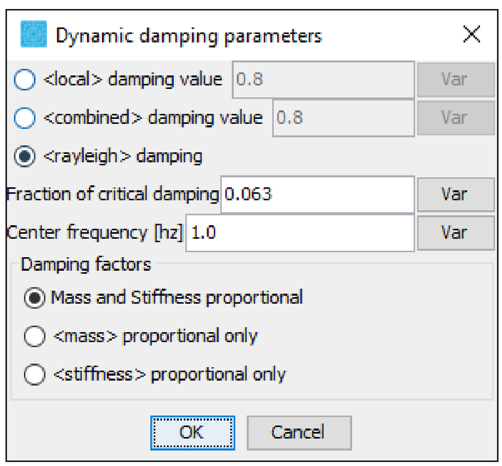

Figure 1.132 Rayleigh damping parameters for Rayleigh damping simulation

Example 1.28 "GREDUCE.FIS" – Reduce elastic moduli by modulus reduction factor

```
;Name:greduce
;Input:_prat/float/0.3/Poisson's ratio
;Input:_gfac/float/0.8/modulus reduction factor
def greduce
   pfac = (2.0*(1.0+_prat))/(3.0*(1.0-2.0*_prat))
   loop i (1,izones)
      loop j (1,jzones)
         shear_mod(i,j)=_gfac*shear_mod(i,j)
         bulk_mod(i,j)=shear_mod(i,j) * pfac
         if model(i,j) < 0 then
            z_prop(i,j,'shear') = _gfac*z_prop(i,j,'shear')
            z_prop(i,j,'bulk') = z_prop(i,j,'shear') * pfac
         endif
      endloop
   endloop
end
```

If Rayleigh damping alone is used, the results are comparable to those with hysteretic damping. Figure 1.133 plots the x-displacement contours at 40 seconds for Rayleigh damping. Figure 1.134 shows the shear-strain increment contours at this time. Both plots compare reasonably well with those using hysteretic damping (compare to Figures 1.127 and 1.128). Figure 1.135 plots the relative movement at gridpoint (62,29). The displacements are slightly less than those for hysteretic damping (compare to Figure 1.129).

The effect of Rayleigh damping is also evident in the cyclic shear strain response; compare Figure 1.136 to Figures 1.121 and 1.130.

Pore pressure and effective vertical stress histories for the Rayleigh damping run are also similar to those for the hysteretic damping run (compare Figure 1.137 to Figure 1.131).

As material yield is approached, neither Rayleigh damping nor hysteretic damping account for energy dissipation of extensive yielding. Irreversible strain occurs external to both schemes, and dissipation is represented by the Mohr-Coulomb model. The mass-proportional term of Rayleigh damping may inhibit yielding because rigid-body motions that occur during failure are erroneously resisted. Consequently, hysteretic damping may be expected to give larger permanent deformations in this situation, but this condition is believed to be more realistic than one using Rayleigh damping.

This comparison demonstrates the substantial benefit of hysteretic damping. The results are comparable to those using Rayleigh damping for similar damping levels, and the runtime with hysteretic damping is greatly reduced.

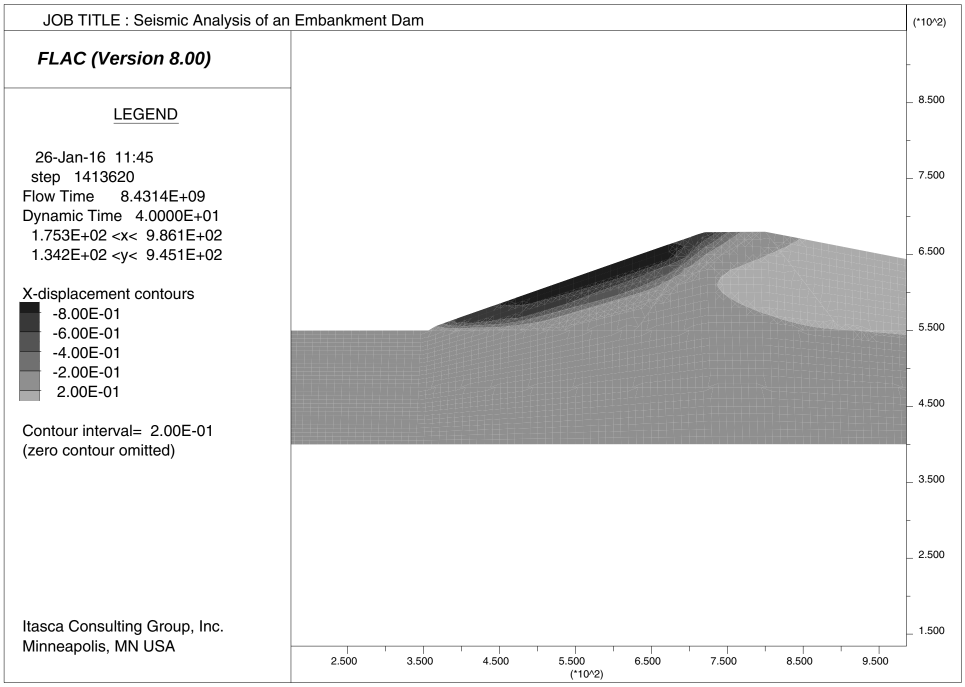

Figure 1.133 x-displacement contours at 40 seconds – Mohr-Coulomb material and Rayleigh damping

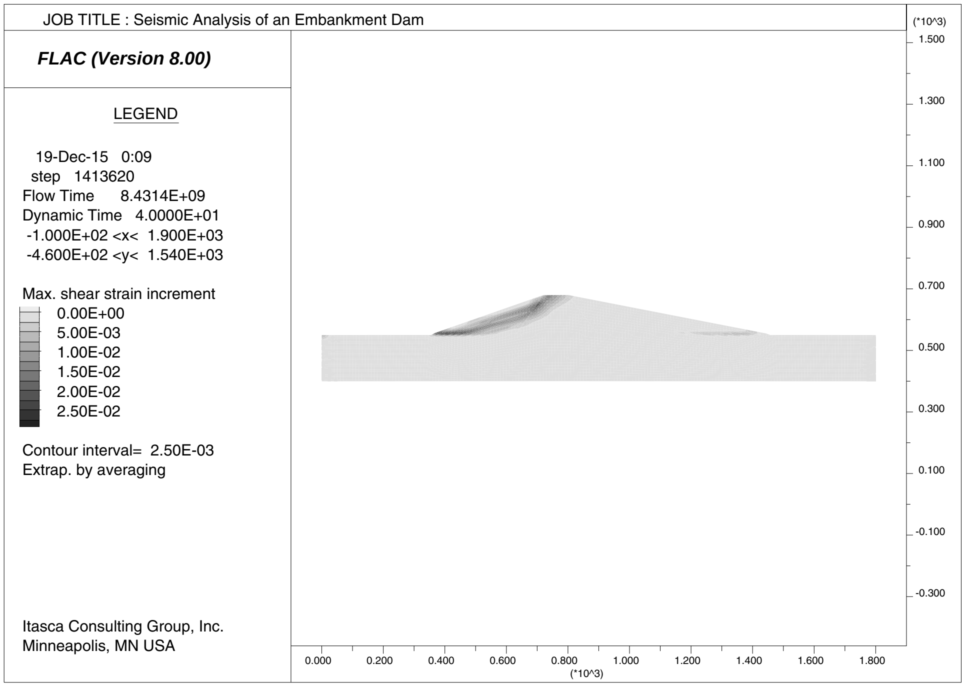

Figure 1.134 Shear-strain increment contours at 40 seconds – Mohr-Coulomb material and Rayleigh damping

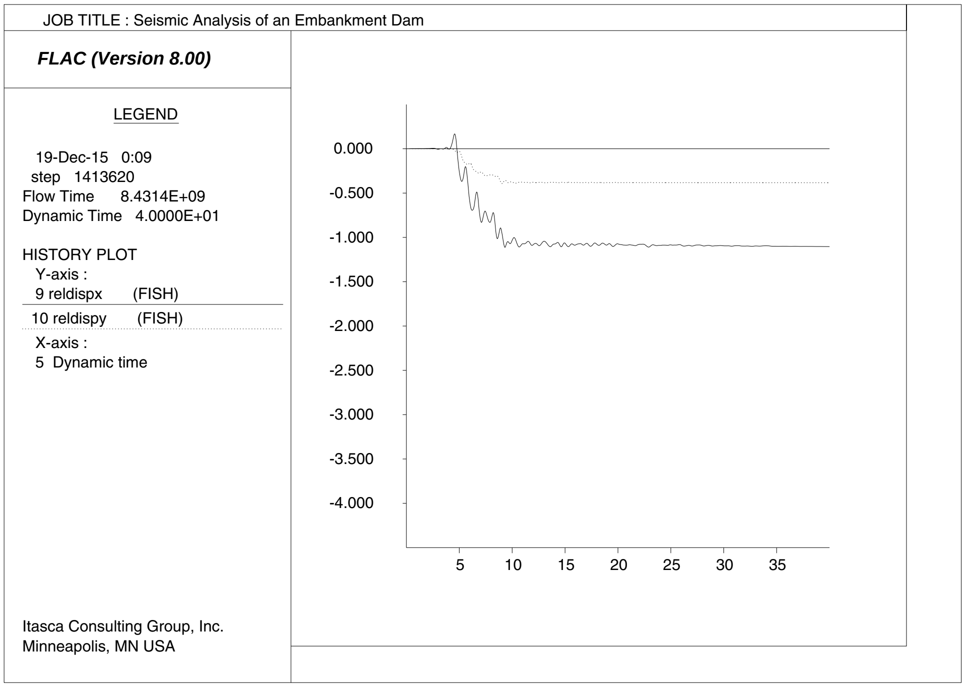

Figure 1.135 Relative displacements at gridpoint (62,29) along upstream slope – Mohr-Coulomb material and Rayleigh damping

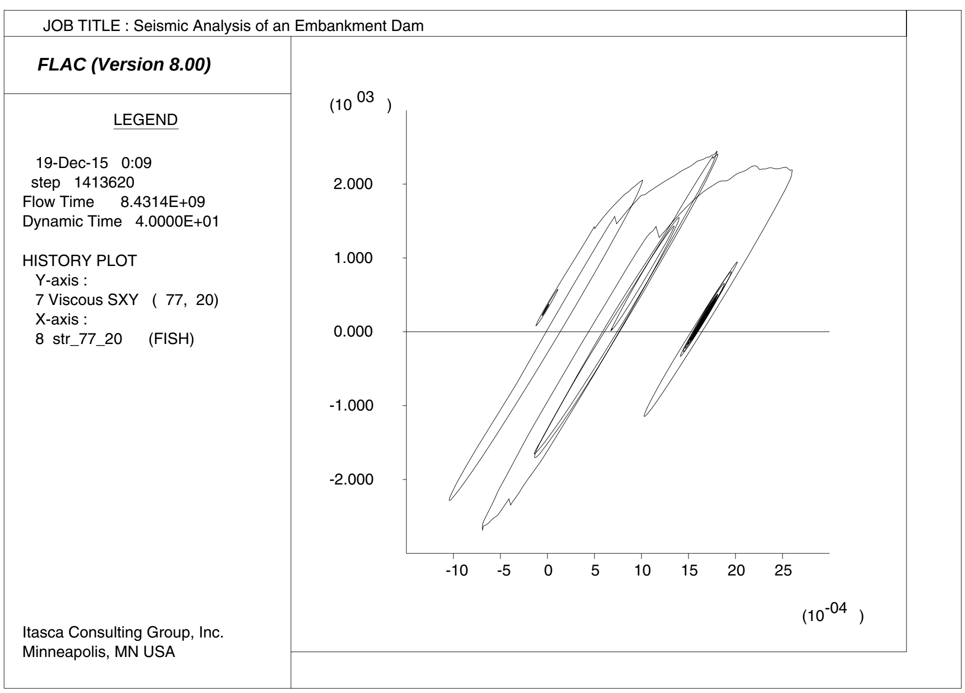

Figure 1.136 Shear stress versus shear strain in embankment soil 2 at zone (77,20) – Mohr-Coulomb material and Rayleigh damping

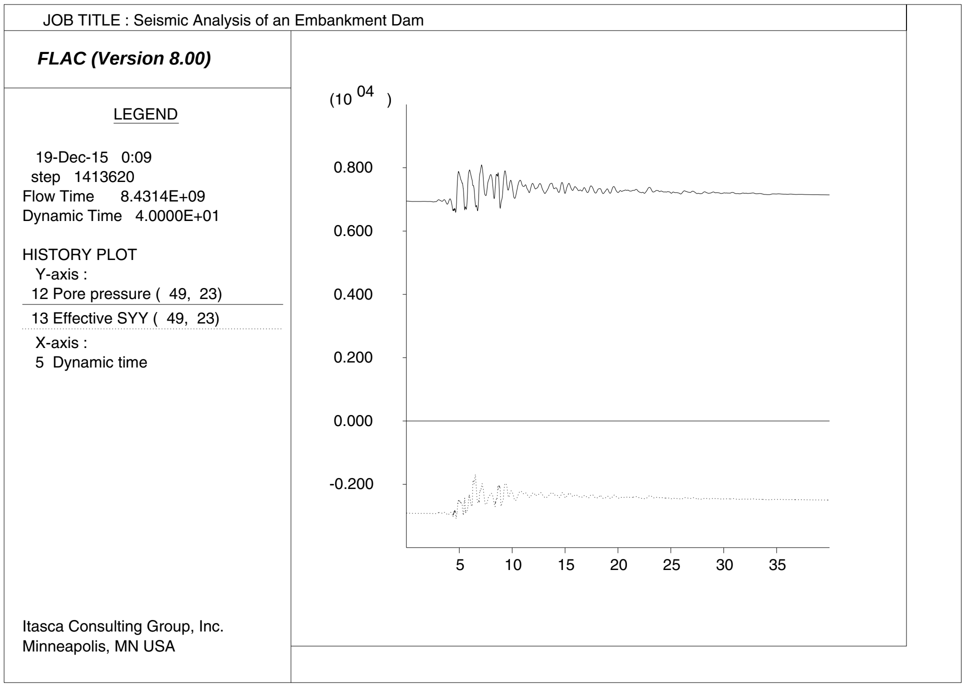

Figure 1.137 Pore-pressure and effective vertical stress near upstream slope – Mohr-Coulomb material and Rayleigh damping

1.6.1.11 Run Seismic Calculation Assuming Liquefaction

The embankment soils are now changed to liquefiable materials. The Finn-Byrne liquefaction model is prescribed for embankment soils 1 and 2, with parameters set to correspond to SPT measurements. For a normalized SPT blow count of 10, the Byrne model parameters are $C_1 = 0.2452$ and $C_2 = 0.8156$ (see Section 1.6.1.3).

The liquefaction simulation starts at the saved state "EDAM6FH.SAV." The embankment soils are changed at this state by using the MATERIAL/MODEL tool. (Note that this tool is activated when the INCLUDE ADVANCED CONSTITUTIVE MODELS? box is checked in the *Model options* dialog.) The REGION range is selected and the DYNAMIC models box is checked in this tool. The FINN model is then assigned to each region of the embankment soils. When the mouse is clicked within one of the embankment soil regions, a dialog opens to prescribe the model properties. Figure 1.138 shows the dialog with the properties selected for embankment soil 1. Note that the FINN/BYRNE radio button is checked in order to prescribe the appropriate parameters for the Byrne formulation. Also, the value for LATENCY is set to 1,000,000 at this stage. This is done to prevent the liquefaction calculation from being activated initially. The model is first checked to make sure that it is still at an equilibrium state when switching materials to the Byrne model, before commencing the dynamic simulation.

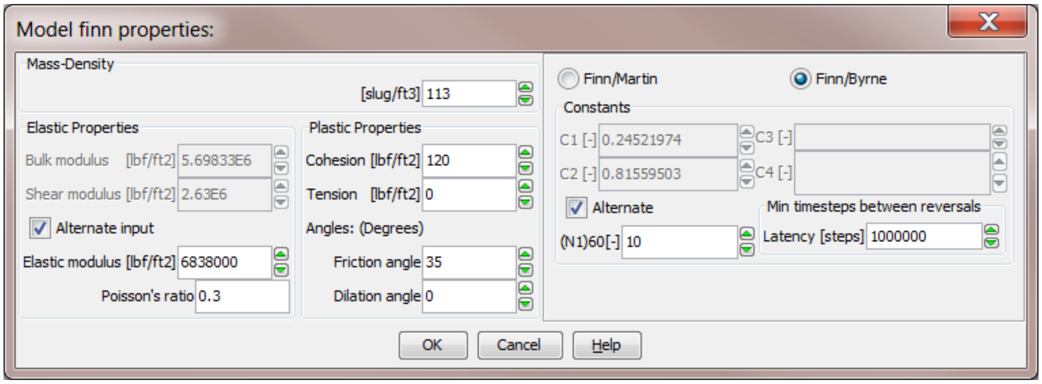

Figure 1.138 Model finn properties dialog with properties for embankment soil 1

The model is now ready for the dynamic analysis. The water bulk modulus is assigned as 4.1×10^6 psf using the SETTINGS/GW tool. The value for latency of the embankment soils is reduced to 50 in the MATERIAL/PROPERTY tool. The dynamic conditions are now set again in the same manner as described above.

Change in pore pressure, or excess pore pressure, is calculated throughout the model in order to evaluate the potential for liquefaction. The normalized excess pore-pressure ratio (or cyclic pore-pressure ratio), $u_e \,/\, \sigma'_c$,* can be used to identify the region of liquefaction in the model. (The excess pore-pressure ratio is calculated in *FISH* function “GETEXCESSPP.FIS,” and the maximum values are stored in *FISH* extra array **ex_6** – see Example 1.29.)

A model state “EDAM7FH.SAV” is created at this point.

The model is now run for a dynamic time of 40 seconds. The results in Figures 1.139 through 1.144 show the effect of pore-pressure generation in the embankment soils. There is now a substantial movement along the upstream face, as shown by figures Figures 1.139 through 1.142. The relative vertical settlement at gridpoint (62,29) is now approximately 1 ft, and the relative shift upstream is approximately 3.5 ft, as shown in Figure 1.142.

A significant increase in pore pressure (and decrease in effective stress) is calculated in the upstream region, as indicated in Figure 1.143. The location of the pore pressure/effective stress measurement is at gridpoint (49,23), which is at a depth of approximately 45 ft below the upstream slope face, and 135 ft from the toe of the upstream slope.

Contours of the cyclic pore-pressure ratio greater than 0.99 are plotted in Figure 1.144. These contours show the extent of the liquefied embankment soils, primarily in the upstream region.

The final state is “EDAM8FH.SAV.”

---

* where u_e is the excess pore-pressure and σ'_c is the initial effective confining stress. Note that a liquefaction state is reached when $u_e \,/\, \sigma'_c = 1$.

Example 1.29 "GETEXCESSPP.FIS" – Excess pore pressure ratio

```
;Name:getExcesspp
;Input:nsample/int/50/sampling interval
;Input:nstep/int/1/smpling substep
;Note:Calculates excess pore pressure ratio
;Note:ex_2 - stores init. pore pressure state (saved in savepp.fis)
;Note:ex_3 - stores init. eff. confining stress (calculated in savepp.fis)
;Note:ex_4 - calculates exc. pore pressure ratio: ex_5/ex_3
;Note:ex_5 - calculates exc. pore pressure (pp(i,j) - ex_2(i,j))
;Note:ex_6 - stores max. exc. pore press. ratio (set to zero in savepp.fis)
def getExcesspp
   whilestepping
   if nstep = nsample then
   loop i (1,izones)
      loop j (1,jzones)
         if pp(i,j) > ex_2(i,j) then
            ex_5(i,j) = pp(i,j) - ex_2(i,j)
         else
            ex_5(i,j) = 0.0
         endif
         ex_4(i,j) = abs(ex_5(i,j)/ex_3(i,j))
         ex_6(i,j)= max(ex_6(i,j),abs(ex_4(i,j)))
      endloop
   endloop
   nstep = 1
   endif
   nstep = nstep + 1
end
```

The liquefaction run is repeated using only Rayleigh damping, with the same damping and modulus-reduction parameters as the simulation with Mohr-Coulomb material (damping ratio of 0.063, center frequency of 1.0 Hz and modulus reduction factor of 0.8). The same plots created for the liquefaction run with hysteretic damping are recreated for the run with Rayleigh damping. See Figures 1.145 through 1.150. As the figures show, the results are very similar. The final state in this case is "EDAM8FR.SAV."

Comments

This simple example assumes that the initial shear modulus, G_{max} (before the seismic loading), is uniform throughout each material unit. It may be more appropriate to vary G_{max} for soils as a function of the in-situ effective stress (e.g., see Kramer 1996). An initial variation can be implemented during the static loading stage.

This example also assumes that the shear strength parameters of the liquefiable soils do not change. It has been shown (e.g., Olson et al. 2000) that if the effective stress goes to zero, the shear strength reduces to a strain-mobilized (liquefied) shear strength, which implies a residual cohesion. There are several ways to incorporate a change of strength envelope in the *FLAC* model, such that residual cohesion is developed as the material liquefies. For example, a *FISH* function can be used to adjust the strength parameters as a function of change in the effective confining stress. A more rigorous approach is to modify a bilinear strength model (such as the strain-softening bilinear model, **MODEL subiquitous**) to include the liquefaction behavior (e.g., the Byrne model). The existing **MODEL finn** in *FLAC* incorporates the pore-pressure generation effect into the Mohr-Coulomb model. This can also be done with other models, using either the *FISH* constitutive model facility (see Section 2.8 in the ***FISH*** **volume**) or the C++ DLL model facility (see Section 2 in **Constitutive Models**) to create a user-defined model.

If there is a potential for flow slides to occur either at liquefaction or during post-liquefaction, the automatic rezoning logic in *FLAC* can be used to simulate the development of the deformed flow-slide state. See Section 4 in **Theory and Background** for further information.

Example Application 18 *Earthquake Loading of a Pile-Supported Wharf* (see Section 18 in the **Examples volume**) illustrates an approach to reduce material strength at the onset of liquefaction as defined by the cyclic pore-pressure ratio. The example also demonstrates the application of the automatic rezoning logic to correct for overly distorted mesh conditions that develop during the simulation.

Acknowledgment

This example is derived from data provided by Dr. Nason McCullough of CH2MHill. His assistance and critical review of this exercise are gratefully acknowledged.

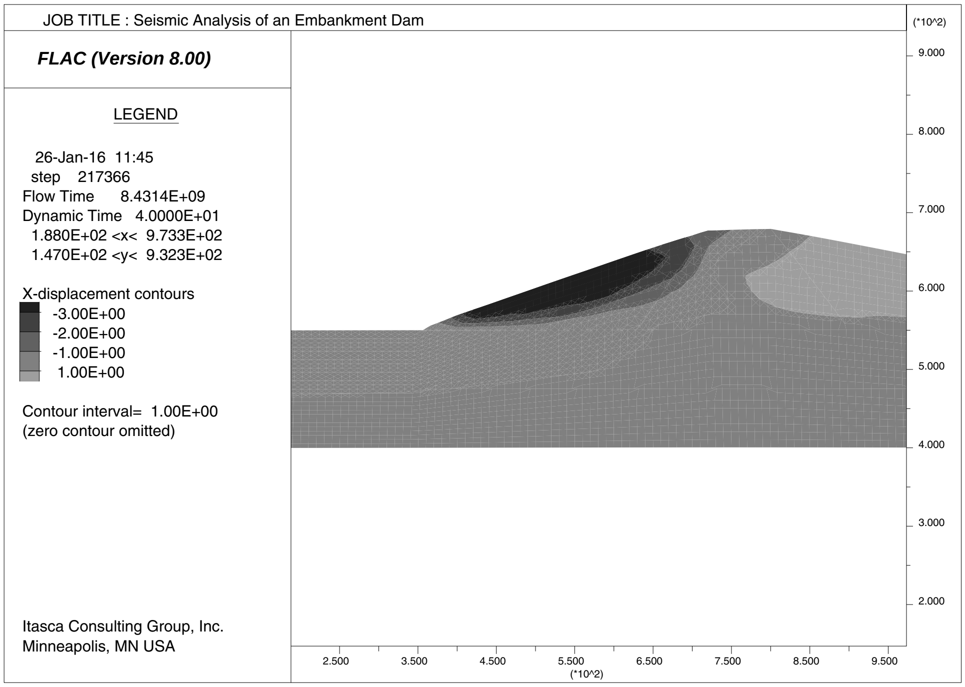

Figure 1.139 x-displacement contours at 40 seconds – Byrne (liquefaction) material and hysteretic damping

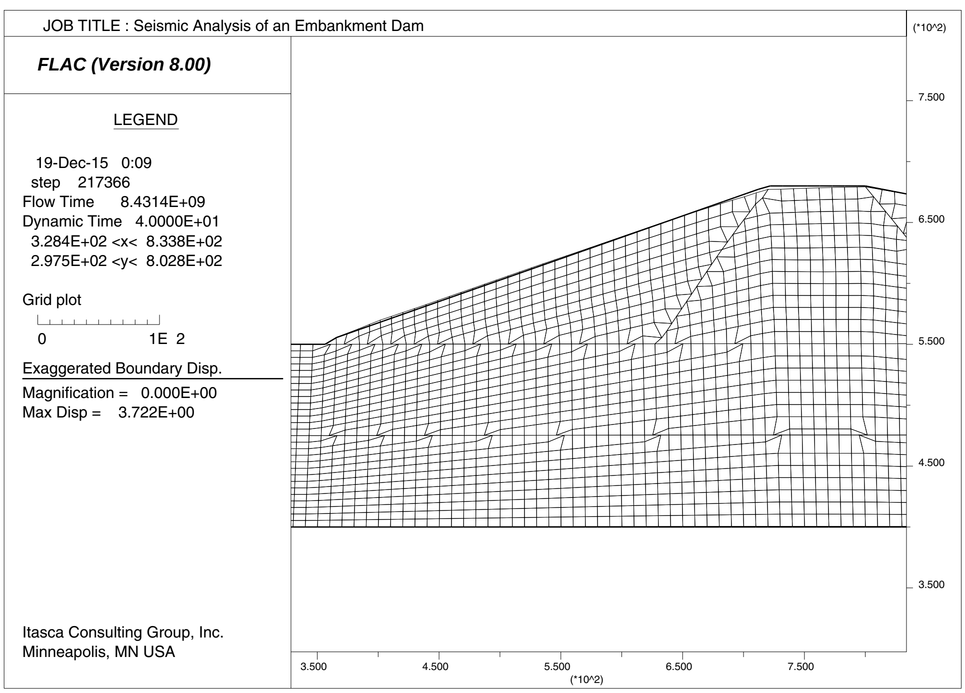

Figure 1.140 Deformed grid at 40 seconds – Byrne (liquefaction) material and hysteretic damping

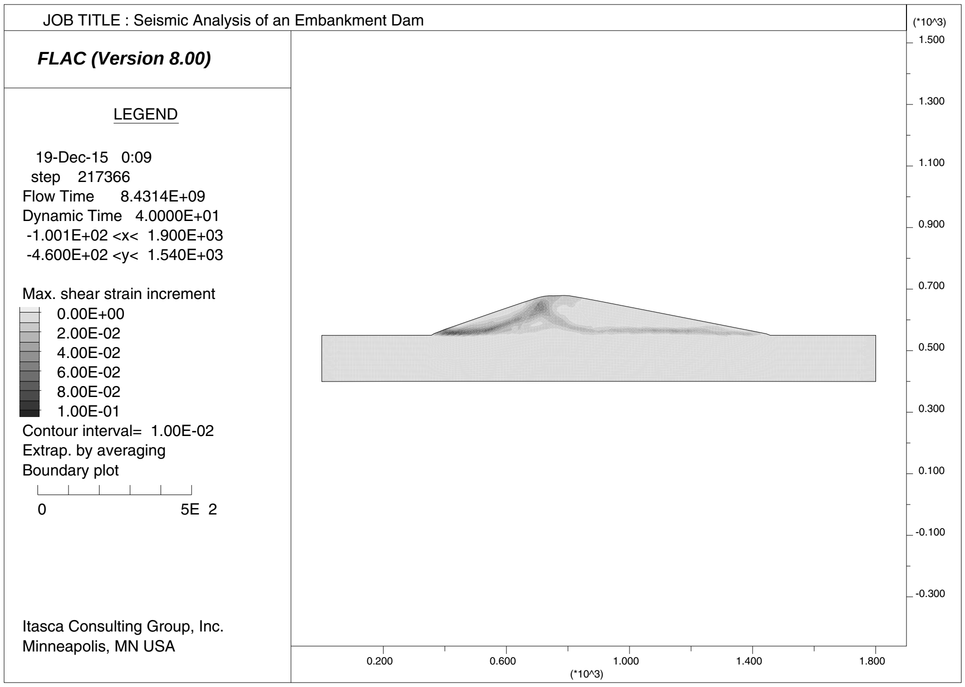

Figure 1.141 Shear-strain increment contours at 40 seconds – Byrne (liquefaction) material and hysteretic damping

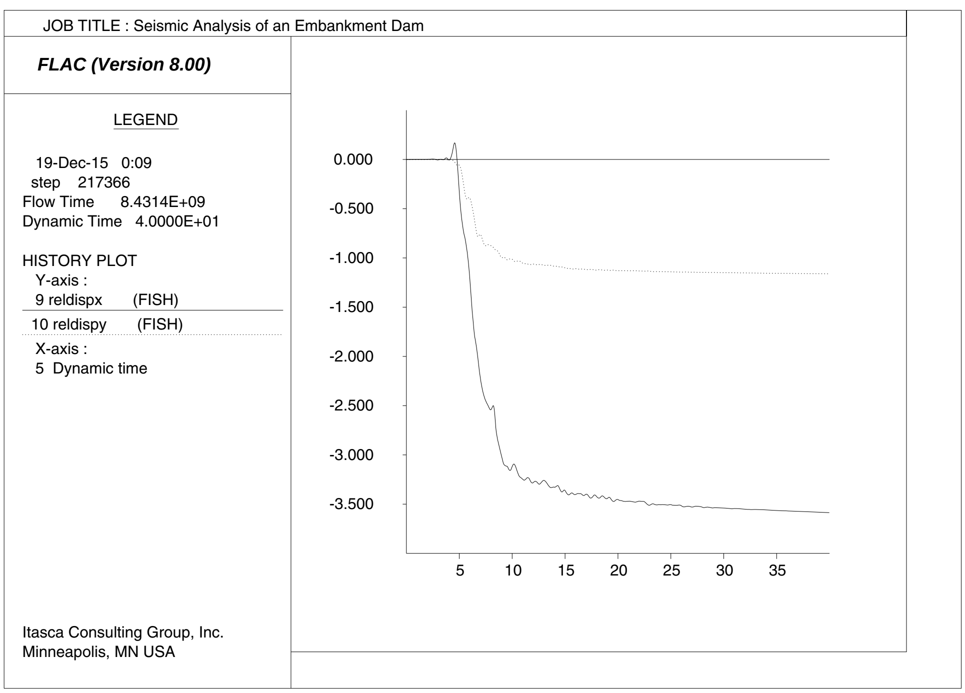

Figure 1.142 Relative displacements at gridpoint (62,29) along upstream slope – Byrne (liquefaction) material and hysteretic damping

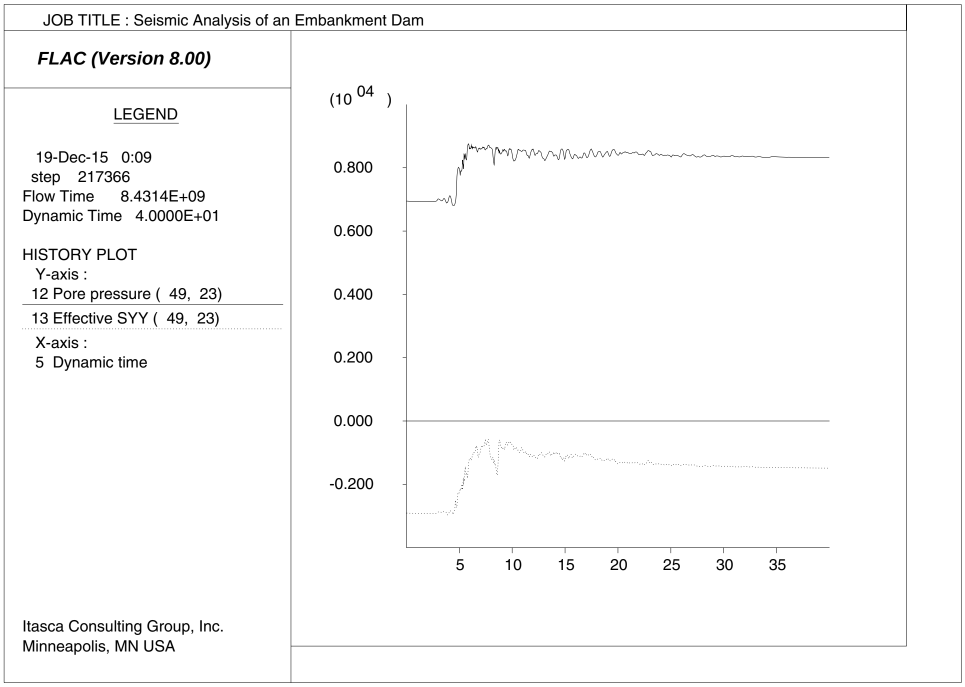

Figure 1.143 Pore-pressure and effective vertical stress near upstream slope – Byrne (liquefaction) material and hysteretic damping

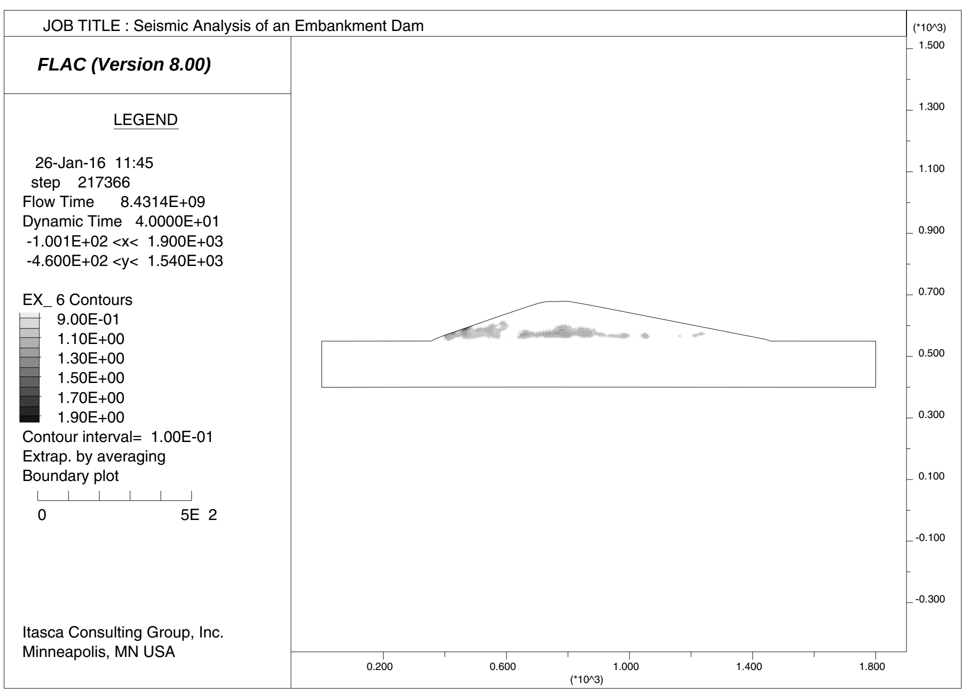

Figure 1.144 Excess pore-pressure ratio contours (values greater than 0.99) – Byrne (liquefaction) material and hysteretic damping

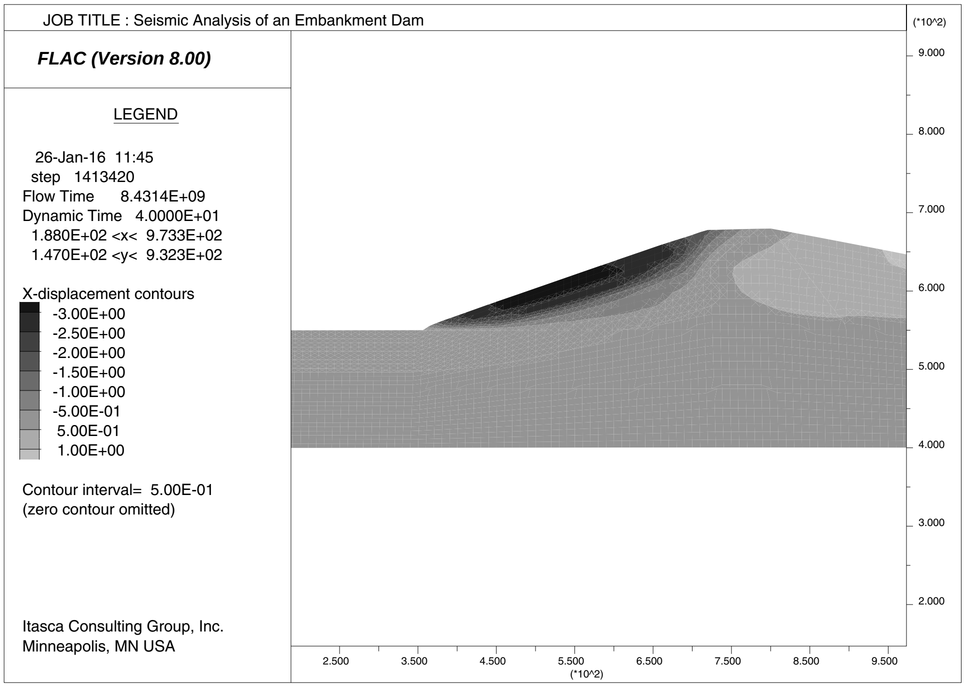

Figure 1.145 x-displacement contours at 40 seconds – Byrne (liquefaction) material and Rayleigh damping

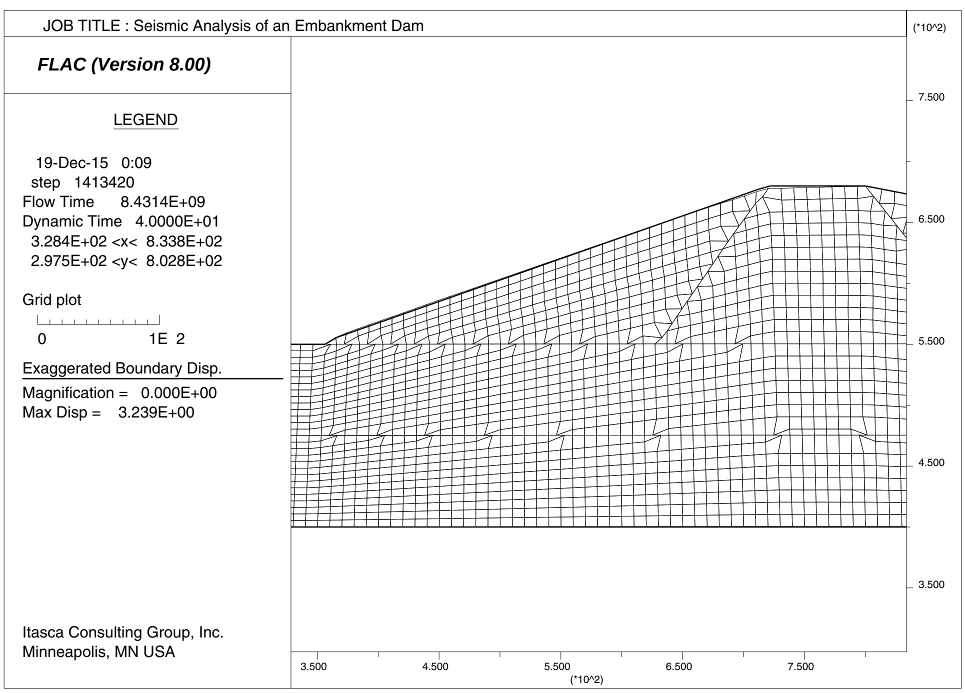

Figure 1.146 Deformed grid at 40 seconds – Byrne (liquefaction) material and Rayleigh damping

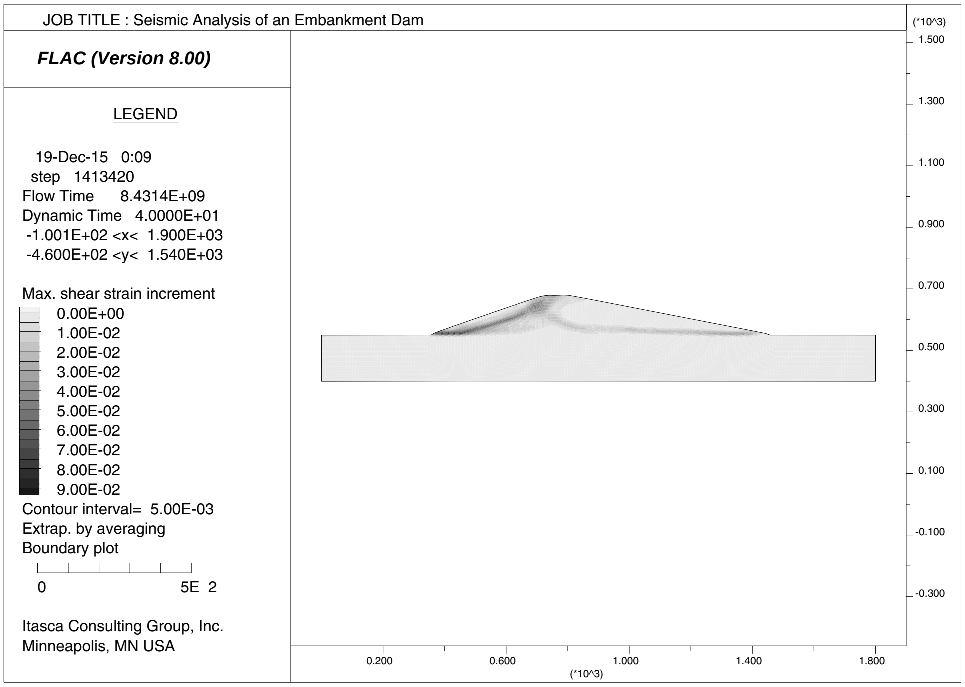

Figure 1.147 Shear-strain increment contours at 40 seconds – Byrne (liquefaction) material and Rayleigh damping

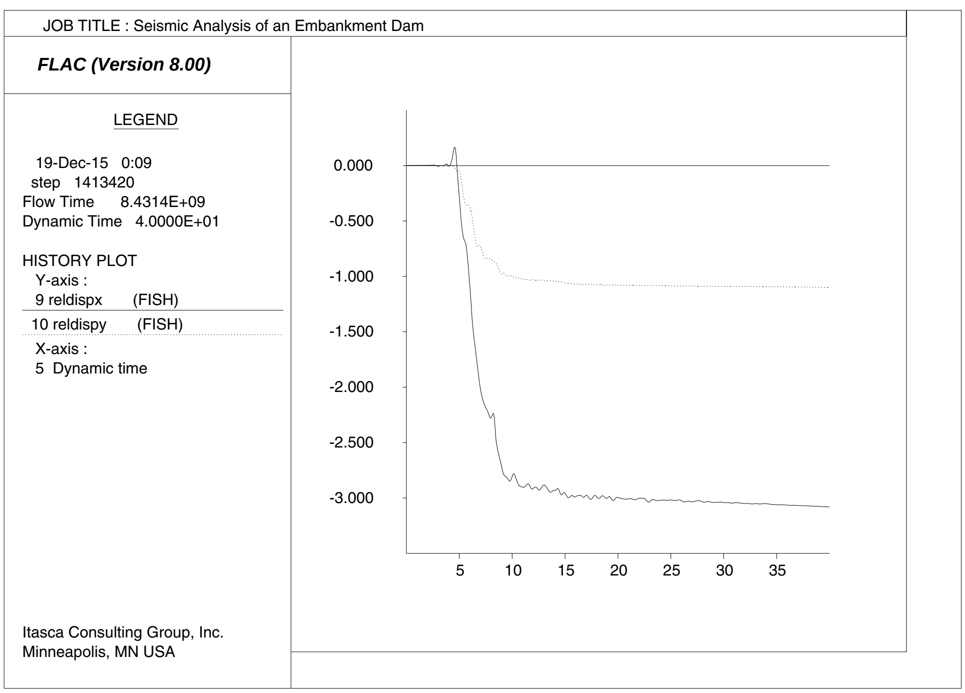

Figure 1.148 Relative displacements at gridpoint (62,29) along upstream slope – Byrne (liquefaction) material and Rayleigh damping

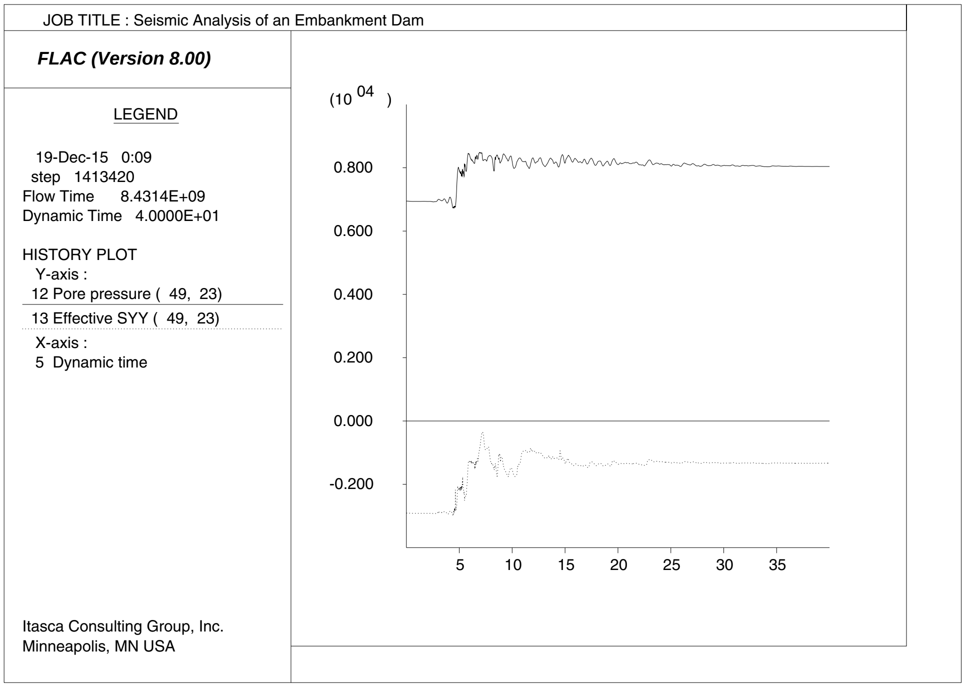

Figure 1.149 Pore-pressure and effective vertical stress near upstream slope – Byrne (liquefaction) material and Rayleigh damping

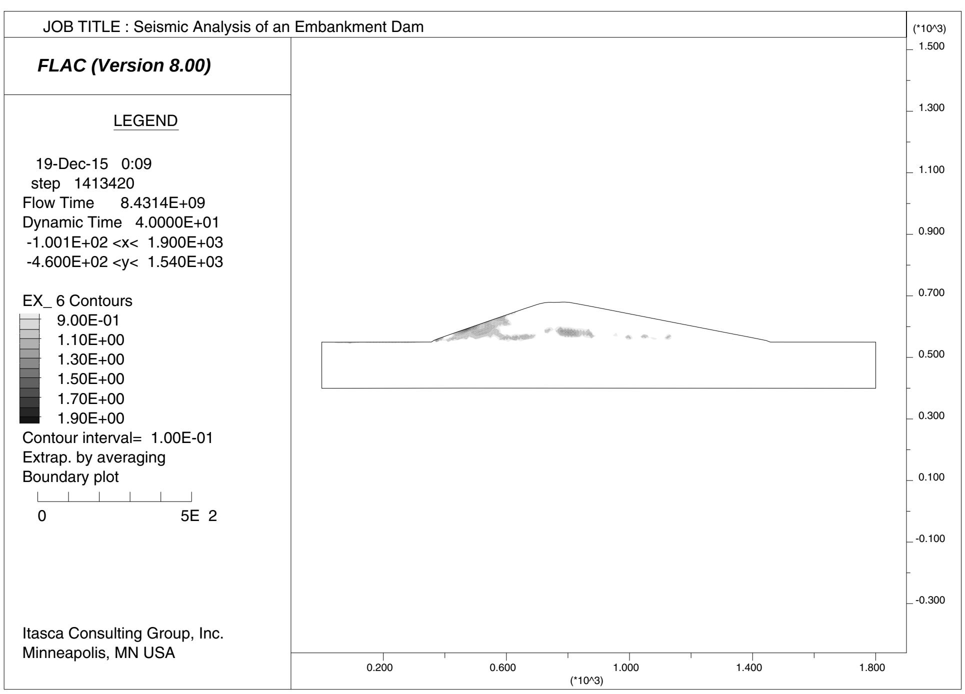

Figure 1.150 Excess pore-pressure ratio contours (values greater than 0.99) – Byrne (liquefaction) material and Rayleigh damping

Example 1.30 "EARTHDAM.DAT" – Seismic analysis of an embankment dam

```
;Project Record Tree export
;Title: Earth Dam
;File:earthdam.dat
;Units: Imperial: foot-slug-second;Branch 1:edam1.sav
; Source: <no name>
config gwflow dynamic extra 20
grid 180,28
gen 0.0,400.0 0.0,550.0 1800.0,550.0 1800.0,400.0 i=1,181 j=1,29
; Define nonlinear edges and interpolate subgrids
gen row 2,29 10.192606 550.0 20.385212 550.0 30.577818 550.0 40.770424 &
 550.0 50.963028 550.0 61.155636 550.0 71.348236 550.0 81.54085 550.0 &
 91.73345 550.0 101.926056 550.0 112.11866 550.0 122.31127 550.0 132.5038 &
 550.0 142.69647 550.0 152.88908 550.0 163.0817 550.0 173.27429 550.0 &
 183.4669 550.0 193.6595 550.0 203.85211 550.0 214.04471 550.0 224.23732 &
 550.0 234.42993 550.0 244.62254 550.0 254.81514 550.0 265.00775 550.0 &
 275.20035 550.0 285.39294 550.0 295.58557 550.0 305.77817 550.0 315.9707 &
 550.0 326.1634 550.0 336.356 550.0 346.54858 550.0 356.36005 552.2346 &
 365.97638 555.61334 375.59268 558.992 385.209 562.3707 394.82532 565.749 &
 404.44165 569.1281 414.05795 572.50684 423.67426 575.88556 433.2906 &
 579.2642 442.90692 582.643 452.52322 586.02167 462.13953 589.4004 &
 471.75586 592.77905 481.3722 596.1578 490.98846 599.5365 500.6048 602.91 &
 510.22113 606.29395 519.83746 609.6726 529.45374 613.0513 539.07007 &
 616.43005 548.68634 619.8087 558.3027 623.18744 567.919 626.56616 577.53 &
 629.9448
gen row 60,29 587.1517 633.32355 596.76794 636.7023 606.3842 640.08093 &
 616.0006 643.45966 625.6169 646.8384 635.2333 650.2171 644.84955 653.595 &
 654.4659 656.9745 664.08215 660.35315 673.6985 663.7319 683.31476 667.11 &
 692.9311 670.4893 702.54736 673.868 712.1638 677.24677 721.8868 680.0 &
 732.07935 680.0 742.2719 680.0 752.46454 680.0 762.6571 680.0 772.8498 &
 680.0 783.0424 680.0 793.235 680.0 803.3648 679.3471 813.3709 677.4057 &
 823.3768 675.4642 833.3829 673.52277 843.3888 671.5813 853.3948 669.6398 &
 863.4008 667.6983 873.40686 665.7569 883.4128 663.8154 893.4188 661.8739 &
 903.4248 659.93243 913.43085 657.991 923.4367 656.04956 933.4428 654.108 &
 943.4488 652.1666 953.45483 650.2252 963.4607 648.2837 973.4668 646.3423 &
 983.4727 644.40076 993.47876 642.45935 1003.48474 640.5179 1013.4908 &
 638.5764 1023.4967 636.63495 1033.5028 634.6935 1043.5088 632.7521 &
 1053.5146 630.81055 1063.5208 628.86914 1073.5267 626.9276 1083.5326 &
 624.9862 1093.5386 623.0447 1103.5447 621.1033 1113.5507 619.16174 &
 1123.5566 617.22034
gen row 115,29 1133.5627 615.27893 1143.5687 613.3374 1153.5747 611.396 &
 1163.5807 609.45447 1173.5867 607.51306 1183.5927 605.5716 1193.5986 &
 603.6301 1203.6045 601.68866 1213.6106 599.7472 1223.6166 597.8057 &
 1233.6226 595.86426 1243.6285 593.92285 1253.6345 591.9814 1263.6405 &
```

```
 590.0399 1273.6466 588.09845 1283.6525 586.157 1293.6586 584.21545 &
 1303.6647 582.27405 1313.6707 580.3325 1323.6765 578.3911 1333.6825 &
 576.44965 1343.6885 574.5082 1353.6946 572.5667 1363.7006 570.62524 &
 1373.7065 568.68384 1383.7124 566.7424 1393.7184 564.8009 1403.7245 &
 562.85944 1413.7305 560.91797 1423.7366 558.9765 1433.7426 557.03503 &
 1443.7485 555.09357 1453.7544 553.1521 1463.7605 551.21063 1473.8367 &
 549.99994 1484.0294 550.0 1494.2218 550.0 1504.4146 550.0 1514.607 550.0 &
 1524.7997 550.0 1534.9923 550.0 1545.1849 550.0 1555.3774 550.0 1565.570 &
 550.0 1575.7627 550.0 1585.9553 550.0 1596.148 550.0 1606.3407 550.0 &
 1616.5332 550.0 1626.7257 550.0 1636.9185 550.0 1647.1111 550.0 1657.303 &
 550.0 1667.4961 550.0 1677.6887 550.0
gen row 170,29 1687.8813 550.0 1698.074 550.0 1708.2666 550.0 1718.4592 &
 550.0 1728.6519 550.0 1738.8445 550.0 1749.0371 550.0 1759.2297 550.0 &
 1769.4224 550.0 1779.6149 550.0 1789.8075 550.0
gen bilinear i=1,181 j=1,29
model elastic i=1,180 j=1,28
; Fixed boundary conditions
fix x i=1 j=1,29
fix x i=181 j=1,29
fix x y i=1,181 j=1
gen line 0.0,475.0 1800.0,475.0
gen line 350.0,550.0 1470.0,550.0
gen line 720.0 680.0 630.0 550.0
gen line 800.0,680.0 900.0,550.0
mark i 74 j 28
mark i 74 j 29
mark i 64 j 19
ini x 717.2 y 673.1 i 74 j 28
ini x 633.0 y 555.0 i 64 j 19
ini x 800.0 y 680.0 i 82 j 29
group ’foundation:soil 2’ region 83 4
model mohr group ’foundation:soil 2’
prop density=3.88 bulk=1.06308E7 shear=4.90654E6 cohesion=160.0 &
 friction=40.0 dilation=0.0 tension=0.0 group ’foundation:soil 2’
group ’foundation:soil 1’ region 94 11
model mohr group ’foundation:soil 1’
prop density=3.88 bulk=1.06308E7 shear=4.90654E6 cohesion=83.5 &
 friction=40.0 dilation=0.0 tension=0.0 group ’foundation:soil 1’
group ’embankment:soil 1’ region 106 23
model mohr group ’embankment:soil 1’
prop density=3.51 bulk=5.698E6 shear=2.630e6 cohesion=120.0 friction=35.0 &
 dilation=0.0 tension=0.0 group ’embankment:soil 1’
group ’embankment:soil 1’ region 60 22
model mohr group ’embankment:soil 1’
prop density=3.51 bulk=5.698E6 shear=2.630e6 cohesion=120.0 friction=35.0 &
 dilation=0.0 tension=0.0 group ’embankment:soil 1’
```

```
group 'embankment:soil 2' region 79 20
model mohr group 'embankment:soil 2'
prop density=3.73 bulk=5.698E6 shear=2.630e6 cohesion=120.0 friction=35.0 &
 dilation=0.0 tension=0.0 group 'embankment:soil 2'
prop por=0.3 perm=5.25E-9 region 74 3
prop por=0.3 perm=5.25E-8 region 73 11
save edam1.sav

;Branch 2:edam2.sav
model null  group 'embankment:soil 1'
model null  group 'embankment:soil 2'
set gravity=32.2
set flow=off
water density=1.94
set dyn=off
set echo off
call Ininv.fis
set wth=550 k0x=0.5 k0z=0.5
ininv
history 999 unbalanced
solve  elastic
save edam2.sav

;Branch 3:edam3.sav
model mohr group 'embankment:soil 2'
prop density=3.73 bulk=5.698E6 shear=2.630e6 cohesion=120.0 friction=35.0 &
 dilation=0.0 tension=0.0 group 'embankment:soil 2'
model mohr group 'embankment:soil 1'
prop density=3.51 bulk=5.698E6 shear=2.630e6 cohesion=120.0 friction=35.0 &
 dilation=0.0 tension=0.0 group 'embankment:soil 1'
solve
save edam3.sav

;Branch 4:edam4.sav
apply pp 0.0 var 0.0 16866.36 from 71,29 to 1,1
fix  pp i 82 149 j 29
fix  pp i 150 181 j 29
prop por=0.3 perm=5.25E-8 region 59 26
prop por=0.3 perm=5.25E-8 region 100 23
prop por=0.3 perm=5.25E-10 region 76 21
history 1 pp i=48, j=24
history 2 pp i=79, j=17
history 3 pp i=124, j=21
history 4 gwtime
set mechanical=off
set flow=on
```

```
water bulk=4100.0
set fastwb=on
set step 100000000
solve
save edam4.sav

;Branch 5:edam5.sav
apply pressure 0.0 var 0.0 7496.16 from 71,29 to 1,29
set mechanical=on
set flow=off
water bulk=0.0
solve
save edam5.sav

restore 'edam5.sav'
;Branch 0:FoSmode.fsv
; This state should NOT be changed.
solve fos no_restore
save FoSmode.fsv

restore 'edam5.sav'
;Branch 0:edam6e.sav
water bulk=4100000.0
set dyn=on
set =large
call table104.dat
initial xdisp 0 ydisp 0
initial xvel 0 yvel 0
set echo off
call strain_hist.fis
strain_hist
set echo off
call reldispx.fis
reldispx
set echo off
call inipp.fis
inipp
set echo off
call excpp.fis
excpp
history 5 dytime
history 7 vsxy i=77, j=20
history 8 str_77_20
history 9  reldispx
history 10 reldispy
history 11 excpp
```

```
history 12 pp i=49, j=23
history 13 esyy i=49, j=23
history 14 xaccel i=77, j=1
history 15 xaccel i=77, j=29
history 16 xaccel i=172, j=29
history 17 xaccel i=9, j=29
history 18 xvel i=77, j=1
history 19 xvel i=77, j=29
history 20 xvel i=172, j=29
history 21 xvel i=9, j=29
history 22 xvel i=77, j=18
history nstep 100
set step=10000000
call mon_ex.fis
mon_ex
save edam6e.sav

;Branch 1:edam7e.sav
prop coh 1e10 tens 1e10 notnull
apply ffield
apply sxy -9358.0 hist table 104 from 1,1 to 181,1
apply xquiet yquiet from 1,1 to 181,1
save edam7e.sav

;Branch 2:edam8e.sav
solve dytime 40.0
save edam8e.sav

;Branch 3:edam9e.sav
hist write 14 vs 5  table 14
call fft_tables.fis
set fft_inp1=14 fft_inp2=24
fft_tables
call Fft.fis
fftransform
;
hist write 15 vs 5  table 15
set fft_inp1=15 fft_inp2=25
fft_tables
fftransform
;
hist write 16 vs 5  table 16
set fft_inp1=16 fft_inp2=26
fft_tables
fftransform
;
```

```
hist write 17 vs 5  table 17
set fft_inp1=17 fft_inp2=27
fft_tables
fftransform
;
hist write 18 vs 5  table 18
set fft_inp1=18 fft_inp2=28
fft_tables
fftransform
;
hist write 19 vs 5  table 19
set fft_inp1=19 fft_inp2=29
fft_tables
fftransform
;
hist write 20 vs 5  table 20
set fft_inp1=20 fft_inp2=30
fft_tables
fftransform
;
hist write 21 vs 5  table 21
set fft_inp1=21 fft_inp2=31
fft_tables
fftransform
;
hist write 22 vs 5  table 22
set fft_inp1=22 fft_inp2=32
fft_tables
fftransform
;
hist 33 read acc_deconv.his
hist 34 read acc_target.his
hist write 33  table 33
hist write 34  table 34
save edam9e.sav

restore 'edam5.sav'
;Branch 0:edam6mh.sav
water bulk=4100000.0
set dyn=on
set =large
call table104.dat
initial xdisp 0 ydisp 0
initial xvel 0 yvel 0
set echo off
call strain_hist.fis
```

```
strain_hist
set echo off
call reldispx.fis
reldispx
set echo off
call inipp.fis
inipp
set echo off
call excpp.fis
excpp
history 5 dytime
history 7 vsxy i=77, j=20
history 8 str_77_20
history 9  reldispx
history 10 reldispy
history 11 excpp
history 12 pp i=49, j=23
history 13 esyy i=49, j=23
history 14 xaccel i=77, j=1
history 15 xaccel i=77, j=29
history 16 xaccel i=172, j=29
history 17 xaccel i=9, j=29
history 18 xvel i=77, j=1
history 19 xvel i=77, j=29
history 20 xvel i=172, j=29
history 21 xvel i=9, j=29
history 22 xvel i=77, j=18
history nstep 100
set step=10000000
save edam6mh.sav

;Branch 1:edam7mh.sav
ini dy_damp hyst default -3.156 1.904
ini dy_damp rayleigh 0.002 1.0 stiffness
apply ffield
apply sxy -9358.0 hist table 104 from 1,1 to 181,1
apply xquiet yquiet from 1,1 to 181,1
save edam7mh.sav

;Branch 2:edam8mh.sav
solve dytime 40.0
save edam8mh.sav

restore 'edam5.sav'
;Branch 0:edam6mr.sav
water bulk=4100000.0
```

```
set dyn=on
set =large
call table104.dat
initial xdisp 0 ydisp 0
initial xvel 0 yvel 0
set echo off
call strain_hist.fis
strain_hist
set echo off
call reldispx.fis
reldispx
set echo off
call inipp.fis
inipp
set echo off
call excpp.fis
excpp
history 5 dytime
history 7 vsxy i=77, j=20
history 8 str_77_20
history 9  reldispx
history 10 reldispy
history 11 excpp
history 12 pp i=49, j=23
history 13 esyy i=49, j=23
history 14 xaccel i=77, j=1
history 15 xaccel i=77, j=29
history 16 xaccel i=172, j=29
history 17 xaccel i=9, j=29
history 18 xvel i=77, j=1
history 19 xvel i=77, j=29
history 20 xvel i=172, j=29
history 21 xvel i=9, j=29
history 22 xvel i=77, j=18
history nstep 100
set step=10000000
save edam6mr.sav

;Branch 1:edam7mr.sav
call greduce.fis
set _prat=0.30
set _gfac=0.8
greduce
set dy_damping rayleigh=0.063 1.0
apply ffield
apply sxy -9358.0 hist table 104 from 1,1 to 181,1
```

```
apply xquiet yquiet from 1,1 to 181,1
save edam7mr.sav

;Branch 2:edam8mr.sav
solve dytime 40.0
save edam8mr.sav

restore 'edam5.sav'
;Branch 0:edam6fh.sav
model finn region 80 21
prop density=3.73 bulk=5698000.0 shear=2630000.0 cohesion=120.0 &
 friction=35.0 ff_latency=1000000 ff_c1=0.24522 ff_c2=0.81559 ff_switch=1 &
 region 80 21
model finn region 60 25
prop density=3.51 bulk=5698000.0 shear=2630000.0 cohesion=120.0 &
 friction=35.0 ff_latency=1000000 ff_c1=0.24522 ff_c2=0.81559 ff_switch=1 &
 region 60 25
model finn region 107 25
prop density=3.51 bulk=5698000.0 shear=2630000.0 cohesion=120.0 &
 friction=35.0 ff_latency=1000000 ff_c1=0.24522 ff_c2=0.81559 ff_switch=1 &
 region 107 25
solve
water bulk=4100000.0
set dyn=on
set =large
call table104.dat
initial xdisp 0 ydisp 0
initial xvel 0 yvel 0
set echo off
call strain_hist.fis
strain_hist
set echo off
call reldispx.fis
reldispx
set echo off
call inipp.fis
inipp
set echo off
call excpp.fis
excpp
history 5 dytime
history 7 vsxy i=77, j=20
history 8 str_77_20
history 9  reldispx
history 10 reldispy
history 11 excpp
```

```
history 12 pp i=49, j=23
history 13 esyy i=49, j=23
history 14 xaccel i=77, j=1
history 15 xaccel i=77, j=29
history 16 xaccel i=172, j=29
history 17 xaccel i=9, j=29
history 18 xvel i=77, j=1
history 19 xvel i=77, j=29
history 20 xvel i=172, j=29
history 21 xvel i=9, j=29
history nstep 100
set step=10000000
prop ff_latency 50 region 78 19
prop ff_latency 50 region 60 22
prop ff_latency 50 region 103 26
save edam6fh.sav

;Branch 1:edam7fh.sav
initial hyst default -3.156 1.904
set dy_damping rayleigh=0.0020 1.0 stiffness
apply ffield
apply sxy -9358.0 hist table 104 from 1,1 to 181,1
apply xquiet yquiet from 1,1 to 181,1
set echo off
call savepp.fis
savepp
set echo off
call getExcesspp.fis
set nsample=50 nstep=1
getExcesspp
save edam7fh.sav

;Branch 2:edam8fh.sav
solve dytime 40.0
save edam8fh.sav

restore 'edam5.sav'
;Branch 0:edam6fr.sav
model finn region 80 21
prop density=3.73 bulk=5698000.0 shear=2630000.0 cohesion=120.0 &
 friction=35.0 ff_latency=1000000 ff_c1=0.24522 ff_c2=0.81559 ff_switch=1 &
 region 80 21
model finn region 60 25
prop density=3.51 bulk=5698000.0 shear=2630000.0 cohesion=120.0 &
 friction=35.0 ff_latency=1000000 ff_c1=0.24522 ff_c2=0.81559 ff_switch=1 &
 region 60 25
```

```
model finn region 107 25
prop density=3.51 bulk=5698000.0 shear=2630000.0 cohesion=120.0 &
 friction=35.0 ff_latency=1000000 ff_c1=0.24522 ff_c2=0.81559 ff_switch=1 &
 region 107 25
solve
water bulk=4100000.0
set dyn=on
set =large
call table104.dat
initial xdisp 0 ydisp 0
initial xvel 0 yvel 0
set echo off
call strain_hist.fis
strain_hist
set echo off
call reldispx.fis
reldispx
set echo off
call inipp.fis
inipp
set echo off
call excpp.fis
excpp
history 5 dytime
history 7 vsxy i=77, j=20
history 8 str_77_20
history 9  reldispx
history 10 reldispy
history 11 excpp
history 12 pp i=49, j=23
history 13 esyy i=49, j=23
history 14 xaccel i=77, j=1
history 15 xaccel i=77, j=29
history 16 xaccel i=172, j=29
history 17 xaccel i=9, j=29
history 18 xvel i=77, j=1
history 19 xvel i=77, j=29
history 20 xvel i=172, j=29
history 21 xvel i=9, j=29
history nstep 100
set step=10000000
prop ff_latency 50 region 78 19
prop ff_latency 50 region 60 22
prop ff_latency 50 region 103 26
save edam6fr.sav
```

```
;Branch 1:edam7fr.sav
set echo off
call greduce.fis
set _prat=0.30
set _gfac=0.8
greduce
set dy_damping rayleigh=0.063 1.0
apply ffield
apply sxy -9358.0 hist table 104 from 1,1 to 181,1
apply xquiet yquiet from 1,1 to 181,1
set echo off
call savepp.fis
savepp
set echo off
call getExcesspp.fis
set nsample=50 nstep=1
getExcesspp
save edam7fr.sav

;Branch 2:edam8fr.sav
solve dytime 40.0
save edam8fr.sav

;*** plot commands ***
;plot name: Unbalanced force
plot hold history 999
;plot name: pp hist
plot hold history 1 line 2 line 3 line vs 4
;plot name: pp
plot hold  pp fill
;plot name: ssi
plot hold  ssi fill int 0.01
;plot name: ydisp
plot hold  ydisp fill zero
;plot name: reldisp
plot hold history 9 10 vs 5
;plot name: syy
plot hold syy fill
;plot name: pp - esyy hist
plot hold history 12 line 13 line vs 5
;plot name: xdisp
plot hold  xdisp fill min -4.1 zero inv
;plot name: exc pp rat
plot hold  ex_6 zone fill min 0.99 bound
;plot name: stress v strain
plot hold history 7 line vs 8
```

```
;plot name: max shear strain
plot hold ex_10 zone alias 'max shear strain' fill
;plot name: xvel at base vs top
plot hold history 18 line 19 line vs 5
;plot name: compare vel
label table 104
input velocity
label table 18
xvelocity at (77,1)
plot hold table 104 line 18 line alias 'compare base velocities'
;plot name: Plot 1
plot hold history 16 line vs 5
;plot name: grid
plot hold grid bound magnify 0.0 white
```