Northeastern University

Department of Civil and Environmental Engineering

CIVE 7978 Independent Study

Spring 2018

Use of Engineering Software (ProShake, GeoStudio Slope/W and FLAC) in the Field of Geotechnical Earthquake Engineering

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April 2, 2018

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Project Description

This independent study report provides documentation an evidence of knowledge gained in performing:

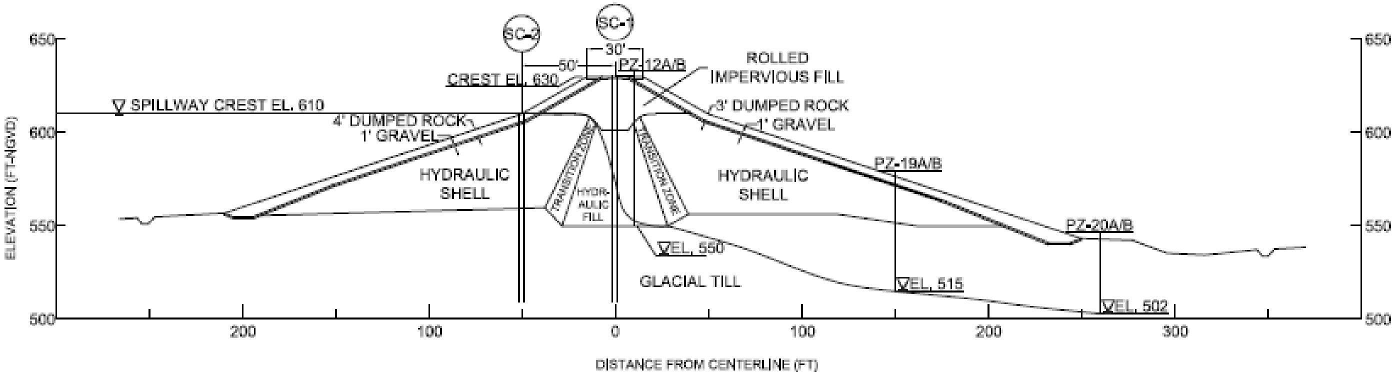
1. Site response analysis using ProShake
2. Psuedo-static slope stability analysis using GeoStudio Slope/W
3. 2-D seismic analysis using FLAC 2D

1. Site Response Analysis using ProShake

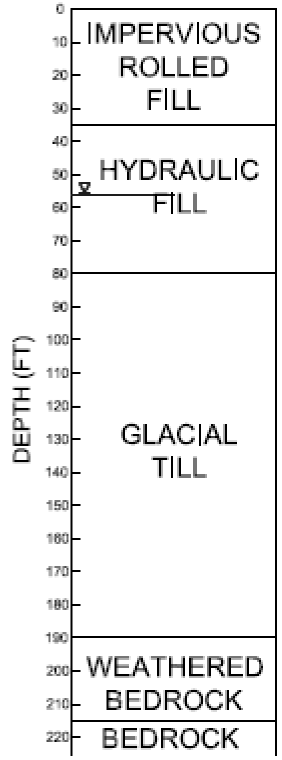
The example ProShake run in this independent study uses the cross section of the Knightville Dam which is located on the Westfield River in Huntington, MA. The dam provides flood protection to Huntington, Westfield, and West Springfield region. The Knightville Dam is an earth fill embankment with a height of 160 ft. There are two different embankment slopes which are 3H:1V for 140ft and 2.5H:1V for 20 ft from the surface, respectively.

Figure 1: Knightville Dam

The dam cross section and a soil column representing the crest region of the dam are shown in Figure 2. The soil profile consists of about 110 ft glacial till under the Knightville Embankment Dam. Thirty feet of weathered bedrock underlies the glacial till and hard bedrock is located below weathered bedrock.



SECTION A-A NEAR STA. 4+82



SC-1 SOIL COLUMN SC-1
STA. 4+82, AT C/L

Figure 2: Dam Section and soil column

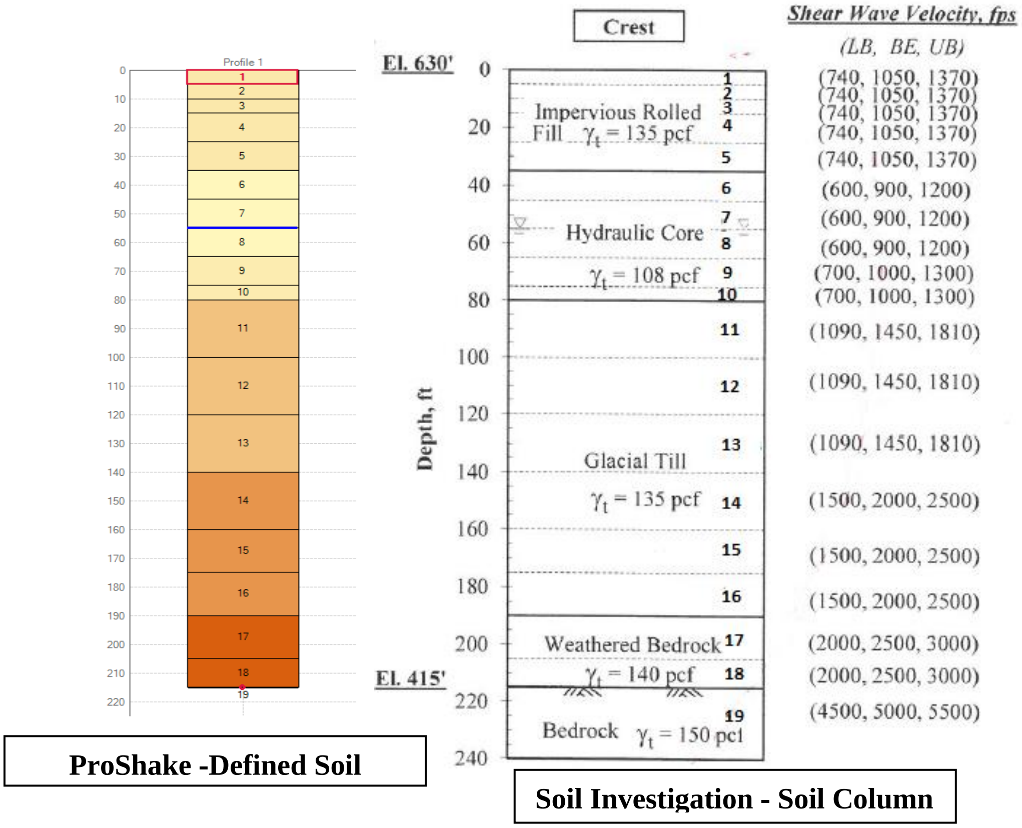
ProShake was used to obtain response spectra of the ground surface motion at the crest of the Knightville Dam. Depth plots such as peak acceleration, shear stress, and shear strain vs. depth were also investigated.

1.1. Input Parameters

Three ranges of shear wave velocity were used for each soil layer and they were Lower Bound (LB), Best Estimate (BE), and Upper Bound (UP). ProShake analyses were performed for each shear velocity range.

1.1.1. Layer Definition

There are five soil layers defined in the soil column (Figure 3) which are: impervious rolled fill, hydraulic core, glacial till, weathered bedrock and bedrock. In order to get more accurate results of seismic response of the soil column the main layers were divided into nineteen sub-layers, as shown in the Figure 3.

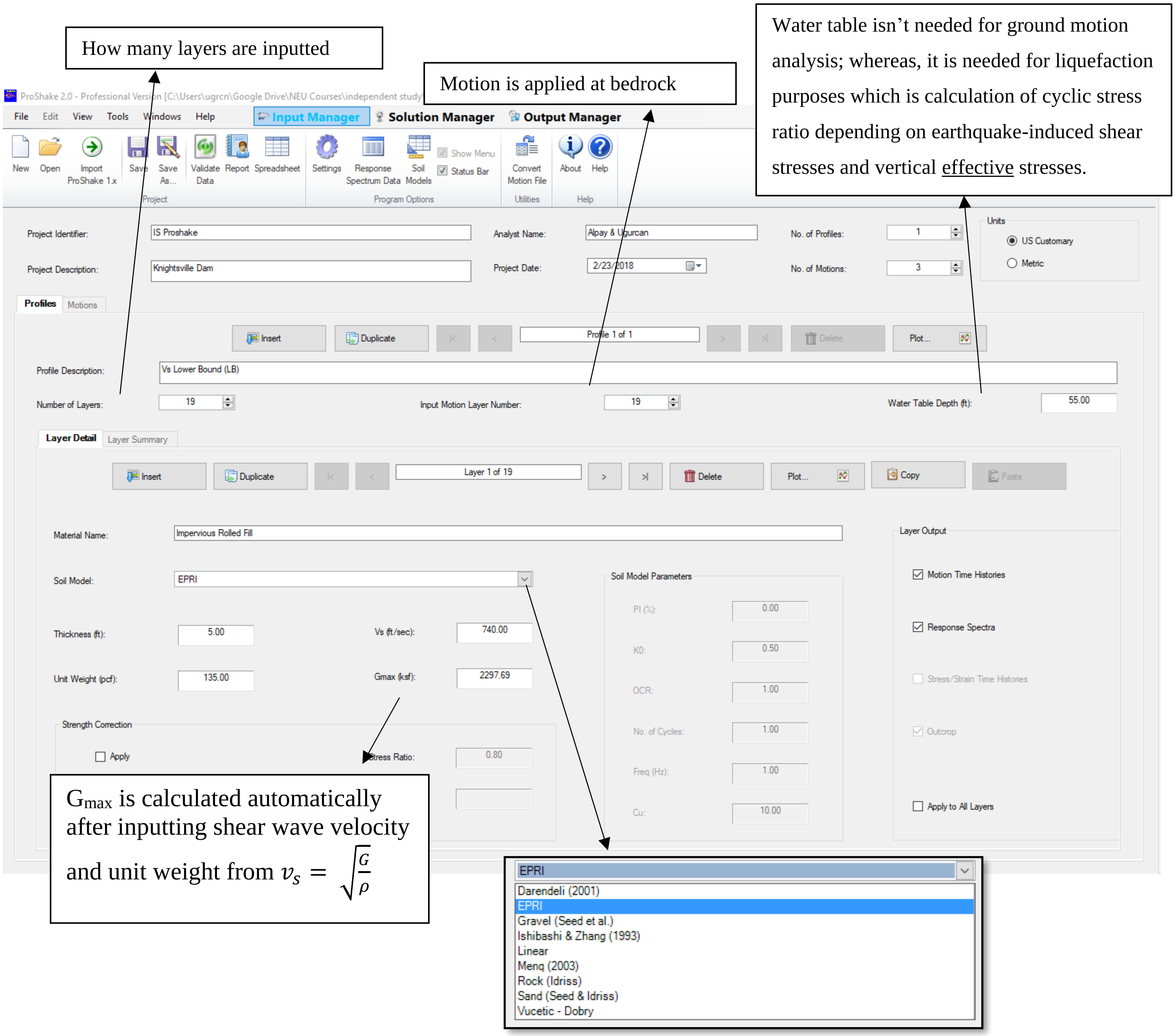


ProShake -Defined Soil

Soil Investigation - Soil Column

Figure 3: Layered Soil Column

The input motion was applied at the outcropping of bedrock. The water table was inputted as 55 ft. below from the top of soil column. For each sub-layer, material name, soil model, thickness, unit weight and shear wave velocity were inputted and G_{max} was estimated automatically by using unit weight and shear wave velocity. How to input these parameters is shown in the Figure 4.



How many layers are inputted

Motion is applied at bedrock

Water table isn't needed for ground motion analysis; whereas, it is needed for liquefaction purposes which is calculation of cyclic stress ratio depending on earthquake-induced shear stresses and vertical effective stresses.

Project Identifier: IS Proshake

Analyst Name: Alpay & Ugurcan

No. of Profiles: 1

Units: ● US Customary ○ Metric

Project Description: Knightsville Dam

Project Date: 2/23/2018

No. of Motions: 3

Profile 1 of 1

Profile Description: Vs Lower Bound (LB)

Number of Layers: 19

Input Motion Layer Number: 19

Water Table Depth (ft): 55.00

Layer 1 of 19

Material Name: Impervious Rolled Fill

Soil Model: EPRI

Thickness (ft): 5.00

Vs (ft/sec): 740.00

Unit Weight (pcf): 135.00

Gmax (ksf): 2297.69

Strength Correction

☐ Apply

Stress Ratio: 0.80

PI (%): 0.00

K0: 0.50

OCR: 1.00

No. of Cycles: 1.00

Freq (Hz): 1.00

Cu: 10.00

☑ Motion Time Histories

☑ Response Spectra

☐ Stress/Strain Time Histories

☑ Outcrop

☐ Apply to All Layers

G_{max} is calculated automatically after inputting shear wave velocity and unit weight from $v_s = \sqrt{\frac{G}{\rho}}$

EPRI

Darendeli (2001)
EPRI
Gravel (Seed et al.)
Ishibashi & Zhang (1993)
Linear
Menq (2003)
Rock (Idriss)
Sand (Seed & Idriss)
Vucetic - Dobry

Figure 4: Input for Layer Definition

There are different soil models available at ProShake to select different modulus reduction and damping ratio models to find shear strains.

Soil model: Soil models are selected to use corresponding modulus reduction and damping increase curves. Shear strains are calculated by using G_{max} at first, then using modulus reduction and damping model for corresponding soil model, shear strains are calculated with a number of iterations until it converges. In the analysis, Electric Power Research Institute (EPRI) model (Figure 5) and Idriss (Figure 6) model were used for sands and rocks, respectively.

- **Electric Power Research Institute (EPRI) for sands:**

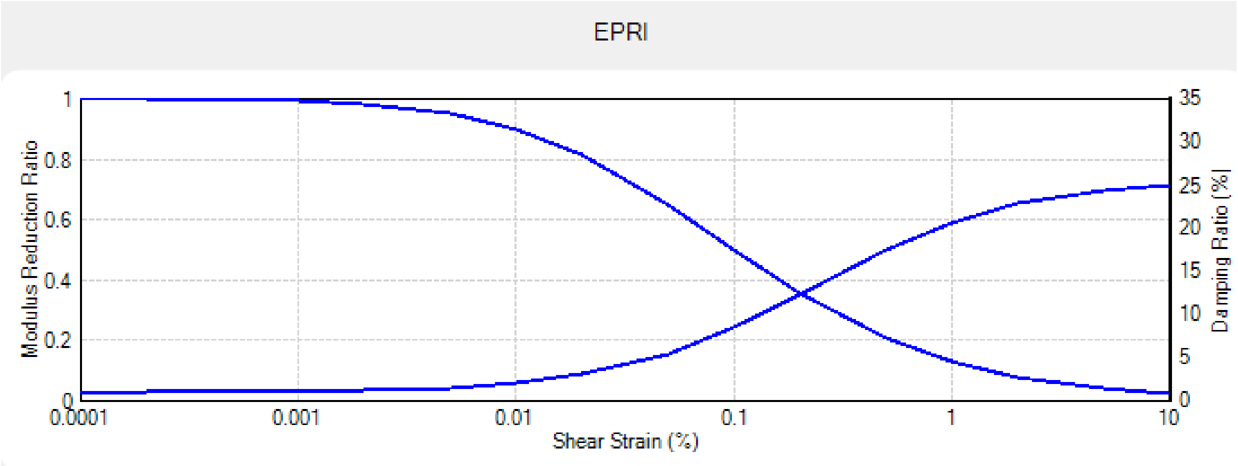


Figure 5: EPRI soil model

- **Idriss for rock:**

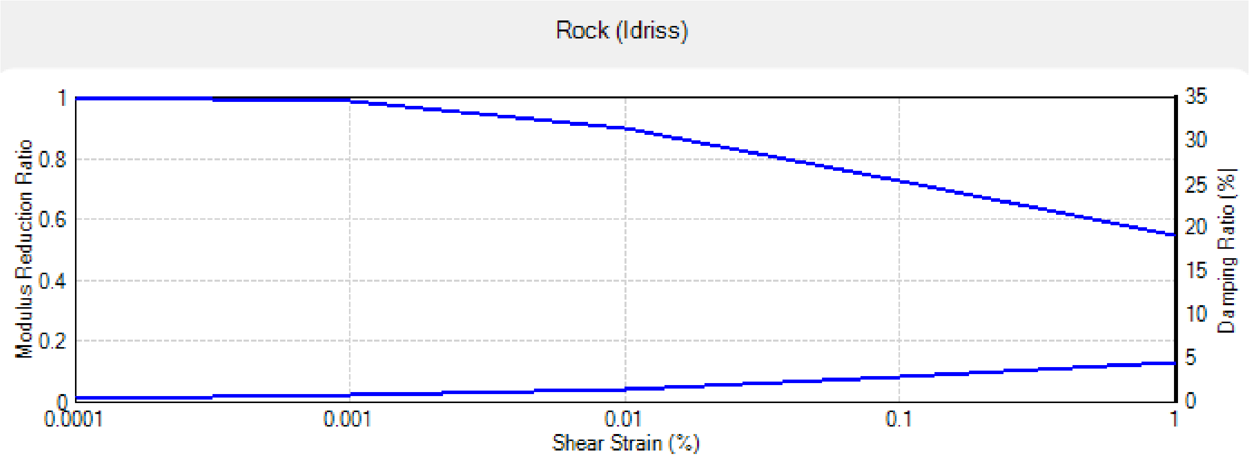


Figure 6: Idriss soil model

Knightville Dam Soil Profile: Soil column for lower bound shear wave velocity of Knightville Dam was inputted as below table:

Table 1.1: Soil Layer Properties for LB Shear Wave Velocity

Layer Number	Material Name	Thickness	Unit Weight	Vs	G Max	Soil Model ID	Output Outcrop
1	Impervious Rolled Fill	5.00	135.0	740.0	2297.7	EPRI	True
2	Impervious Rolled Fill	5.00	135.0	740.0	2297.7	EPRI	False
3	Impervious Rolled Fill	5.00	135.0	740.0	2297.7	EPRI	False
4	Impervious Rolled Fill	10.00	135.0	740.0	2297.7	EPRI	False
5	Impervious Rolled Fill	10.00	135.0	740.0	2297.7	EPRI	False
6	Hydraulic Core	10.00	108.0	600.0	1208.4	EPRI	False
7	Hydraulic Core	10.00	108.0	600.0	1208.4	EPRI	False
8	Hydraulic Core	10.00	108.0	600.0	1208.4	EPRI	False
9	Hydraulic Core	10.00	108.0	700.0	1644.8	EPRI	False
10	Hydraulic Core	5.00	108.0	700.0	1644.8	EPRI	False
11	Glacial Till	20.00	135.0	1090.0	4985.2	EPRI	False
12	Glacial Till	20.00	135.0	1090.0	4985.2	EPRI	False
13	Glacial Till	20.00	135.0	1090.0	4985.2	EPRI	False
14	Glacial Till	20.00	135.0	1500.0	9440.9	EPRI	False
15	Glacial Till	15.00	135.0	1500.0	9440.9	EPRI	False
16	Glacial Till	15.00	135.0	1500.0	9440.9	EPRI	False
17	Weathered Bedrock	15.00	140.0	2000.0	17405.4	Rock (Idriss)	False
18	Weathered Bedrock	10.00	140.0	2000.0	17405.4	Rock (Idriss)	False
19	Bedrock	0.00	150.0	4500.0	94408.5	Rock (Idriss)	True

For granular materials column for as impervious rolled fill, hydraulic core and glacial till, EPRI soil model was applied. Weathered bedrock can also be modeled as granular material and so as EPRI method but since its shear wave velocity was about 2000 ft/sec, it was modeled as rock and rock (Idriss) soil model was used for weathered bedrock and bedrock layer. First and last layer were defined as outcrop. Input motion is an outcrop motion, i.e., if it was recorded at, or is intended to represent the motion at, a free surface. If the outcrop is not established for a layer, the input motion will be applied at the input motion location as if the motion was recorded at that depth. Soil column properties for BE, UB shear wave velocities are tabulated at the Appendix A section.

1.1.2. Motion Inputs

Three earthquake motions were inputted into the ProShake. The earthquakes were first converted into motion files for ProShake analysis. Effective strain ratio (ESR) has an empirical relation with an earthquake magnitude which is (M-1)/10 and ESR is a strain reduction factor to calculate effective shear strain with maximum shear strain defined as:

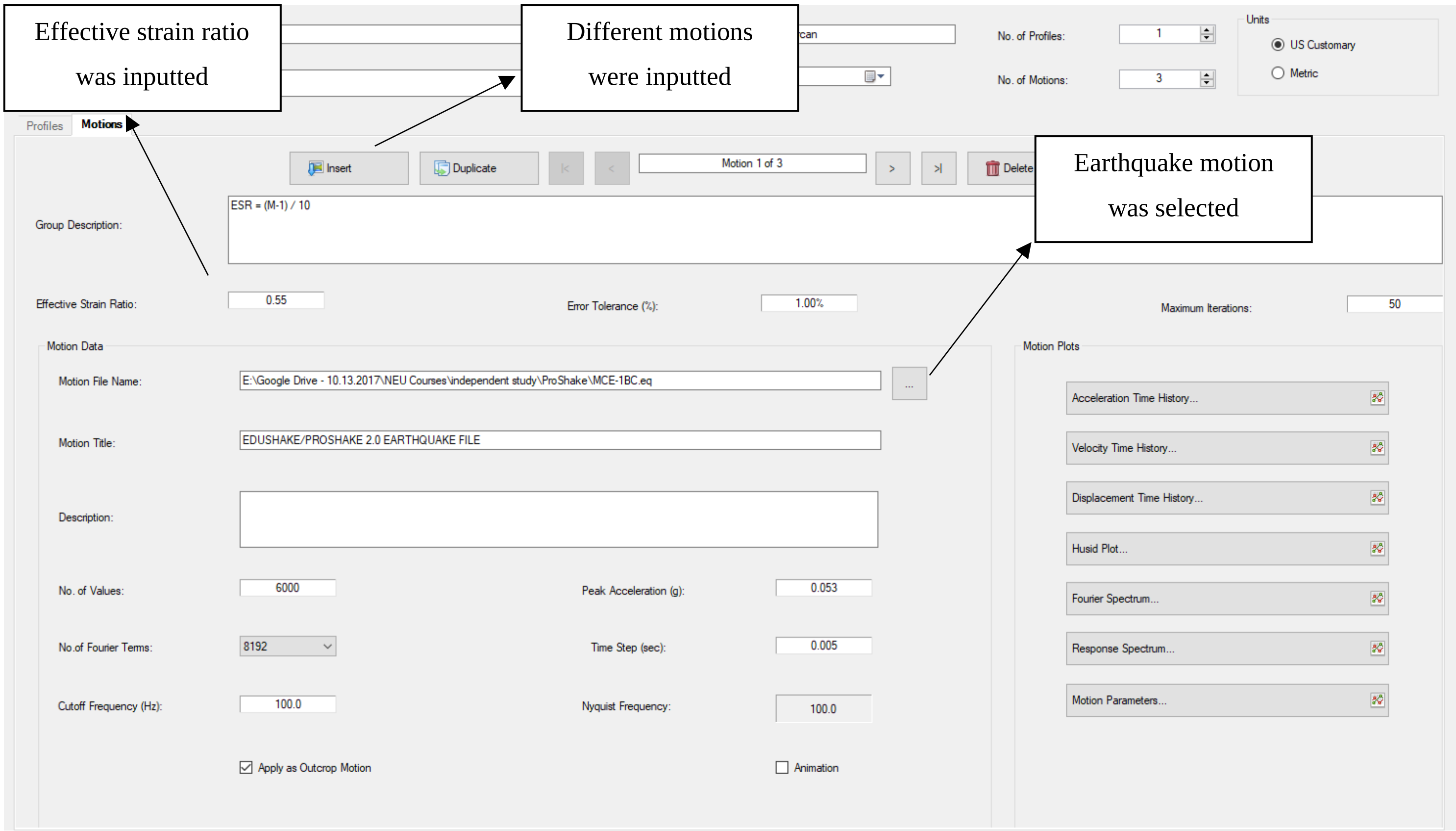
$$\gamma_{eff} = R_{\gamma}\ x\ \gamma_{max} \rightarrow R_{\gamma}: strain\ reduction\ factor, \qquad \gamma_{eff} = effective\ shear\ strain$$

ESR is typically taken as 0.65; however, magnitude of 6.5 earthquake (California region earthquake) is assumed and **ESR was used as 0.55**. Peak acceleration is automatically obtained from the earthquake motions which are inputted. If the peak acceleration is changed, the whole motion is scaled up/down depending on the changed peak acceleration. For the project, peak acceleration was left as it was in the earthquake motions. Also, time step is taken from the motion data.

The software also gets cutoff frequency as an input for computational purposes. Typically, 20-50 Hz and 100 Hz cutoff frequencies are used for West and East cost of the United States, respectively.

Damping ratio was used in the calculation of response spectra was 5%.

Figure 7 shows some of the details of the input motion file.



Effective strain ratio was inputted

Different motions were inputted

Earthquake motion was selected

No. of Profiles: 1

No. of Motions: 3

Units: ● US Customary ○ Metric

Motion 1 of 3

Group Description: ESR = (M-1) / 10

Effective Strain Ratio: 0.55

Error Tolerance (%): 1.00%

Maximum Iterations: 50

Motion Data

Motion File Name: E:\Google Drive - 10.13.2017\NEU Courses\independent study\ProShake\MCE-1BC.eq

Motion Title: EDUSHAKE/PROSHAKE 2.0 EARTHQUAKE FILE

Description:

No. of Values: 6000

Peak Acceleration (g): 0.053

No.of Fourier Terms: 8192

Time Step (sec): 0.005

Cutoff Frequency (Hz): 100.0

Nyquist Frequency: 100.0

☑ Apply as Outcrop Motion

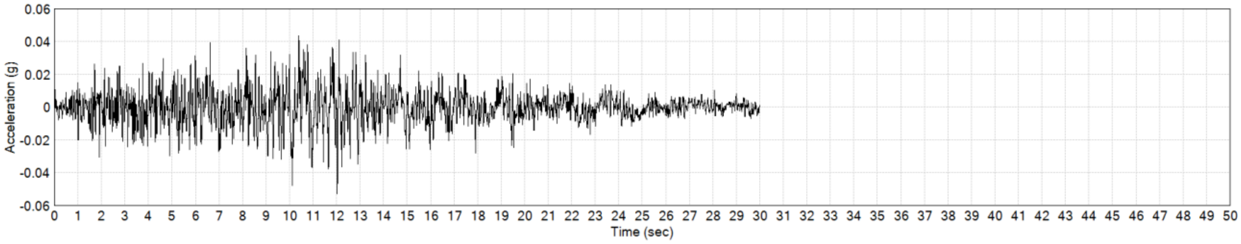
☐ Animation

Figure 7: Motion inputs in ProShake

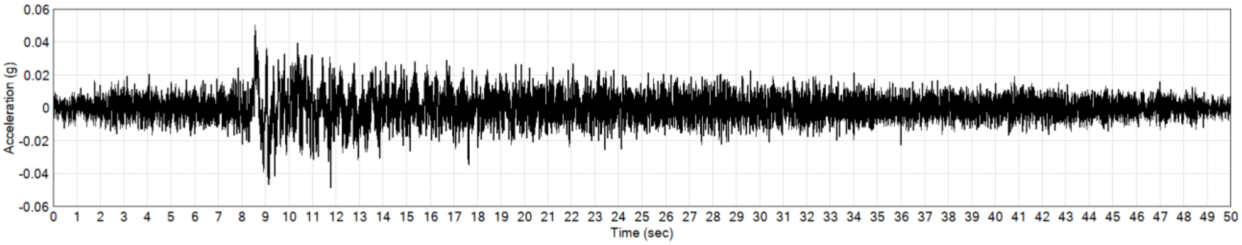
Acceleration Time Histories:

Figure 8 indicates input motions used in Proshake.

- **Earthquake motion MCE-1BC:**



- **Earthquake motion MCE-2BC:**



- **Earthquake motion MCE-3BC:**

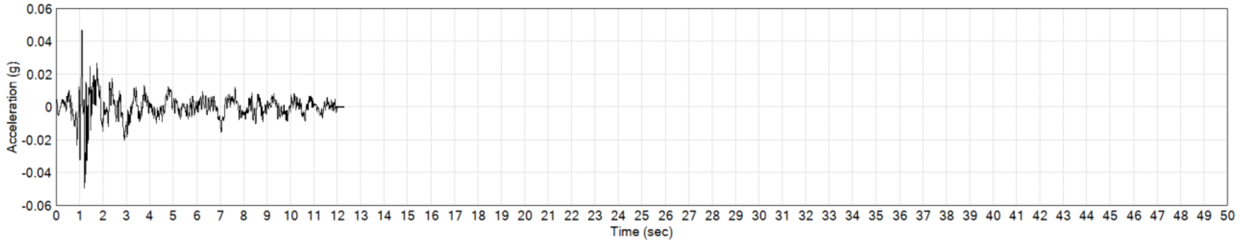


Figure 8: Acceleration Time History for MCE-1BC, MCE-2BC and MCE-3BC

1.2. Analysis and Results

Soil behavior is nonlinear and inelastic which means that the shear modulus of the soil changes during seismic shakings. Although the soil is known as nonlinear and inelastic, the ProShake cannot use nonlinear stress-strain behavior due to how the software solves the equation of motion.

To approximate nonlinearity, the software uses an equivalent linear approach. Linear analyses are performed iteratively by using modulus reduction and damping ratio to get effective shear strain. This process is repeated until the computed effective strain does not change from the iteration to the next.

1.2.1. Response Spectra

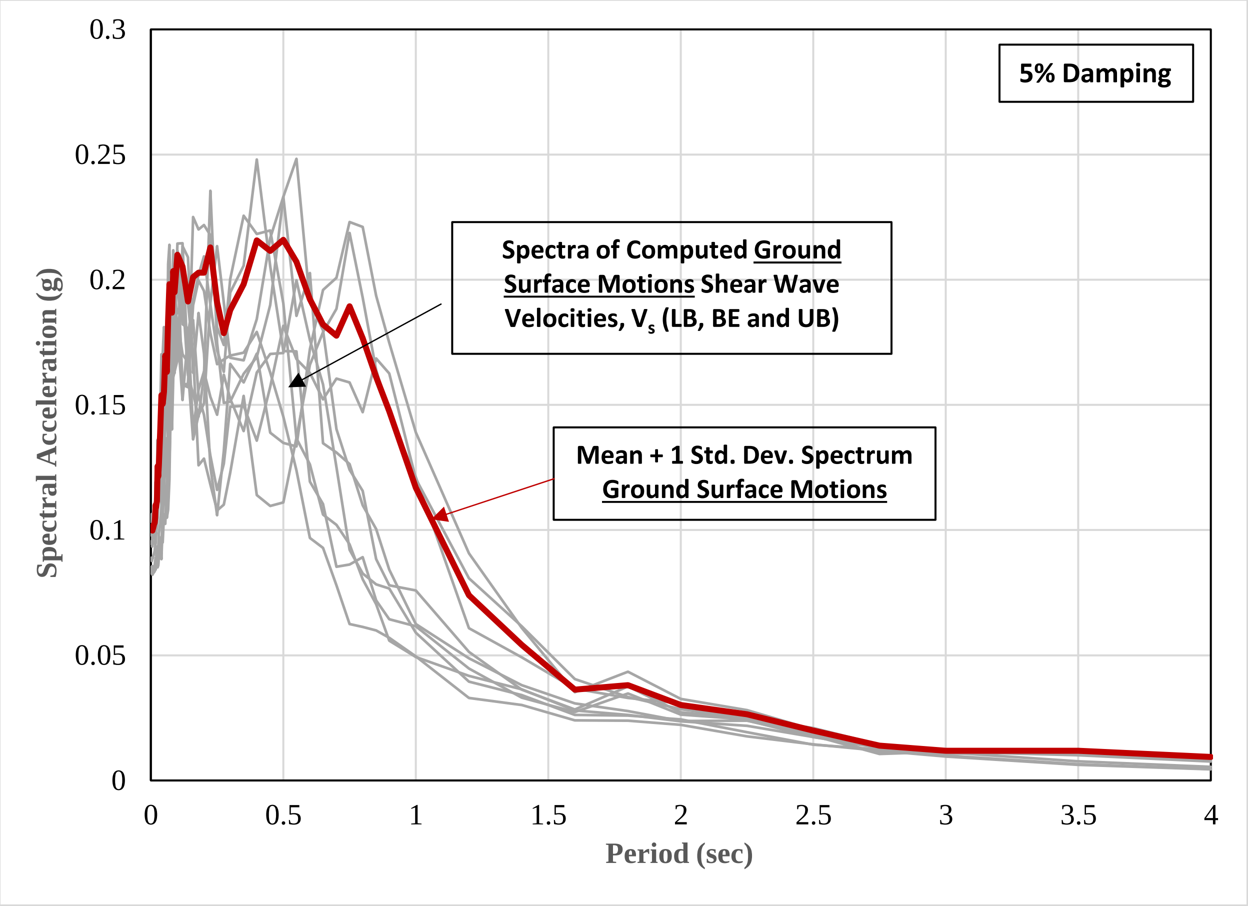


Figure 9: Response Spectrum for all Shear Wave Velocities (LB, BE and UB)

From the response spectrum plot shown in Figure 9, the peak spectral acceleration is about 0.22g and the natural period of the structure range between 0.1 – 0.6 sec gives the peak spectral accelerations.

1.2.2. Depth Plots

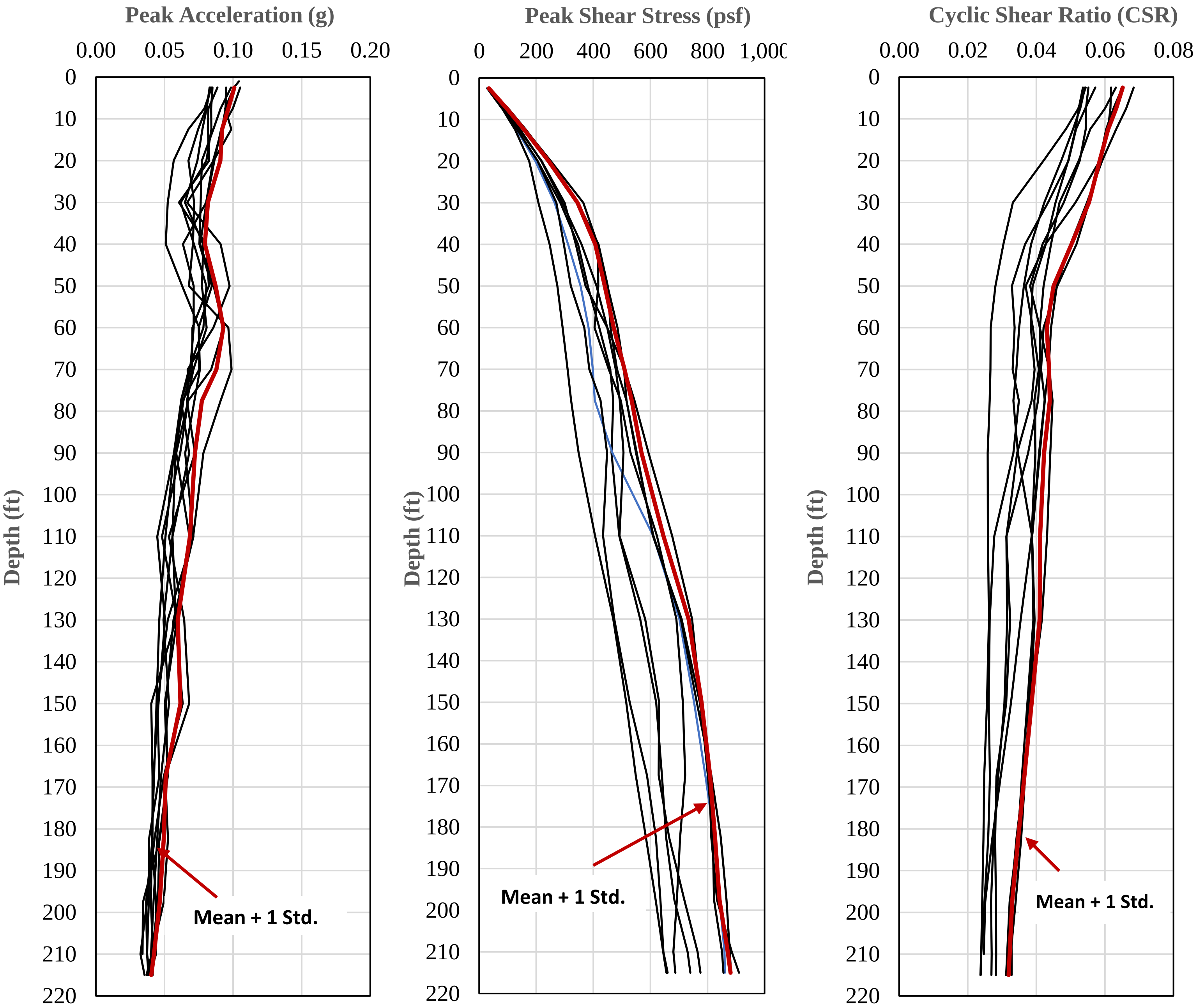


Figure 6: Peak Shear Stress, Peak Acceleration and CSR for Shear Wave Velocities (LB, BE and UB)

Appendix A: ProShake

A.1. Input Files

○ LB Shear Wave Velocity

Layer Number	Material Name	Thickness	Unit Weight	Vs	G Max	Soil Model ID	Output Outcrop
1	Impervious Rolled Fill	5.00	135.0	740.0	2297.7	EPRI	True
2	Impervious Rolled Fill	5.00	135.0	740.0	2297.7	EPRI	False
3	Impervious Rolled Fill	5.00	135.0	740.0	2297.7	EPRI	False
4	Impervious Rolled Fill	10.00	135.0	740.0	2297.7	EPRI	False
5	Impervious Rolled Fill	10.00	135.0	740.0	2297.7	EPRI	False
6	Hydraulic Core	10.00	108.0	600.0	1208.4	EPRI	False
7	Hydraulic Core	10.00	108.0	600.0	1208.4	EPRI	False
8	Hydraulic Core	10.00	108.0	600.0	1208.4	EPRI	False
9	Hydraulic Core	10.00	108.0	700.0	1644.8	EPRI	False
10	Hydraulic Core	5.00	108.0	700.0	1644.8	EPRI	False
11	Glacial Till	20.00	135.0	1090.0	4985.2	EPRI	False
12	Glacial Till	20.00	135.0	1090.0	4985.2	EPRI	False
13	Glacial Till	20.00	135.0	1090.0	4985.2	EPRI	False
14	Glacial Till	20.00	135.0	1500.0	9440.9	EPRI	False
15	Glacial Till	15.00	135.0	1500.0	9440.9	EPRI	False
16	Glacial Till	15.00	135.0	1500.0	9440.9	EPRI	False
17	Weathered Bedrock	15.00	140.0	2000.0	17405.4	Rock (Idriss)	False
18	Weathered Bedrock	10.00	140.0	2000.0	17405.4	Rock (Idriss)	False
19	Bedrock	0.00	150.0	4500.0	94408.5	Rock (Idriss)	True

○ BE Shear Wave Velocity

Layer Number	Material Name	Thickness	Unit Weight	Vs	G Max	Soil Model ID	Output Outcrop
1	Impervious Rolled Fill	5.00	135.0	1050.0	4626.0	EPRI	True
2	Impervious Rolled Fill	5.00	135.0	1050.0	4626.0	EPRI	False
3	Impervious Rolled Fill	5.00	135.0	1050.0	4626.0	EPRI	False
4	Impervious Rolled Fill	10.00	135.0	1050.0	4626.0	EPRI	False
5	Impervious Rolled Fill	10.00	135.0	1060.0	4714.6	EPRI	False
6	Hydraulic Core	10.00	108.0	900.0	2719.0	EPRI	False
7	Hydraulic Core	10.00	108.0	900.0	2719.0	EPRI	False
8	Hydraulic Core	10.00	108.0	900.0	2719.0	EPRI	False

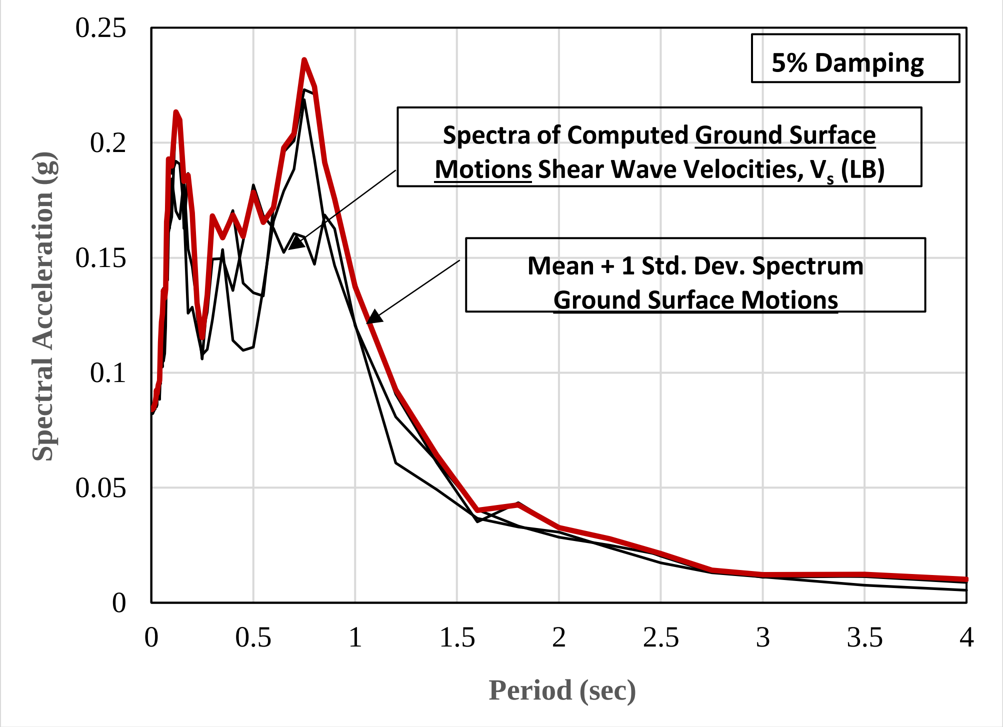
9	Hydraulic Core	10.00	108.0	1000.0	3356.7	EPRI	False
10	Hydraulic Core	5.00	108.0	1000.0	3356.7	EPRI	False
11	Glacial Till	20.00	135.0	1450.0	8822.0	EPRI	False
12	Glacial Till	20.00	135.0	1450.0	8822.0	EPRI	False
13	Glacial Till	20.00	135.0	1450.0	8822.0	EPRI	False
14	Glacial Till	20.00	135.0	2000.0	16783.7	EPRI	False
15	Glacial Till	15.00	135.0	2000.0	16783.7	EPRI	False
16	Glacial Till	15.00	135.0	2000.0	16783.7	EPRI	False
17	Weathered Bedrock	15.00	140.0	2500.0	27195.9	Rock (Idriss)	False
18	Weathered Bedrock	10.00	140.0	2500.0	27195.9	Rock (Idriss)	False
19	Bedrock	25.00	150.0	5000.0	116553.7	Rock (Idriss)	True

UB Shear Wave Velocity

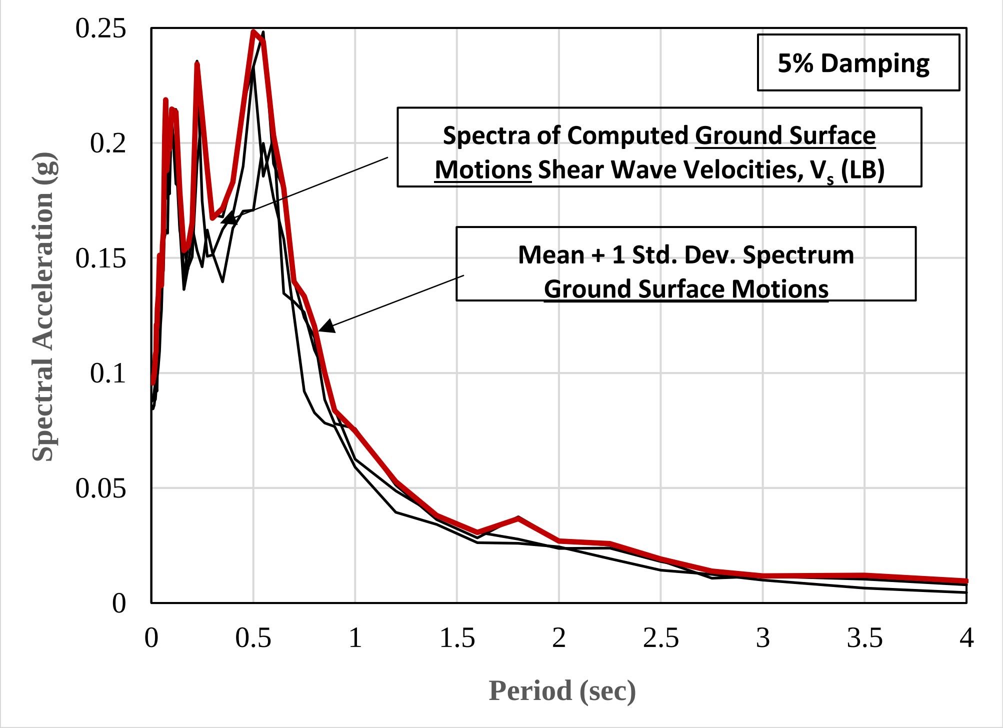
Layer Number	Material Name	Thickness	Unit Weight	Vs	G Max	Soil Model ID	Output Outcrop
1	Impervious Rolled Fill	5.00	135.0	1370.0	7875.4	EPRI	True
2	Impervious Rolled Fill	5.00	135.0	1370.0	7875.4	EPRI	False
3	Impervious Rolled Fill	5.00	135.0	1370.0	7875.4	EPRI	False
4	Impervious Rolled Fill	10.00	135.0	1370.0	7875.4	EPRI	False
5	Impervious Rolled Fill	10.00	135.0	1370.0	7875.4	EPRI	False
6	Hydraulic Core	10.00	108.0	1200.0	4833.7	EPRI	False
7	Hydraulic Core	10.00	108.0	1200.0	4833.7	EPRI	False
8	Hydraulic Core	10.00	108.0	1200.0	4833.7	EPRI	False
9	Hydraulic Core	10.00	108.0	1300.0	5672.9	EPRI	False
10	Hydraulic Core	5.00	108.0	1300.0	5672.9	EPRI	False
11	Glacial Till	20.00	135.0	1810.0	13746.3	EPRI	False
12	Glacial Till	20.00	135.0	1810.0	13746.3	EPRI	False
13	Glacial Till	20.00	135.0	1810.0	13746.3	EPRI	False
14	Glacial Till	20.00	135.0	2500.0	26224.6	EPRI	False
15	Glacial Till	15.00	135.0	2500.0	26224.6	EPRI	False
16	Glacial Till	15.00	135.0	2500.0	26224.6	EPRI	False
17	Weathered Bedrock	15.00	140.0	3000.0	39162.1	Rock (Idriss)	False
18	Weathered Bedrock	10.00	140.0	3000.0	39162.1	Rock (Idriss)	False
19	Bedrock	25.00	150.0	5500.0	141030.0	Rock (Idriss)	True

A.2. Response Spectra

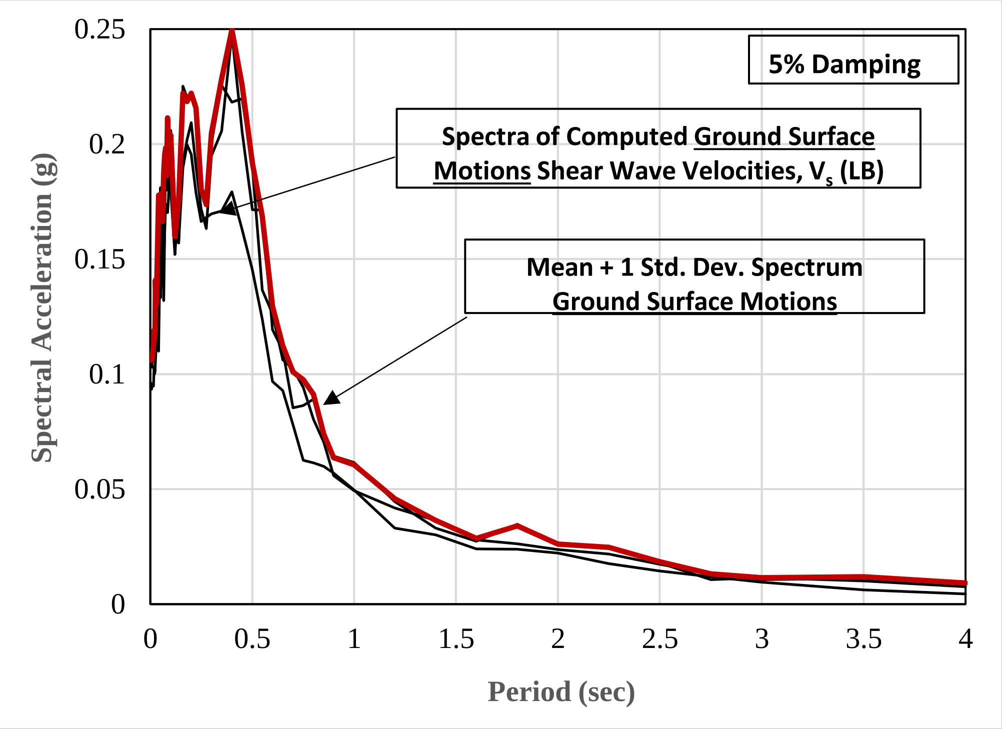
- **LB Shear Wave Velocity**



- **BE Shear Wave Velocity**

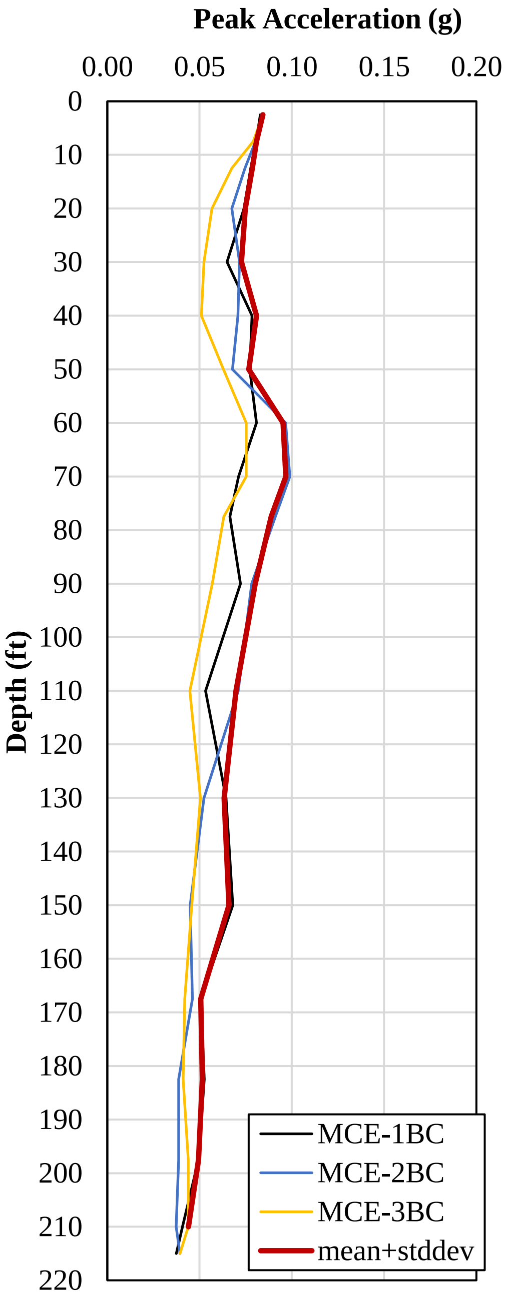


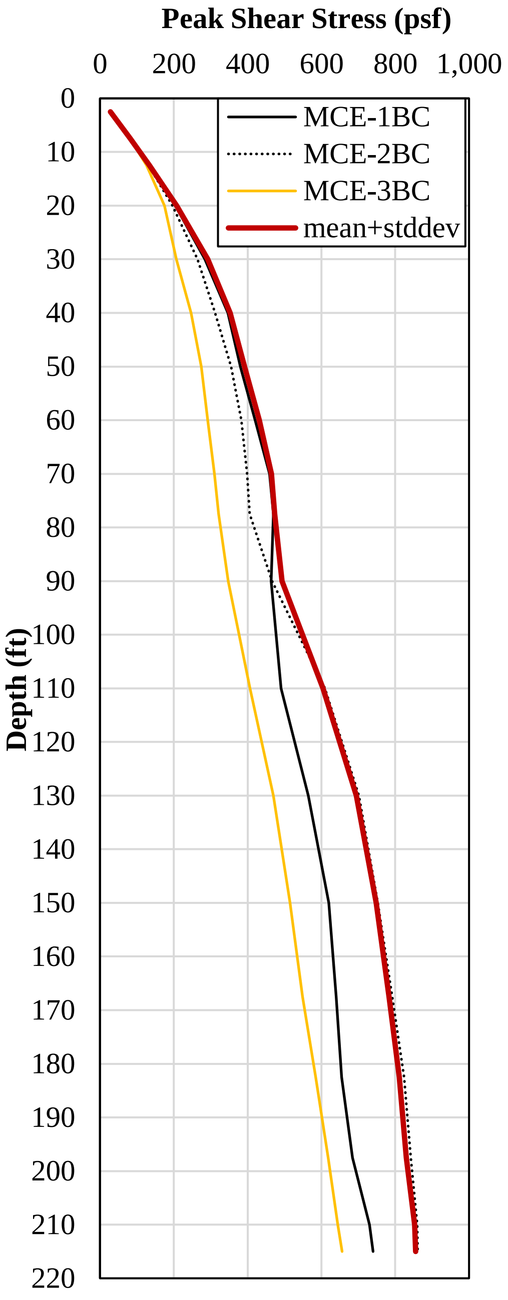
- **UB Shear Wave Velocity**

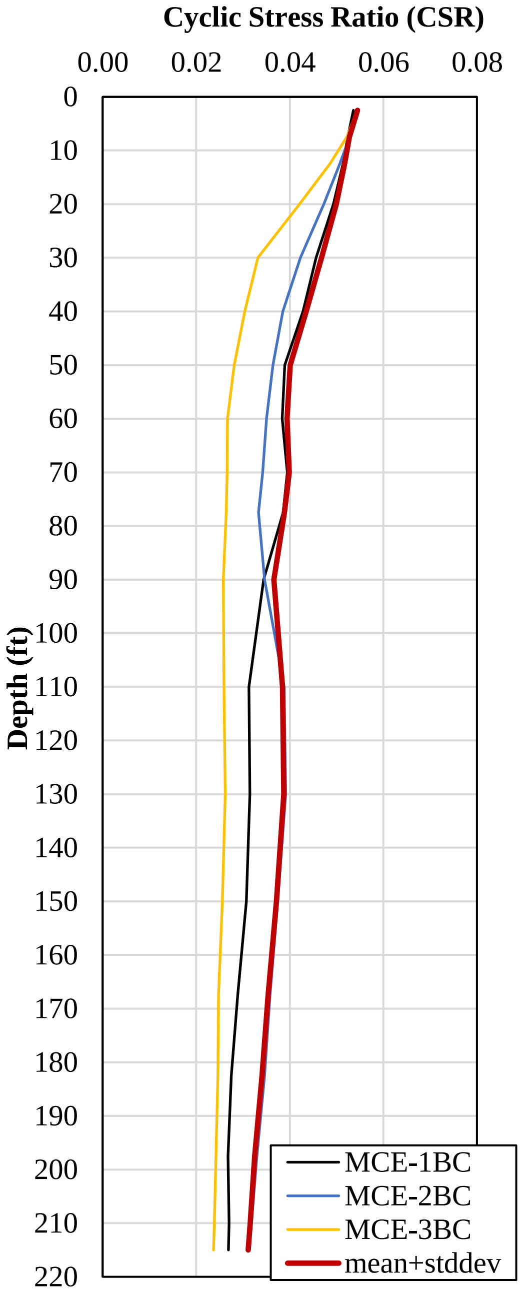


A.3. Depth Plots

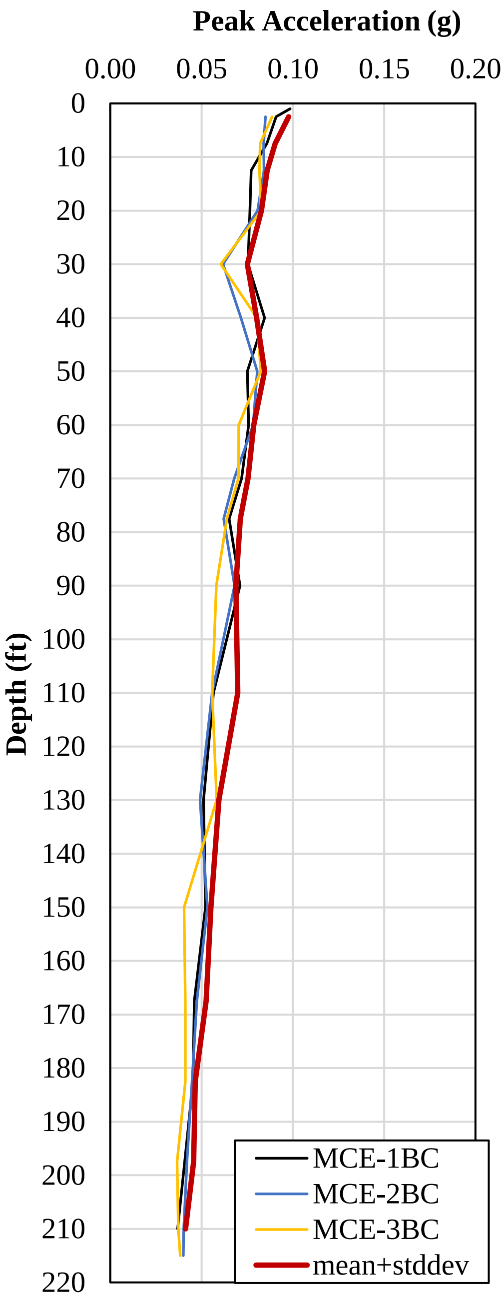
- ○ **LB Shear Wave Velocity**

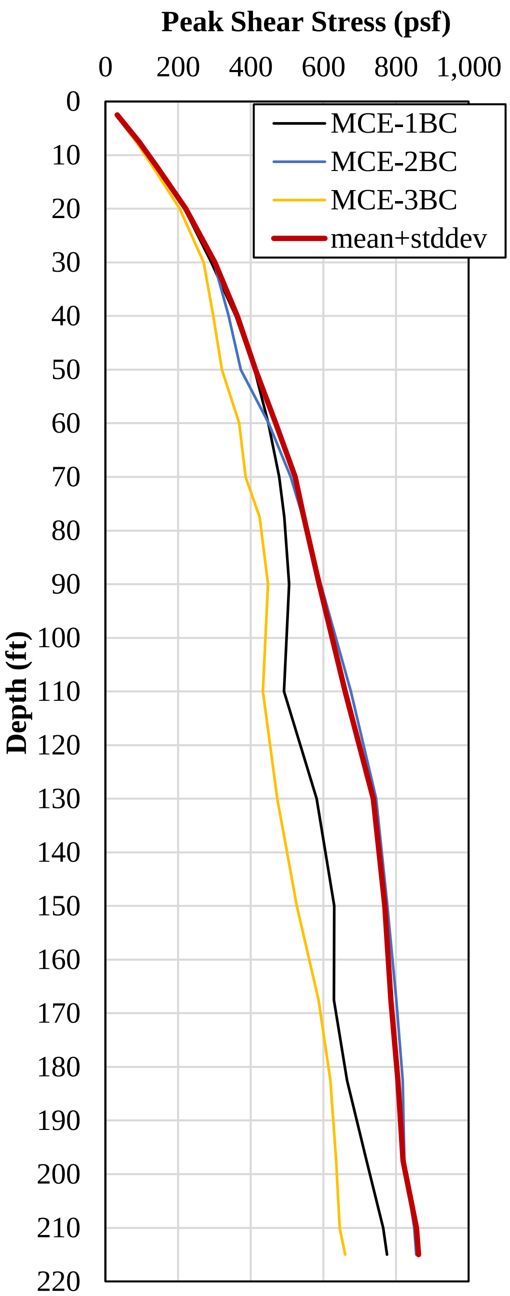


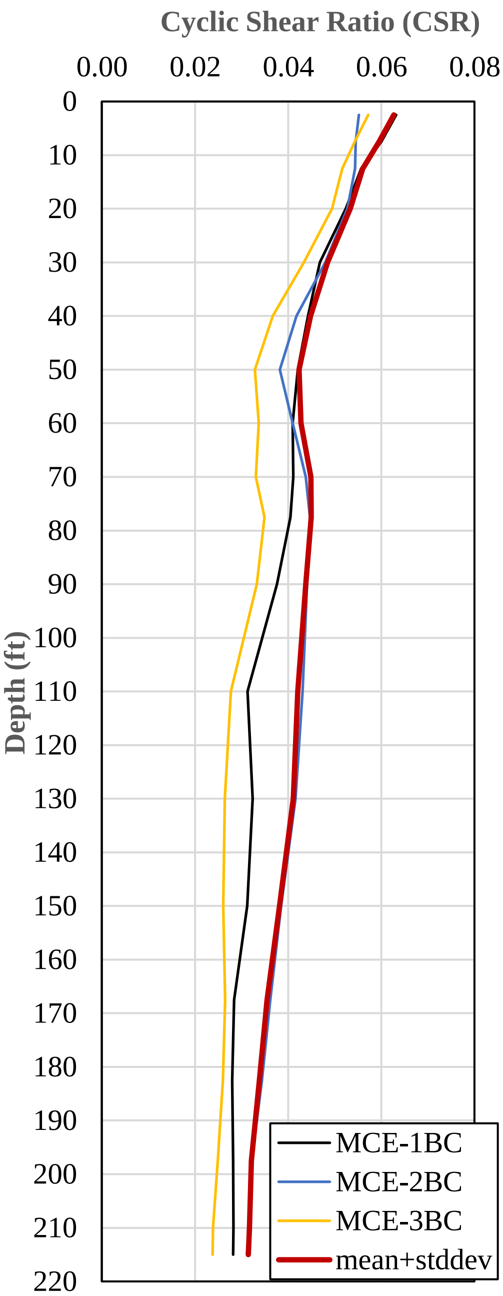




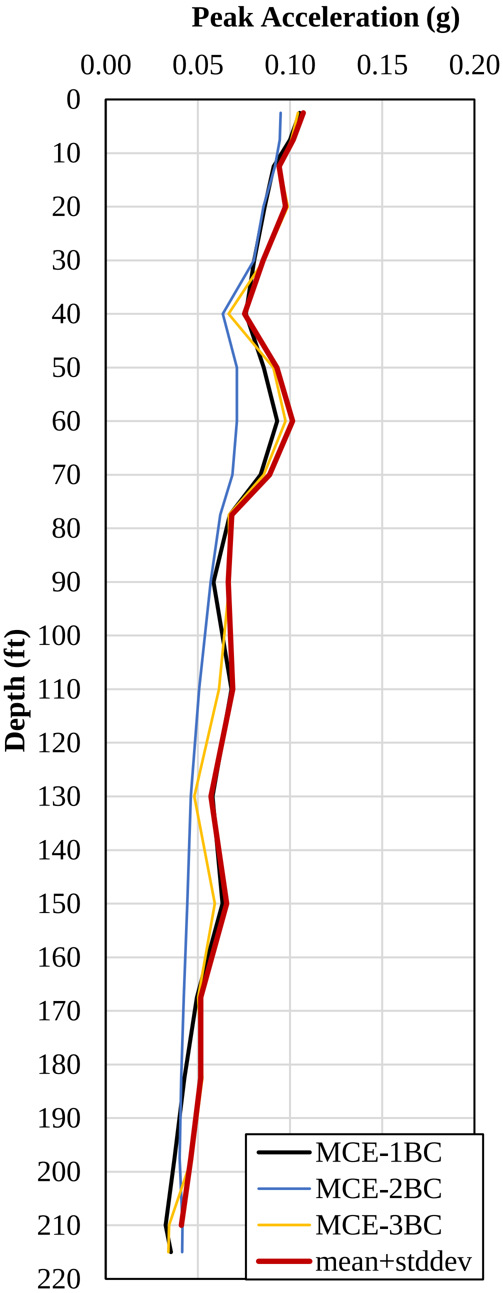
- **BE Shear Wave Velocity**

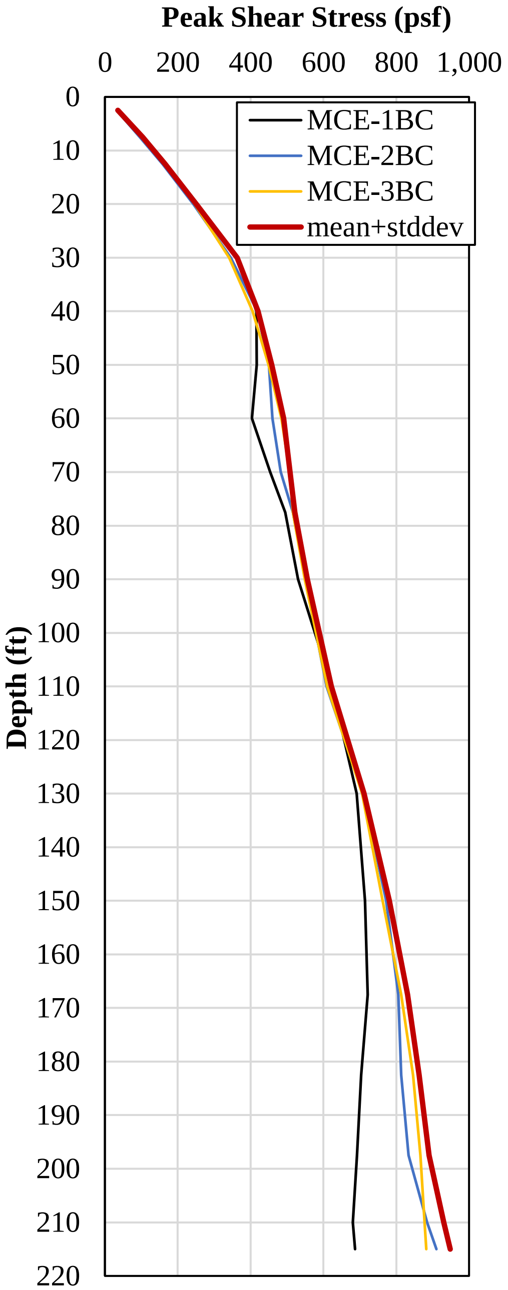


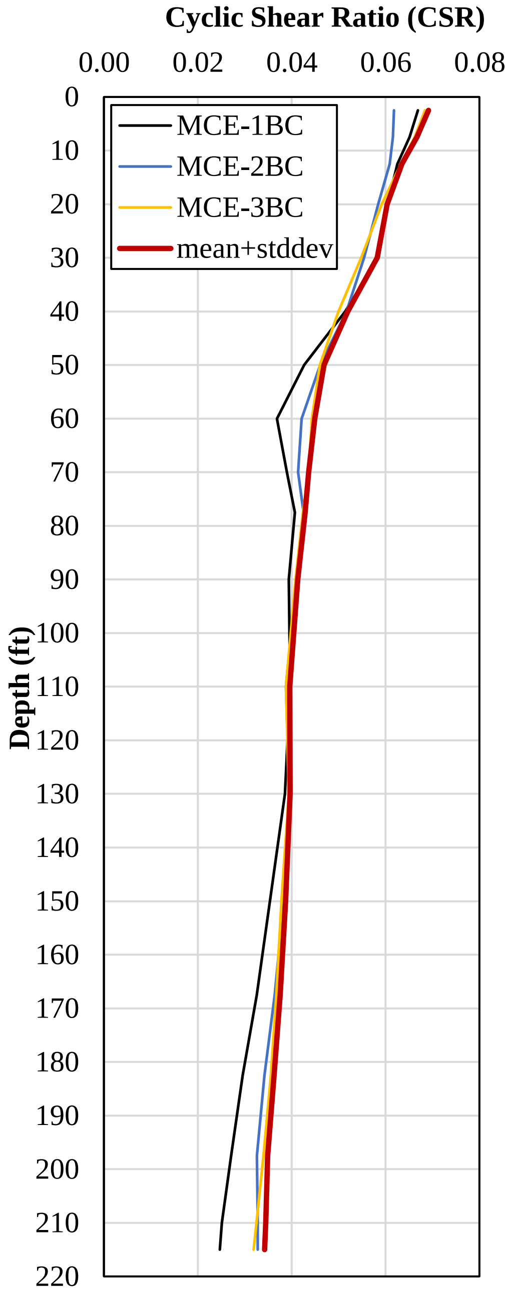




- **UB Shear Wave Velocity**







3. Slope Stability Analysis Using GeoStudio Slope/W

3.1. GeoStudio 2007

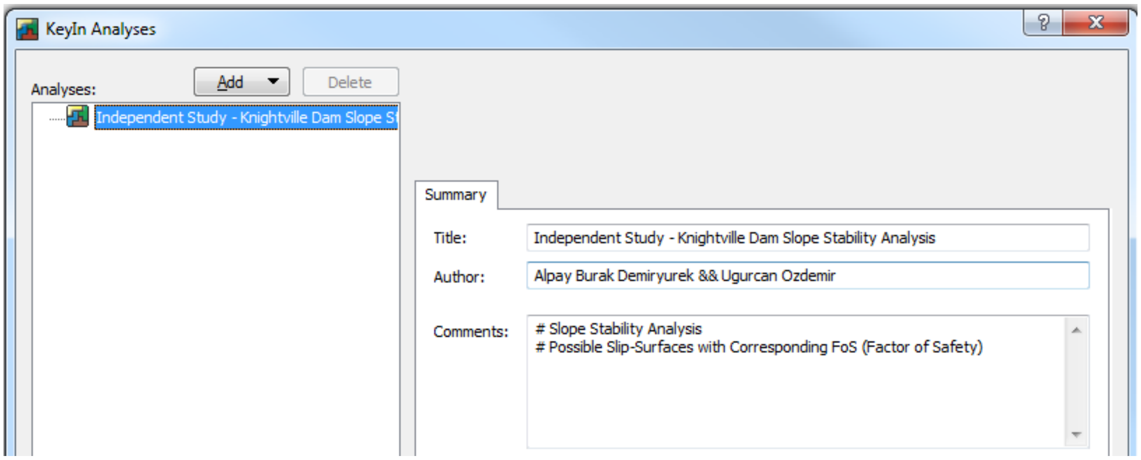
GeoStudio 2007 is a product suite for geotechnical modeling developed by GEOSLOPE. One of the program in GeoStudio is SLOPE/W which perform slope stability analysis. Slope/W was included in this independent study.

3.2. SLOPE/W

In this study SLOPE/W was used for slope stability analysis of Knightville Dam.

3.2.1.1. Setting up the Slope/W Analysis File

- Start creating a new project from “File → New” tab of GeoStudio 2007.
- In the **KeyIn Analyses** dialog box, enter analysis title, author and comments (Fig. 10)



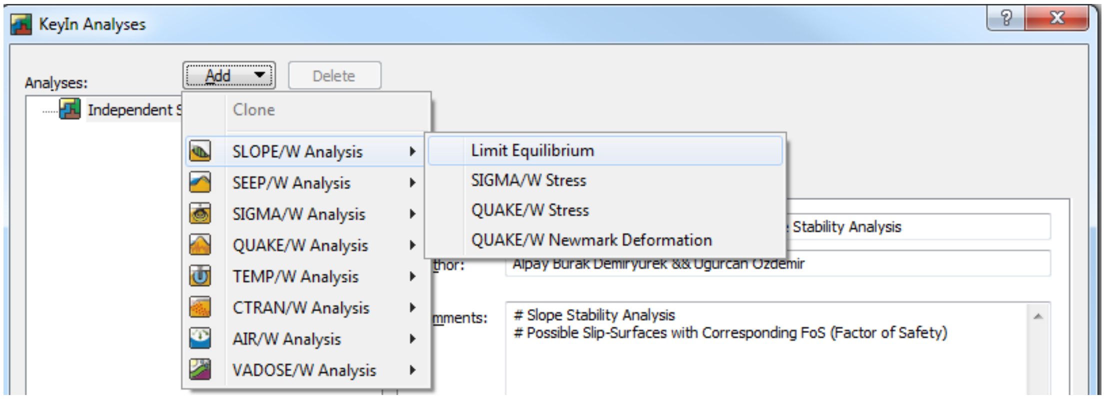
Title: Independent Study - Knightville Dam Slope Stability Analysis

Author: Alpay Burak Demiryurek && Ugurcan Ozdemir

Comments: # Slope Stability Analysis
Possible Slip-Surfaces with Corresponding FoS (Factor of Safety)

Figure 10: GeoSlope Analysis Setup

- Click on “Add” dropdown button and select “Slope/W→Limit Equilibrium” (Fig. 11)



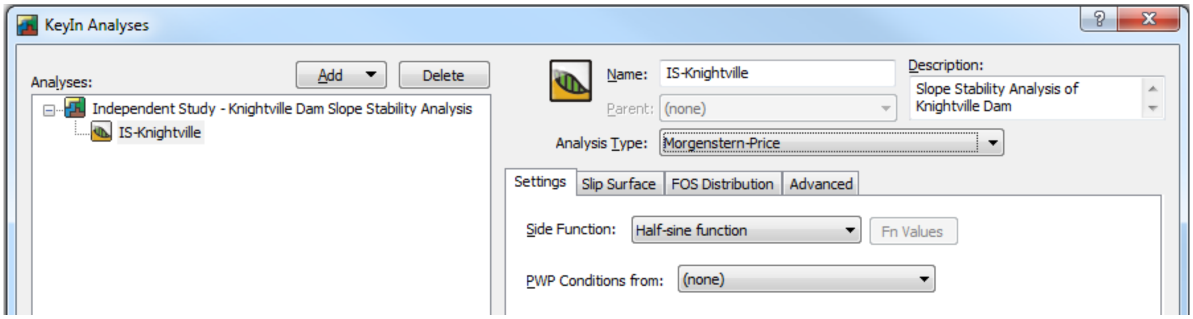
Stability Analysis

thor: Alpay Burak Demiryurek && Ugurcan Ozdemir

mments: # Slope Stability Analysis
Possible Slip-Surfaces with Corresponding FoS (Factor of Safety)

Figure 11: Slope/W Analysis Creation

- Next, enter the name and description for the analysis (Figure 12)



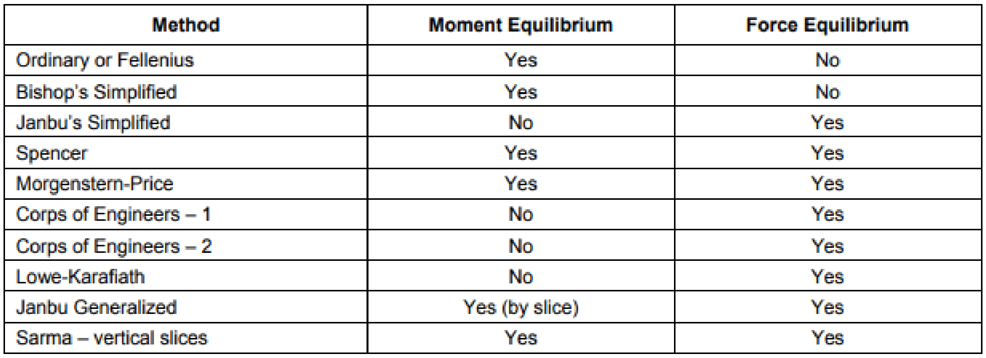
Independent Study - Knightville Dam Slope Stability Analysis
IS-Knightville

Name: IS-Knightville
Parent: (none)
Description: Slope Stability Analysis of Knightville Dam
Analysis Type: Morgenstern-Price
Side Function: Half-sine function
PWP Conditions from: (none)

Figure 12: Model Description

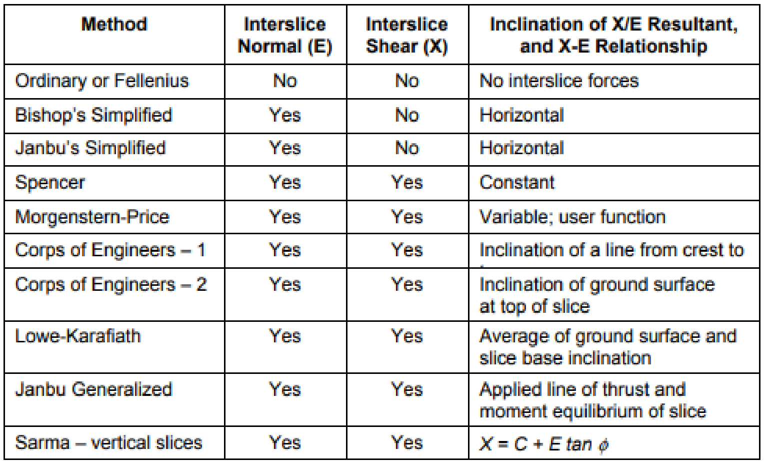
- Under the "Analysis Type", SLOPE/W provides 9 predefined methods. Below tables summarize 1) what equations of statics are satisfied for each method (Table 3-1), and 2) summary of the interslice forces included and assumed relationship between the interslice shear and normal forces (Table 3-2).

Table 3-1: Equations of Statics Satisfied



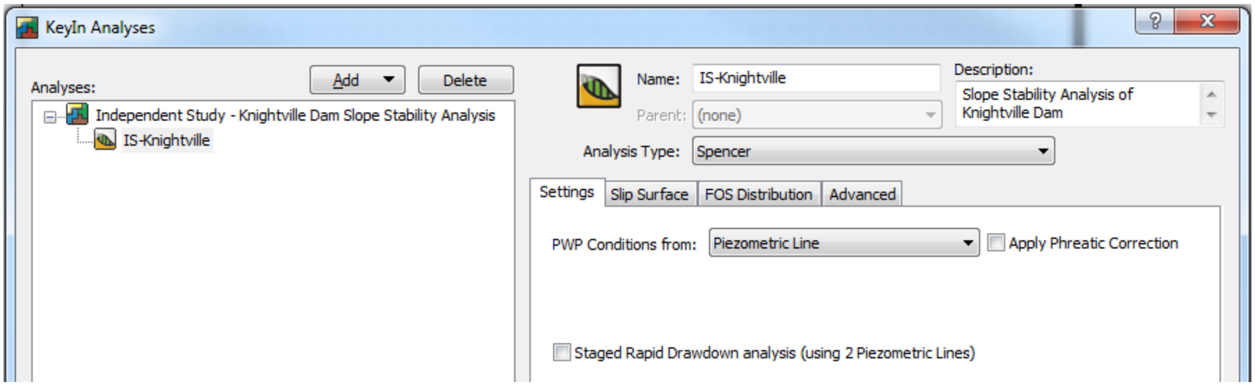
Method	Moment Equilibrium	Force Equilibrium
Ordinary or Fellenius	Yes	No
Bishop's Simplified	Yes	No
Janbu's Simplified	No	Yes
Spencer	Yes	Yes
Morgenstern-Price	Yes	Yes
Corps of Engineers – 1	No	Yes
Corps of Engineers – 2	No	Yes
Lowe-Karafiath	No	Yes
Janbu Generalized	Yes (by slice)	Yes
Sarma – vertical slices	Yes	Yes

Table 3-2: Interslice force characteristics and relationships



Method	Interslice Normal (E)	Interslice Shear (X)	Inclination of X/E Resultant, and X-E Relationship
Ordinary or Fellenius	No	No	No interslice forces
Bishop's Simplified	Yes	No	Horizontal
Janbu's Simplified	Yes	No	Horizontal
Spencer	Yes	Yes	Constant
Morgenstern-Price	Yes	Yes	Variable; user function
Corps of Engineers – 1	Yes	Yes	Inclination of a line from crest to
Corps of Engineers – 2	Yes	Yes	Inclination of ground surface at top of slice
Lowe-Karafiath	Yes	Yes	Average of ground surface and slice base inclination
Janbu Generalized	Yes	Yes	Applied line of thrust and moment equilibrium of slice
Sarma – vertical slices	Yes	Yes	$X = C + E \tan \phi$

- In this particular analysis, “Spencer Method” has chosen as analysis type.
- Under settings tab for pore water pressure conditions, “PWP Conditions from: Piezometric Line” has selected. (Figure 13)



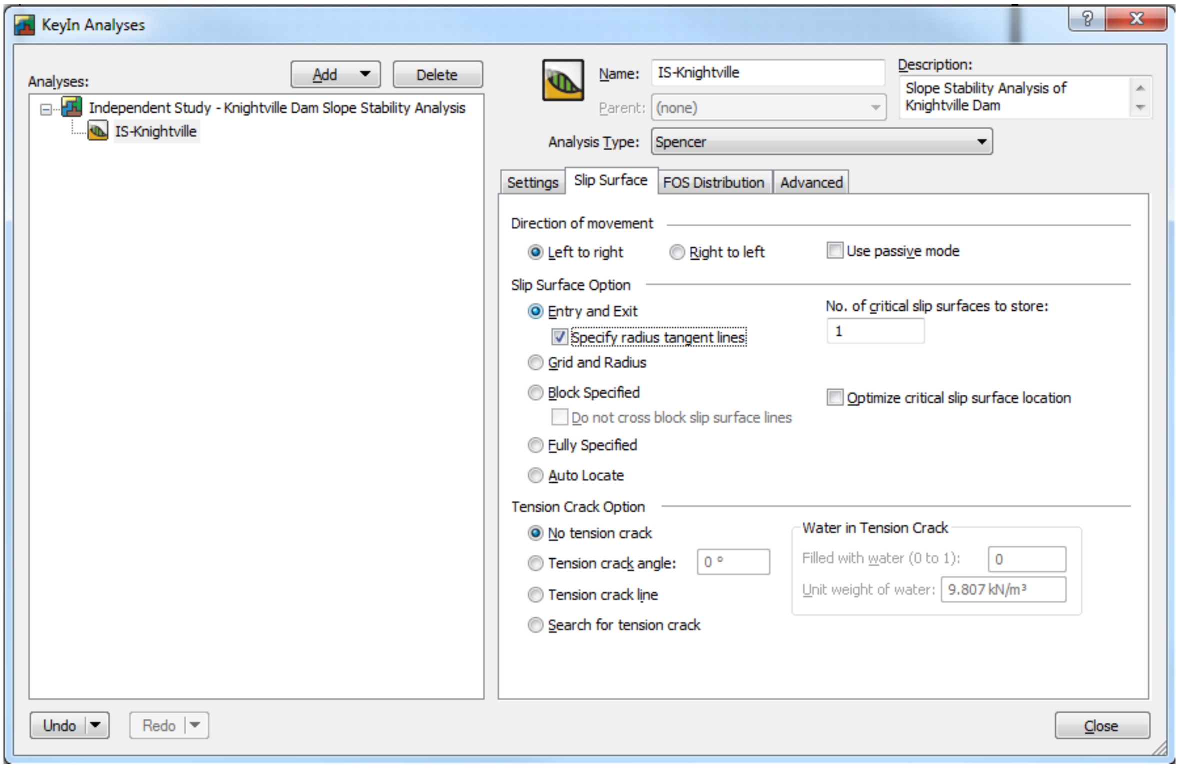
Analyses:
Independent Study - Knightville Dam Slope Stability Analysis
IS-Knightville

Name: IS-Knightville
Parent: (none)
Description: Slope Stability Analysis of Knightville Dam
Analysis Type: Spencer

PWP Conditions from: Piezometric Line
☐ Apply Phreatic Correction
☐ Staged Rapid Drawdown analysis (using 2 Piezometric Lines)

Figure 7: Analysis Settings

- Under “Slip Surface” tab following options were checked. (For right direction of slip surface, created file has been copied, direction of slip changed and enter-exit points redefined.) (Figure 14)



Analyses:
Independent Study - Knightville Dam Slope Stability Analysis
IS-Knightville

Name: IS-Knightville
Parent: (none)
Description: Slope Stability Analysis of Knightville Dam
Analysis Type: Spencer

Direction of movement
● Left to right
○ Right to left
☐ Use passive mode

Slip Surface Option
● Entry and Exit
☑ Specify radius tangent lines
○ Grid and Radius
○ Block Specified
☐ Do not cross block slip surface lines
○ Fully Specified
○ Auto Locate

No. of critical slip surfaces to store: 1
☐ Optimize critical slip surface location

Tension Crack Option
● No tension crack
○ Tension crack angle: 0 °
○ Tension crack line
○ Search for tension crack

Water in Tension Crack
Filled with water (0 to 1): 0
Unit weight of water: 9.807 kN/m³

Figure 8: Slip Surface Settings

- No changes has been made under “FOS Distribution” and “Advanced” tabs.

3.2.1.2. Defining the Problem Geometry

Problem geometry in SLOPE/W defined according to the cross section plan (Figure 15), provided by Department of The Army, of Knightville Dam near station 4+82.

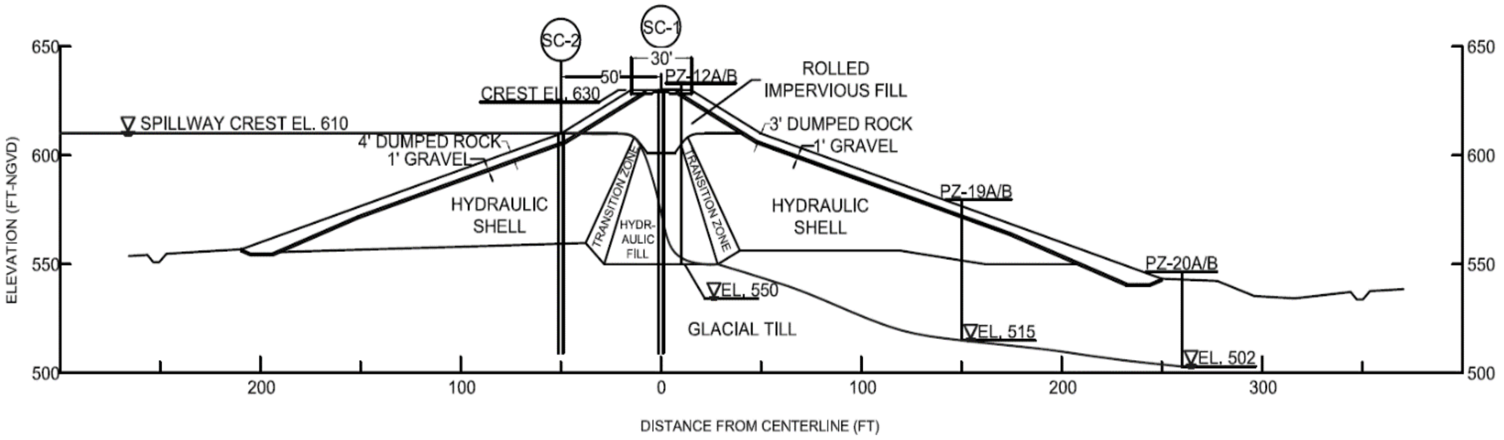
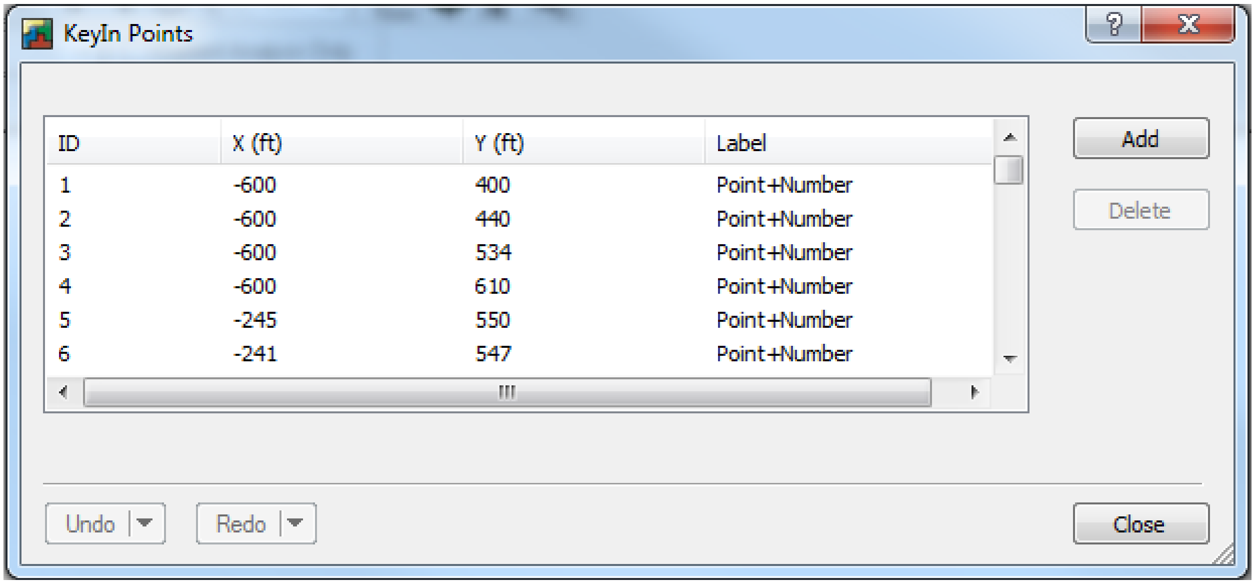


Figure 9: Knightville Dam Cross Section

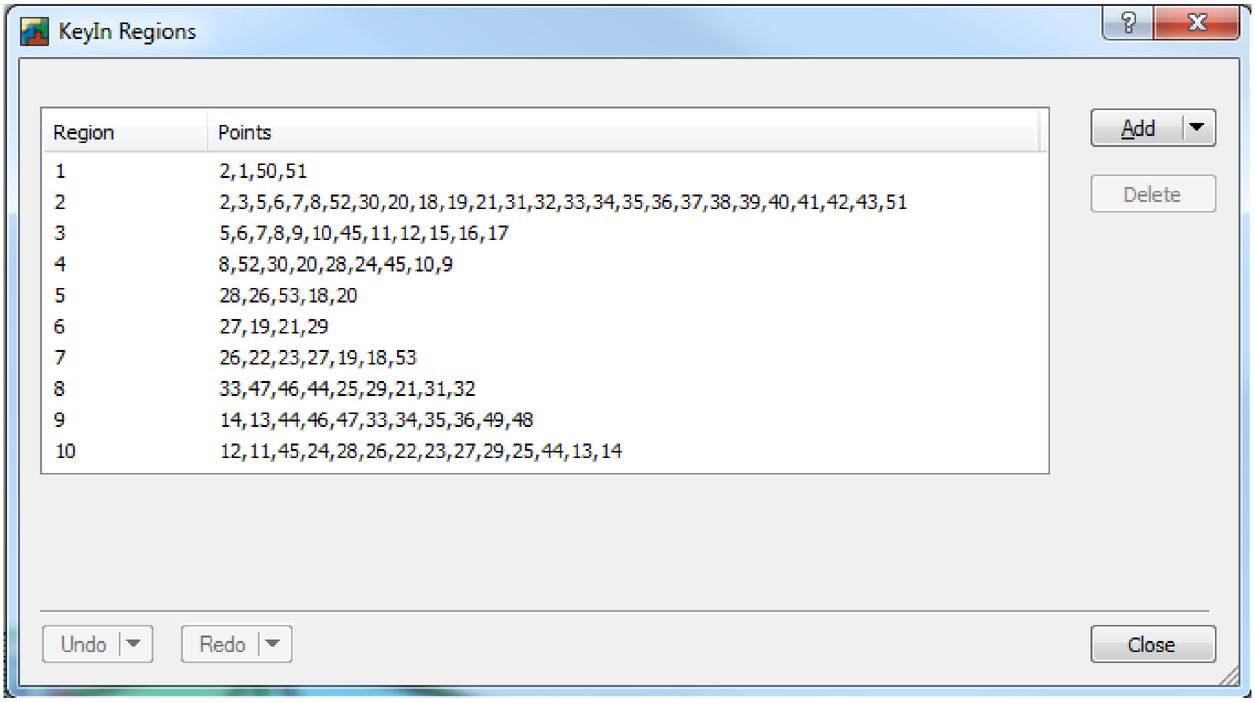
In model domain GeoStudio allows users to draw regions (consists of points) and points. In this analysis, due to irregular shape of the cross section location of points were determined first by importing the cross section in AutoCAD, and then each point coordinate entered in model using “KeyIn→Points→Add” method. Total of 54 points are used in modeling. (Figure 16)



ID	X (ft)	Y (ft)	Label
1	-600	400	Point+Number
2	-600	440	Point+Number
3	-600	534	Point+Number
4	-600	610	Point+Number
5	-245	550	Point+Number
6	-241	547	Point+Number

Figure 10: Point coordinates for the model

Next, for each material and layer regions are defined using already defined points. Total of 10 regions were defined in the Knightville Dam model. (Figure 17)



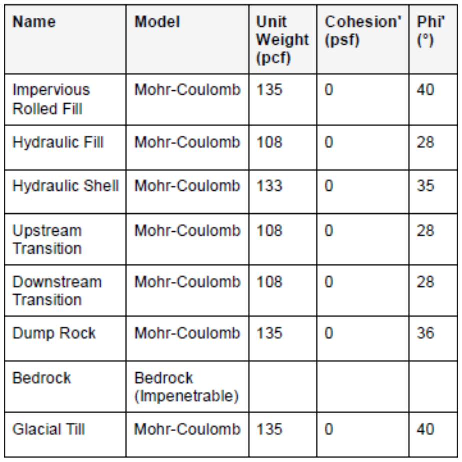
Region	Points
1	2,1,50,51
2	2,3,5,6,7,8,52,30,20,18,19,21,31,32,33,34,35,36,37,38,39,40,41,42,43,51
3	5,6,7,8,9,10,45,11,12,15,16,17
4	8,52,30,20,28,24,45,10,9
5	28,26,53,18,20
6	27,19,21,29
7	26,22,23,27,19,18,53
8	33,47,46,44,25,29,21,31,32
9	14,13,44,46,47,33,34,35,36,49,48
10	12,11,45,24,28,26,22,23,27,29,25,44,13,14

Figure 11: Region definitions in model

3.2.1.3. Defining Materials and assignment to Regions

Materials in the model defined using “KeyIn→Materials” function using provided data in Table 3-3.

Table 3-3 – Material Properties



Name	Model	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)
Impervious Rolled Fill	Mohr-Coulomb	135	0	40
Hydraulic Fill	Mohr-Coulomb	108	0	28
Hydraulic Shell	Mohr-Coulomb	133	0	35
Upstream Transition	Mohr-Coulomb	108	0	28
Downstream Transition	Mohr-Coulomb	108	0	28
Dump Rock	Mohr-Coulomb	135	0	36
Bedrock	Bedrock (Impenetrable)			
Glacial Till	Mohr-Coulomb	135	0	40

Then using “Draw Materials” (Figure 18 option of GeoSlope, materials assigned to corresponding regions in the model.

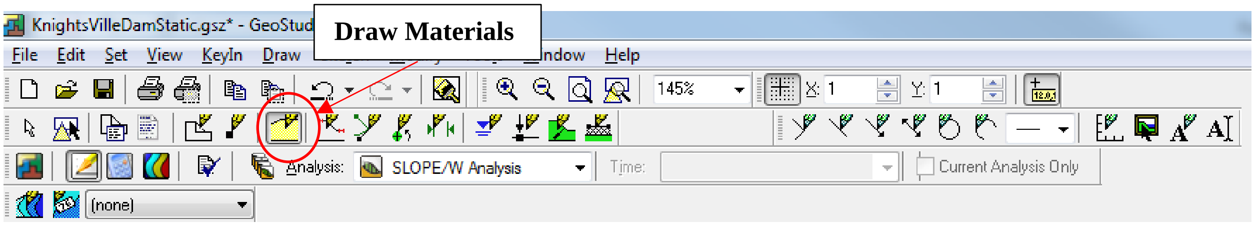
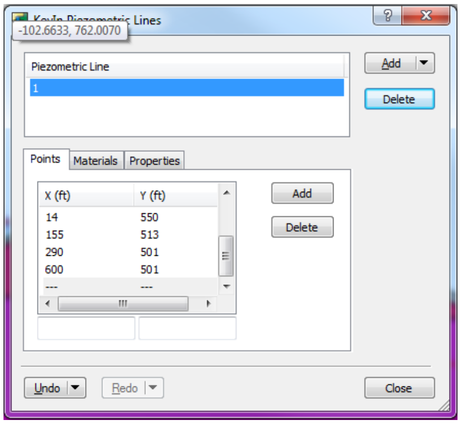


Figure 12: GeoStudio 2007 Draw materials icon

3.2.1.4. Defining Piezometric Line

After defining the materials, piezometric line has been defined using point coordinates under “KeyIn→Pore Water Pressure.. →Add” option. (Figure 19)



X (ft)	Y (ft)
14	550
155	513
290	501
600	501
---	---

Figure 13: Piezometric line points

Figure 20 shows the Knightville Dam model after assignment of materials and piezometric line.

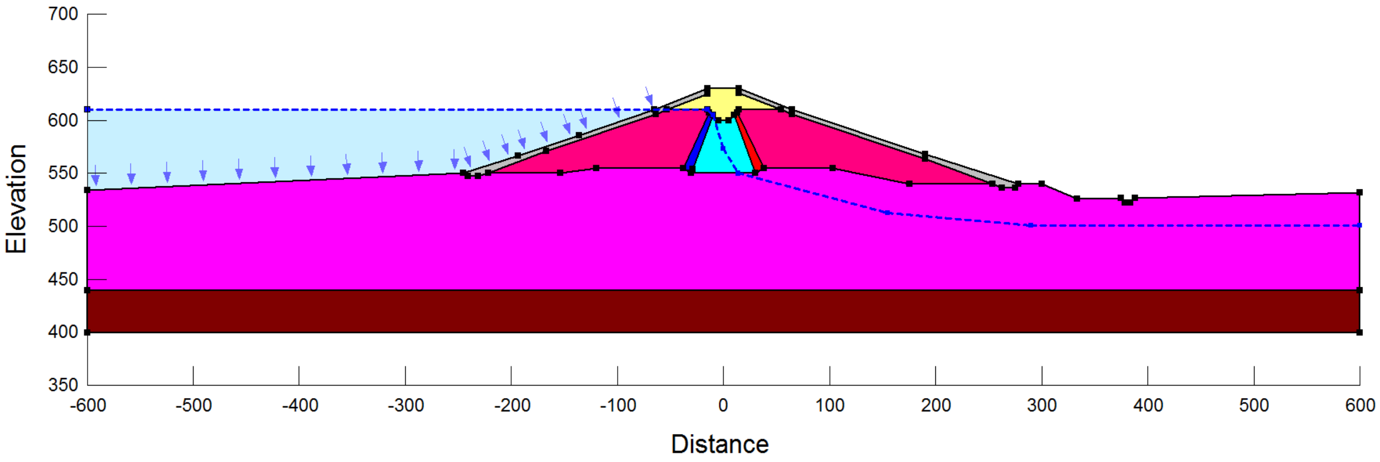
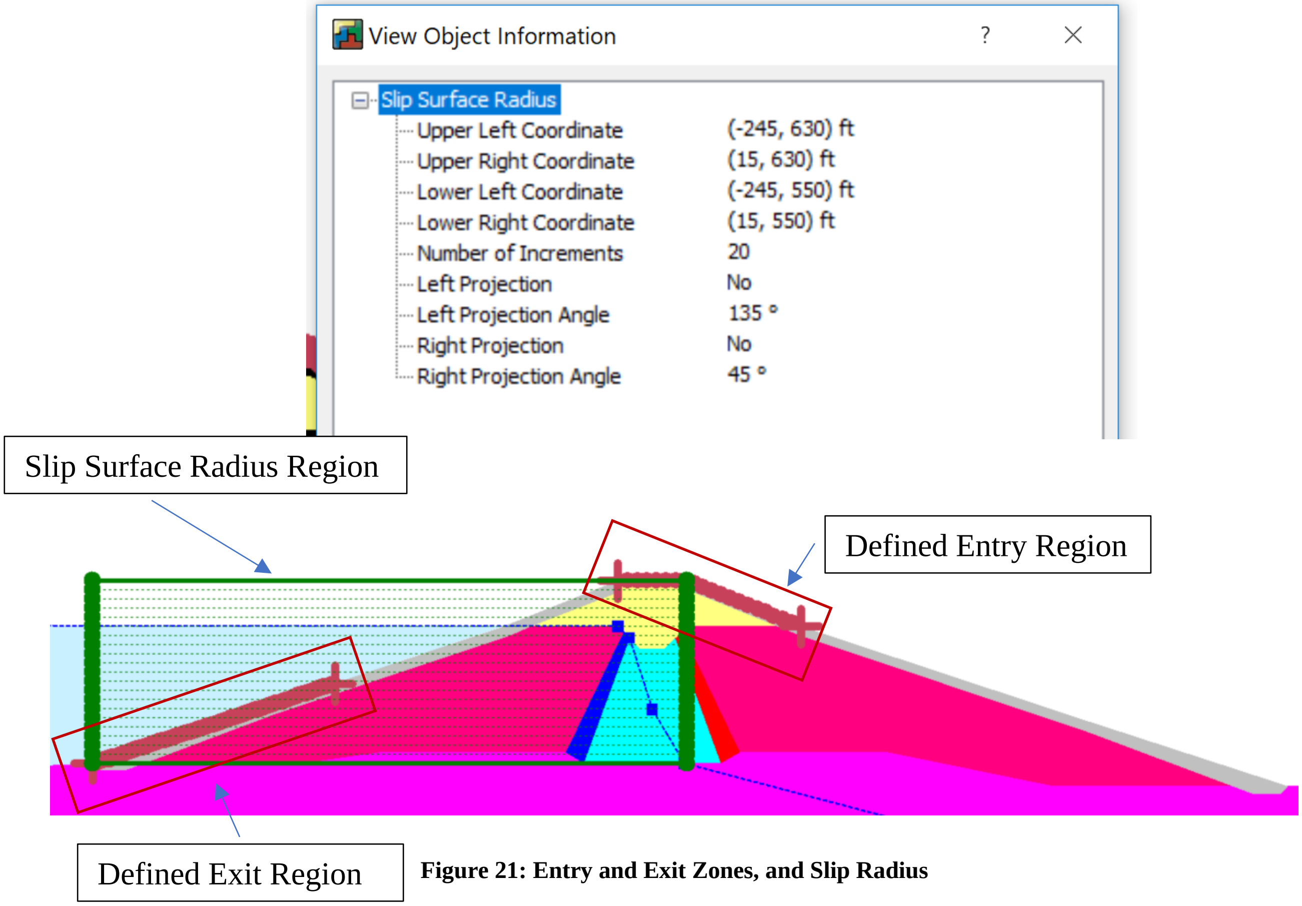


Figure 20: Knightville Dam Model

3.2.1.5. Defining Slip Surface Enter-Exit Regions

Slip surface enter and exit regions defined in “KeyIn→Slip Surfaces→Entry and Exit” option. Decided exit region starts from toe of the dam and ends where the side slope changes using 150 increments over the range and decided entry region starts from the bottom elevation of impervious fill on the right-side slope and ends at left most point of the crest using 20 increments over the range. (Figure 21)

After defining entry and exit ranges for slip surface, using “Draw Slip Surface Radius” method, a region defined for possible slip surfaces with following properties. (Figure 21)



View Object Information

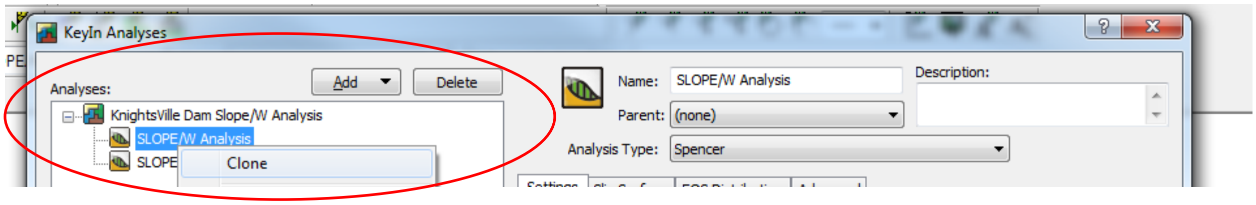
Slip Surface Radius

Upper Left Coordinate	(-245, 630) ft
Upper Right Coordinate	(15, 630) ft
Lower Left Coordinate	(-245, 550) ft
Lower Right Coordinate	(15, 550) ft
Number of Increments	20
Left Projection	No
Left Projection Angle	135 °
Right Projection	No
Right Projection Angle	45 °

Figure 21: Entry and Exit Zones, and Slip Radius

3.2.1.6. Defining Horizontal Seismic Load Coefficient

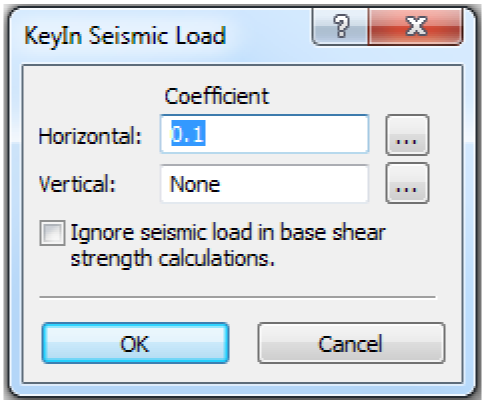
The model created for static analysis cloned as “Seismic Case” in “KeyIn Analysis” by right clicking the analysis and selecting clone (Figure 14). After creating new file, horizontal seismic coefficient defined in “KeyIn→Seismic Load” option as horizontal coefficient equals to 0.1(Figure 15).



Analyses:
KnightsVille Dam Slope/W Analysis
SLOPE/W Analysis
SLOPE

Name: SLOPE/W Analysis
Parent: (none)
Analysis Type: Spencer

Figure 14: Cloning of static analysis



Coefficient
Horizontal: 0.1
Vertical: None
☐ Ignore seismic load in base shear strength calculations.

Figure 15: KeyIn Seismic Load definition pop-up window

3.2.2 Solve Analysis

Once the problem is completely modeled in the DEFINE windows, it should be then checked for errors: Click tool menu button → click verify/optimize button → if no errors were found then it means it is ready for analysis. Pressing the Start button begins the computations.

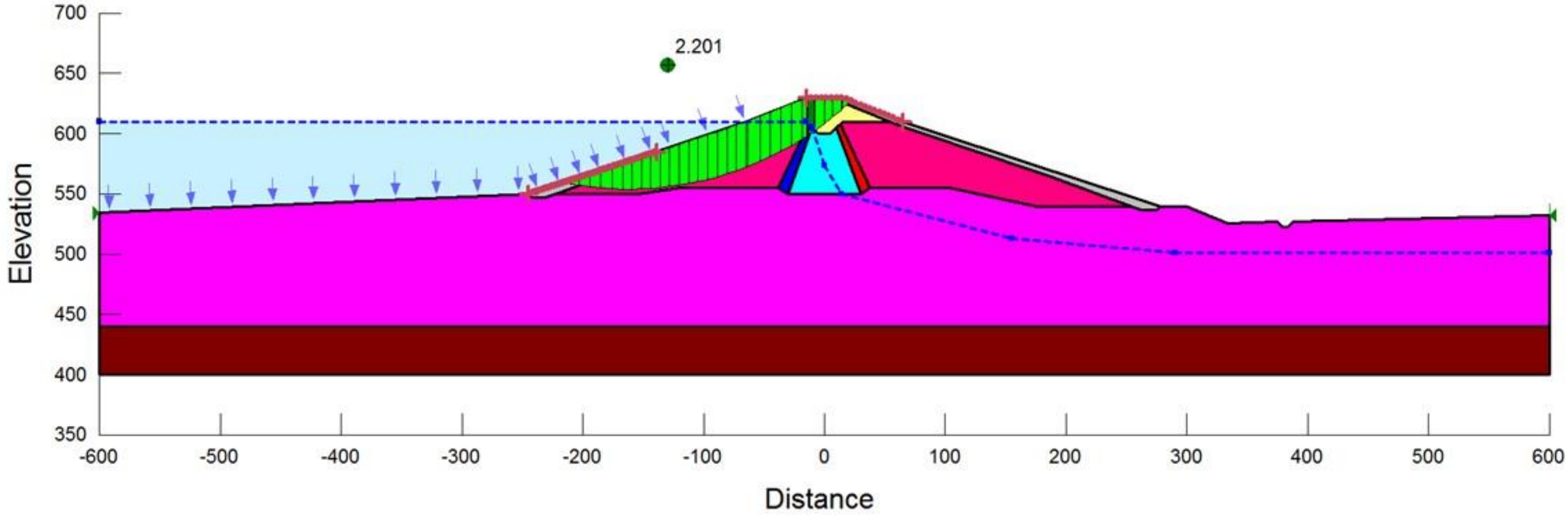
Created Models for static and seismic case analyses separately.

3.2.3 Analysis Results

Once the numerical computation is finished, the CONTOUR button will appear. All the analysis results can be view and extracted in the shading form, graphical form, vector form, or isoline form. This all results can be access through draw menu in the CONTOUR mode.

Analyses results showing factor of safety values and slip surfaces for right to left and right to left slips are shown in Appendix B section for Slope/W.

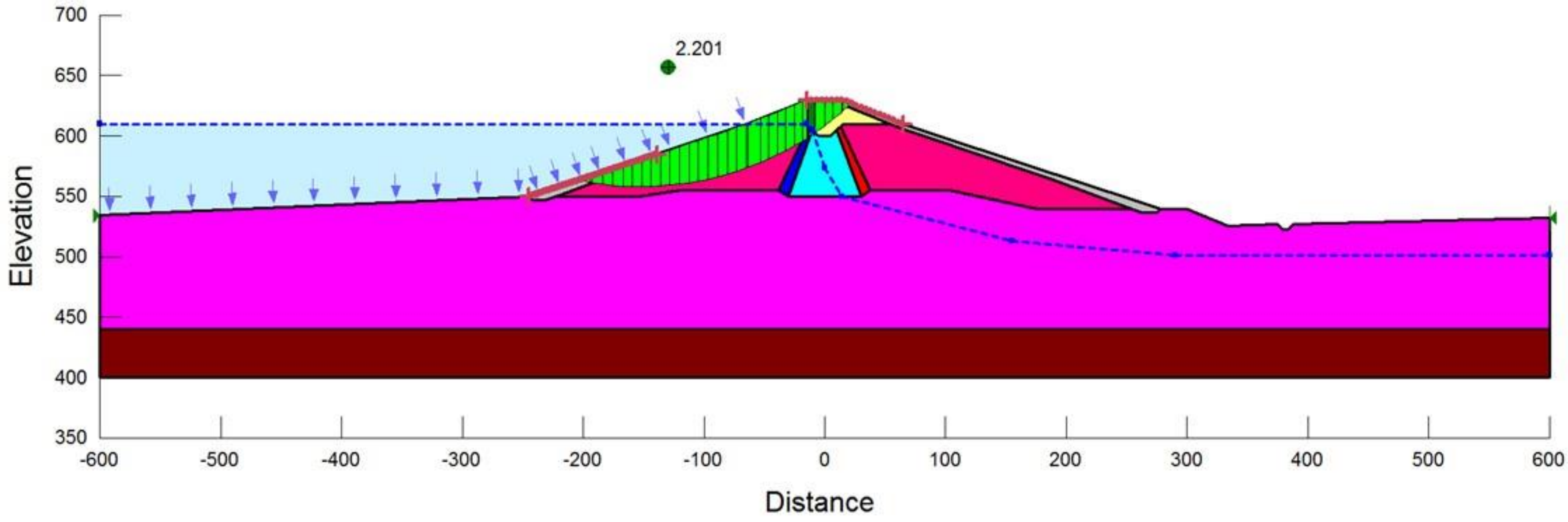
Appendix B: Slope/W



KVD Station 4+82 Static Case, Upstream Circular, Flood El. 610

File Name: IS – KnightvilleDamStaticRightToLeft.gsz

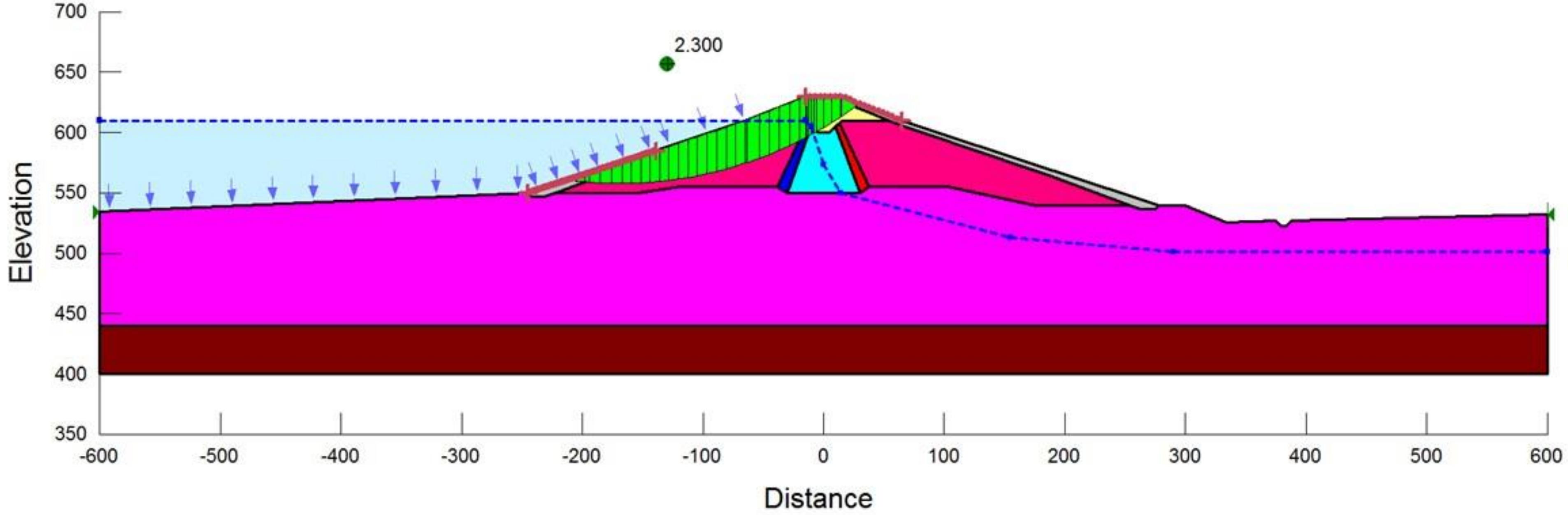
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



KVD Station 4+82 Static Case, Upstream Circular, Flood El. 610

File Name: IS – KnightvilleDamStaticRightToLeft.gsz

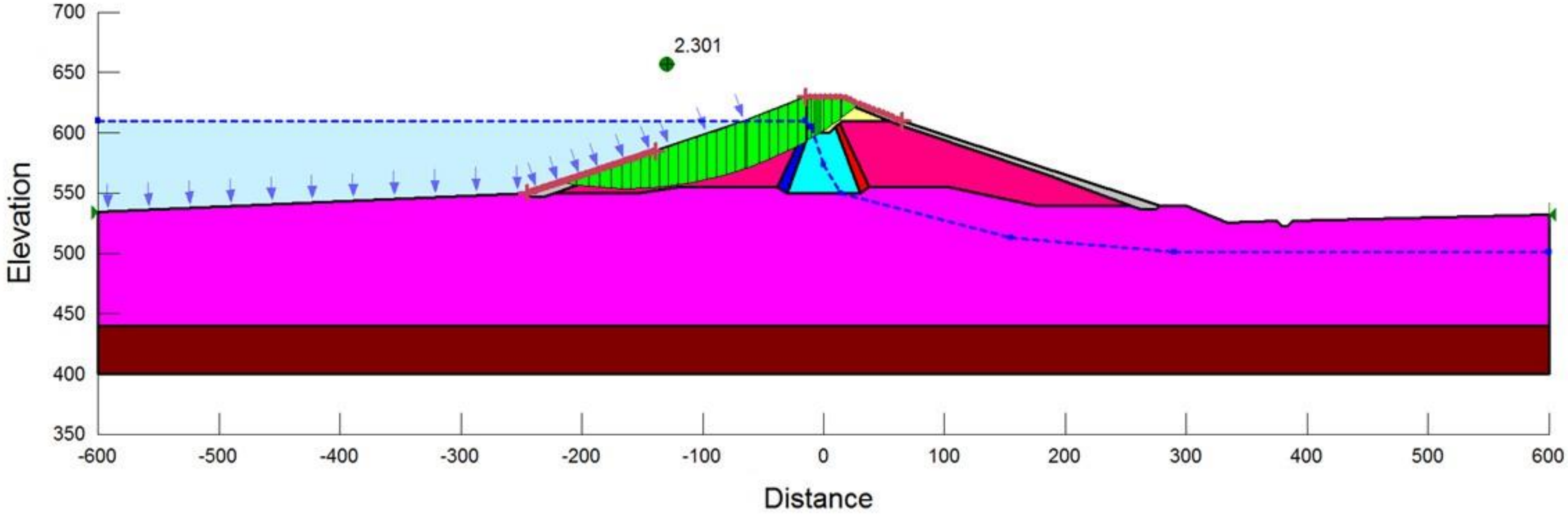
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



KVD Station 4+82 Static Case, Upstream Circular, Flood El. 610

File Name: IS – KnightvilleDamStaticRightToLeft.gsz

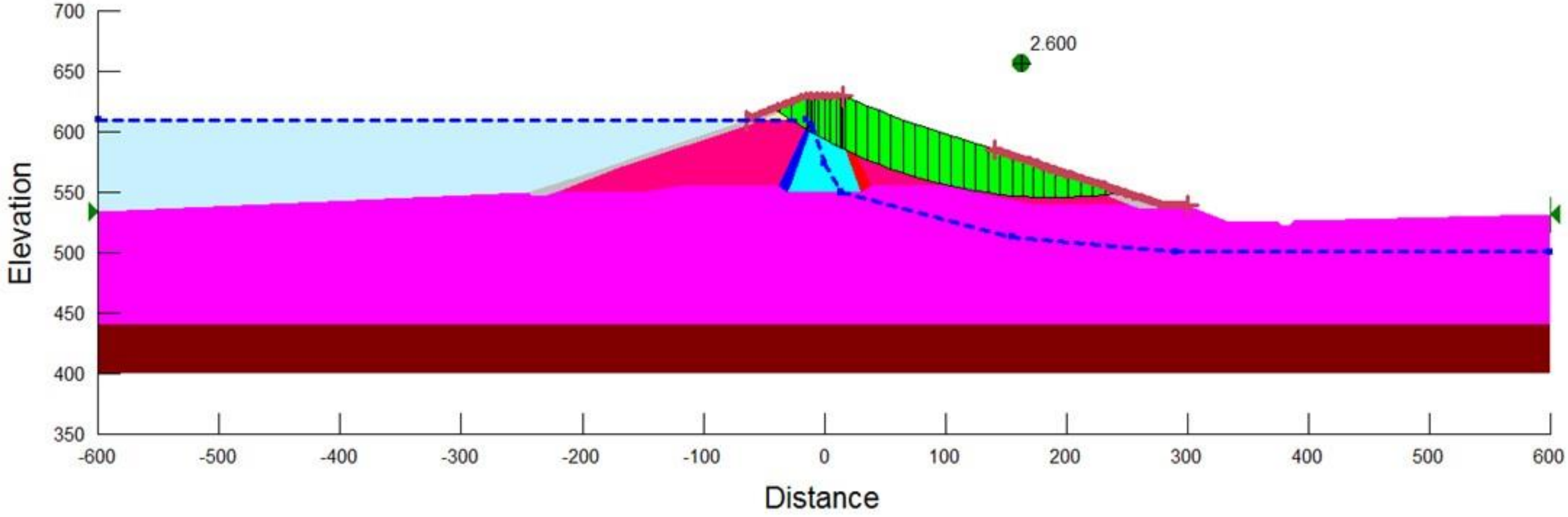
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



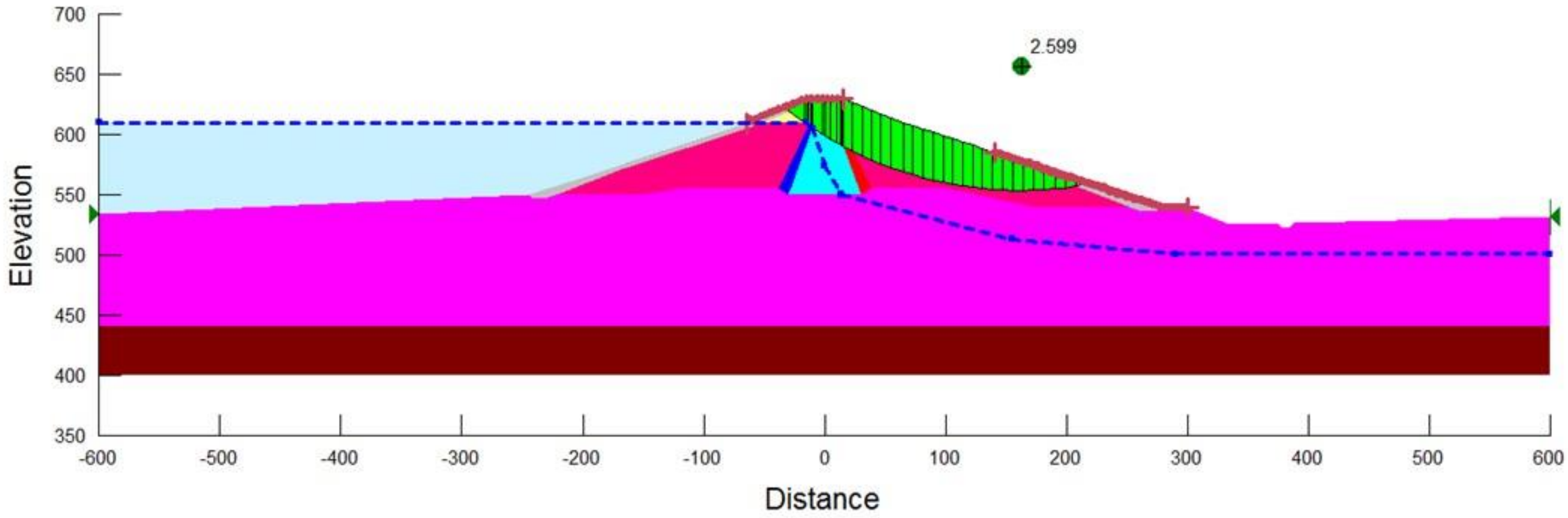
KVD Station 4+82 Static Case, Upstream Circular, Flood El. 610

File Name: IS – KnightvilleDamStaticRightToLeft.gsz

Computed By: Alpay Demiryurek & Ugurcan Ozdemir



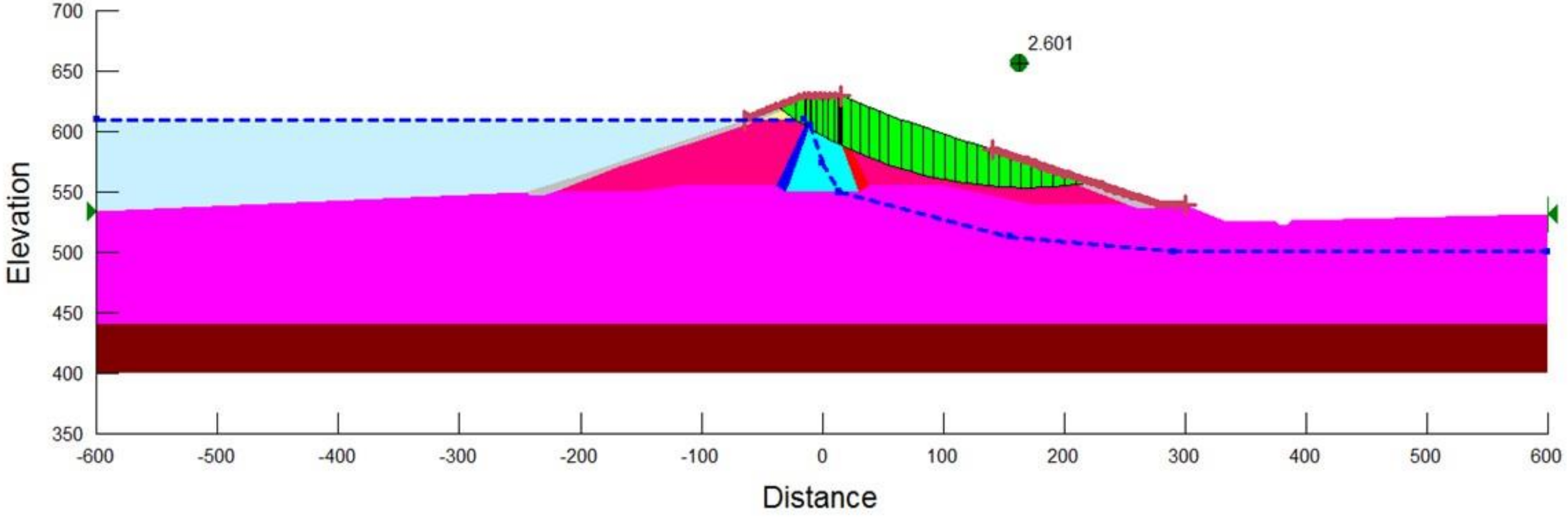
KVD Station 4+82 Static Case, Downstream Circular, Flood El. 610
File Name: IS – KnightvilleDamStaticRightToLeft.gsz
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



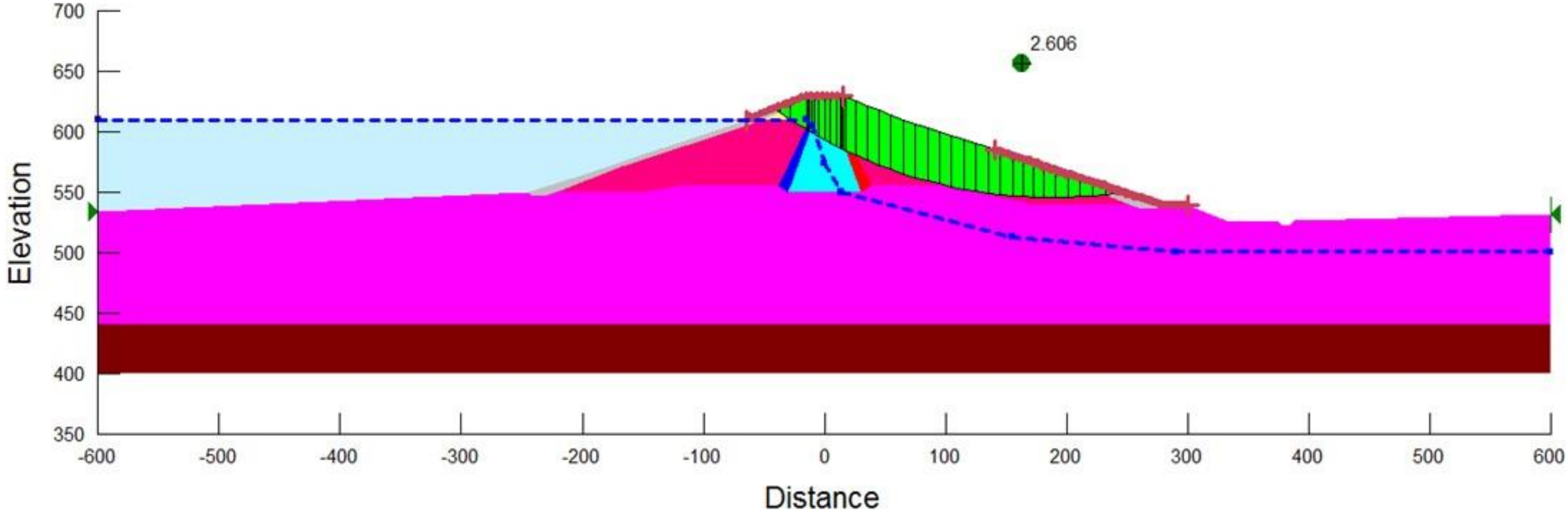
KVD Station 4+82 Static Case, Downstream Circular, Flood El. 610

File Name: IS – KnightvilleDamStaticRightToLeft.gsz

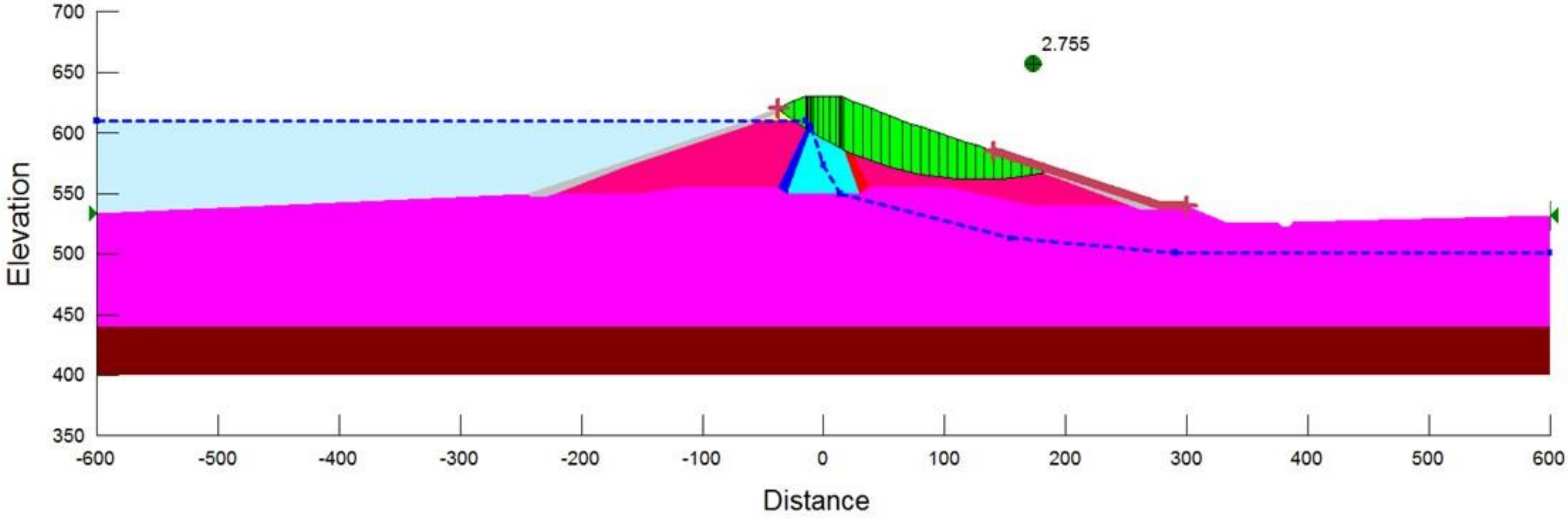
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



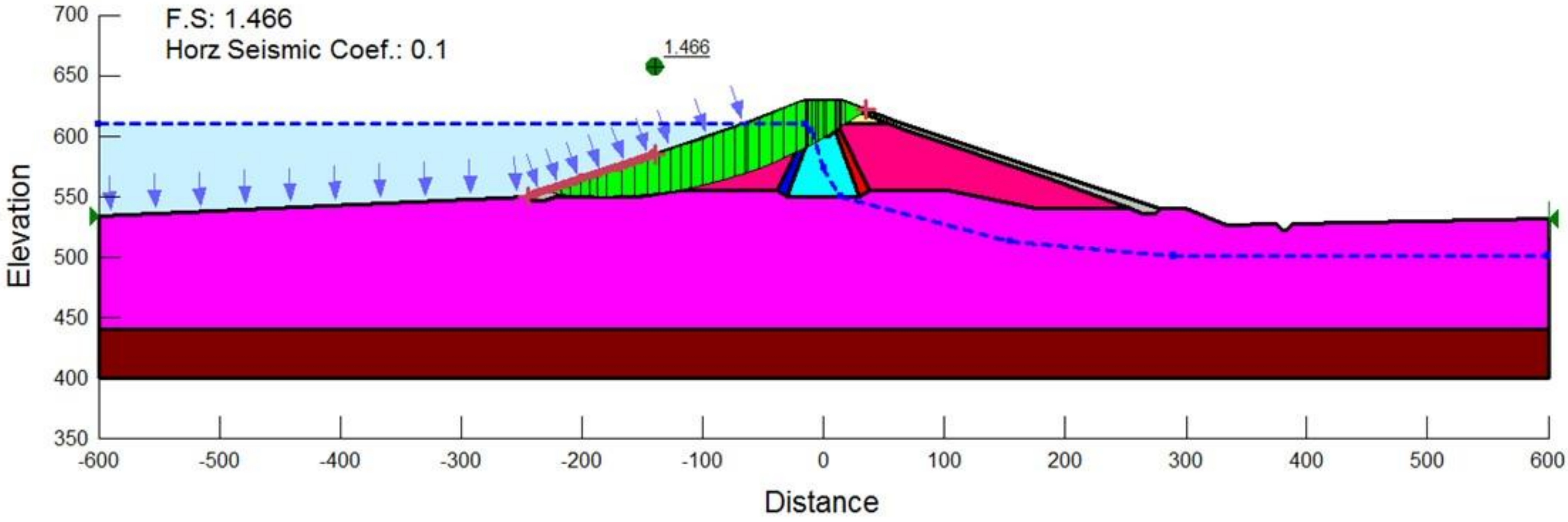
KVD Station 4+82 Static Case, Downstream Circular, Flood El. 610
File Name: IS – KnightvilleDamStaticRightToLeft.gsz
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



KVD Station 4+82 Static Case, Downstream Circular, Flood El. 610
File Name: IS – KnightvilleDamStaticRightToLeft.gsz
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



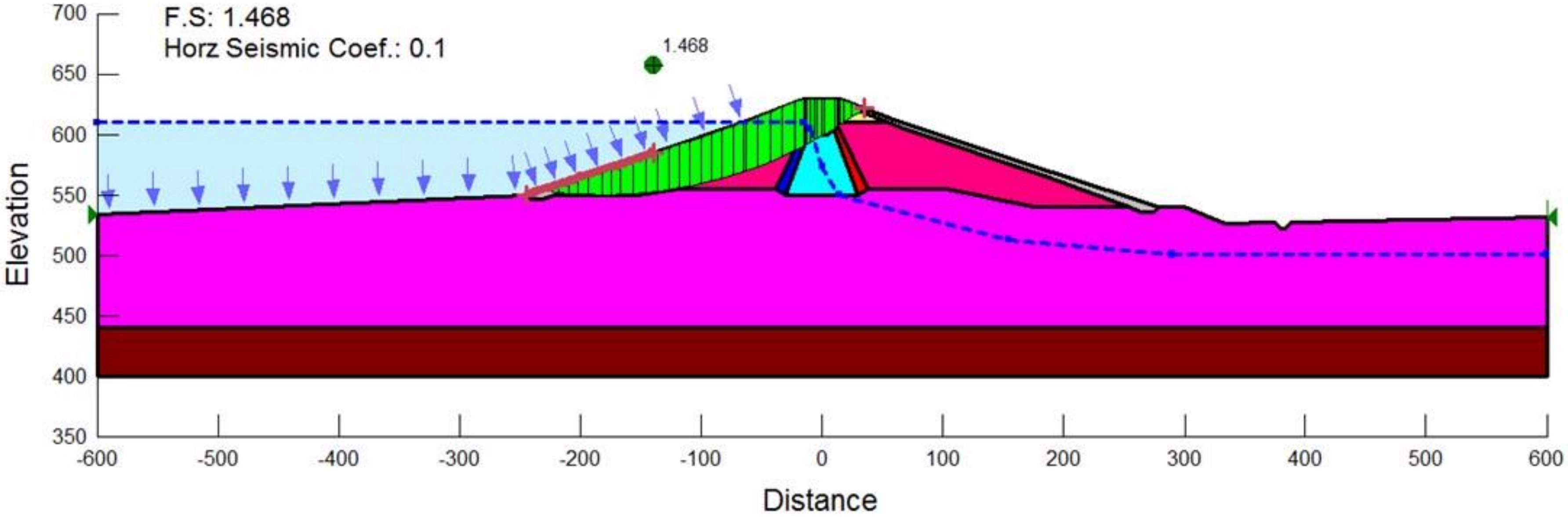
KVD Station 4+82 Static Case, Downstream Circular, Flood El. 610
File Name: IS – KnightvilleDamStaticRightToLeft.gsz
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



KVD Station 4+82 Seismic Case c=0.1g Upstream Circular, Flood El. 610

File Name: IS – KnightvilleDamStatic-Analysis Kh.gsz

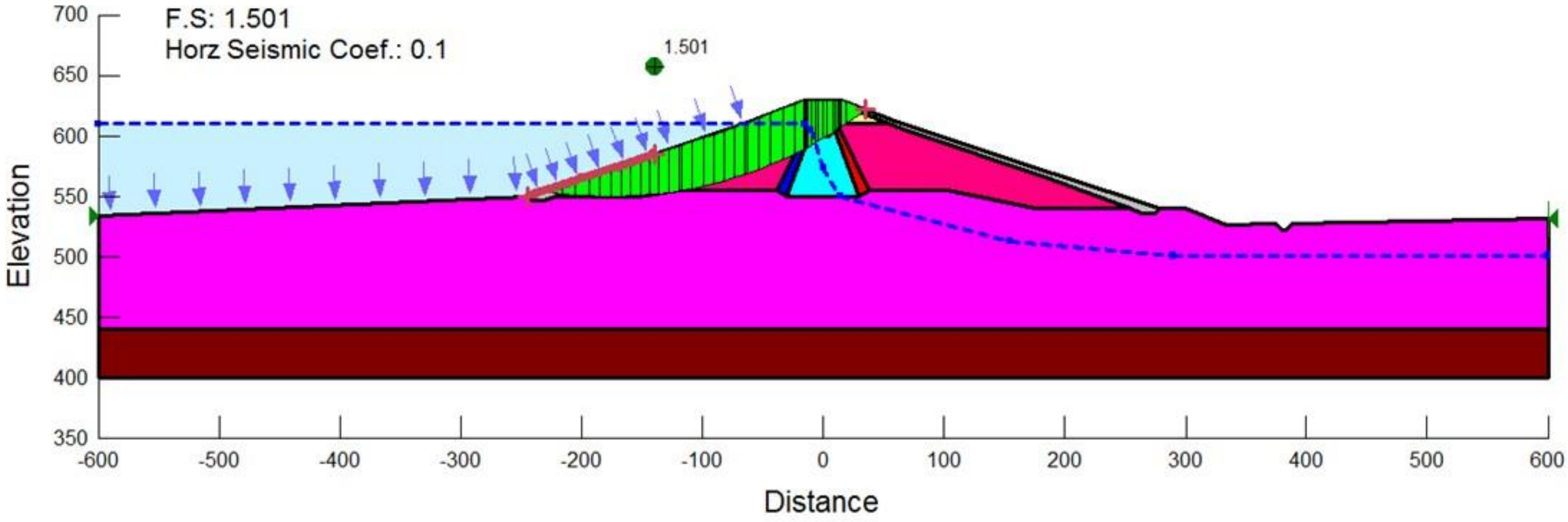
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



KVD Station 4+82 Seismic Case c=0.1g Upstream Circular, Flood El. 610

File Name: IS – KnightvilleDamStatic-Analysis Kh.gsz

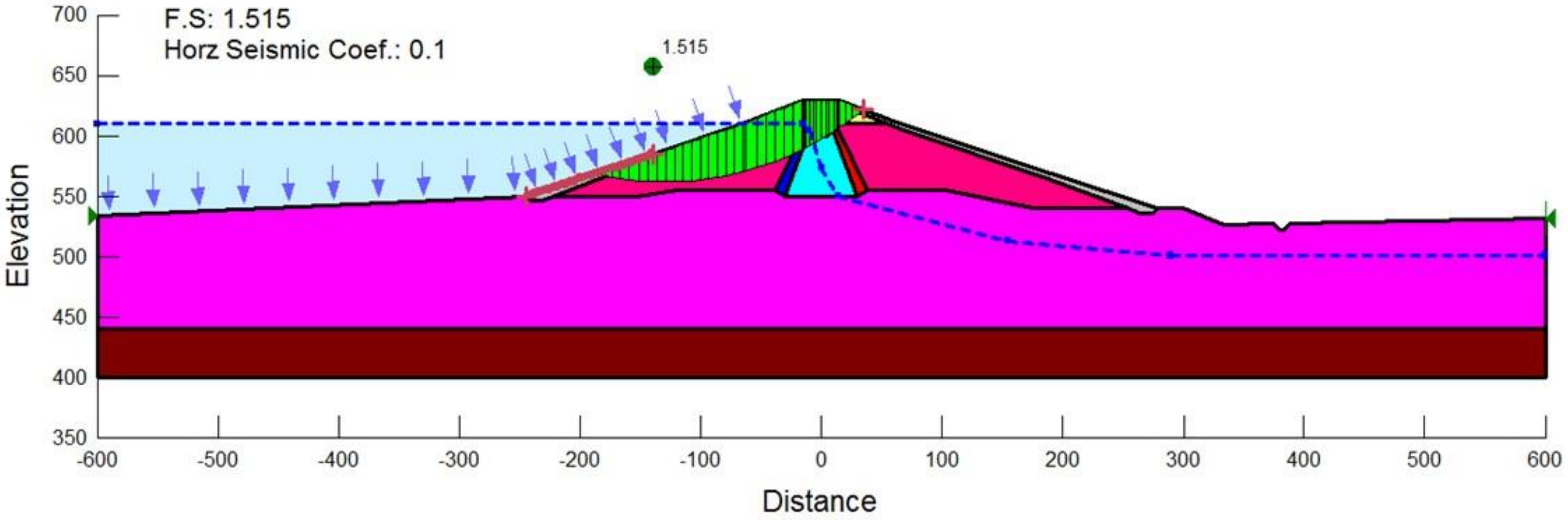
Computed By: Alpay Demiryurek & Ugurcan Ozdemir



KVD Station 4+82 Seismic Case c=0.1g Upstream Circular, Flood El. 610

File Name: IS – KnightvilleDamStatic-Analysis Kh.gsz

Computed By: Alpay Demiryurek & Ugurcan Ozdemir



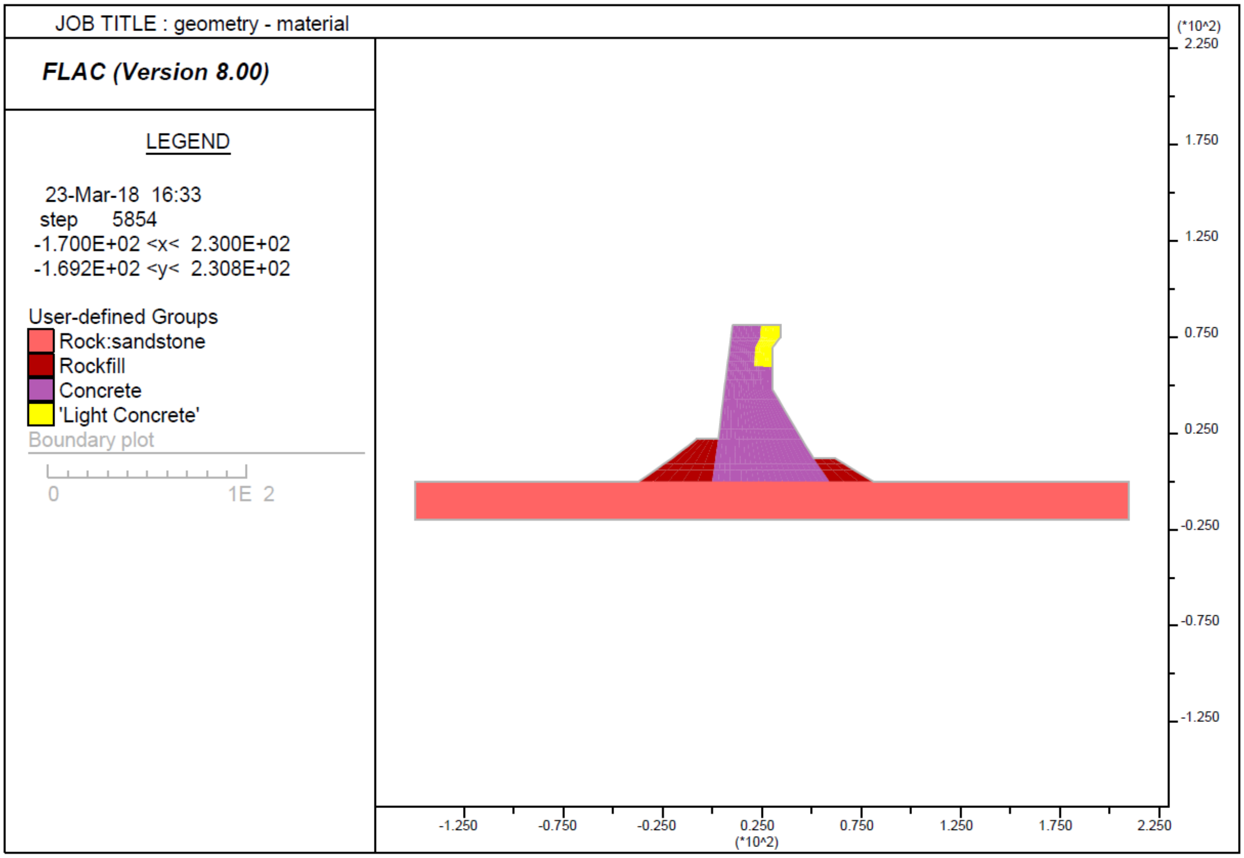
KVD Station 4+82 Seismic Case c=0.1g Upstream Circular, Flood El. 610

File Name: IS – KnightvilleDamStatic-Analysis Kh.gsz

Computed By: Alpay Demiryurek & Ugurcan Ozdemir

3. Seismic Analyses Using FLAC 2-D

Chilhowee dam cross section was studied for FLAC 2-D in this independent study. Figure 22 shows the geometry of the Chilhowee dam geometry as well as water table elevation while the dam is in operation. The model was 390 ft width from side to side and maximum height of the dam was 81.5 ft. The dam was built of concrete and founded on a 20 ft of sandstone rock layer. Since there were hollow section for wing section of the dam, lightweight concrete material was inputted by changing density property (0.5xmass).



Material Type	Material Model	Density (pcf/g)	Bulk Modulus (psf)	Shear Modulus (psf)
Sandstone	Elastic	4.1925	8.175×10^7	3.773×10^7
Rockfill	Elastic	4.3478	1.553×10^6	9.317×10^5
Concrete	Elastic	3.7267	9.275×10^7	6.957×10^7
Light Concrete	Elastic	2.17	9.275×10^7	6.957×10^7

Figure 22: Dam geometry and material definitions

Dynamic analysis was performed by FLAC in a way that horizontal acceleration time history was applied at the bottom boundary. Acceleration history of 0.8xMorganHill record was used in the model. Since the calculation step is 4.097 x 10^{-5} sec used by the software for this model, and the delta-time is 0.005 sec for the motion input, 0.005 / (4.097x10^{-5}) = 122 step is skipped for displaying time histories. Figure 23 indicates the acceleration time history of the motion displayed by the FLAC.

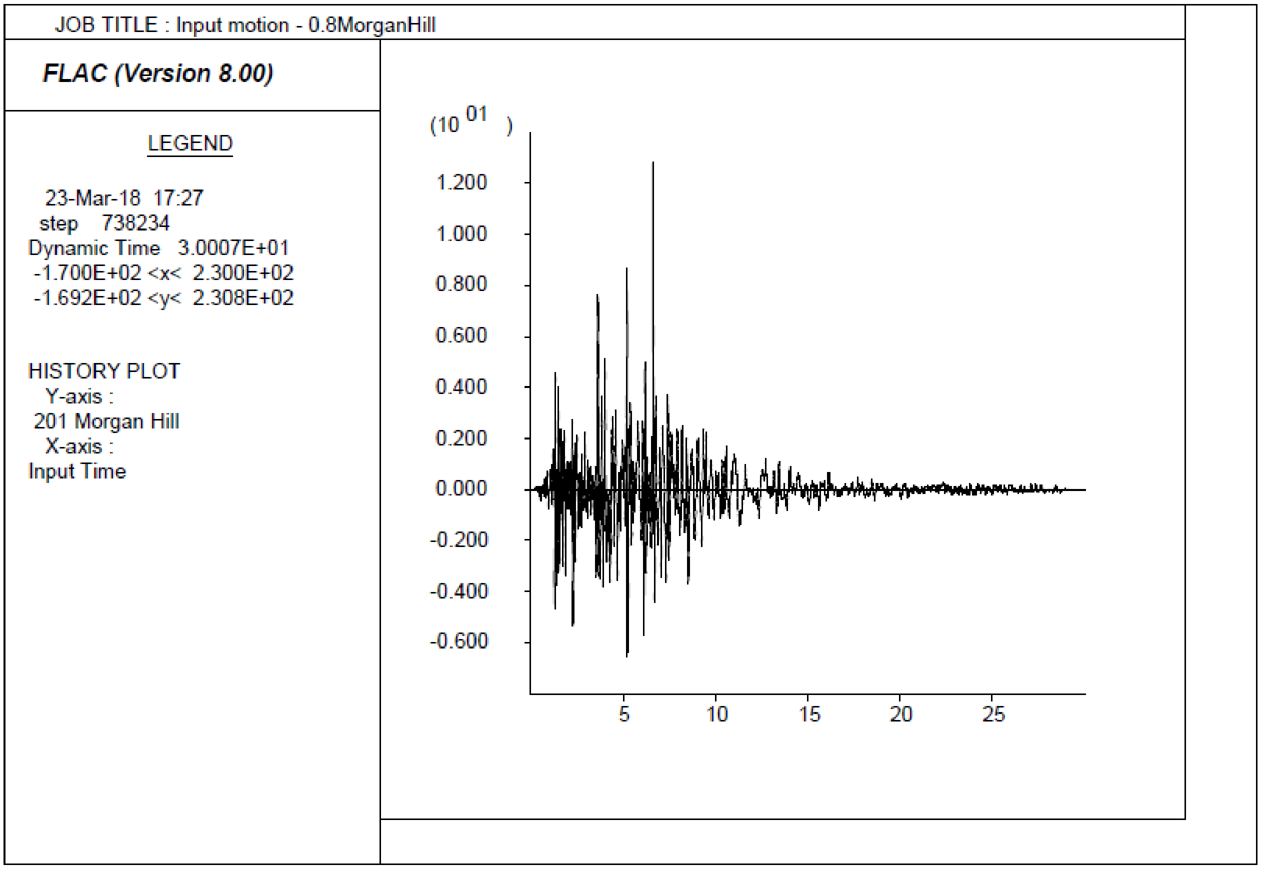
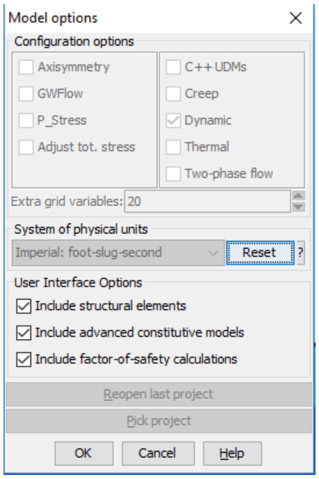


Figure 23: Input Motion of Morgan Hill

3.1. Modeling Procedure

Necessary FLAC model options were set as shown in the Figure 24. Imperial unit system was selected as system units and dynamic option was checked for dynamic mode to be activated.

For building grid for the model, 59 elements in x direction (I in IJ system) and 39 elements in y direction (J in IJ system) were decided. Figure 25 shows generated mesh for each material defined in the model.



Model options

Configuration options

☐ Axisymmetry
☐ GWFlow
☐ P_Stress
☐ Adjust tot. stress
☐ C++ UDMs
☐ Creep
☑ Dynamic
☐ Thermal
☐ Two-phase flow

Extra grid variables: 20

System of physical units

Imperial: foot-slug-second

User Interface Options

☑ Include structural elements
☑ Include advanced constitutive models
☑ Include factor-of-safety calculations

Figure 24: Model options for model

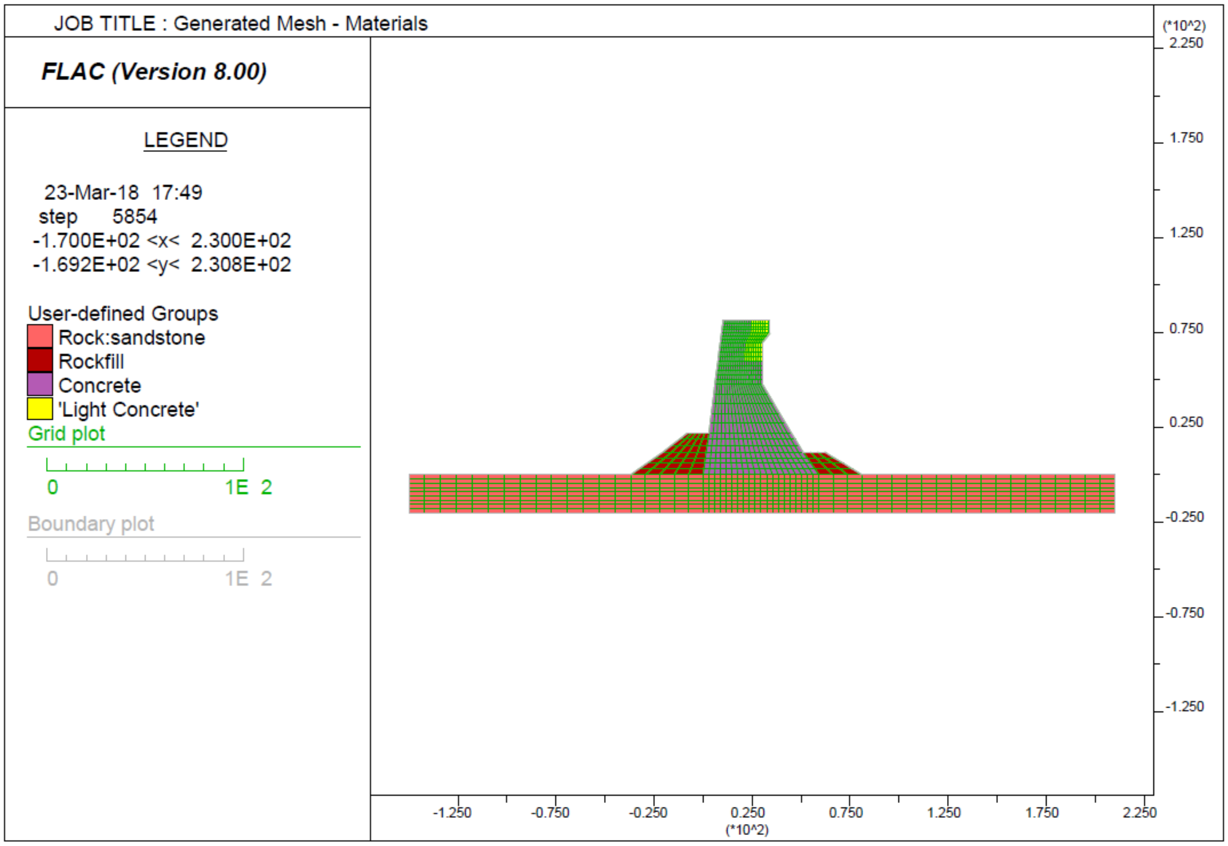


Figure 25: Mesh Generation and Material Definition in the Model

The model was fixed at left and right-hand side in x-direction, and bottom in both direction. Figure 26 indicates how boundary conditions were applied at sides and bottom part of the sandstone.

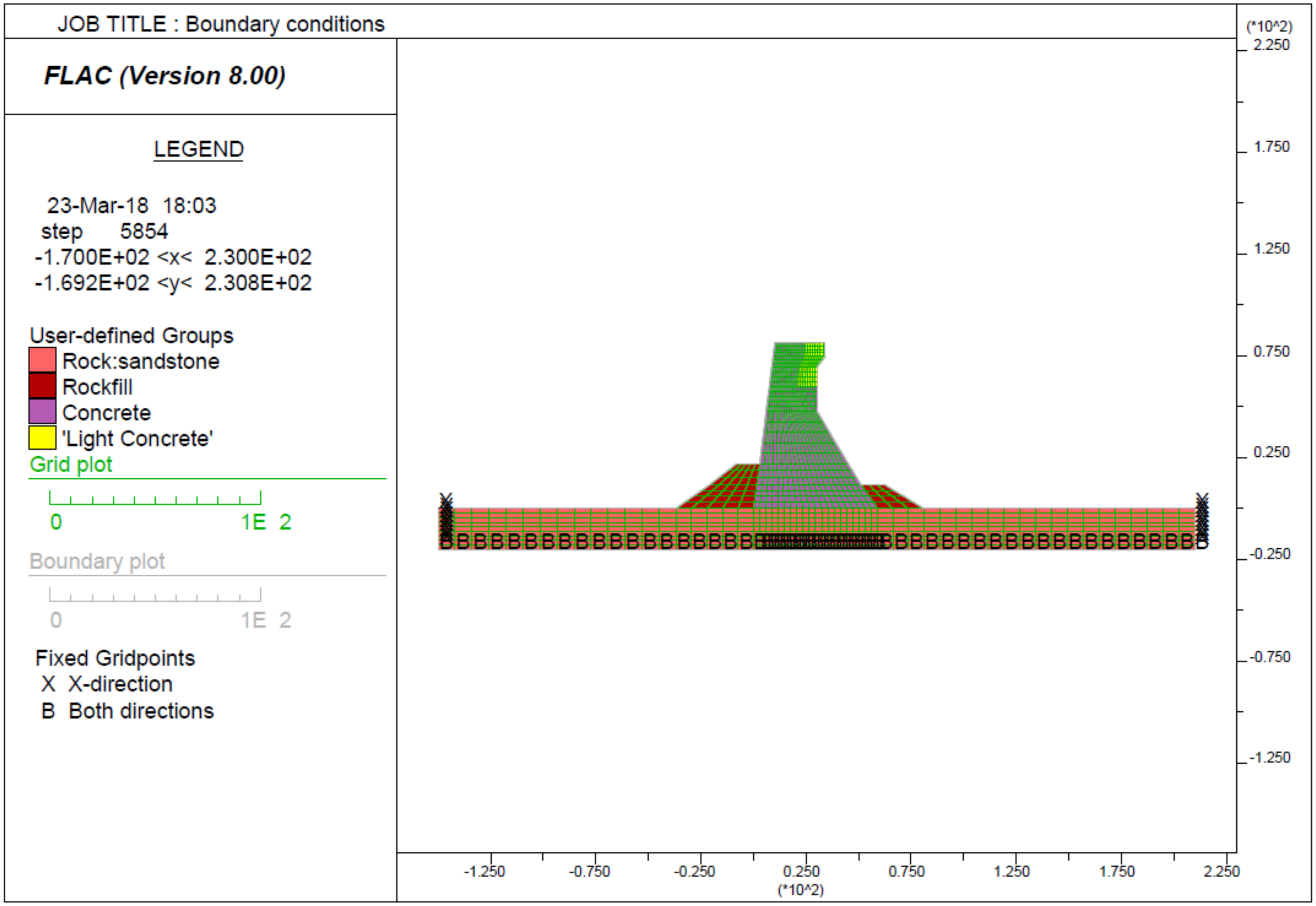


Figure 26: Boundary conditions

Water pressures and initial pore pressures for rockfill material were applied as normal stresses in the model and figure 27 shows the water pressures applied in the model.

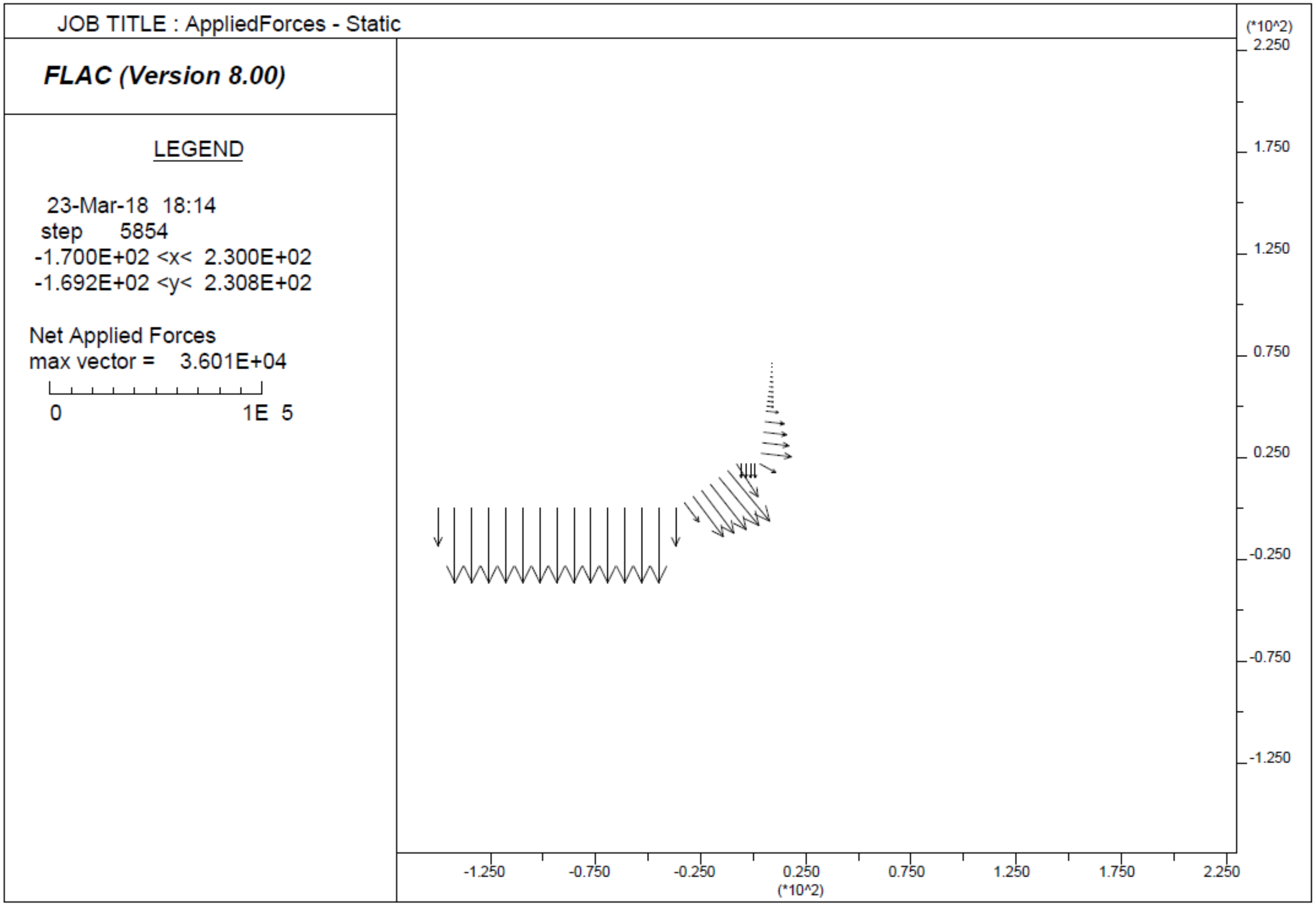


Figure 27: Applied water pressures

Figure 28 shows the model for static analysis.

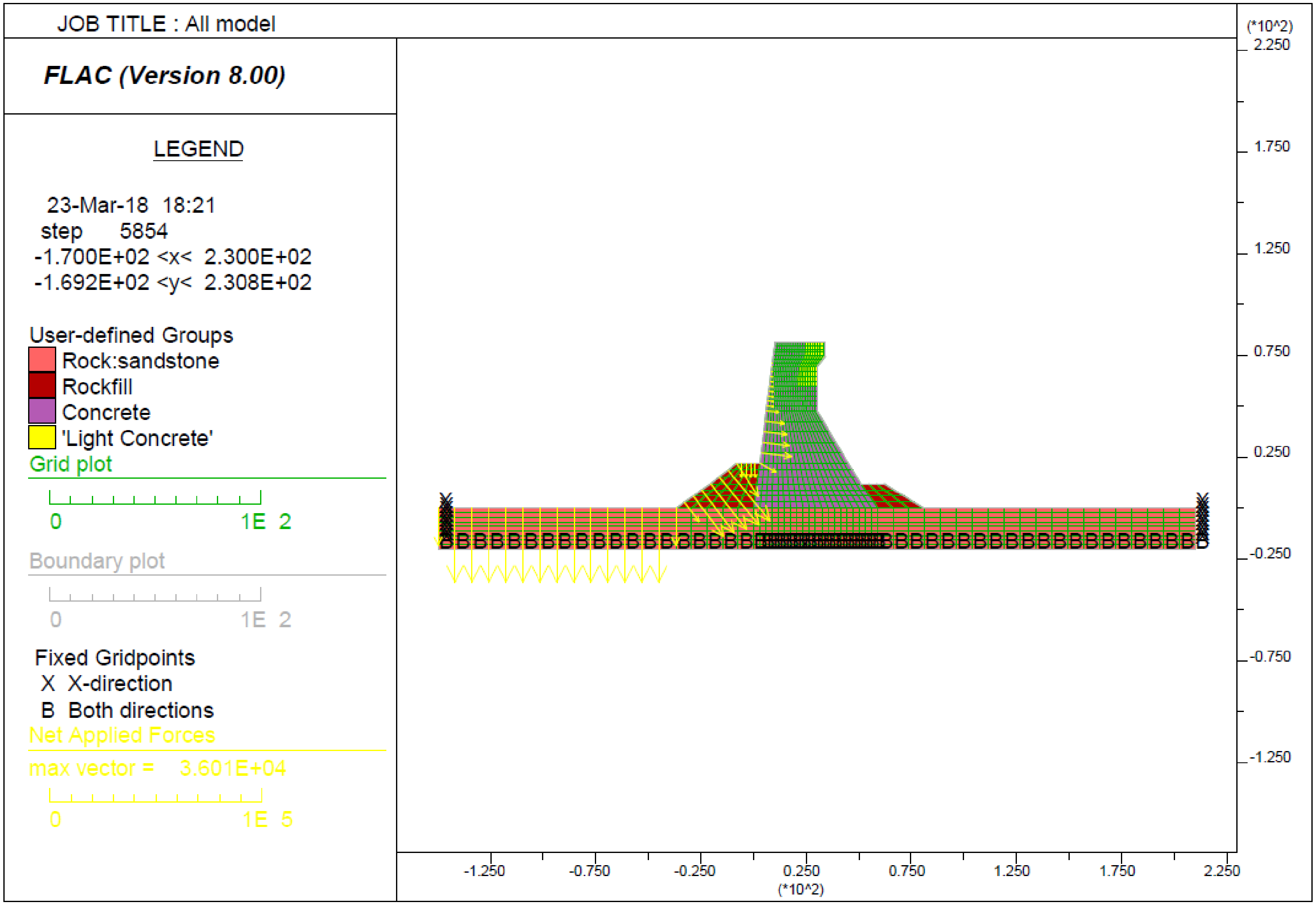
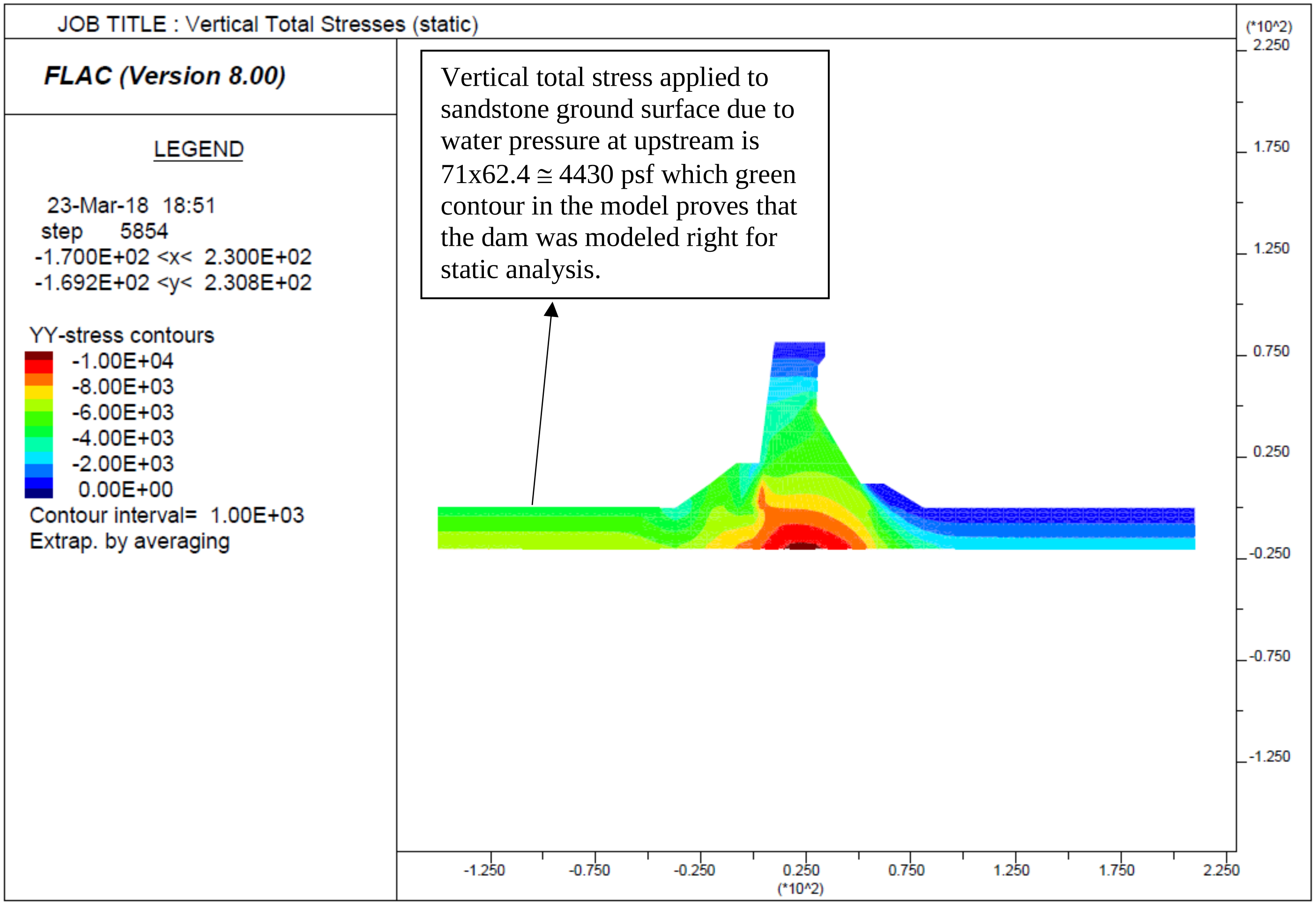


Figure 28: Model for static analysis

3.2. Results and Analysis

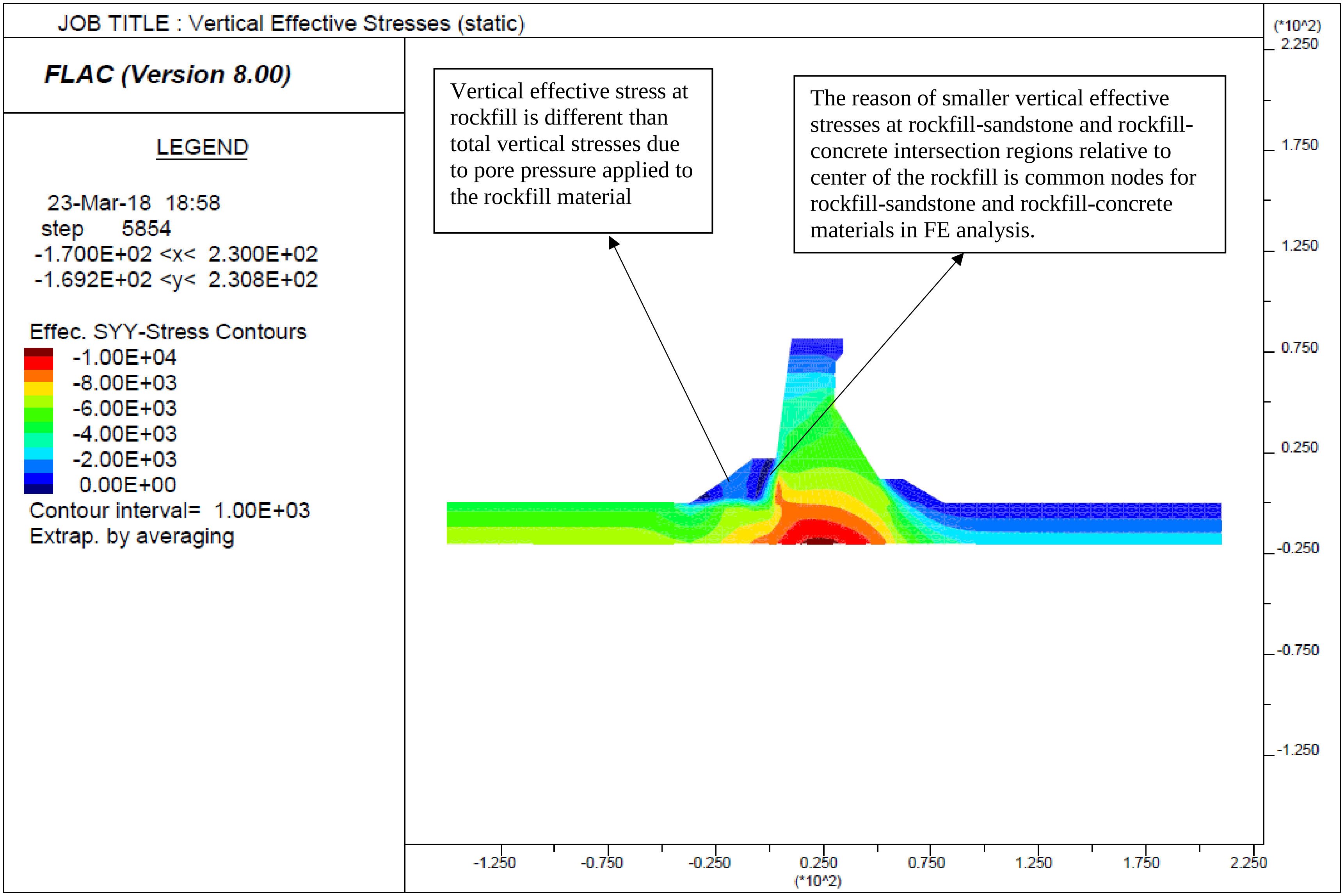
3.2.1. Static Analysis

The model was run for static condition which there was no input motion applied. The figure 29 shows vertical total stresses.



Vertical total stress applied to sandstone ground surface due to water pressure at upstream is 71x62.4 ≅ 4430 psf which green contour in the model proves that the dam was modeled right for static analysis.

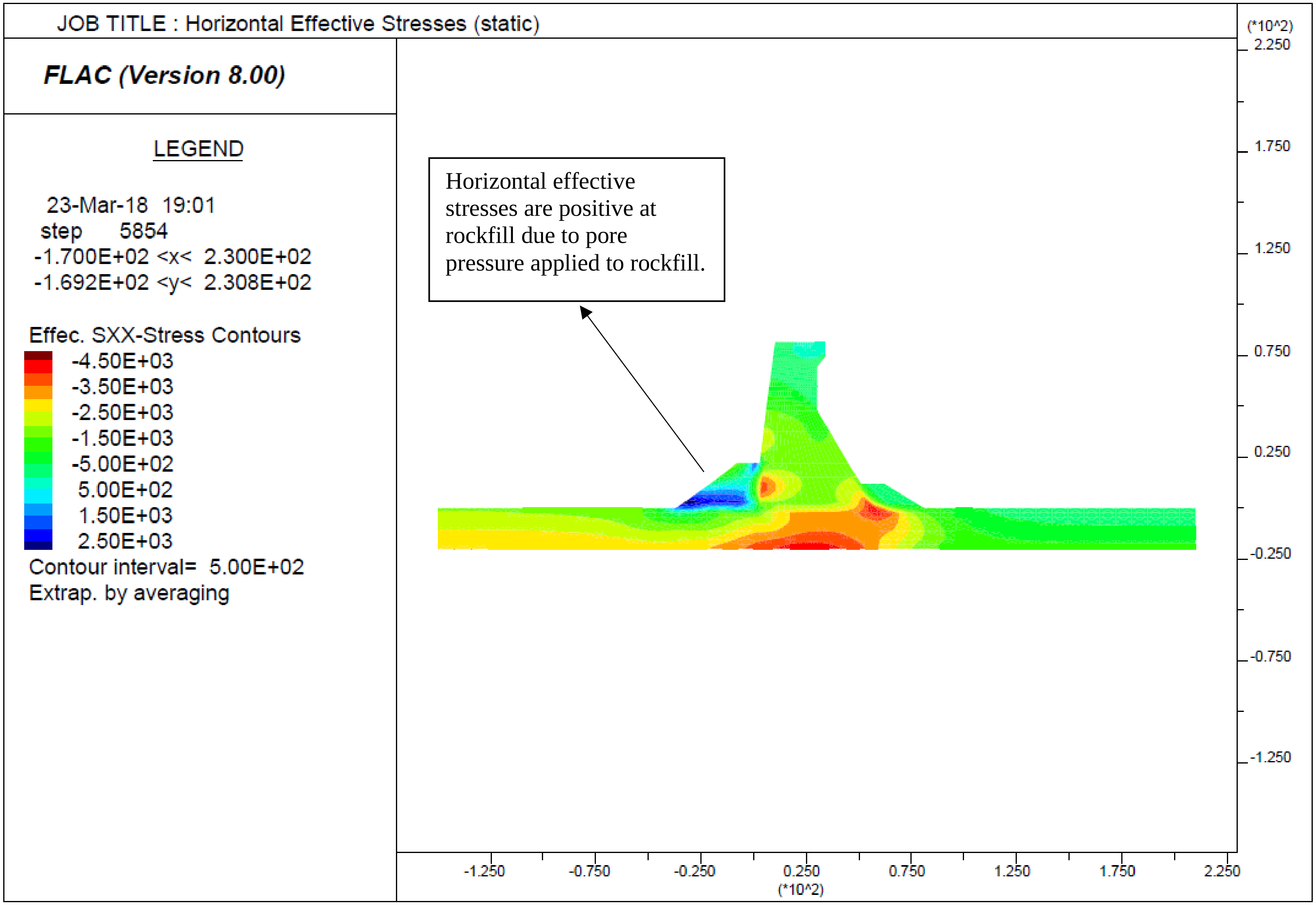
Figure 29: Vertical Total Stresses (Static)



Vertical effective stress at rockfill is different than total vertical stresses due to pore pressure applied to the rockfill material

The reason of smaller vertical effective stresses at rockfill-sandstone and rockfill-concrete intersection regions relative to center of the rockfill is common nodes for rockfill-sandstone and rockfill-concrete materials in FE analysis.

Figure 30: Vertical Effective Stresses



Horizontal effective stresses are positive at rockfill due to pore pressure applied to rockfill.

Figure 31: Horizontal Effective Stresses

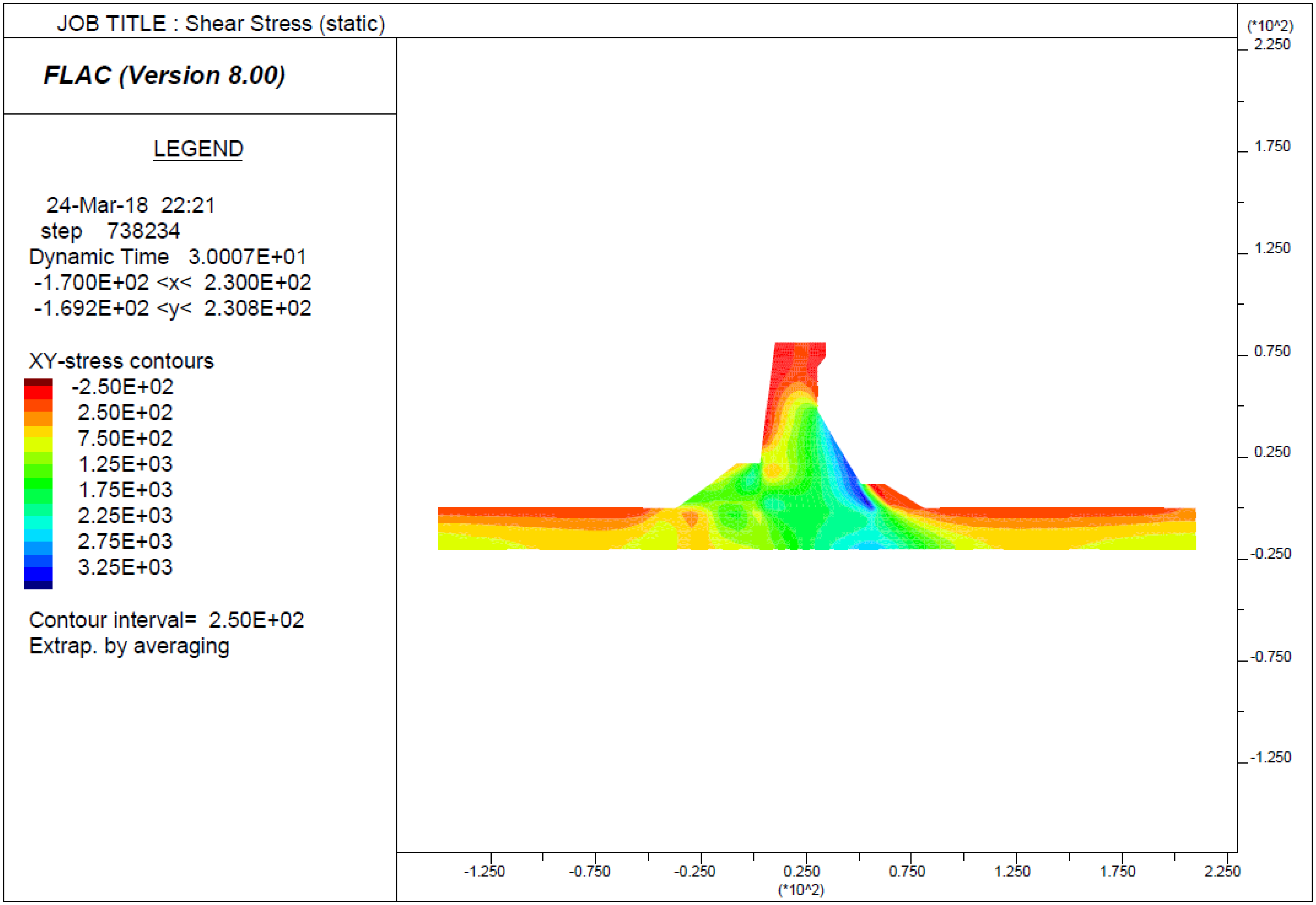
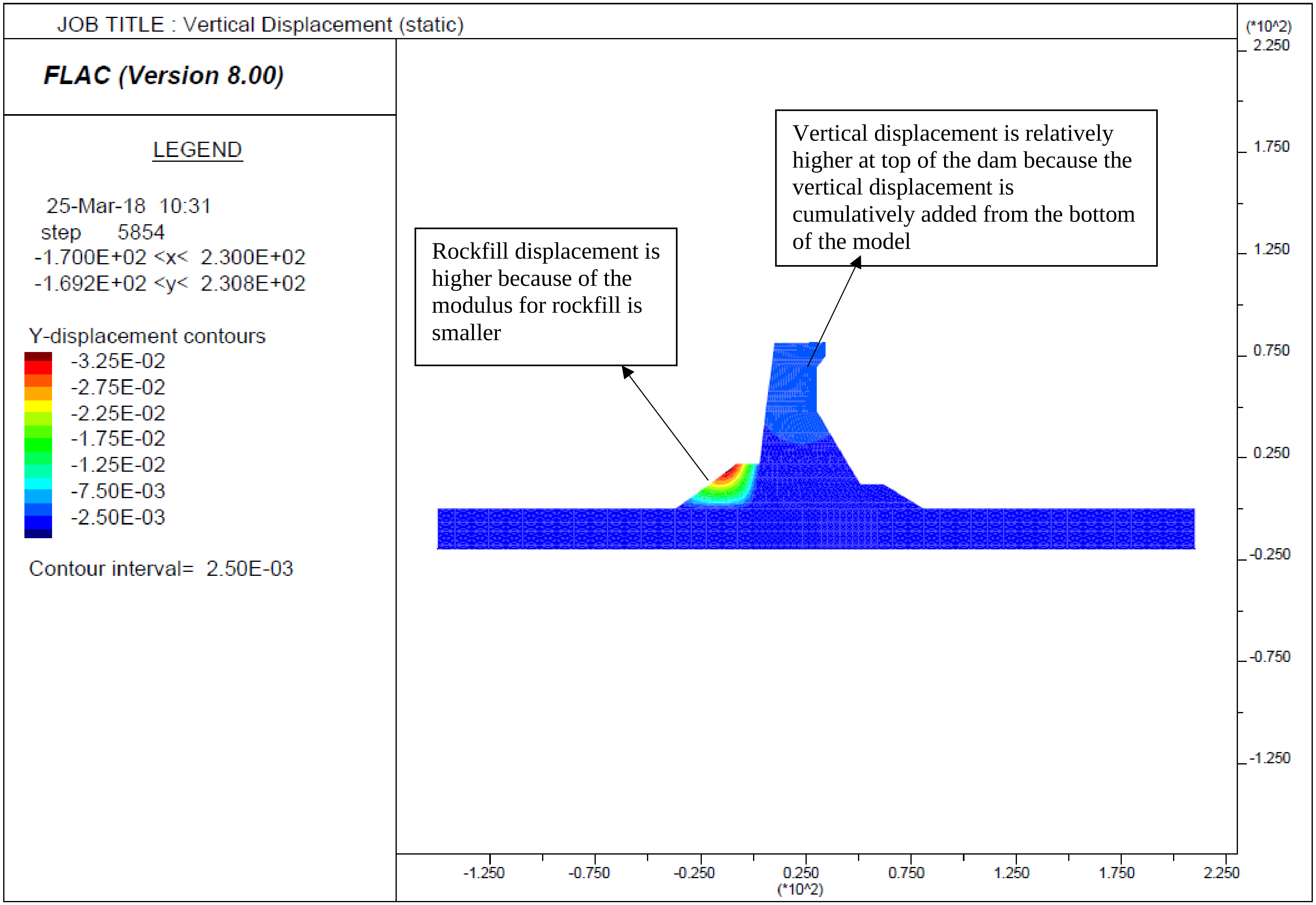


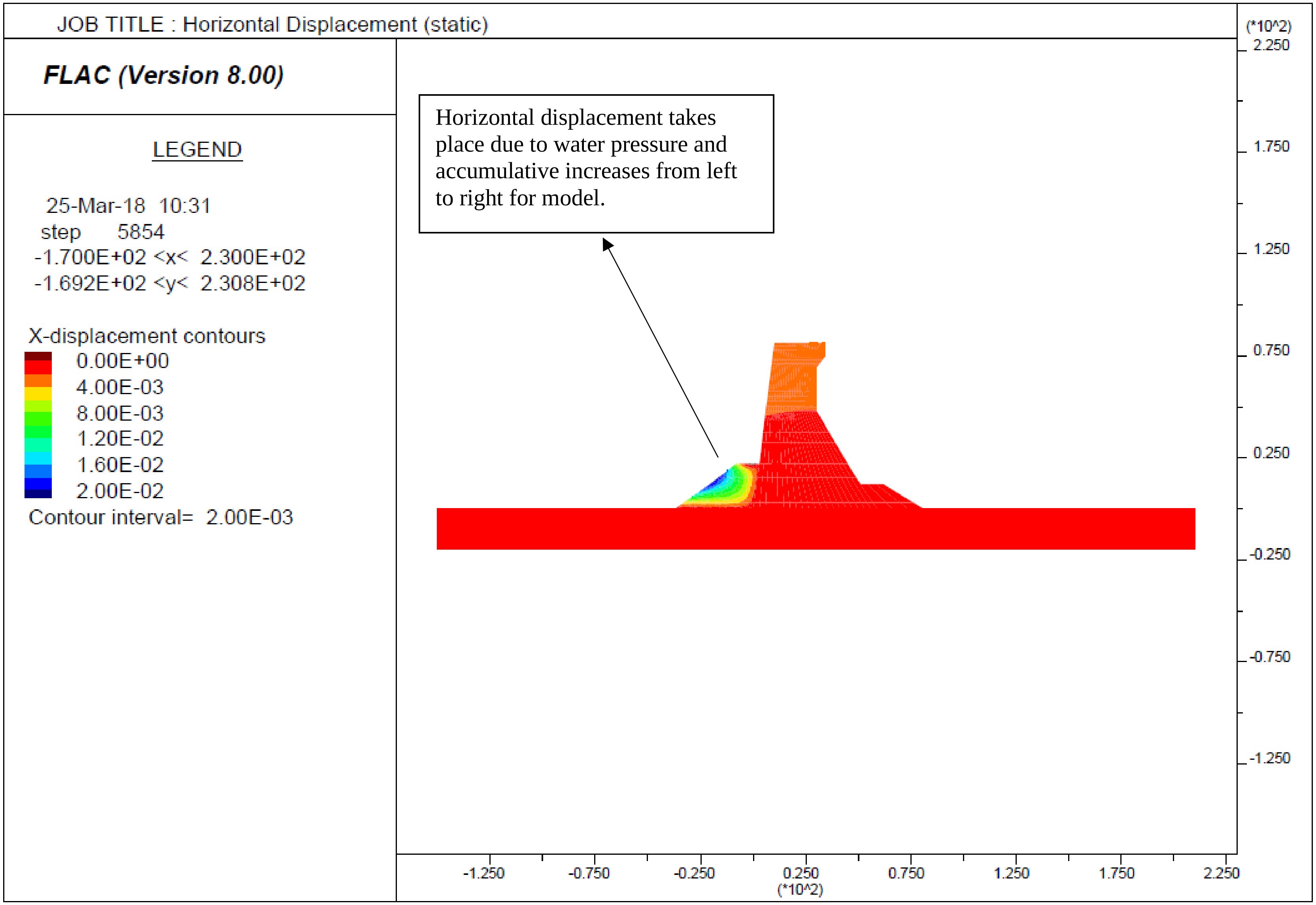
Figure 32: Shear Stresses



Rockfill displacement is higher because of the modulus for rockfill is smaller

Vertical displacement is relatively higher at top of the dam because the vertical displacement is cumulatively added from the bottom of the model

Figure 33: Vertical Displacement (static)



Horizontal displacement takes place due to water pressure and accumulative increases from left to right for model.

Figure 34: Horizontal Displacement (static)

3.2.2. Dynamic Analysis

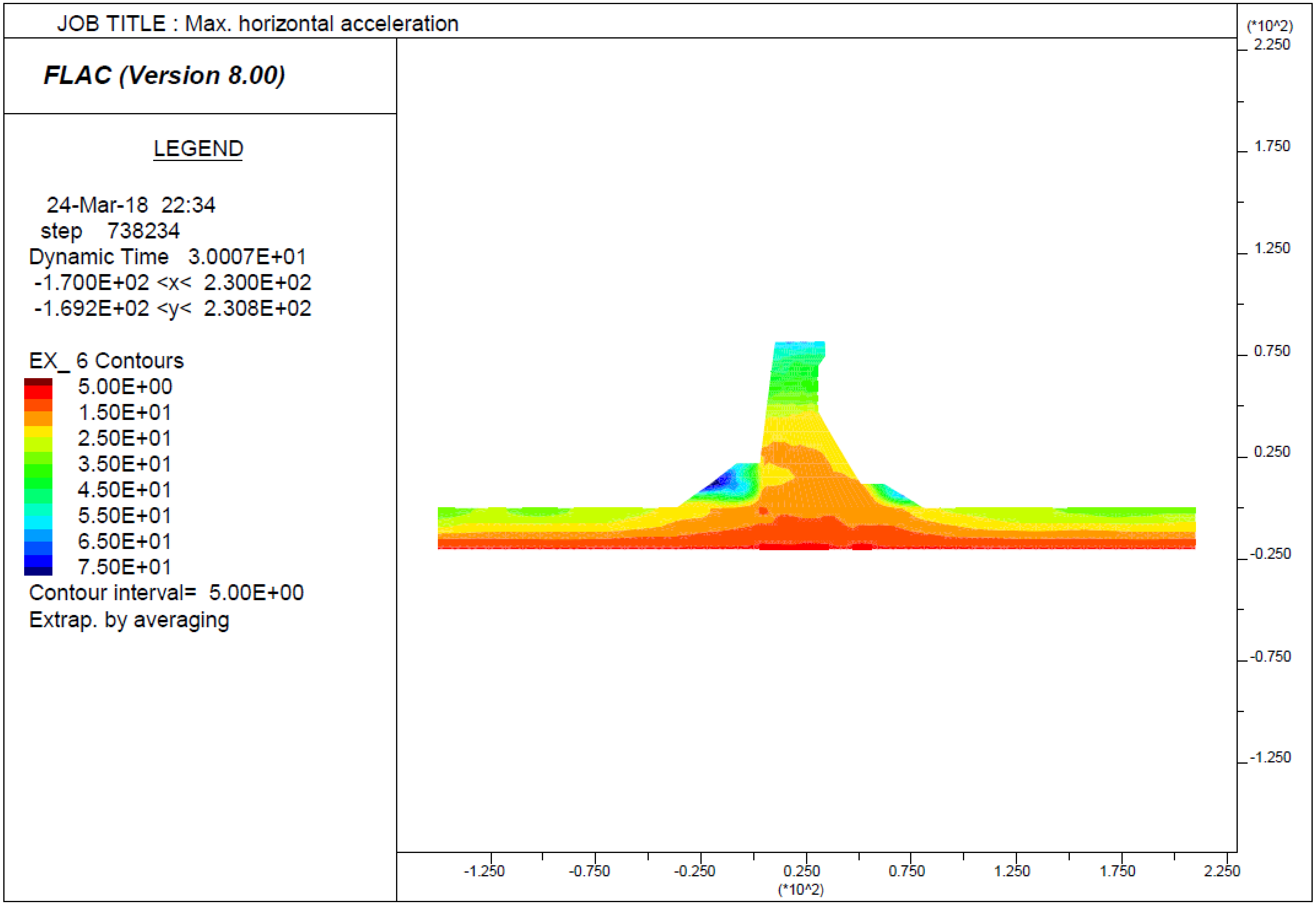


Figure 35: Maximum Horizontal Acceleration

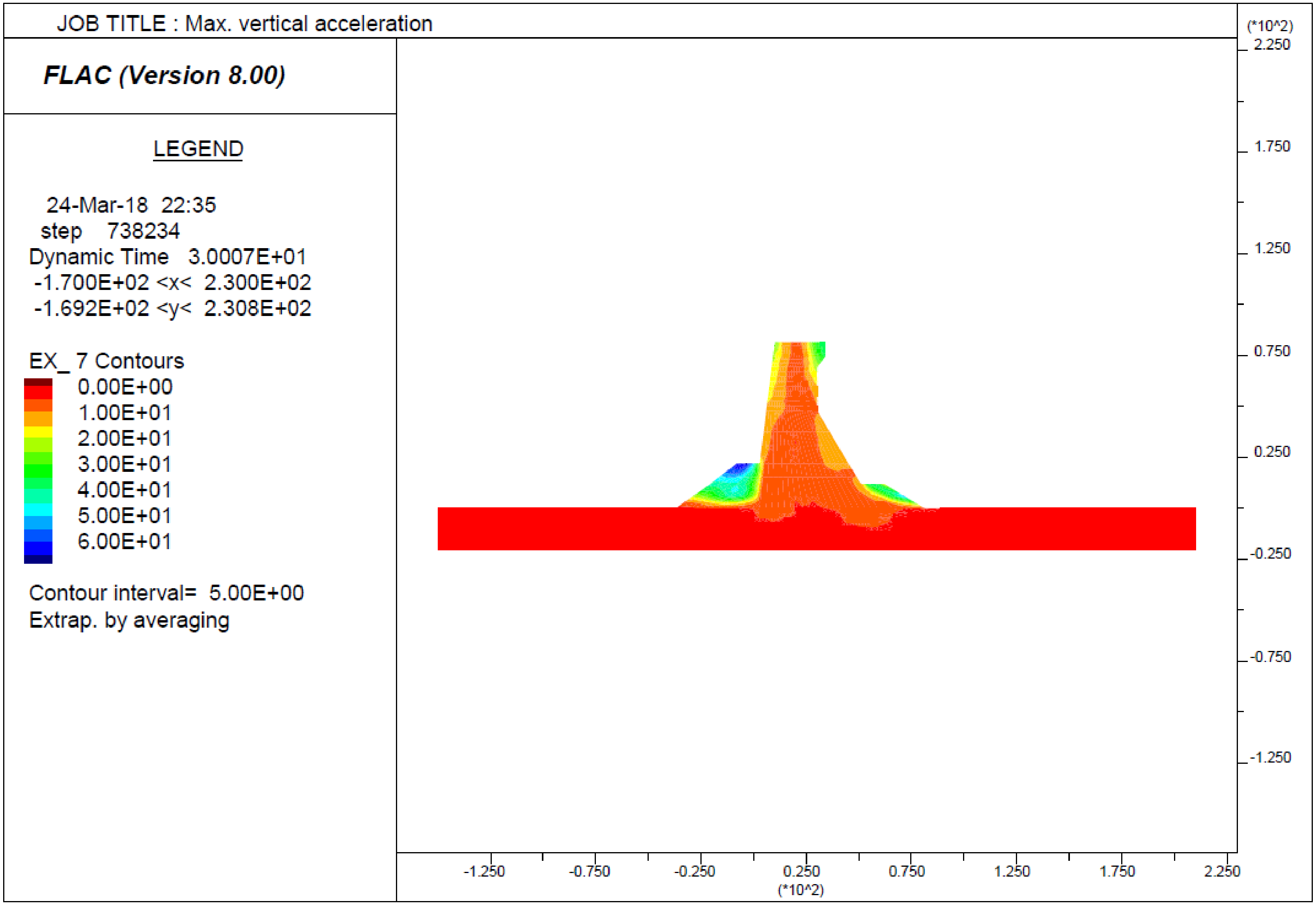


Figure 36: Maximum Vertical Acceleration

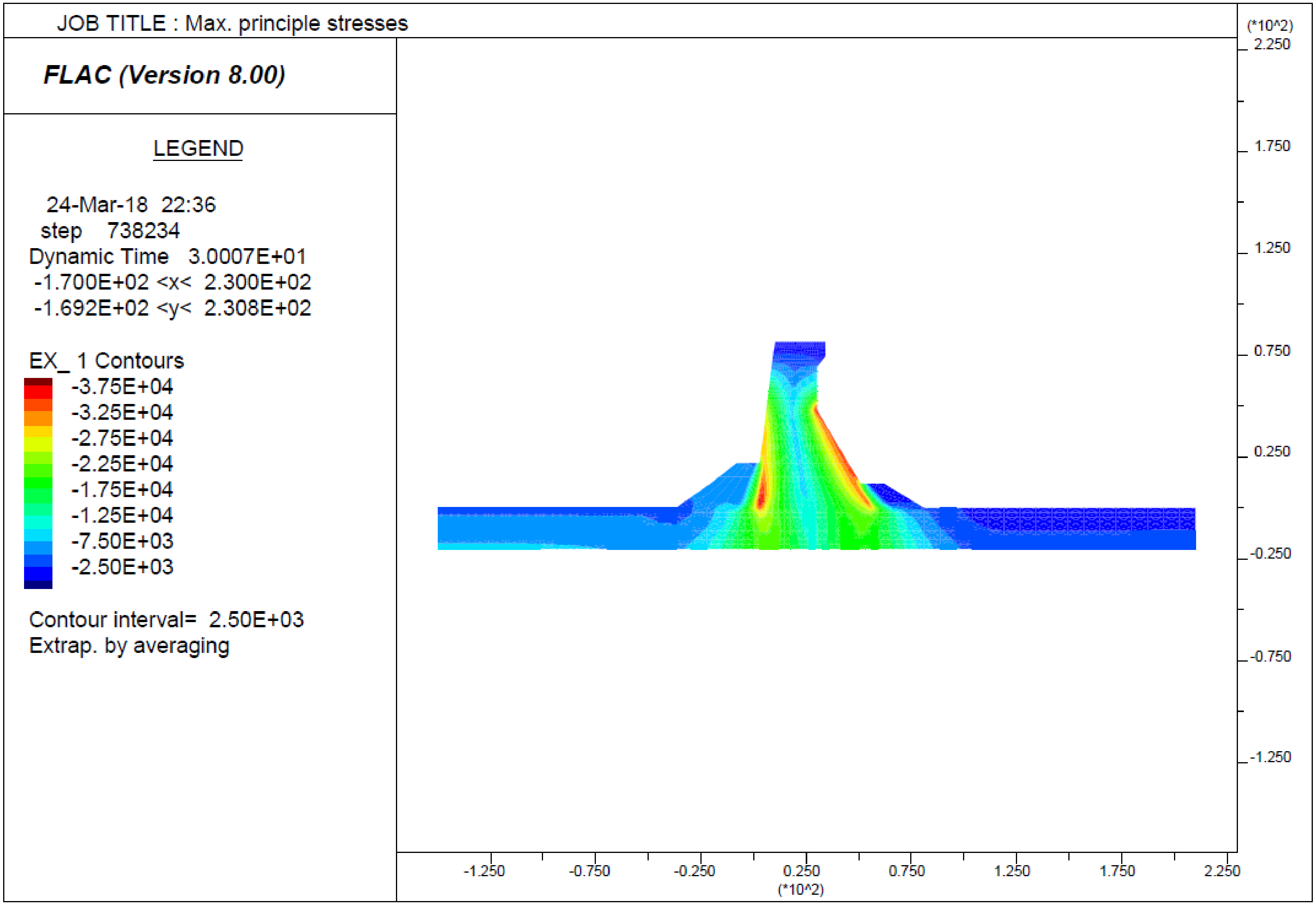


Figure 37: Maximum Principle Stresses

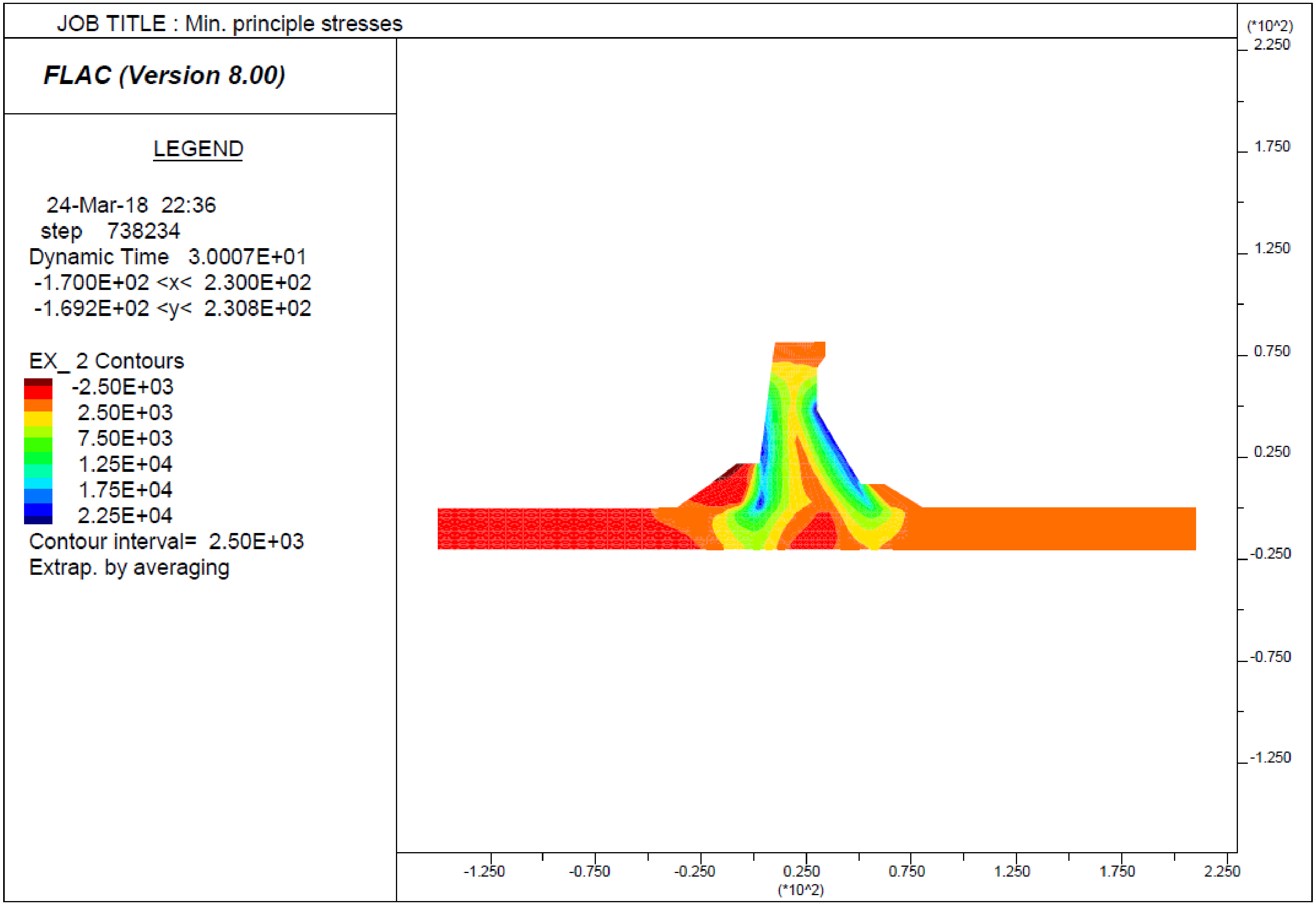


Figure 38: Minimum Principle Stresses

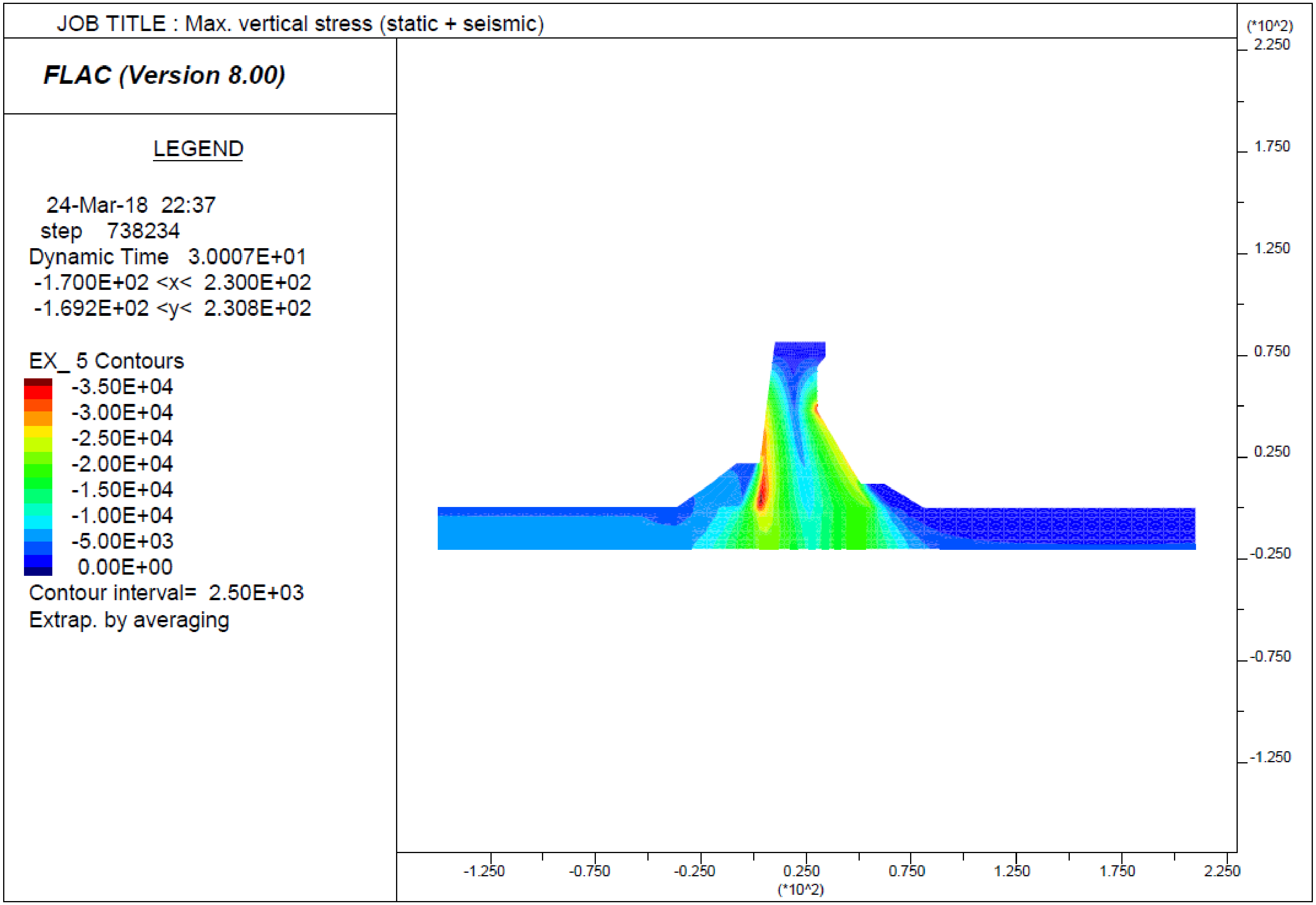
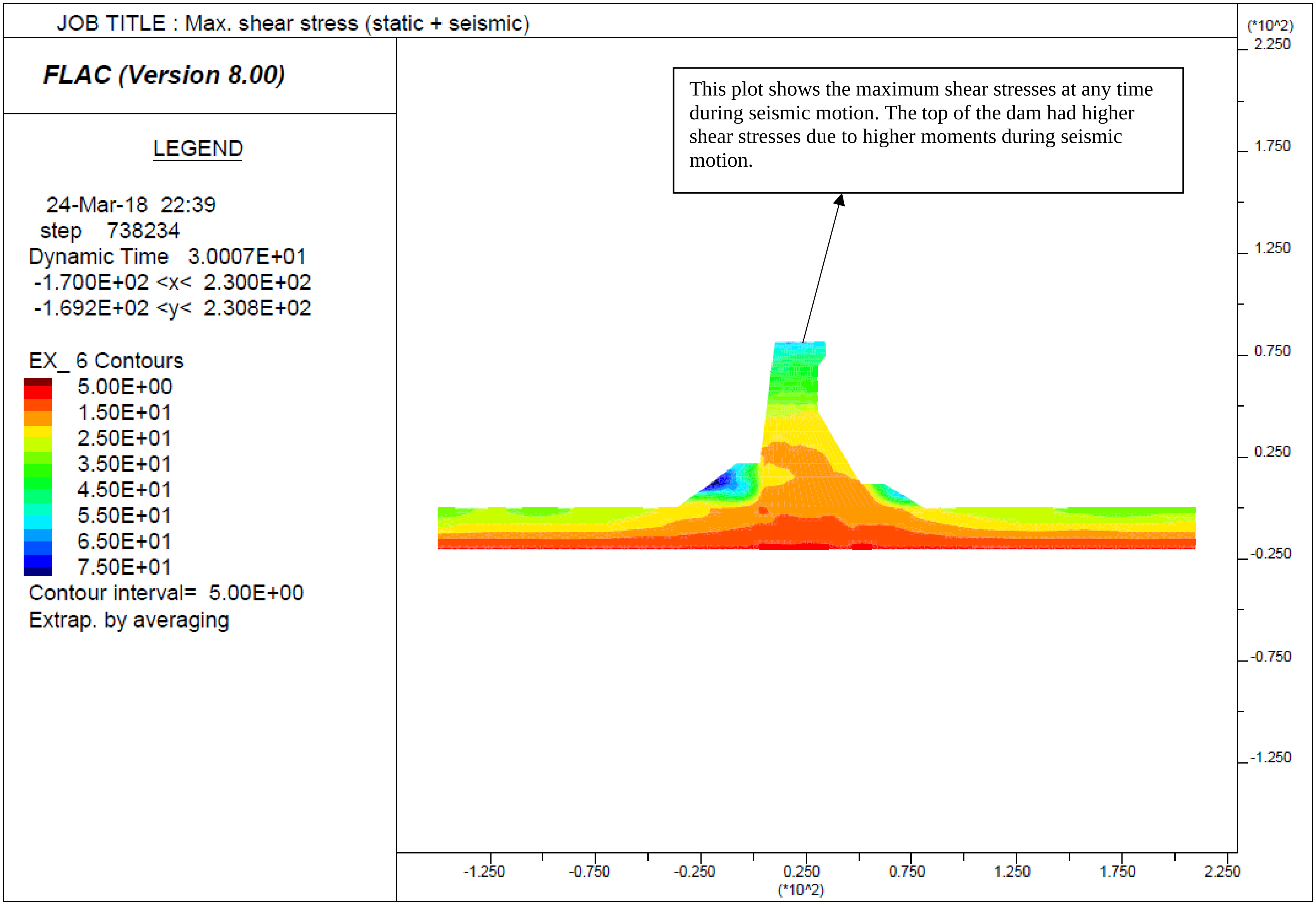
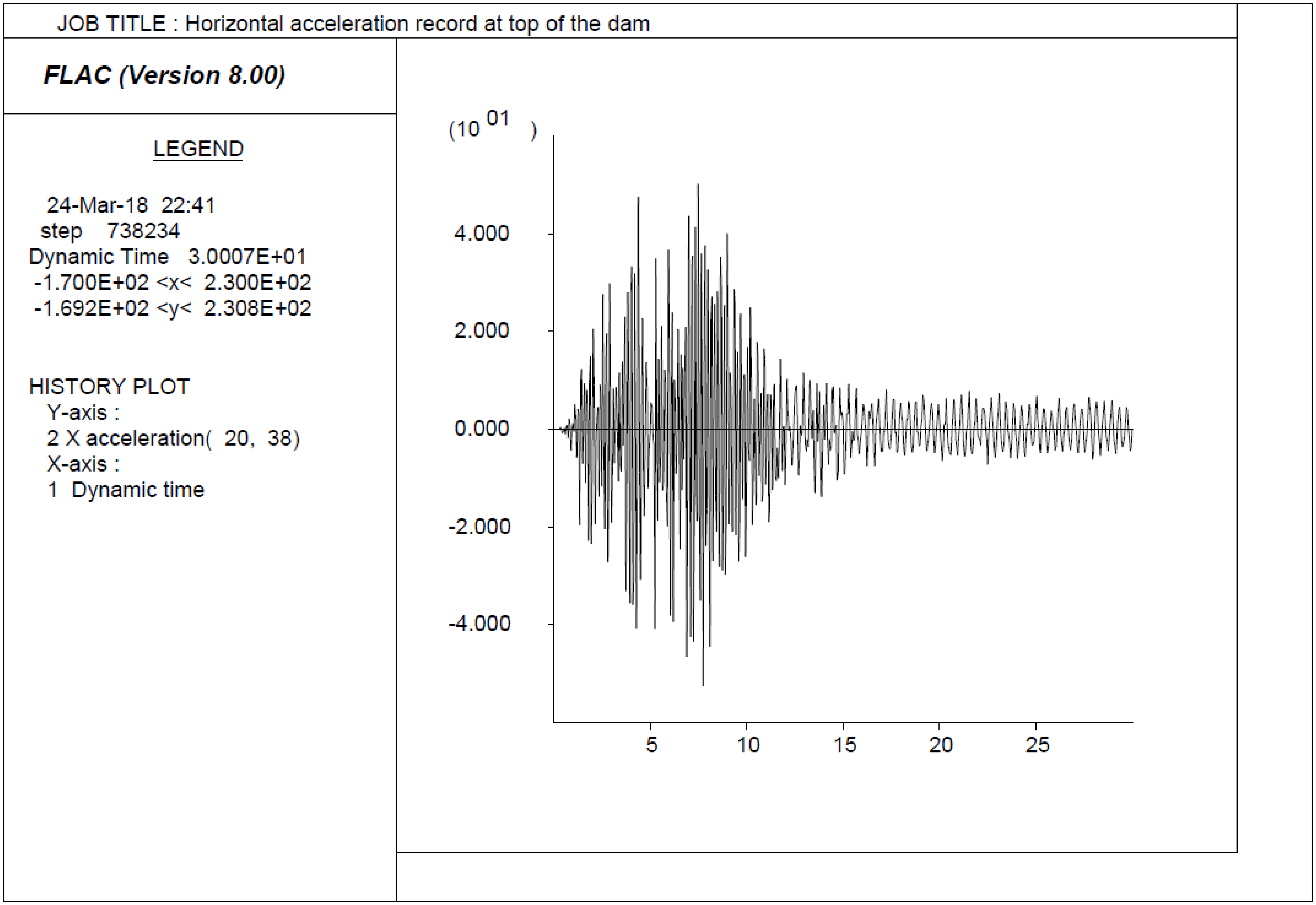


Figure 39: Maximum Vertical Stresses (static + seismic)



This plot shows the maximum shear stresses at any time during seismic motion. The top of the dam had higher shear stresses due to higher moments during seismic motion.

Figure 40: Maximum Shear Stresses (static + seismic)



JOB TITLE : Horizontal acceleration record at top of the dam

FLAC (Version 8.00)

LEGEND

24-Mar-18 22:41
step 738234
Dynamic Time 3.0007E+01
-1.700E+02 <x< 2.300E+02
-1.692E+02 <y< 2.308E+02

HISTORY PLOT
Y-axis :
2 X acceleration(20, 38)
X-axis :
1 Dynamic time

Figure 41: Horizontal Acceleration Record at Top of the Dam

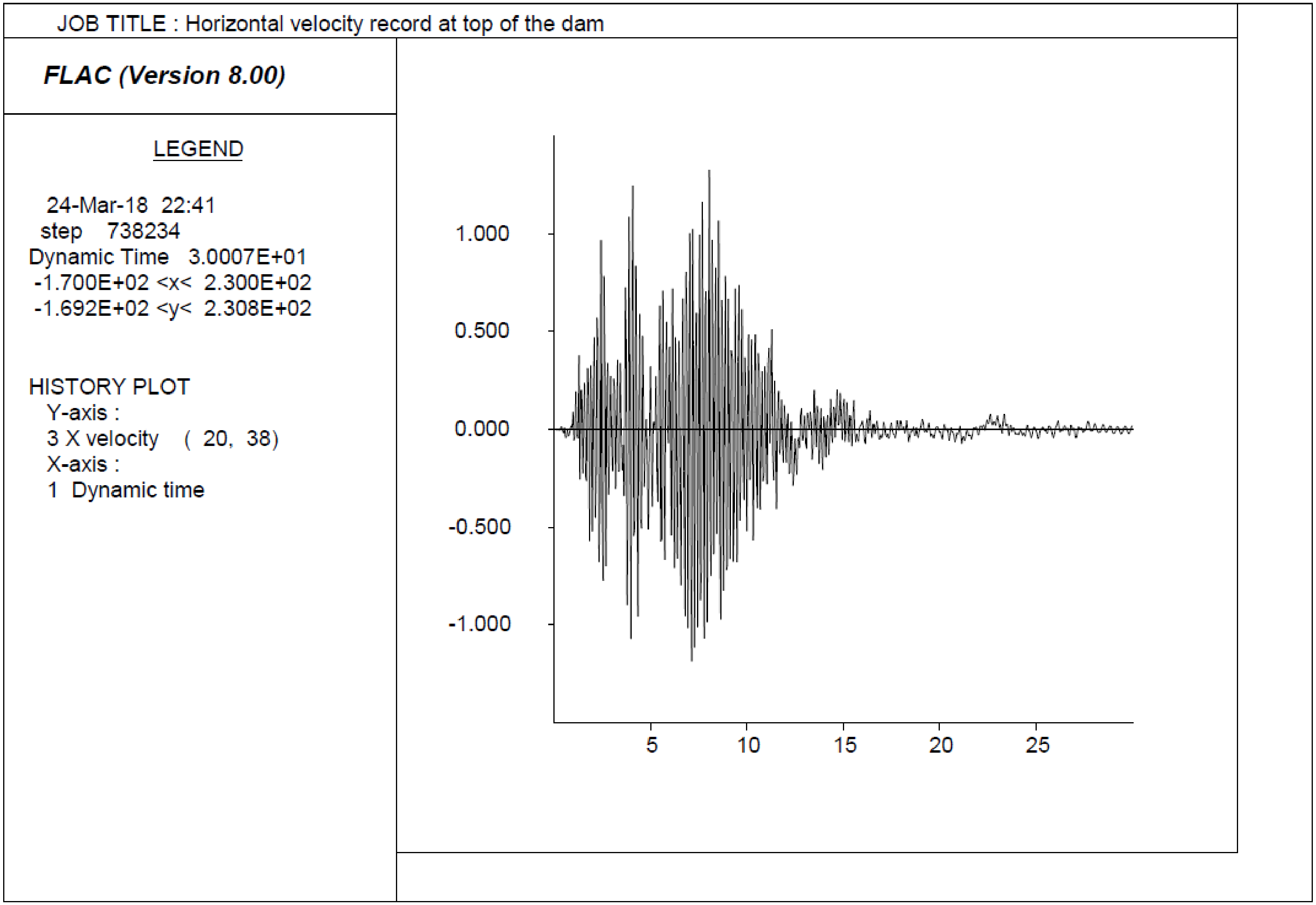
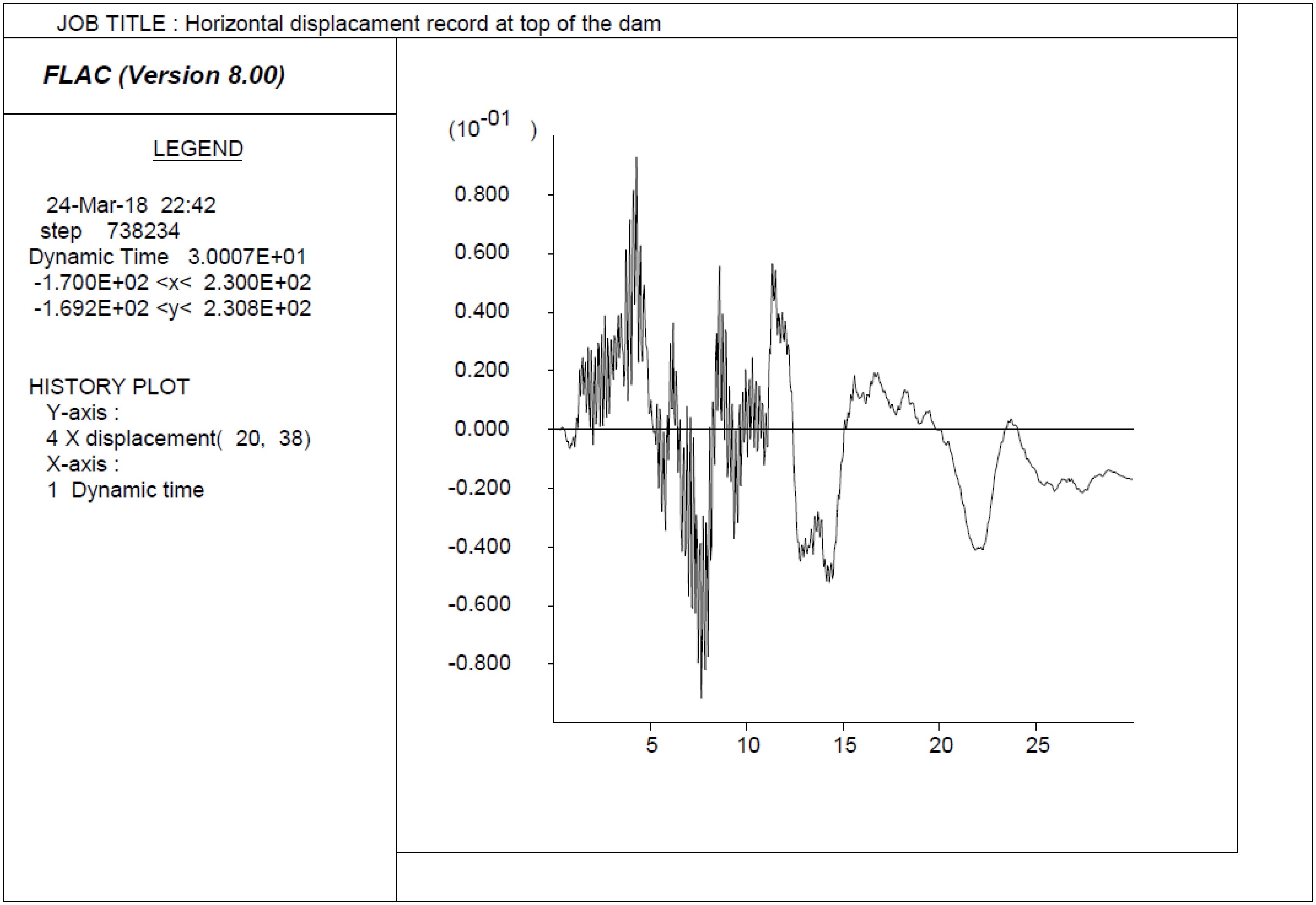
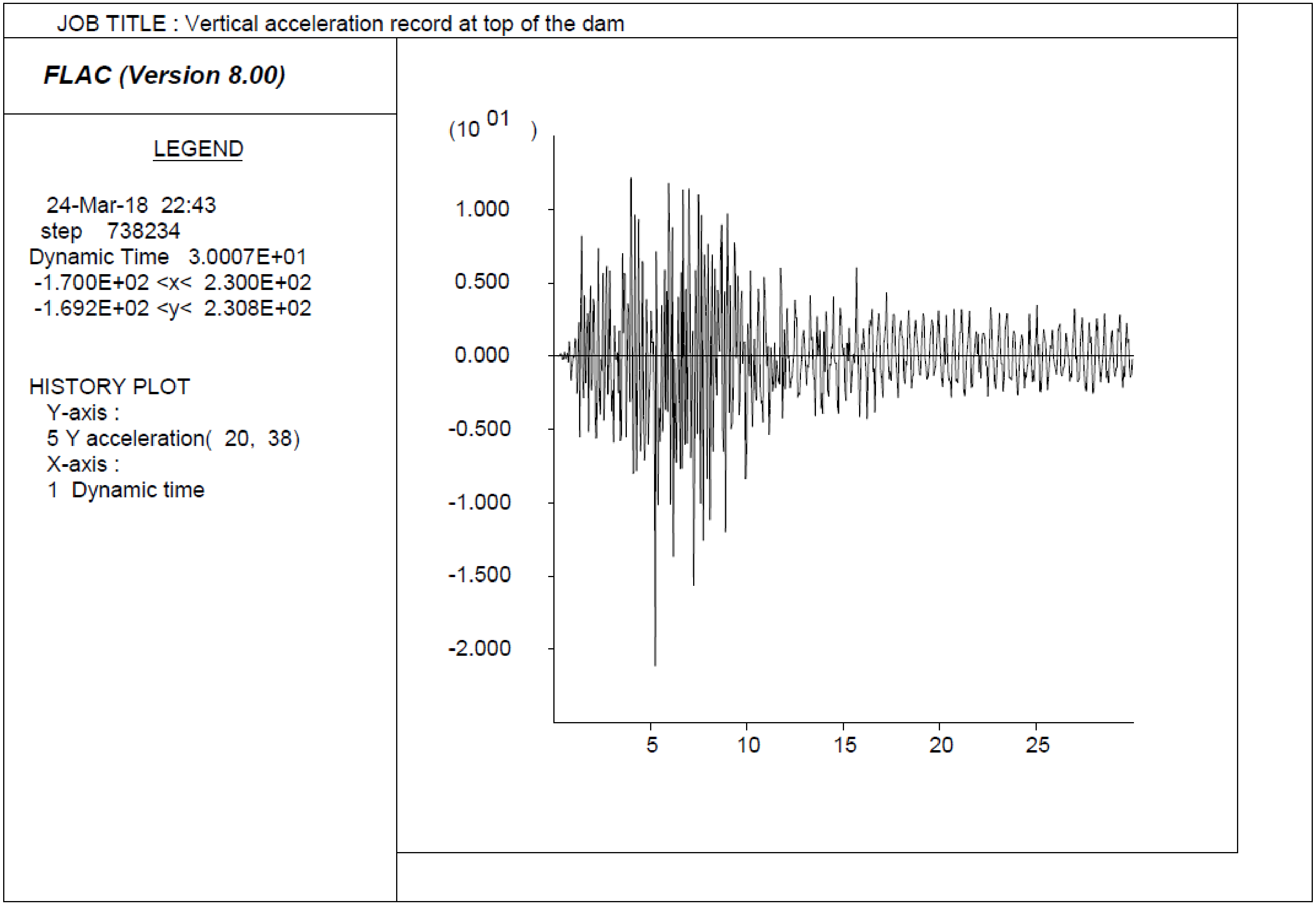


Figure 42: Horizontal Velocity Record at Top of the Dam



```
JOB TITLE : Horizontal displacement record at top of the dam

FLAC (Version 8.00)

LEGEND

  24-Mar-18  22:42
 step    738234
Dynamic Time   3.0007E+01
 -1.700E+02 <x<  2.300E+02
 -1.692E+02 <y<  2.308E+02

HISTORY PLOT
  Y-axis :
  4 X displacement(  20,  38)
  X-axis :
  1  Dynamic time
```

Figure 43: Horizontal Displacement Record at Top of the Dam



JOB TITLE : Vertical acceleration record at top of the dam

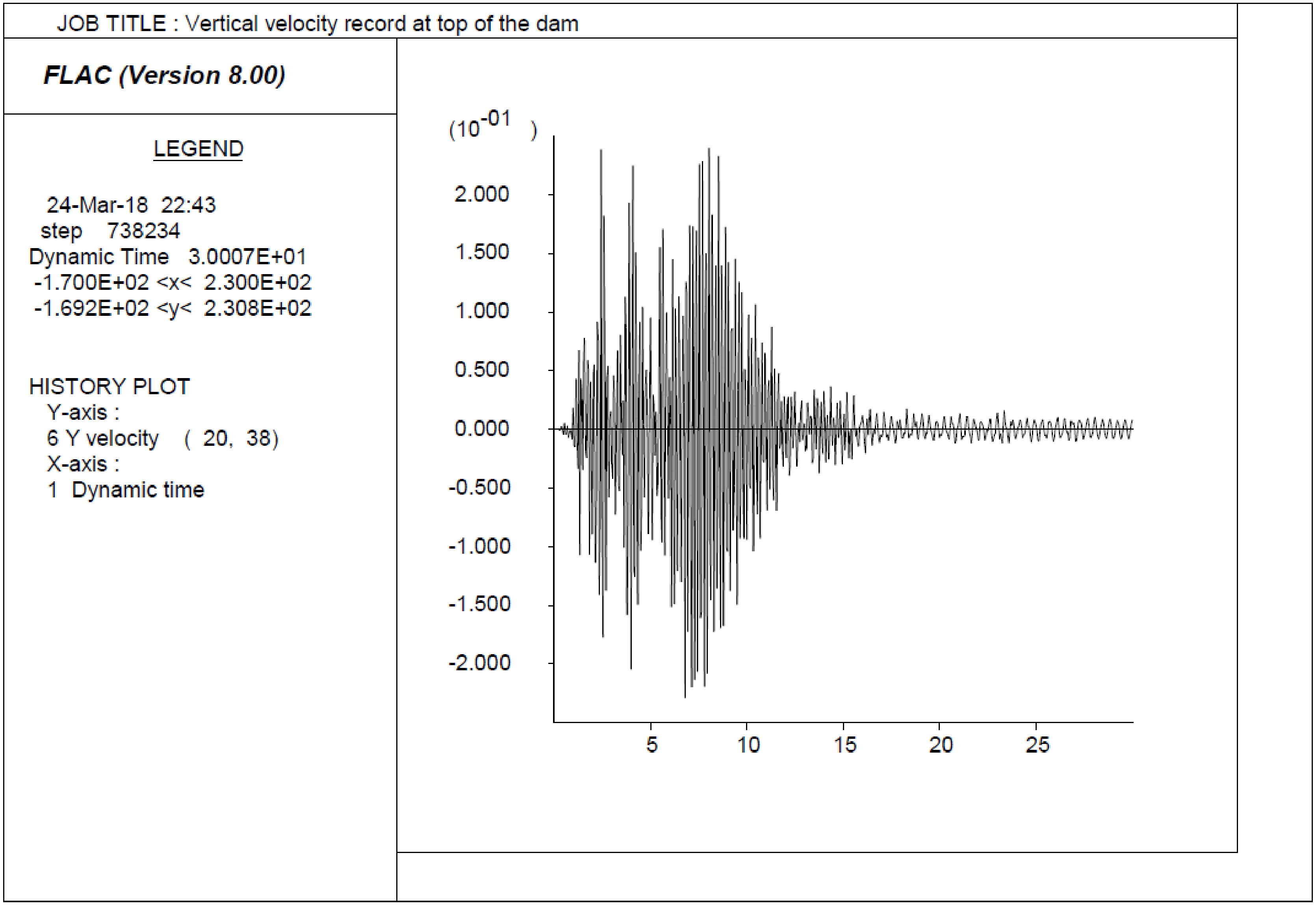
FLAC (Version 8.00)

LEGEND

24-Mar-18 22:43
step 738234
Dynamic Time 3.0007E+01
-1.700E+02 <x< 2.300E+02
-1.692E+02 <y< 2.308E+02

HISTORY PLOT
Y-axis :
5 Y acceleration(20, 38)
X-axis :
1 Dynamic time

Figure 44: 16 Vertical Acceleration Record at Top of the Dam



JOB TITLE : Vertical velocity record at top of the dam

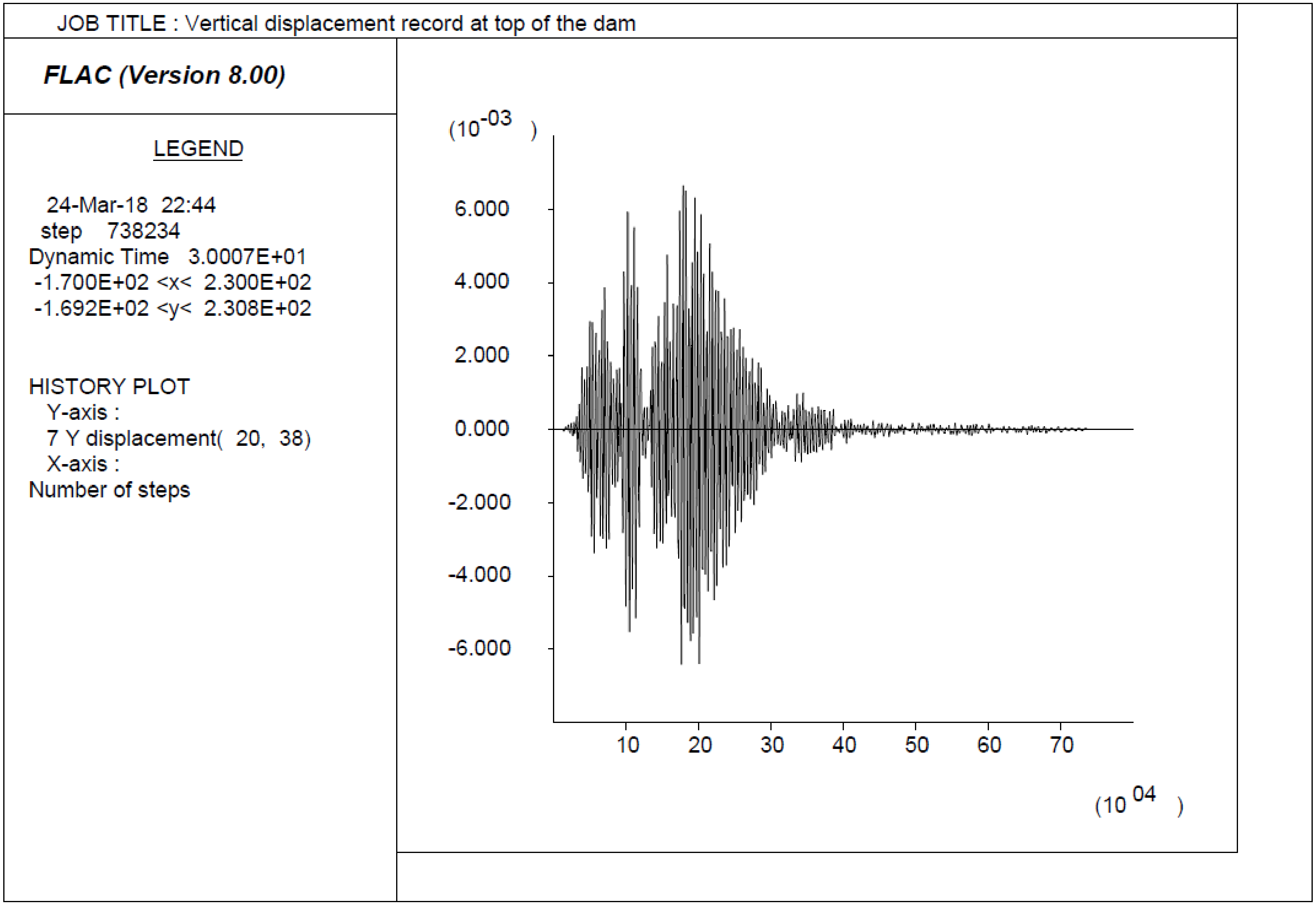
FLAC (Version 8.00)

LEGEND

24-Mar-18 22:43
step 738234
Dynamic Time 3.0007E+01
-1.700E+02 <x< 2.300E+02
-1.692E+02 <y< 2.308E+02

HISTORY PLOT
Y-axis :
6 Y velocity (20, 38)
X-axis :
1 Dynamic time

Figure 45:17 Vertical Velocity Record at Top of the Dam



JOB TITLE : Vertical displacement record at top of the dam

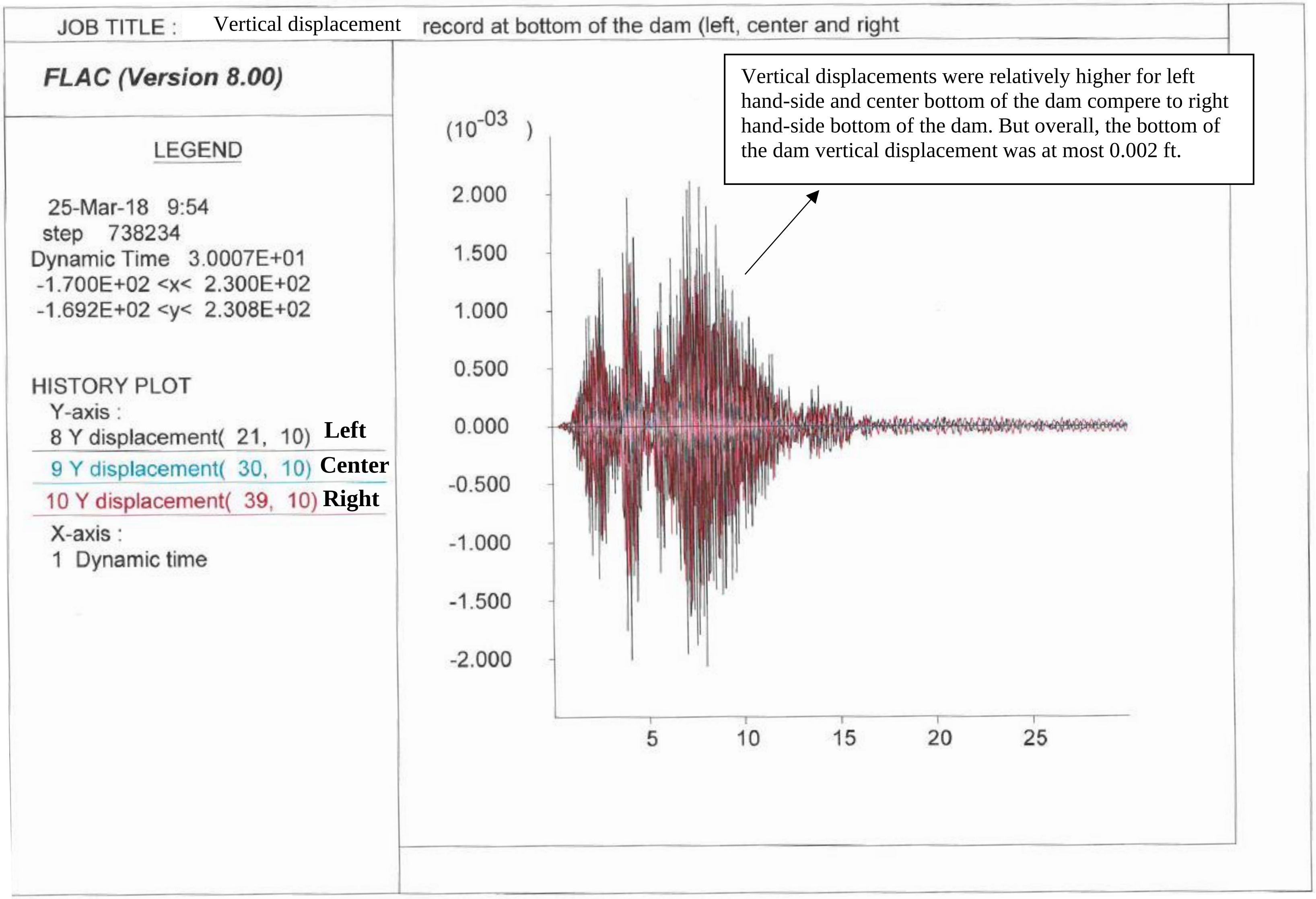
FLAC (Version 8.00)

LEGEND

24-Mar-18 22:44
step 738234
Dynamic Time 3.0007E+01
-1.700E+02 <x< 2.300E+02
-1.692E+02 <y< 2.308E+02

HISTORY PLOT
Y-axis :
7 Y displacement(20, 38)
X-axis :
Number of steps

Figure 46: 18 Vertical Velocity Record at Top of the Dam



JOB TITLE : Vertical displacement record at bottom of the dam (left, center and right

FLAC (Version 8.00)

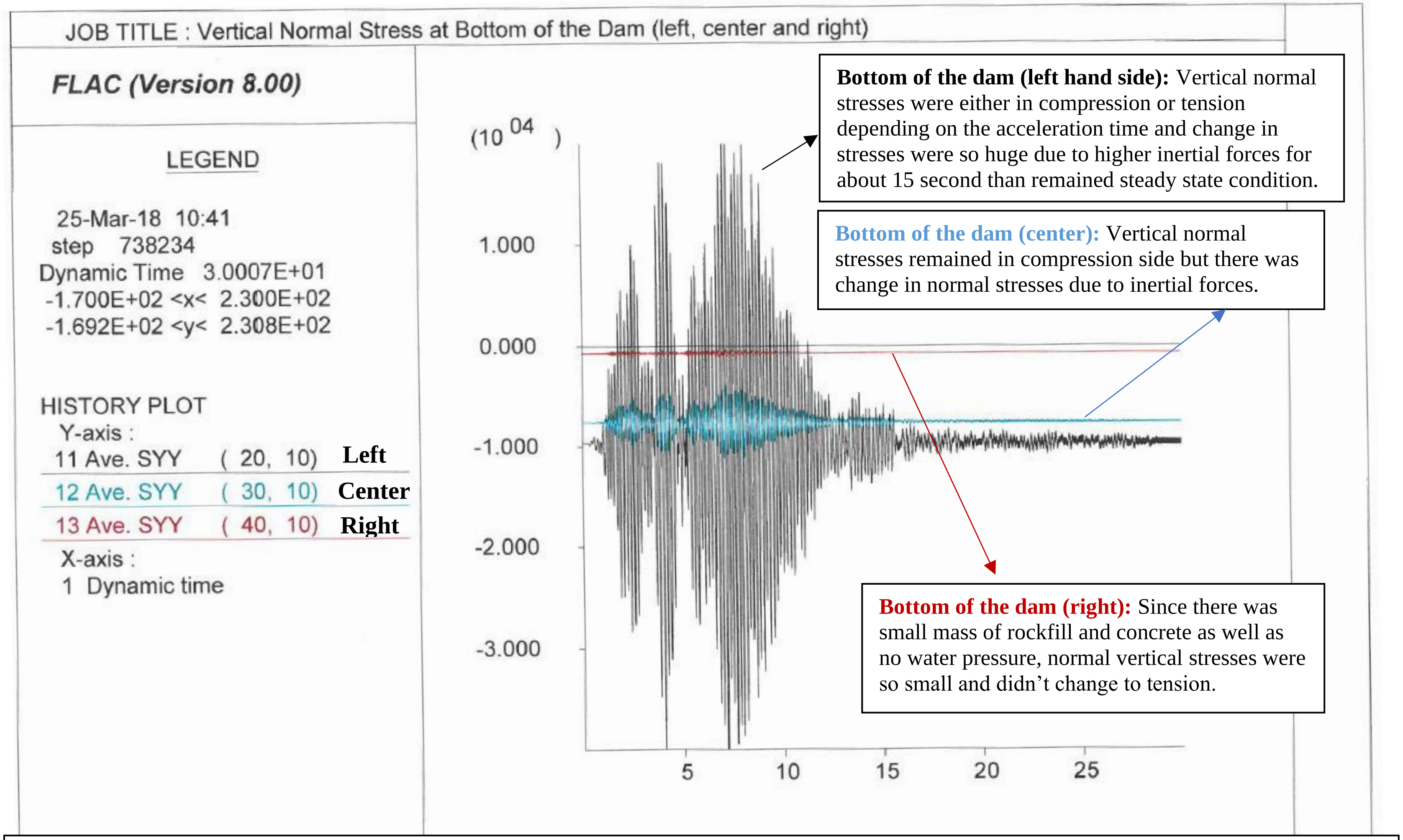
LEGEND

25-Mar-18 9:54
step 738234
Dynamic Time 3.0007E+01
-1.700E+02 <x< 2.300E+02
-1.692E+02 <y< 2.308E+02

HISTORY PLOT
Y-axis :
8 Y displacement(21, 10) **Left**
9 Y displacement(30, 10) **Center**
10 Y displacement(39, 10) **Right**
X-axis :
1 Dynamic time

Vertical displacements were relatively higher for left hand-side and center bottom of the dam compere to right hand-side bottom of the dam. But overall, the bottom of the dam vertical displacement was at most 0.002 ft.

Figure 47: 19 Vertical Displacement Record at Bottom of the Dam (Left, Center, Right)



Bottom of the dam (left hand side): Vertical normal stresses were either in compression or tension depending on the acceleration time and change in stresses were so huge due to higher inertial forces for about 15 second than remained steady state condition.

Bottom of the dam (center): Vertical normal stresses remained in compression side but there was change in normal stresses due to inertial forces.

Bottom of the dam (right): Since there was small mass of rockfill and concrete as well as no water pressure, normal vertical stresses were so small and didn’t change to tension.

Conclusion: there was a tendency for lift-off due to tensional stresses from the left-hand side of the dam for given input motion; therefore, there should be interface layer defined in between dam and sandstone for better model as well as more analyses at different locations at bottom of the dam.

Figure 48: 20 Vertical Normal Stress Record at Bottom of the Dam (Left, Center, Right)

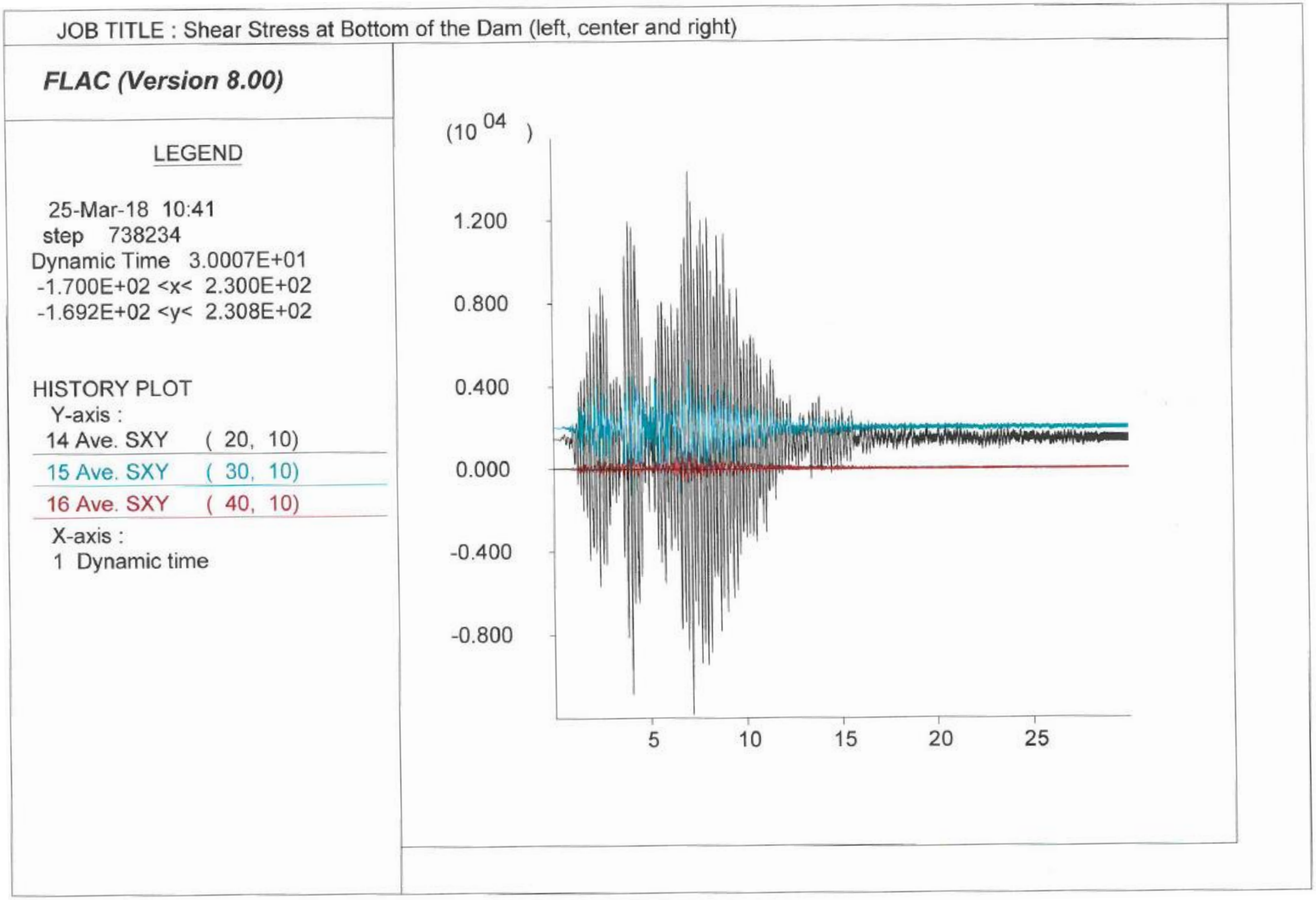


Figure 49: 21 Shear Stress Record at Bottom of the Dam (Left, Center, Right