SUCCESS DAM
SEISMIC DEFORMATION ANALYSIS USING FLAC

Vlad Perlea, Corps of Engineers, Sacramento District

Presentation Overview (1)

- INTRODUCTION
  - Existing Dam
  - Site Seismicity
- DEFORMATION ANALYSIS METHODOLOGY
  - Computer Program and Models
  - Analysis Procedure
  - Modified UBCSAND
- PARAMETRIC STUDY
  - Time Histories, Pool Elevation
  - Strength Parameters, Residual Strength

Presentation Overview (2)

- EVALUATION OF EXISTING DAM
  - Simulation of Dam Construction and Reservoir Filling
  - Prediction of Liquefaction
  - Prediction of Permanent Deformation
  - Results of Parametric Study
- REMEDIATION OPTIONS
  - Modified Dam (Downstream Only)
  - Upstream-Downstream Buttress Modification
- CONCLUSIONS

Site Seismicity

OBE

Probabilistic:
144-year ARP

M 8.0 @ 120 km

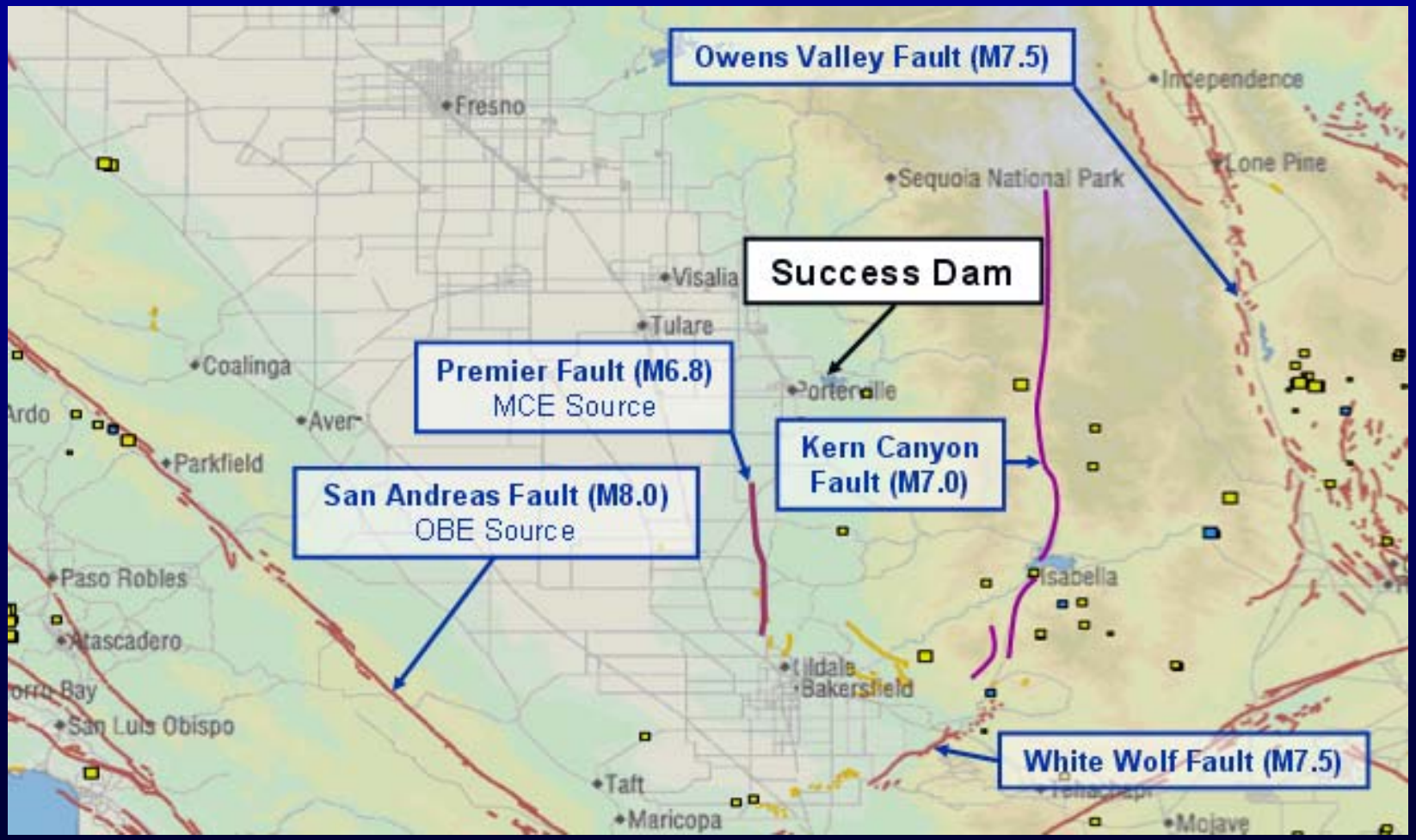
PGA = 0.10g

MCE

Deterministic

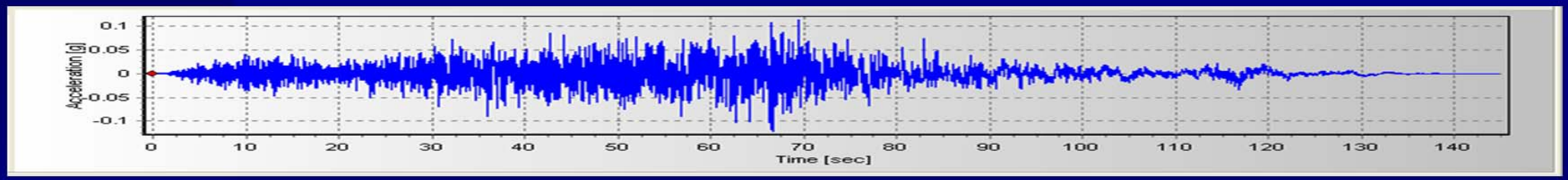
M 6.8 @ 21 km

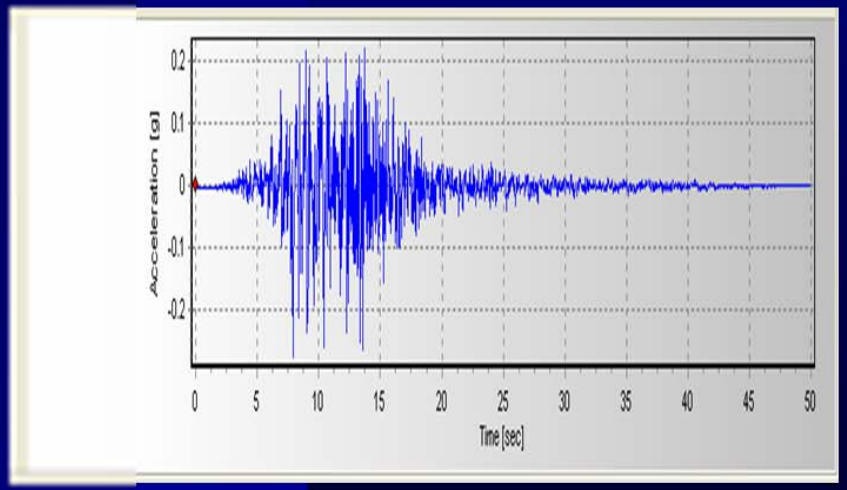
PGA = 0.28g



SUCCESS DAM
Deformation Analysis – Design Earthquakes

OBE: 20 time histories (5 events with 2 components and 2 polarities each)
Example: OBE #8 (2002, Denali, Alaska, TAP PS #11): a_{max} = 0.12g, duration 145 sec.





MCE: 20 time histories (5 events x 2 x 2)
Example: MCE #1 (1989, Loma Prieta, Santa Teresa Hill):
a_{max} = 0.28g, duration 50 sec.

All time histories were:

- Scaled to target response spectrum: - PGA
  - 0.1 to 1.0 sec.
- Deconvolved

Method of Analysis

FLAC Version 5.0

Fast **L**agrangian **A**nalysis of **C**ontinua

- **2-D Finite Difference Program with Dynamic Option**
- **Advantages with respect to other available codes:**
  - Commercially available
  - USACE experience (8 Districts)
  - Programming language that enables the user to define new variables and functions, including the option to use user-defined constitutive models other than those included with FLAC

FLAC Constitutive Models

- **Rock:** elastic model (built in FLAC)
- **All non-liquefiable materials and all materials in post-liquefaction stage with residual strength:**
  Mohr-Coulomb model (built in FLAC)
- **Liquefiable materials:**
  - Corps does not use Finn/Byrne model built in FLAC
  - User-written constitutive models: - URS
    - UBCSAND
    - UBCSAND 904aR (C++)

Empirical Liquefaction Assessment

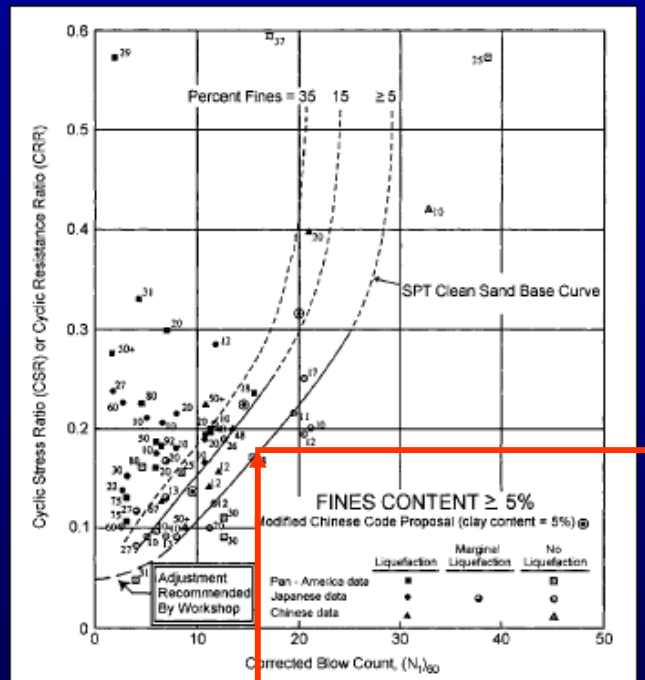
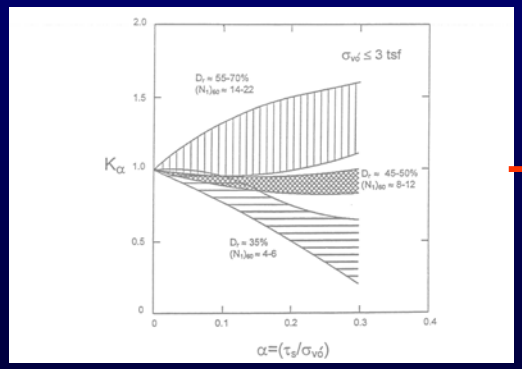


FIG. 2. SPT Clean-Sand Base Curve for Magnitude 7.5 Earthquakes with Data from Liquefaction Case Histories (Modified from Seed et al. 1985)

$$CSR = 0.65\,(a_{max} / g)\,(\sigma_{v0} / \sigma'_{v0})\,r_d$$

$$FS = (CRR_{7.5} / CSR)\ MSF\ K_\alpha\ K_\sigma$$

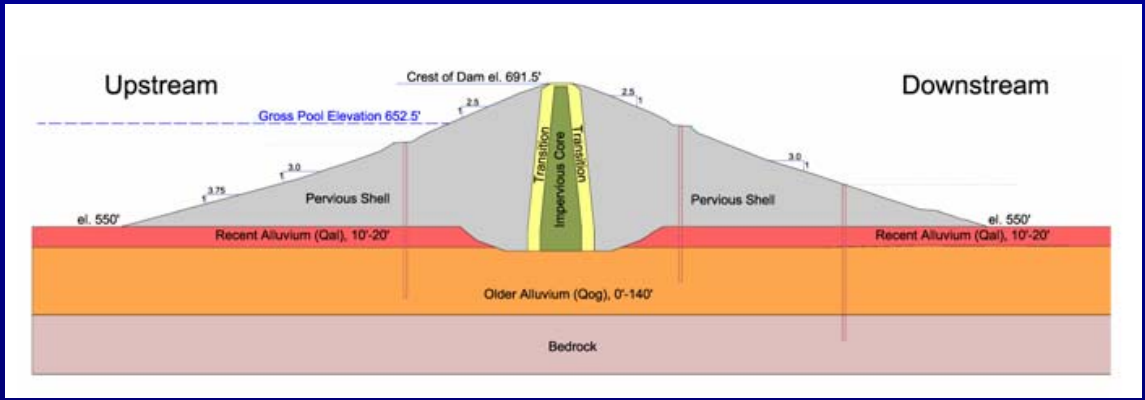
$$MSF = (7.5 / M_w)^{2.56}$$



$$K_\sigma = (\sigma'_{v0} / P_a)^{(f-1)}$$

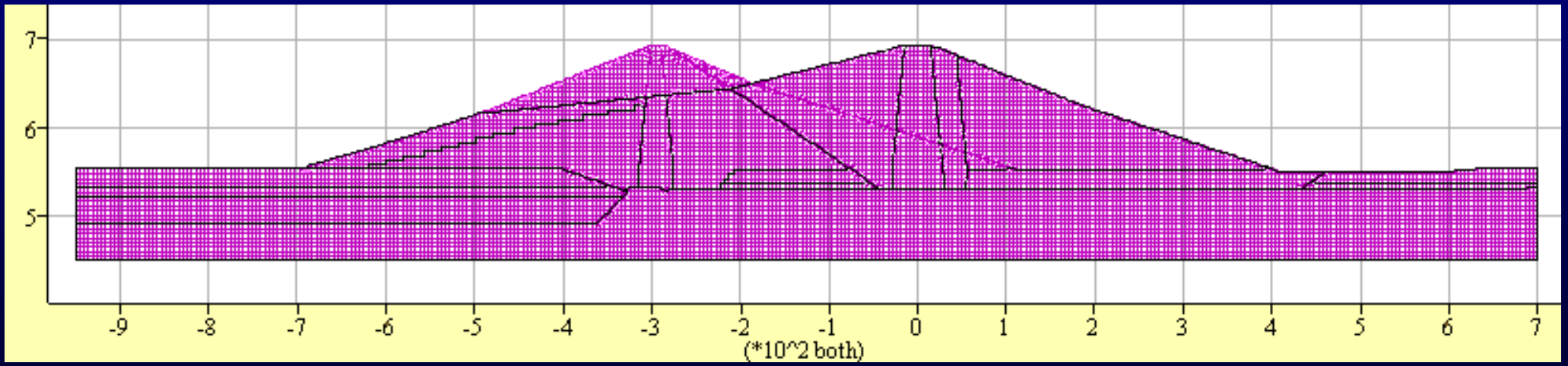
Equivalent $(N_1)_{60}$ Corrected for fines

Existing Dam Evaluation - Mesh

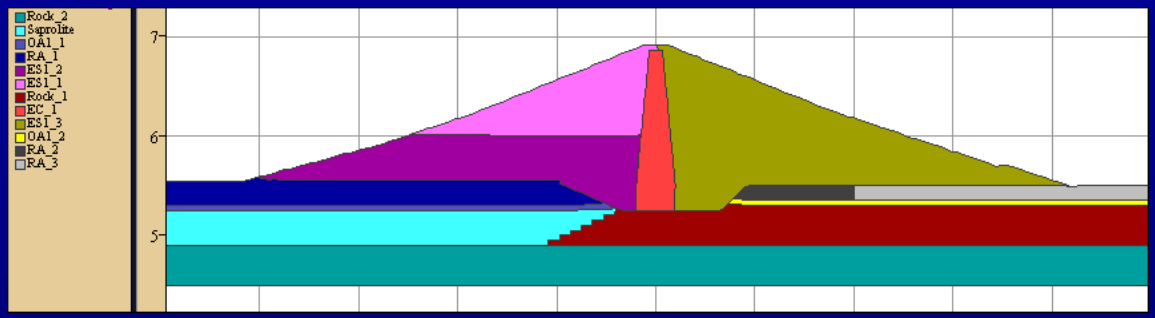


FLAC Mesh at Station 28+50:

- Should accommodate any future additions (berms, buttress)
- 6-8000 quadrilateral zones

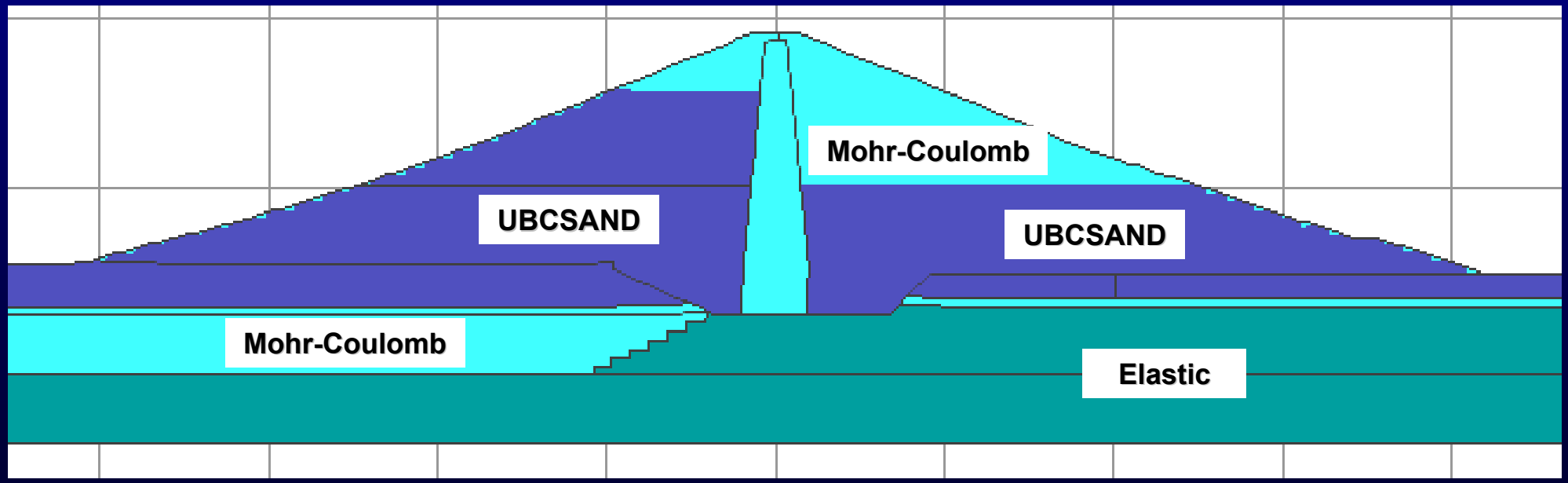


Existing Dam Evaluation - Models



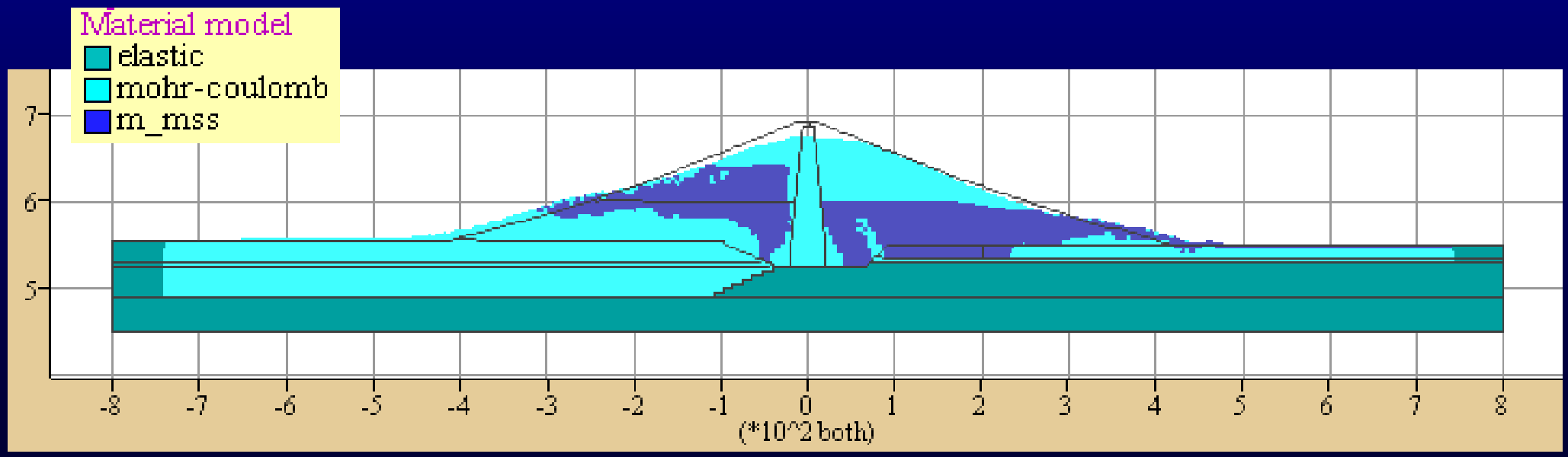
Constitutive models:

- elastic
- Mohr-Coulomb
- UBCSAND 904aR (C++)



Post-Liquefaction Stability

- Switch UBCSAND model to Mohr-Coulomb model in all liquefied zones ($r_u \geq 0.7$ at any time during dynamic loading)
- Reduce strength to post-earthquake condition (residual strength), S_r
- Drop stiffness to post-liquefaction value: $G_{max} = 10\ S_r$
  $B = 100\ G_{max}$

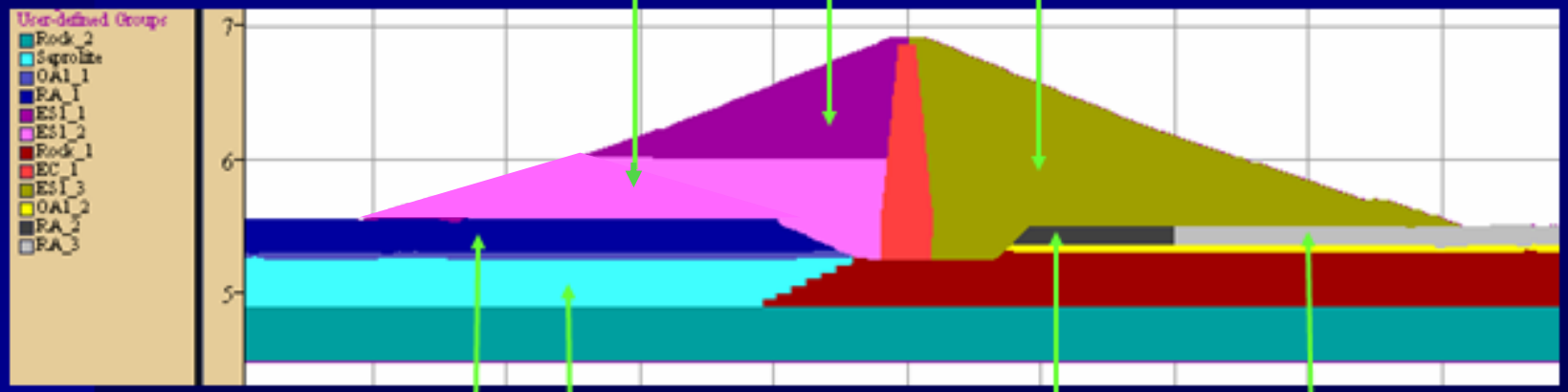


Summary of $N_{1,60}$ Design Values

Existing Dam Model - Station 28+50

Liquefiable shell – $N_{1,60}$ = **18**

Liquefiable shell – $N_{1,60}$ = **26**



Liquefiable alluvium – $N_{1,60}$ = **10**

Liquefiable alluvium – $N_{1,60}$ = **21**

Liquefiable alluvium – $N_{1,60}$ = **10**

Saprolite – low strength and stiffness parameters

RESIDUAL STRENGTH of Liquefied Materials

Idriss and Boulanger, 2007

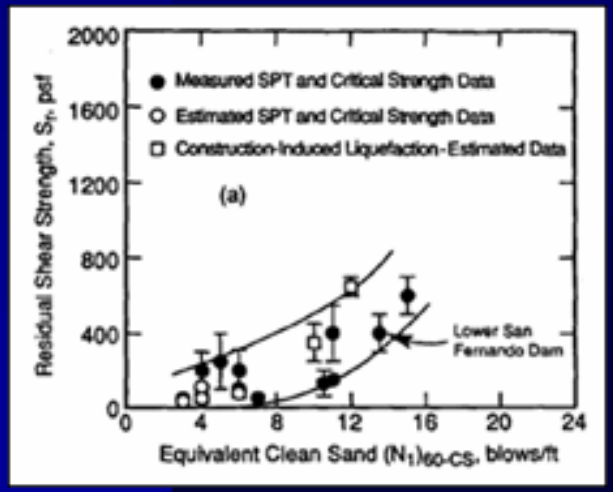
$$S_r = \exp\left[(N_1)_{60\text{-}cs} / 5.1 - ((N_1)_{60\text{-}cs} / 16.5)^2 + ((N_1)_{60\text{-}cs} / 21.4)^3 + 0.8\right] / 0.0479 \quad \text{(psf)}$$

based on

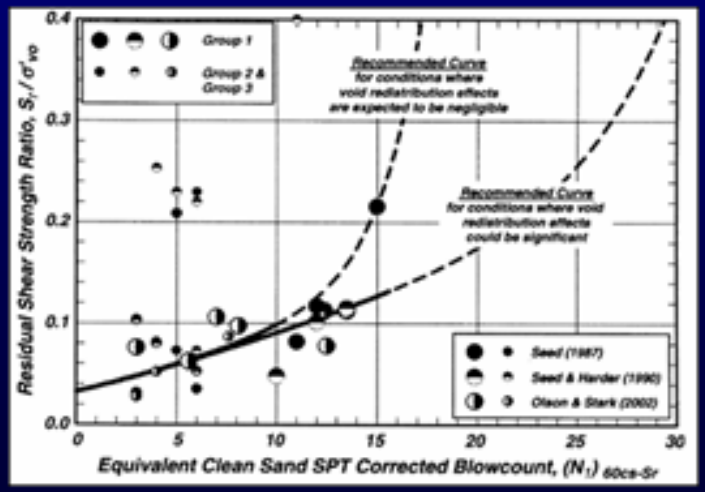
$$S_r / \sigma'_{v0} = \exp\left((N_1)_{60\text{-}cs} / 16 + [((N_1)_{60\text{-}cs} - 16) / 21.2]^3 - 3.0\right) \leq \tan \Phi'$$

based on

Seed and Harder, 1990



Olson and Stark, 2002



Construction and Reservoir Filling Simulation

1) Excavate core trench for existing dam.

2) Construct existing dam

3) Perform seepage analysis for gross pool

4) Perform seepage analysis for conservation pool

5) Excavate backcut

6) Construct modified embankment dam

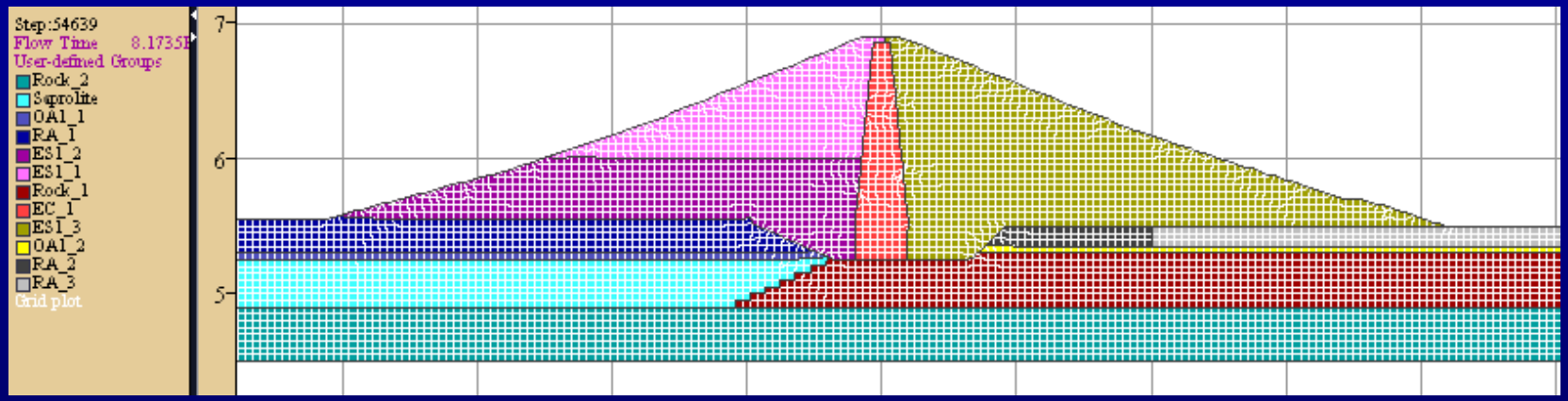
7) Remove crest of existing dam

8) Perform seepage analysis for gross pool.

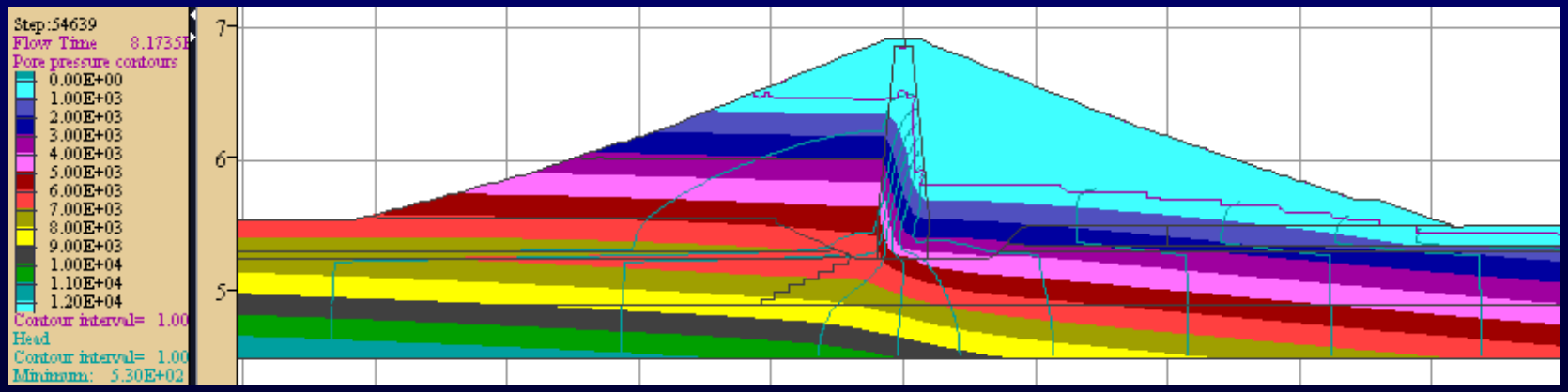
9) Perform seepage analysis for conservation pool.

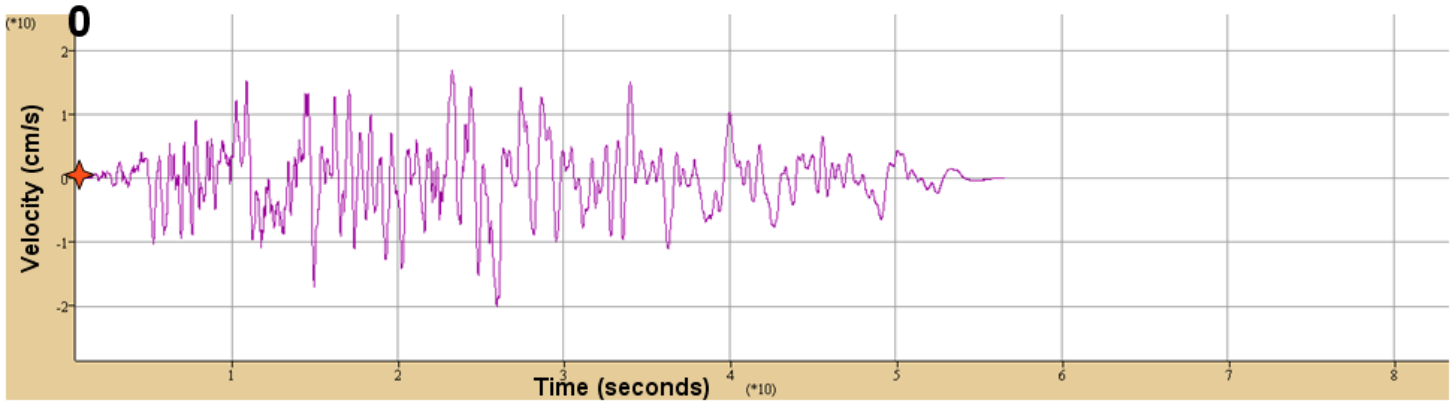
Existing Embankment Evaluation

Materials and FLAC Mesh



Steady State Seepage Condition

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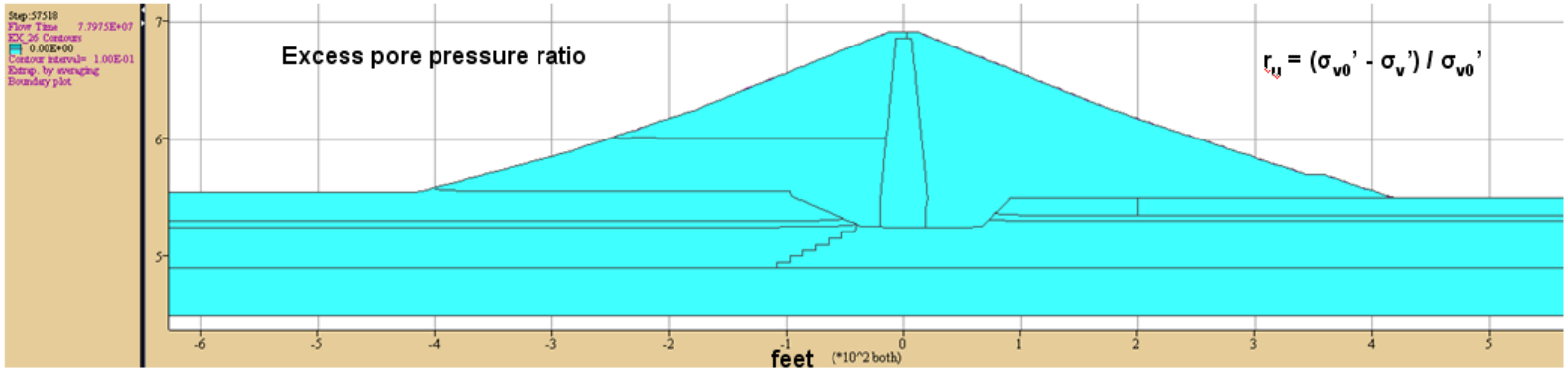
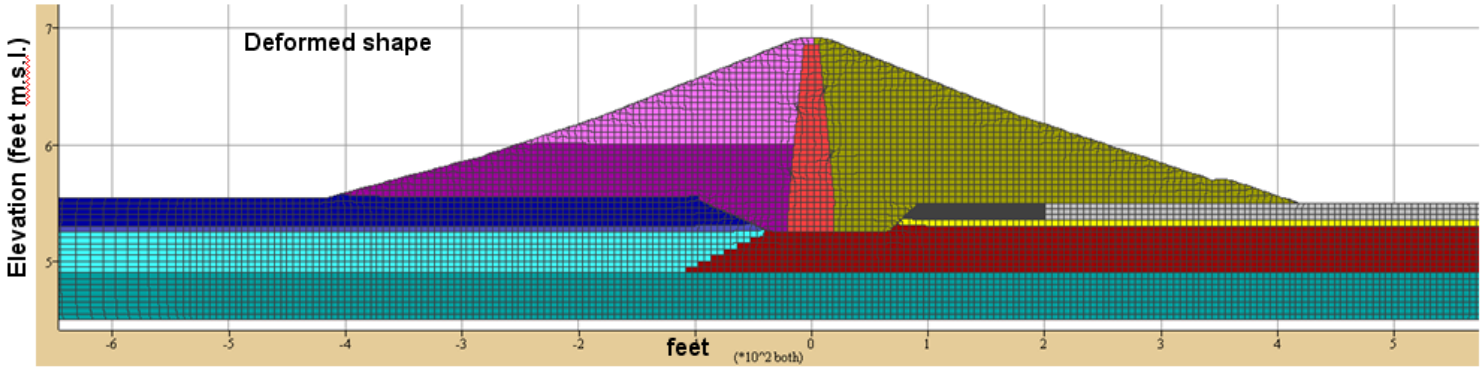
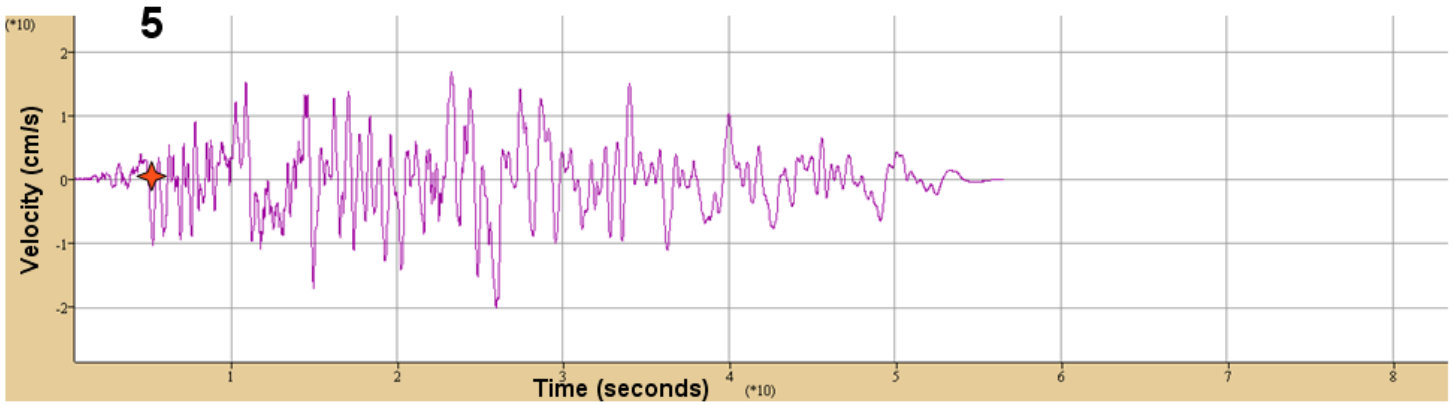
(*10)
Velocity (cm/s)
Time (seconds)
(*10)


Excess pore pressure ratio
$r_u = (\sigma_{v0}' - \sigma_v') / \sigma_{v0}'$
feet
(*10^2 both)


Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)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Velocity (cm/s)
Time (seconds)
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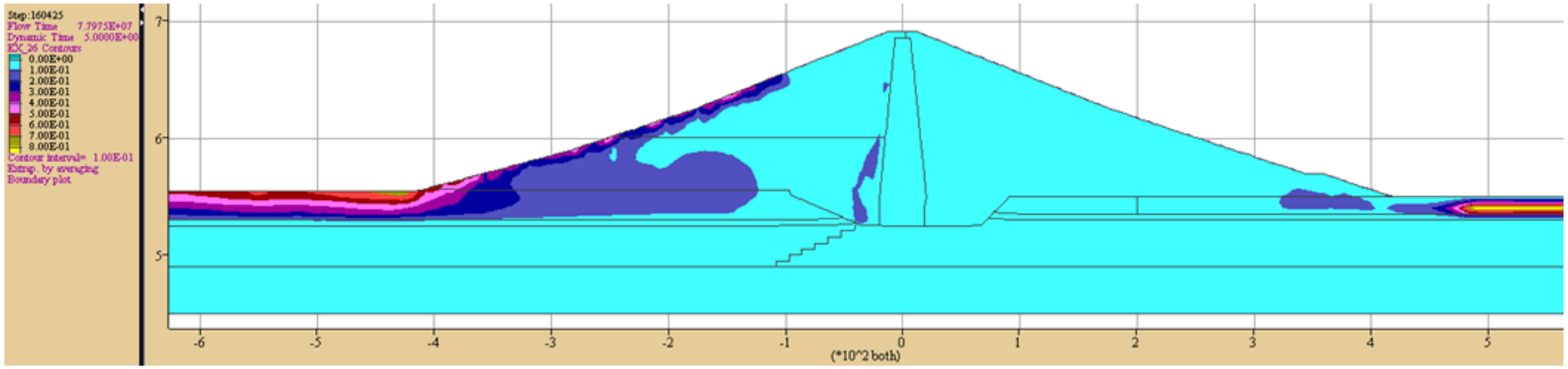
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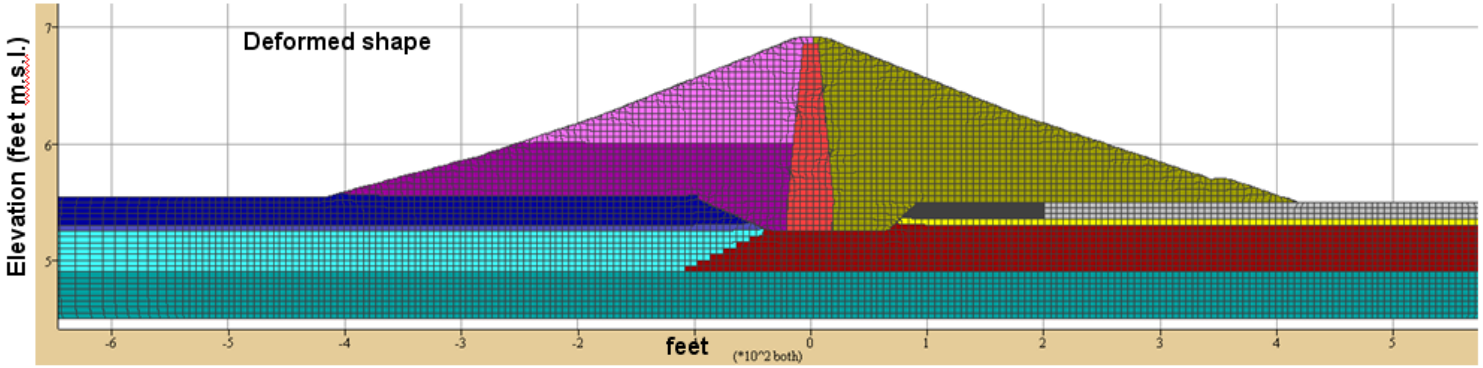
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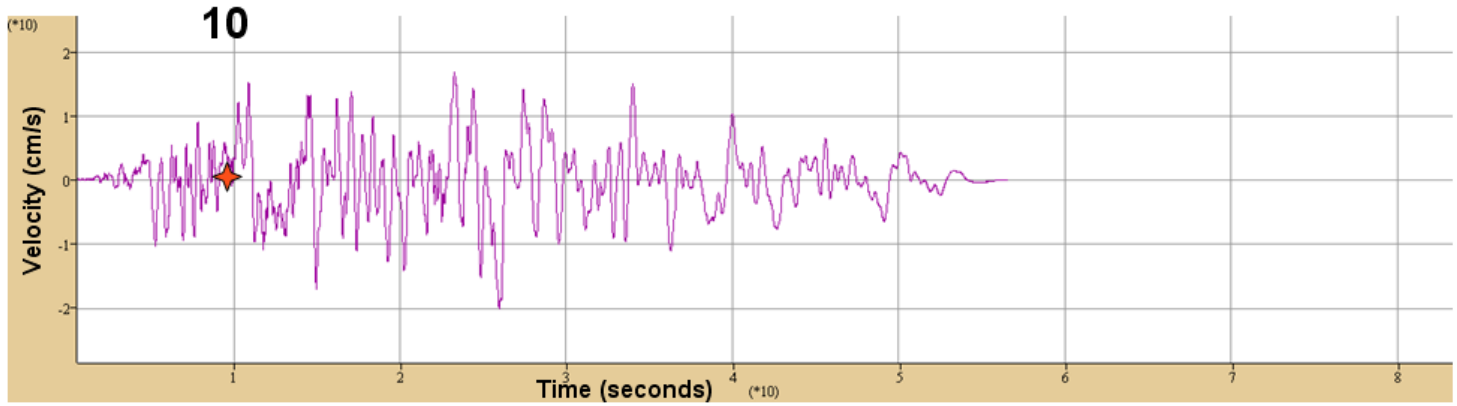
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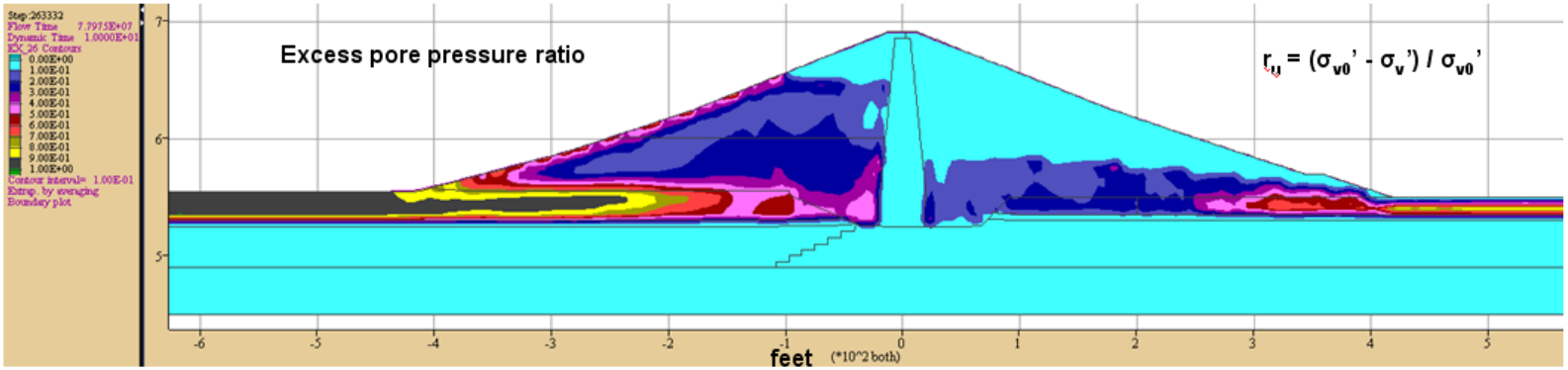
(*10)
Velocity (cm/s)
Time (seconds)
(*10)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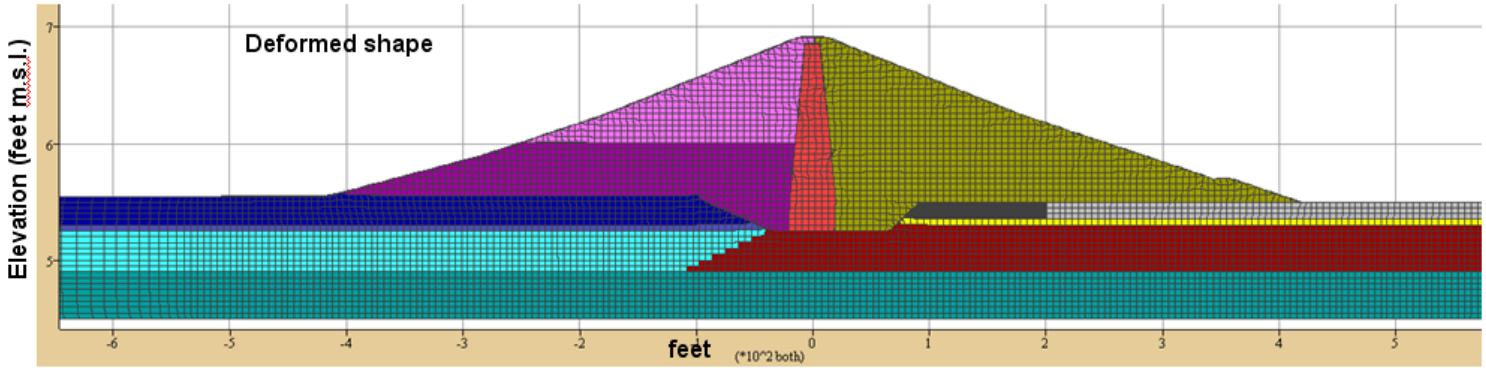
Deformed shape
Elevation (feet m.s.l.)
feet
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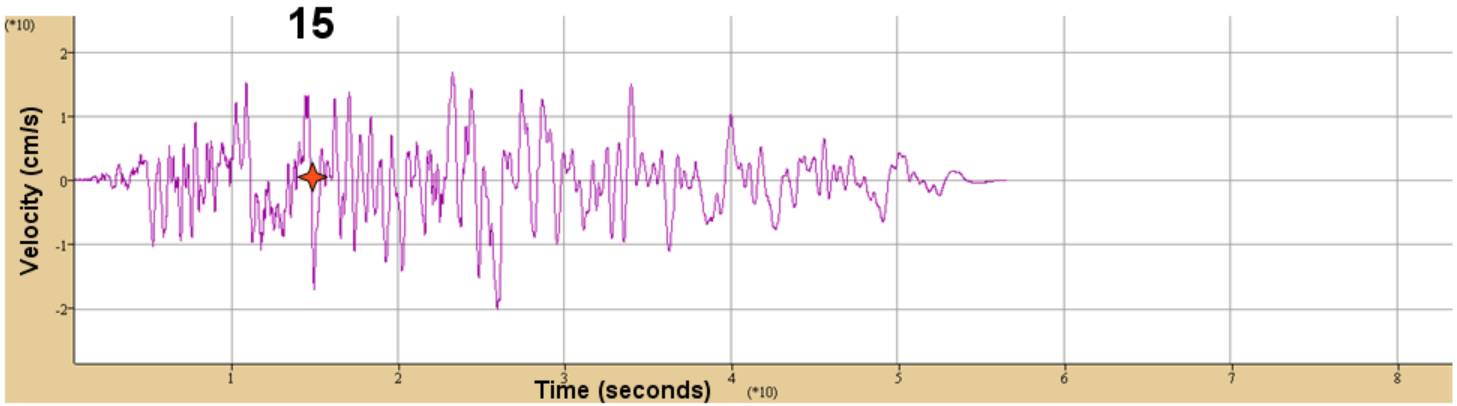
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Velocity (cm/s)
Time (seconds)
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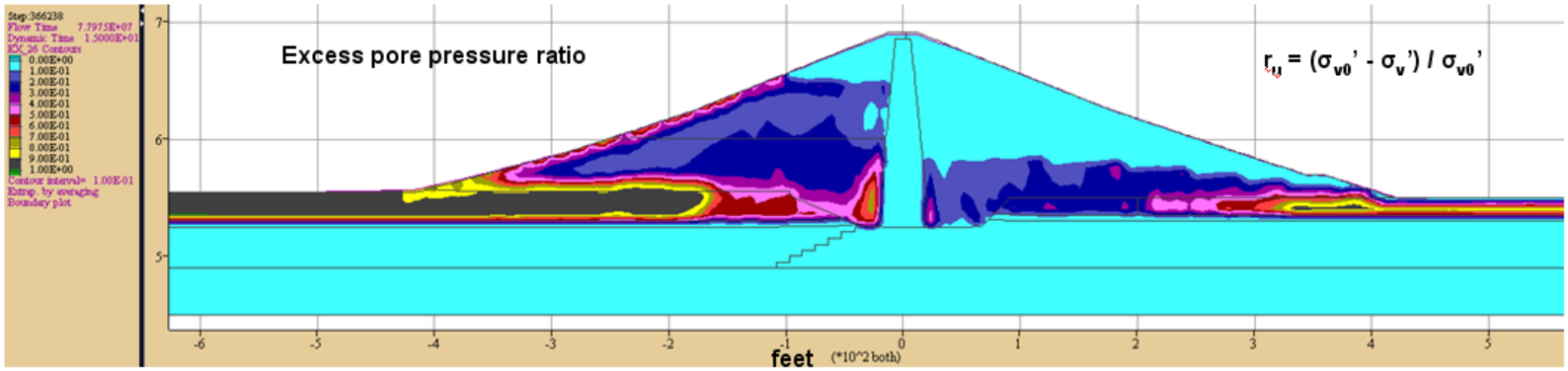
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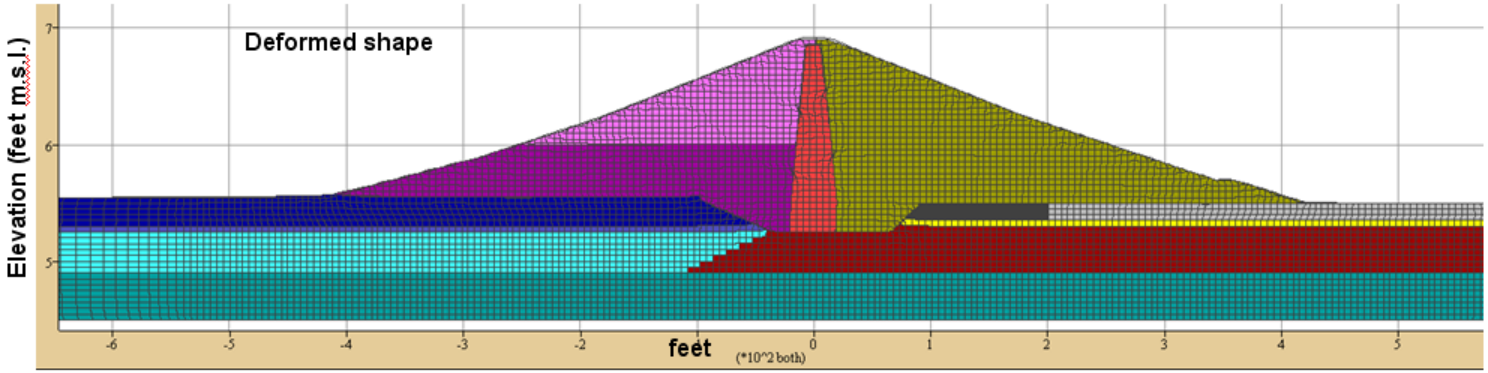
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Elevation (feet m.s.l.)
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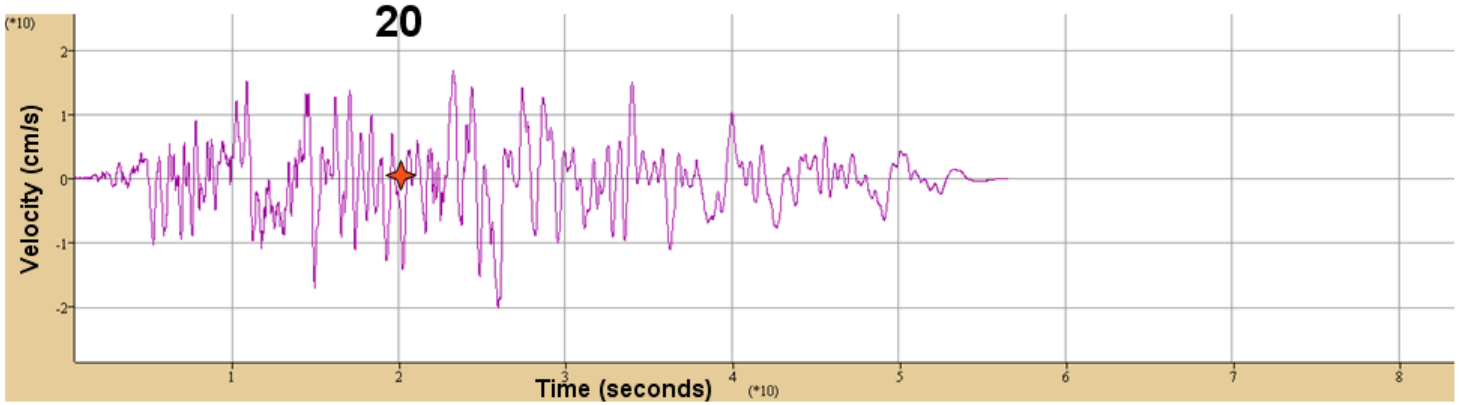
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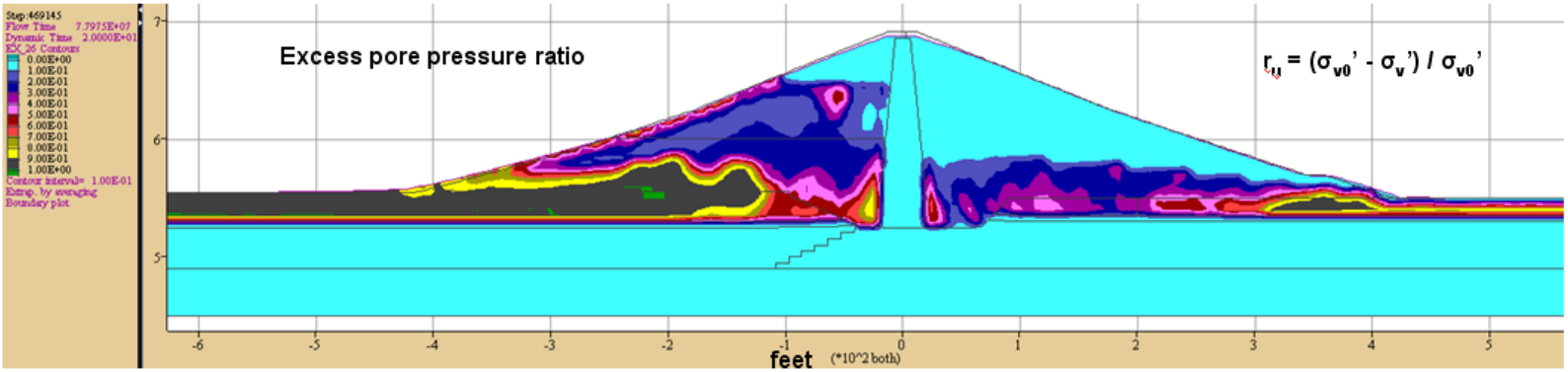
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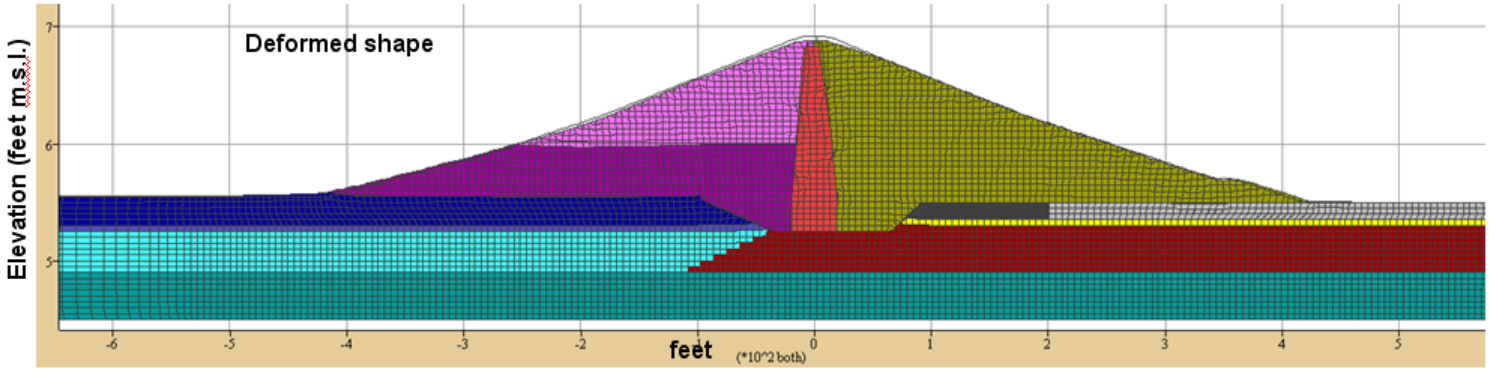
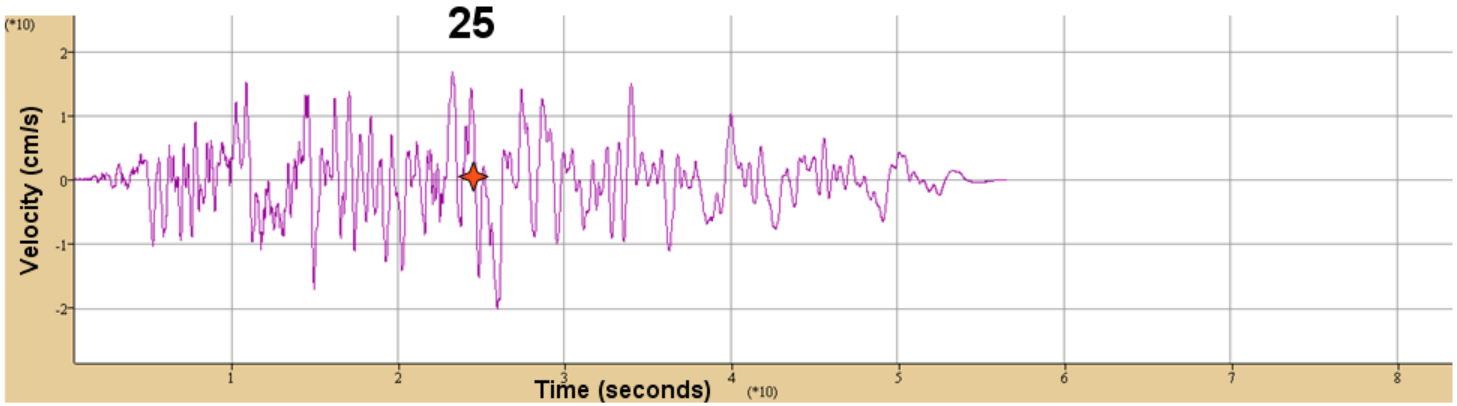

Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)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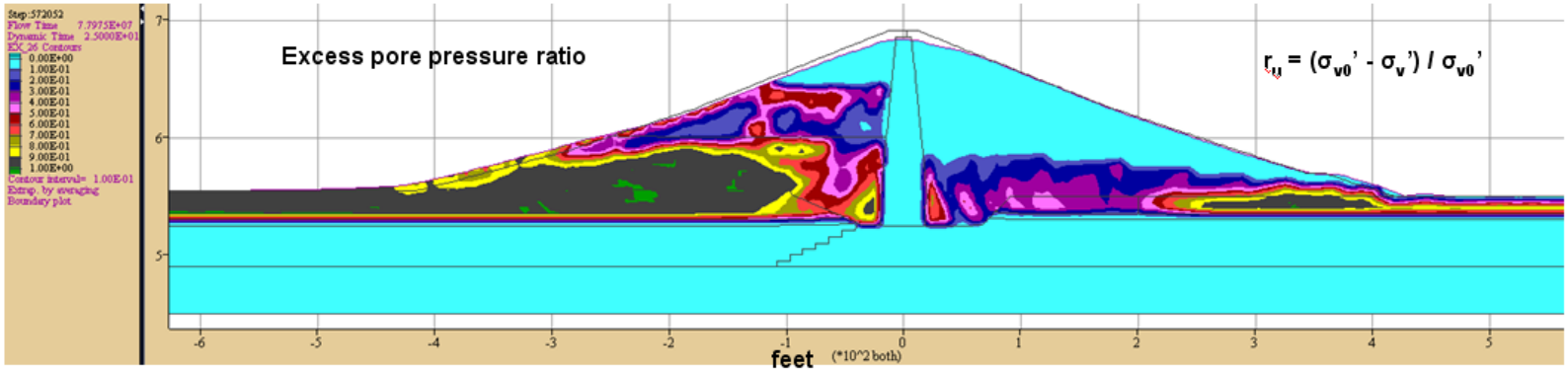
Velocity (cm/s)
Time (seconds)
(*10)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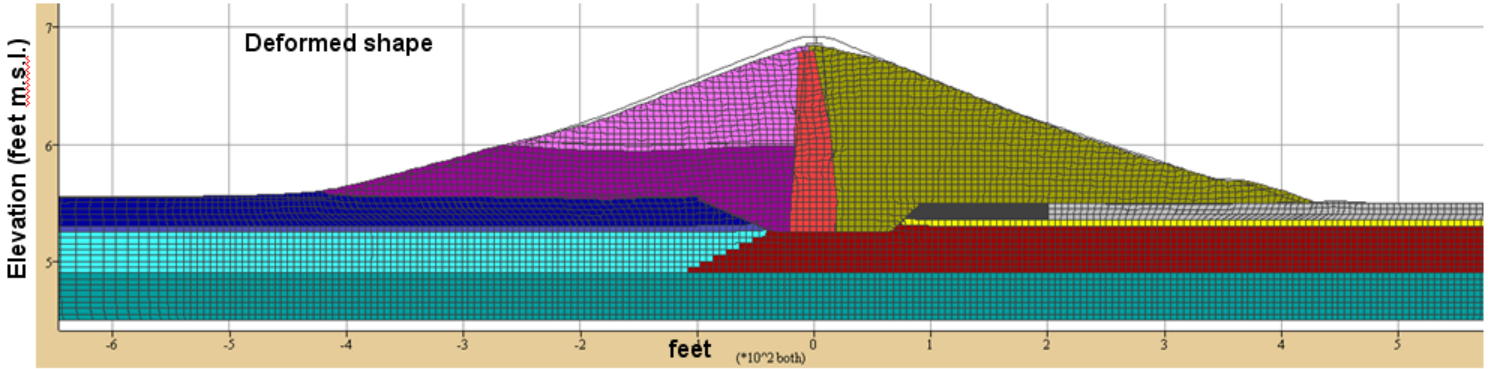
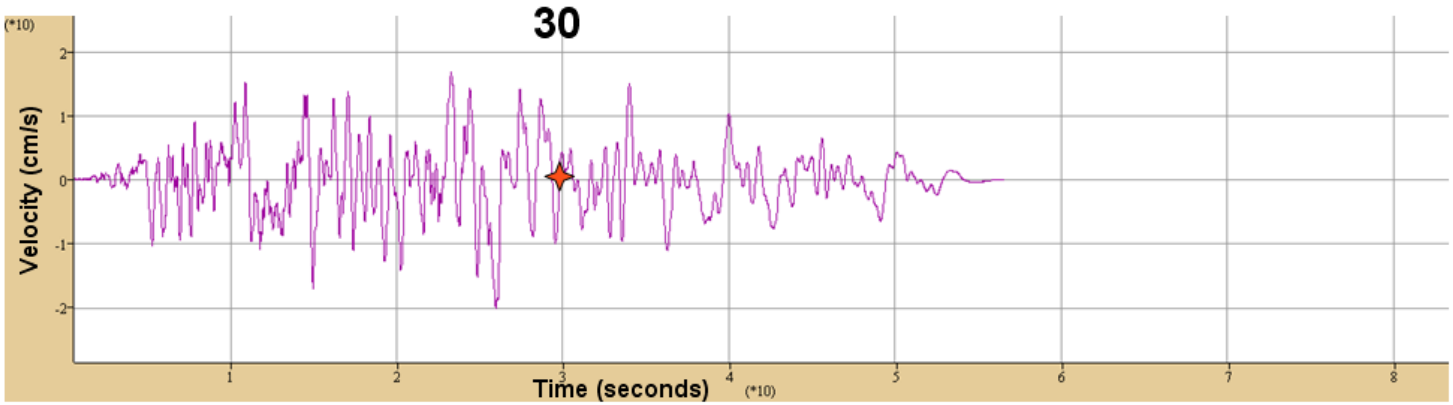

Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)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Time (seconds)
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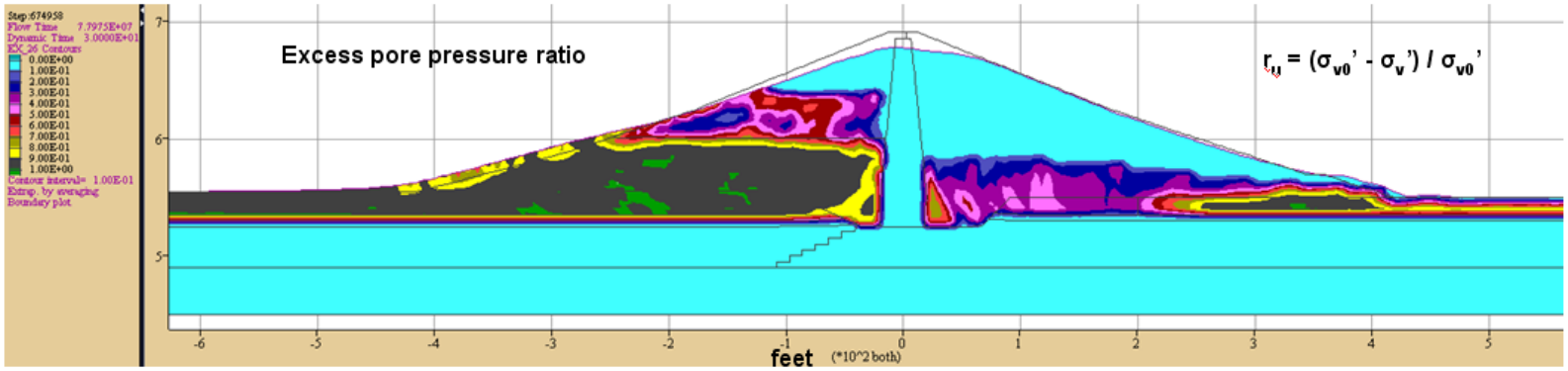
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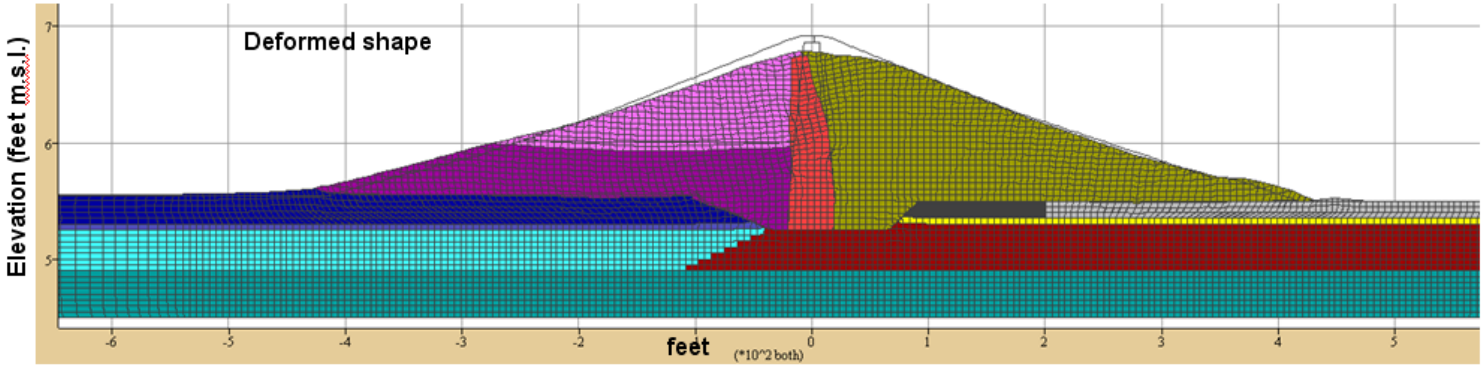
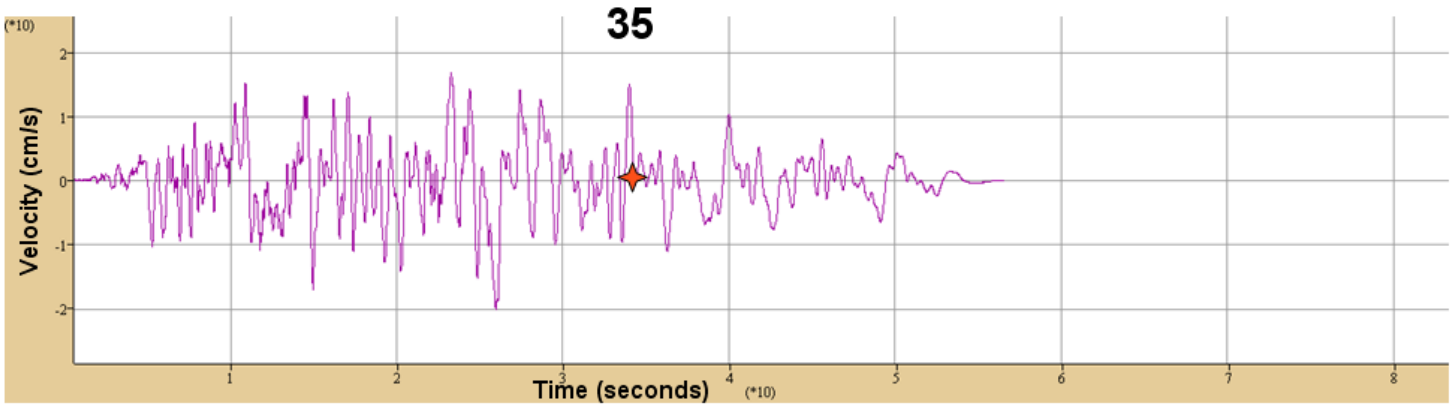
feet
(*10^2 both)


Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)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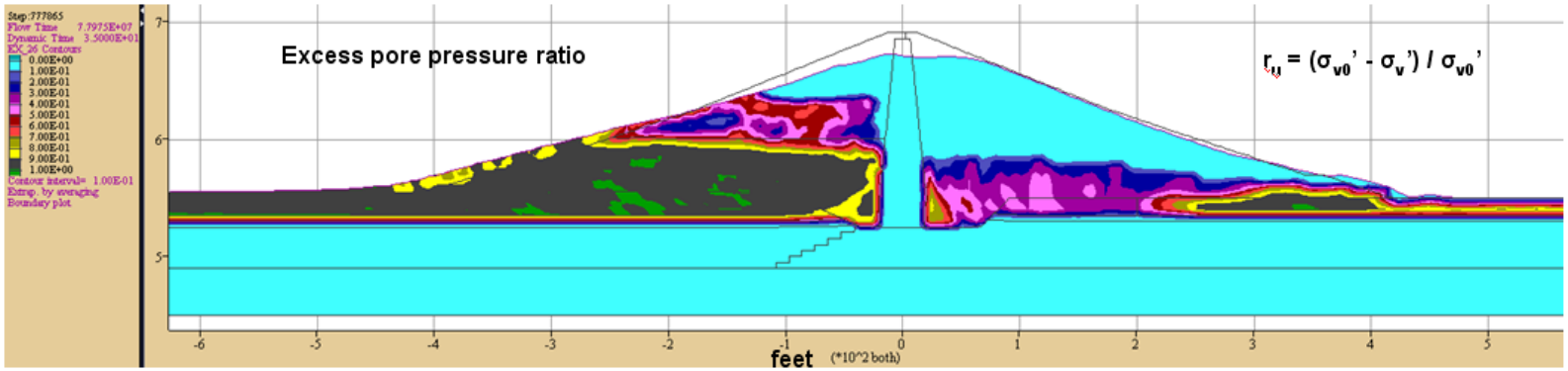
Time (seconds)
(*10)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feet
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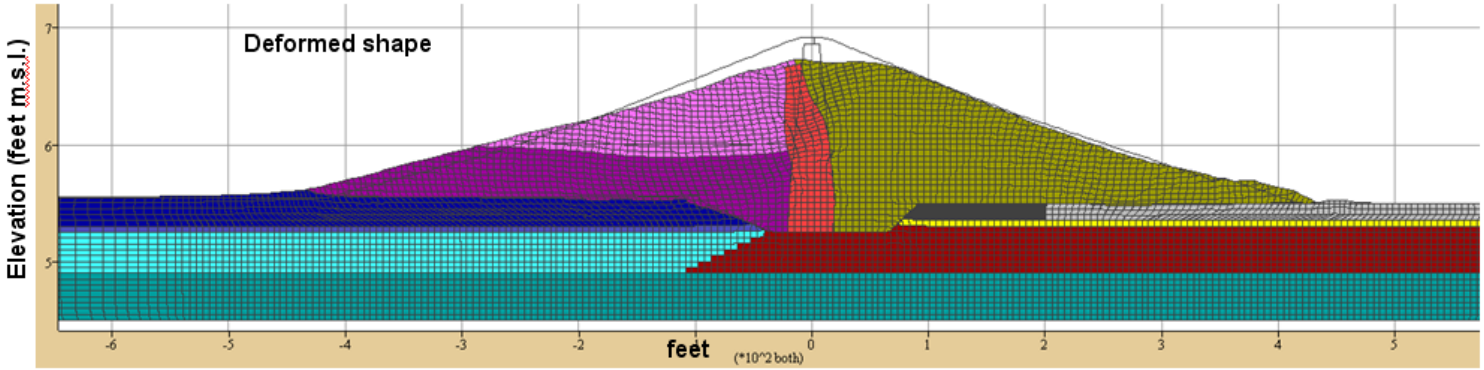
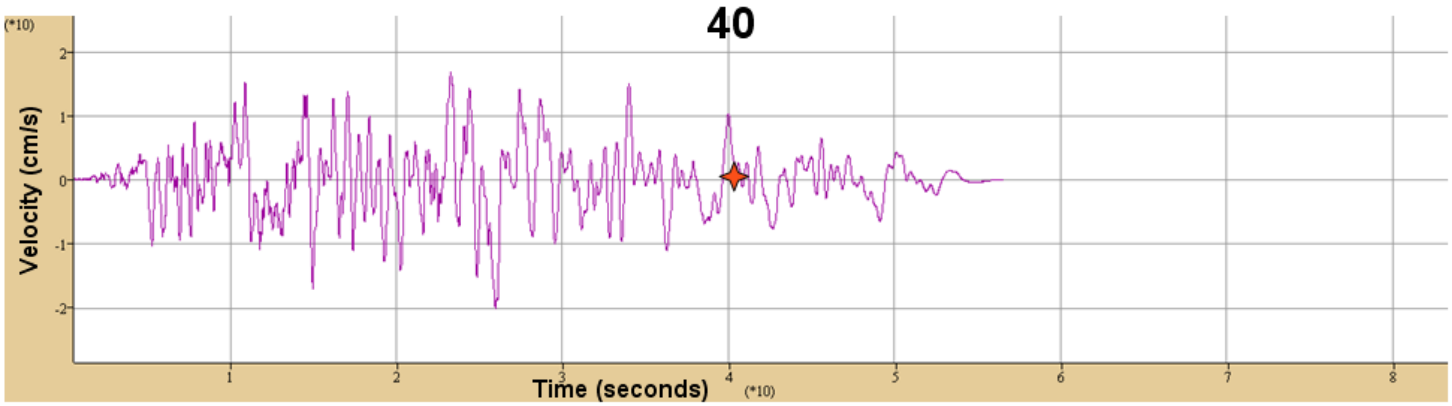

Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)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Velocity (cm/s)
Time (seconds)
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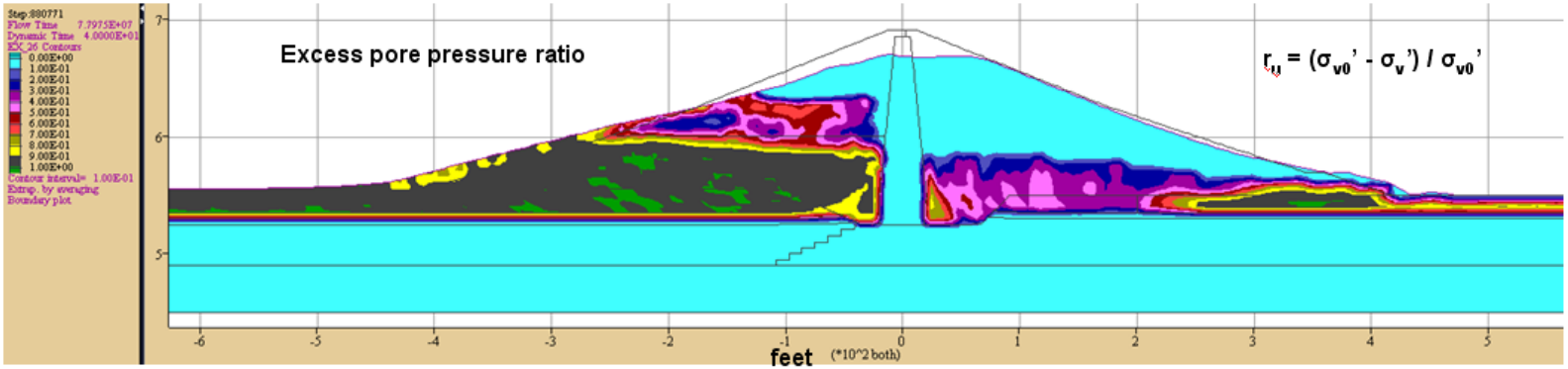
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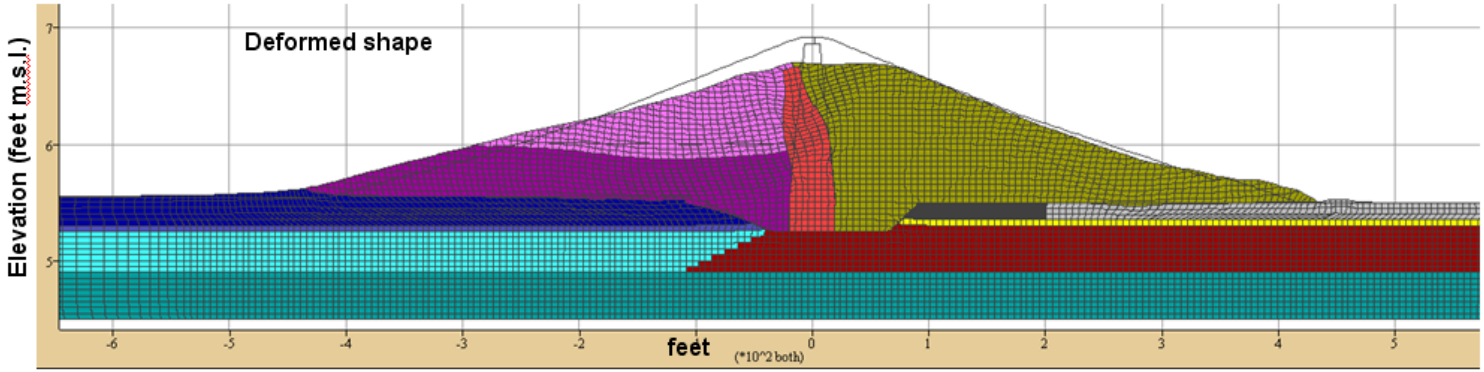
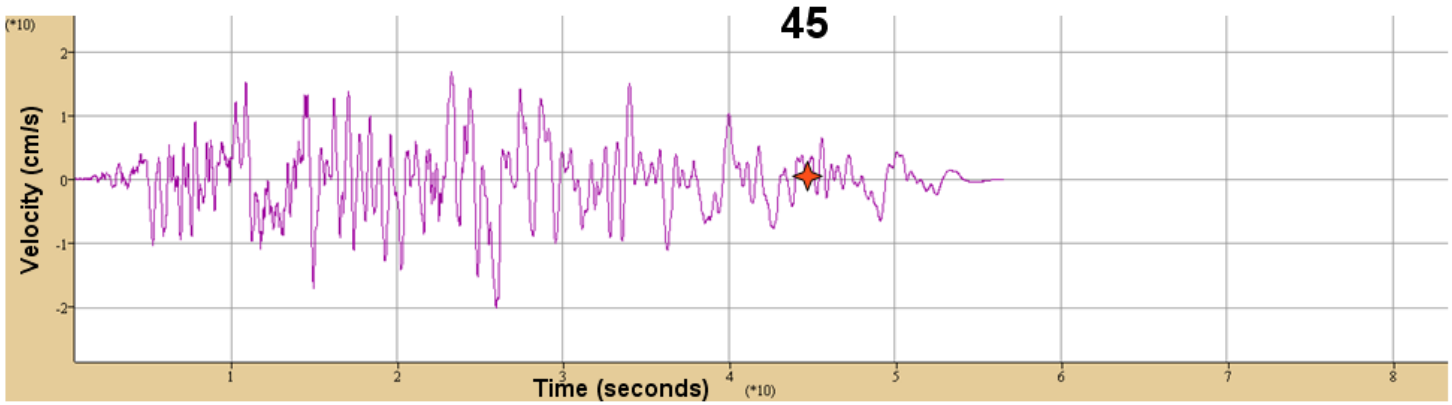
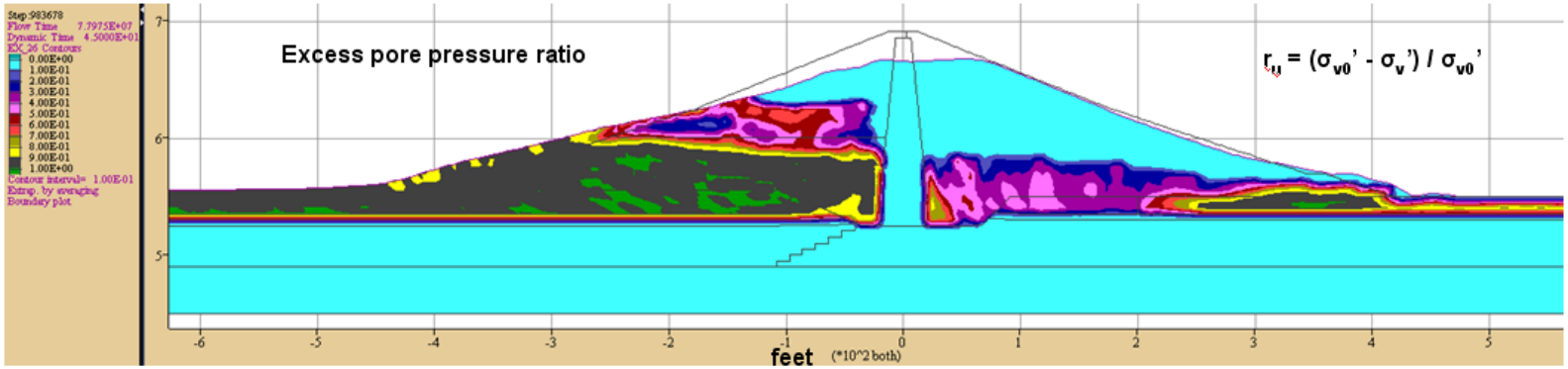
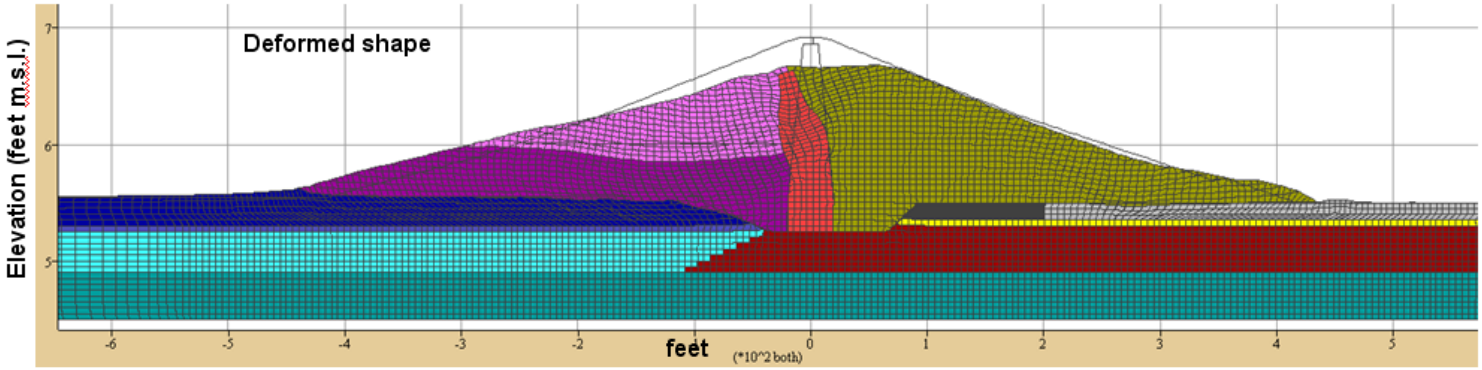
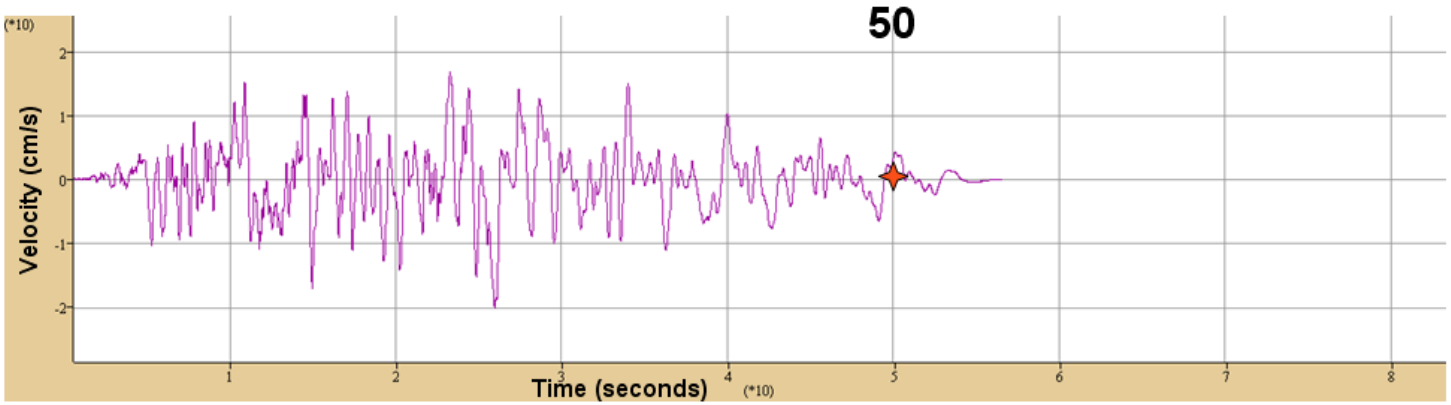

Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)

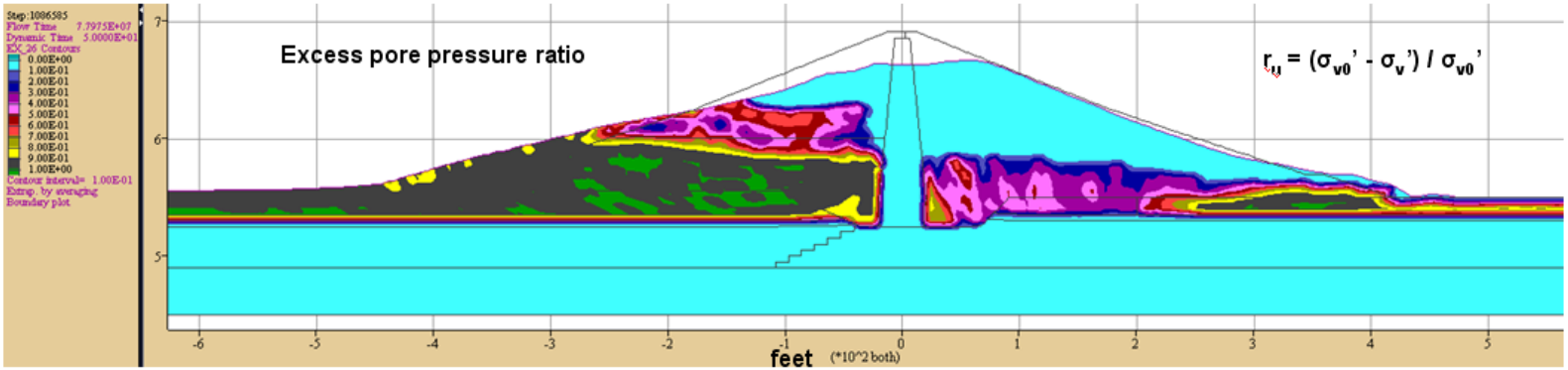
US Army Corps of Engineers
Sacramento District

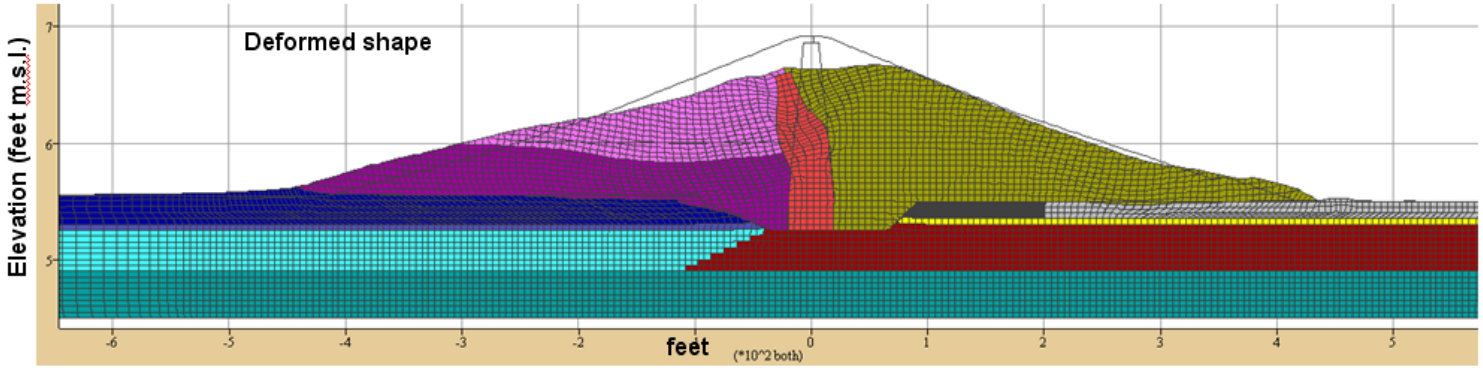




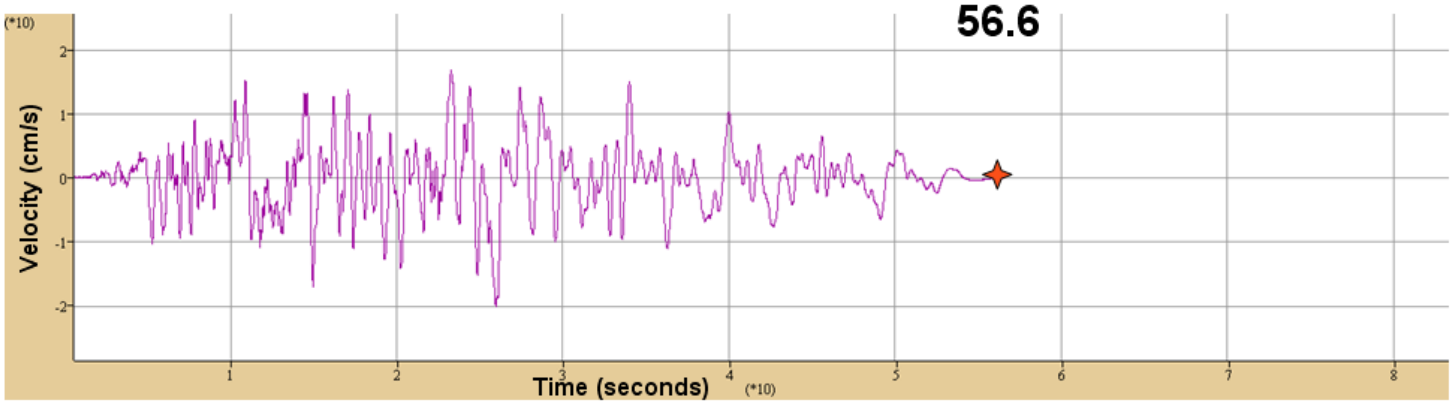


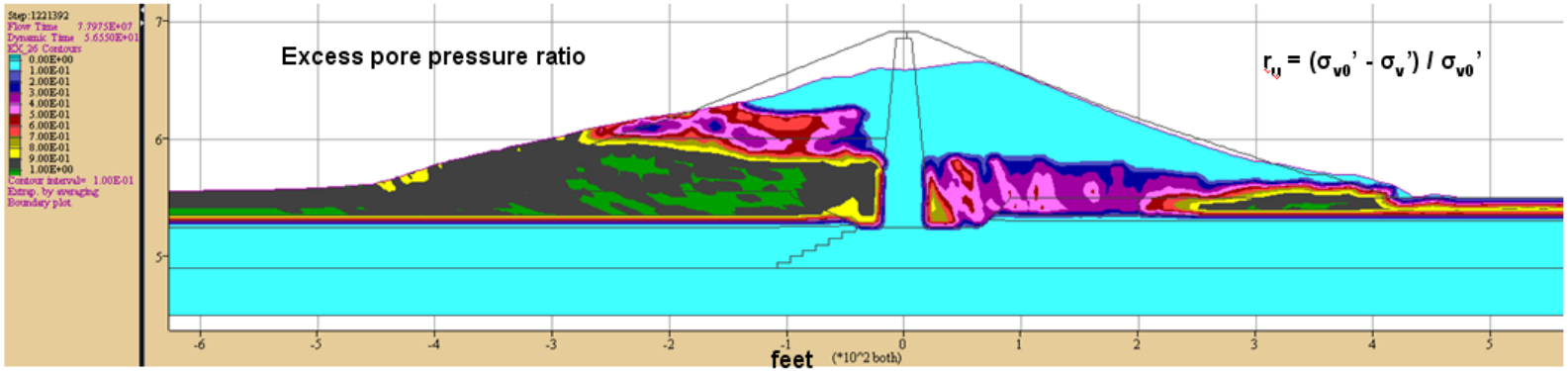

50
(*10)
Velocity (cm/s)
Time (seconds)
(*10)

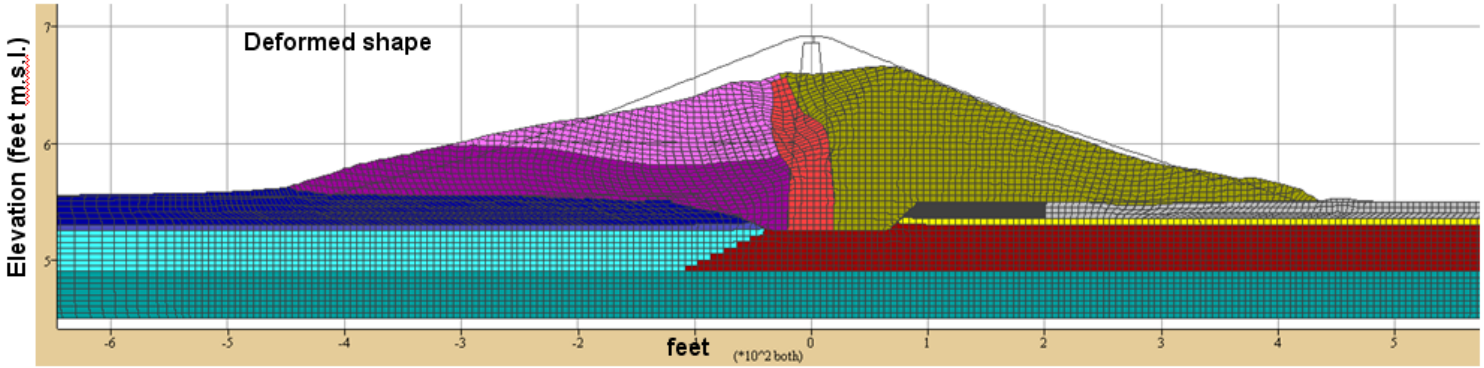

Excess pore pressure ratio
$r_u = (\sigma_{v0}' - \sigma_v') / \sigma_{v0}'$
feet
(*10^2 both)

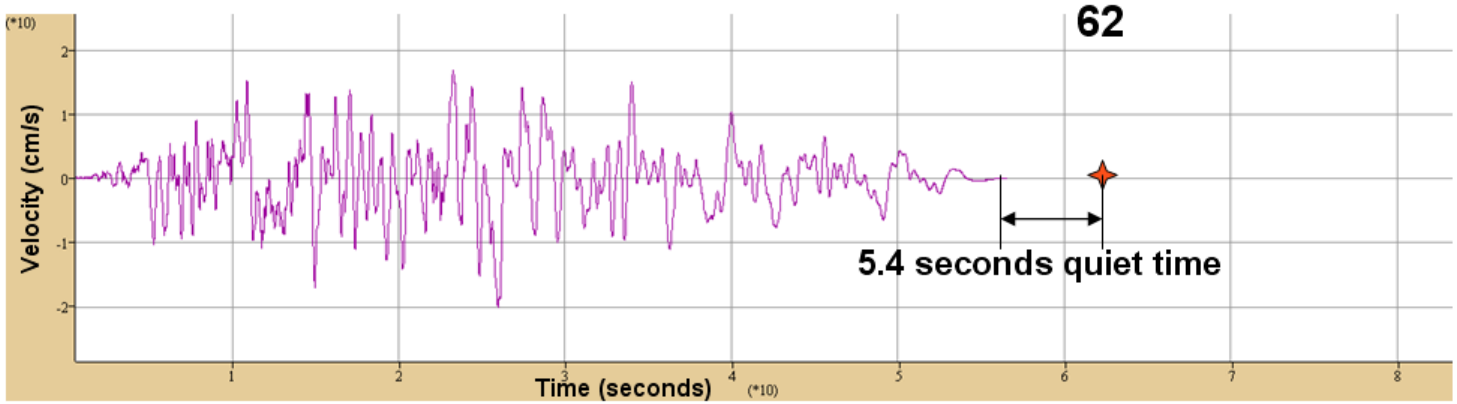

Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)

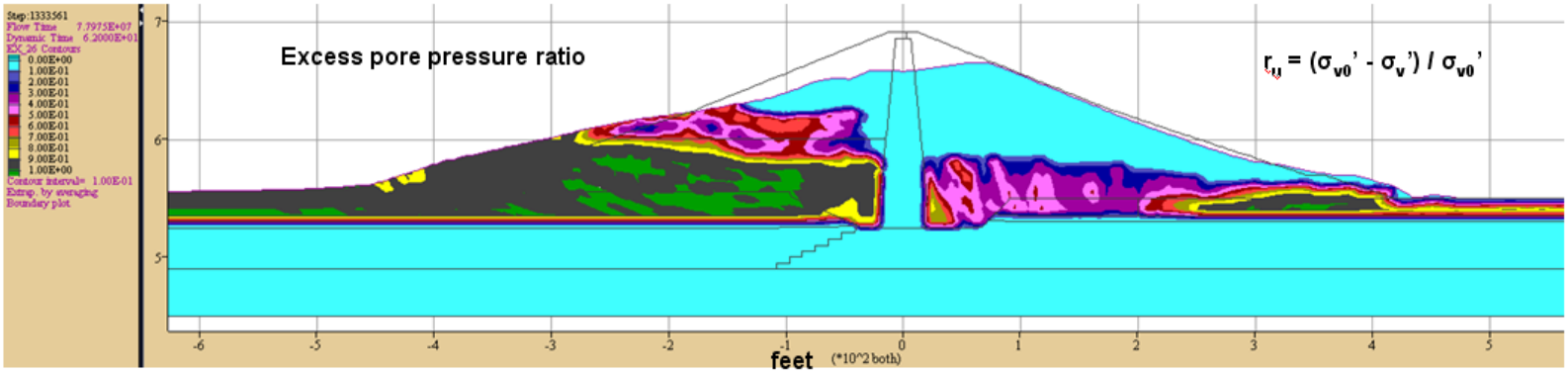
US Army Corps of Engineers
Sacramento District

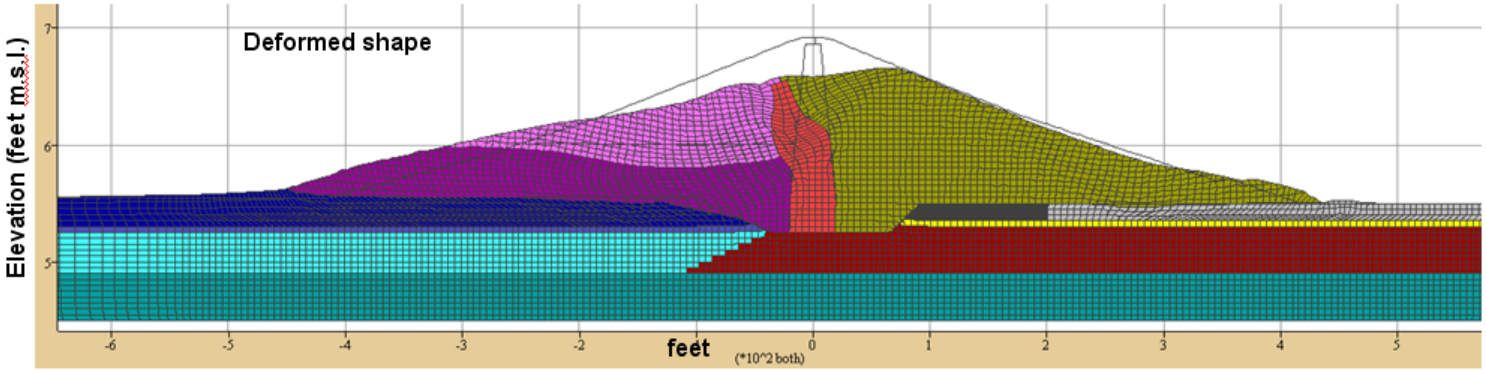


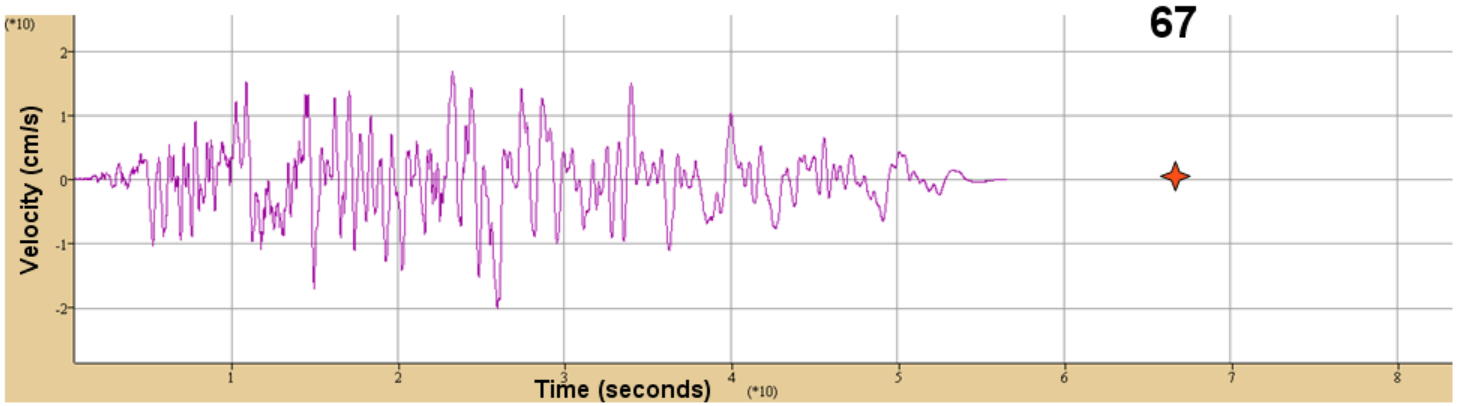


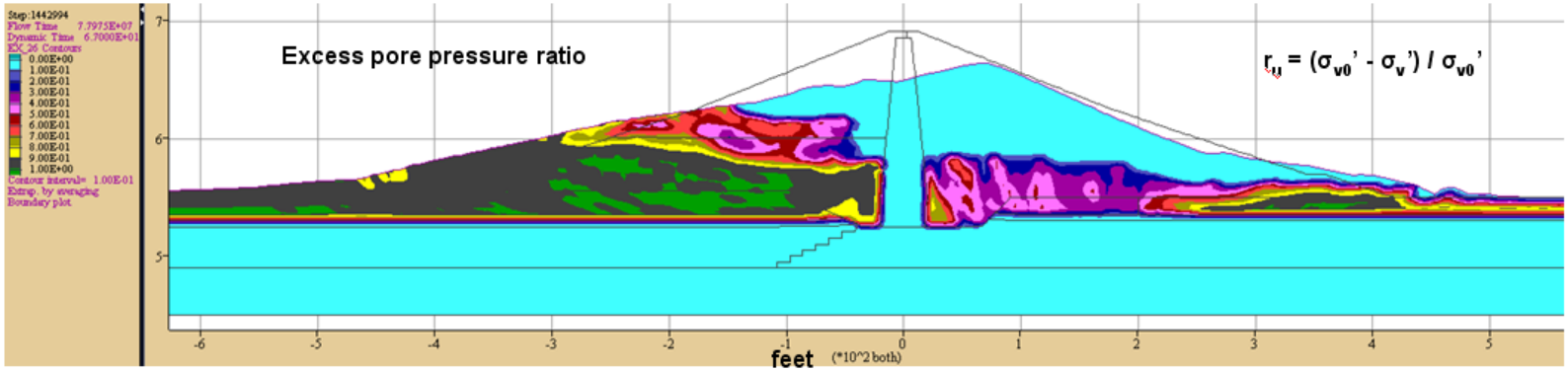


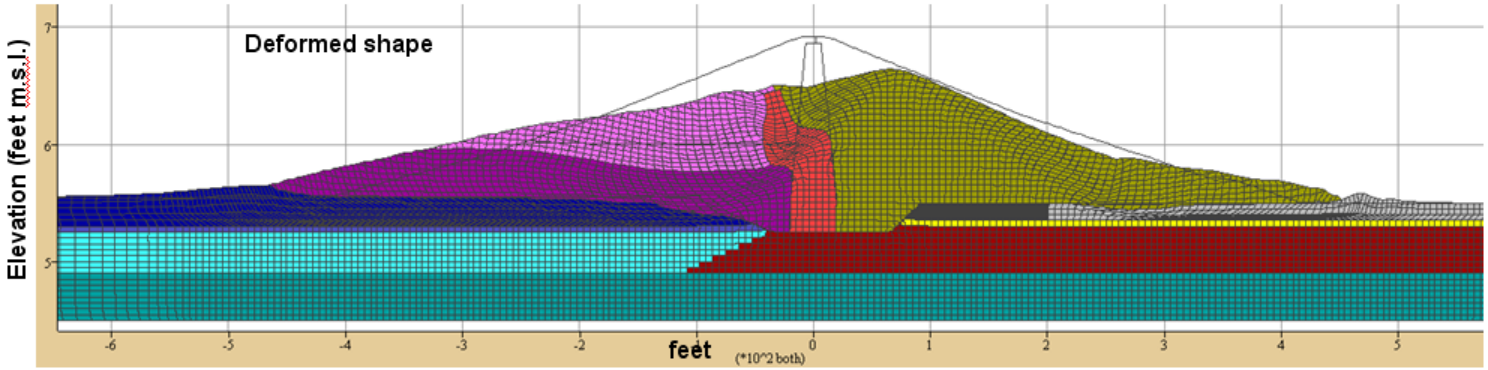

62
Velocity (cm/s)
5.4 seconds quiet time
Time (seconds)

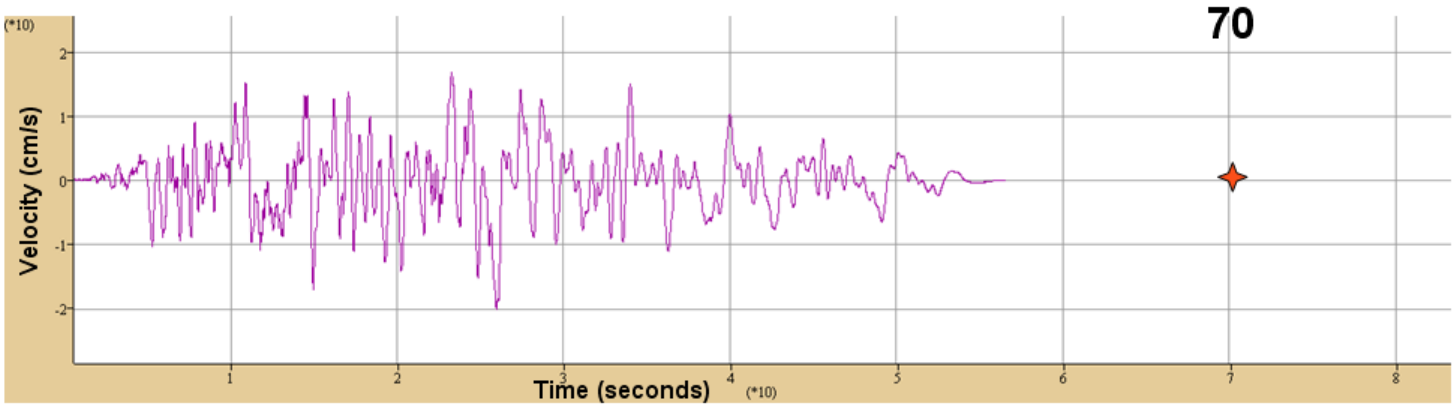

Excess pore pressure ratio
$r_u = (\sigma_{v0}' - \sigma_v') / \sigma_{v0}'$
feet

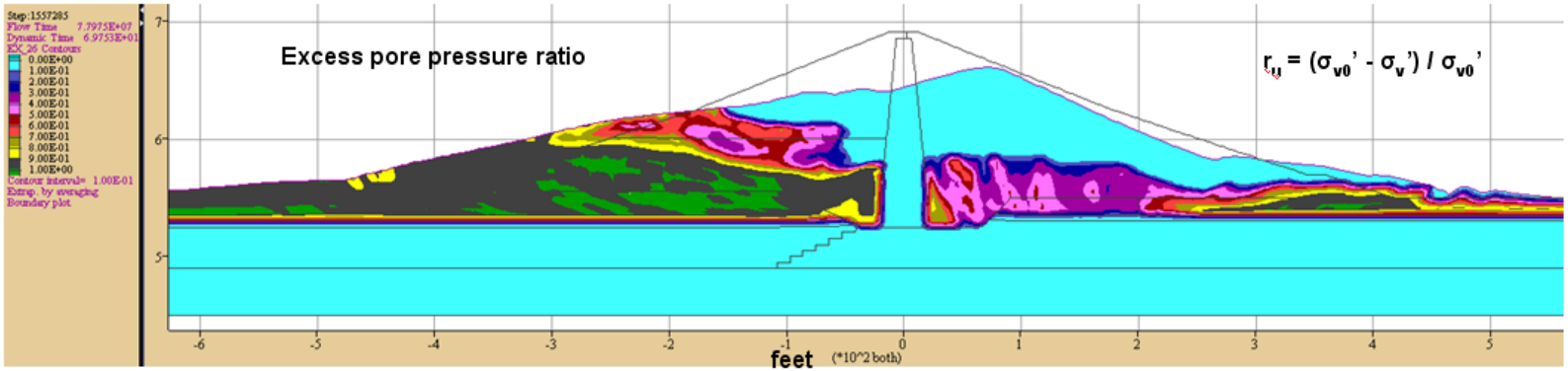

Deformed shape
Elevation (feet m.s.l.)
feet

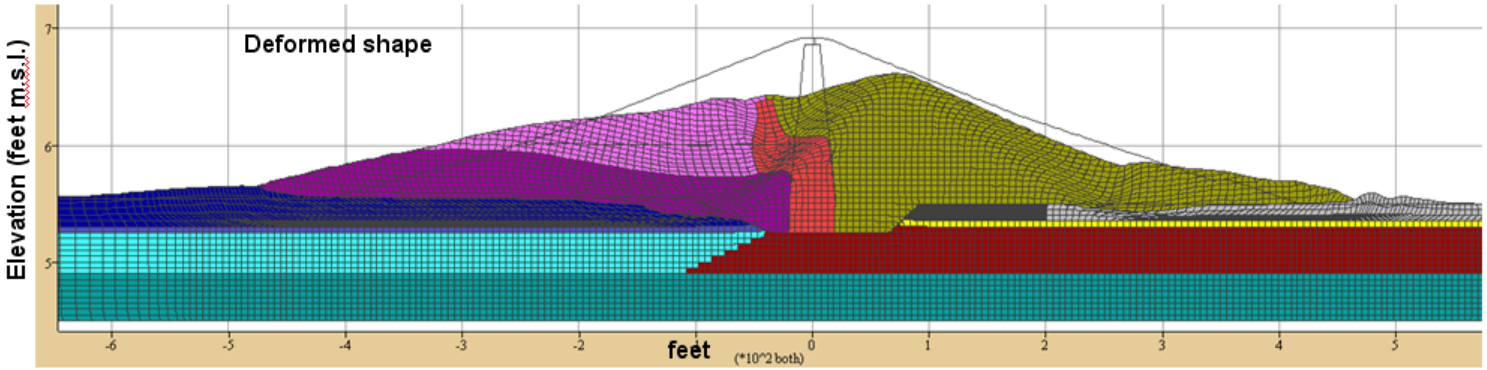

67
(*10)
Velocity (cm/s)
Time (seconds)
(*10)

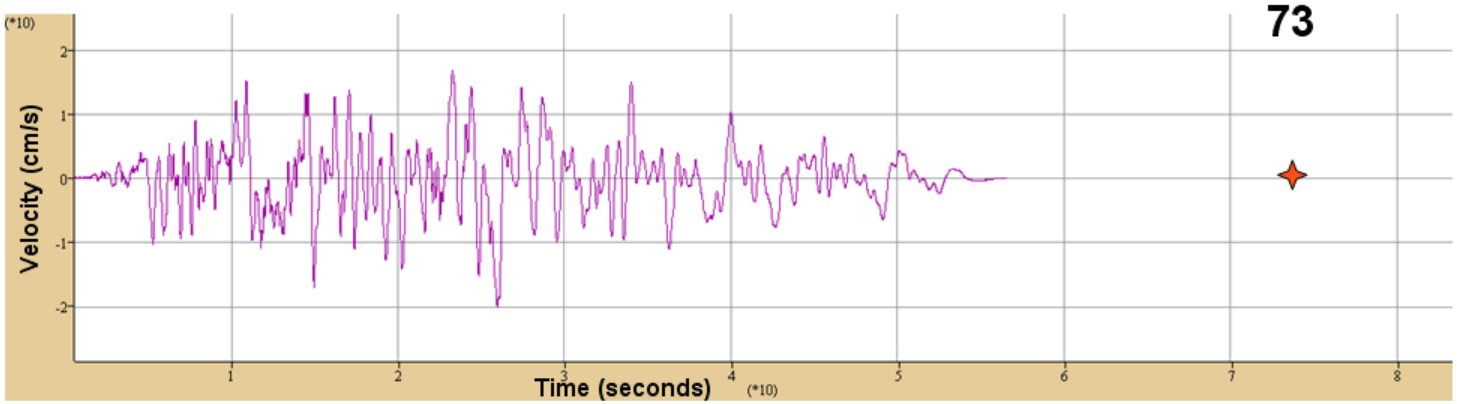

Excess pore pressure ratio
$r_u = (\sigma_{v0}' - \sigma_v') / \sigma_{v0}'$
feet
(*10^2 both)

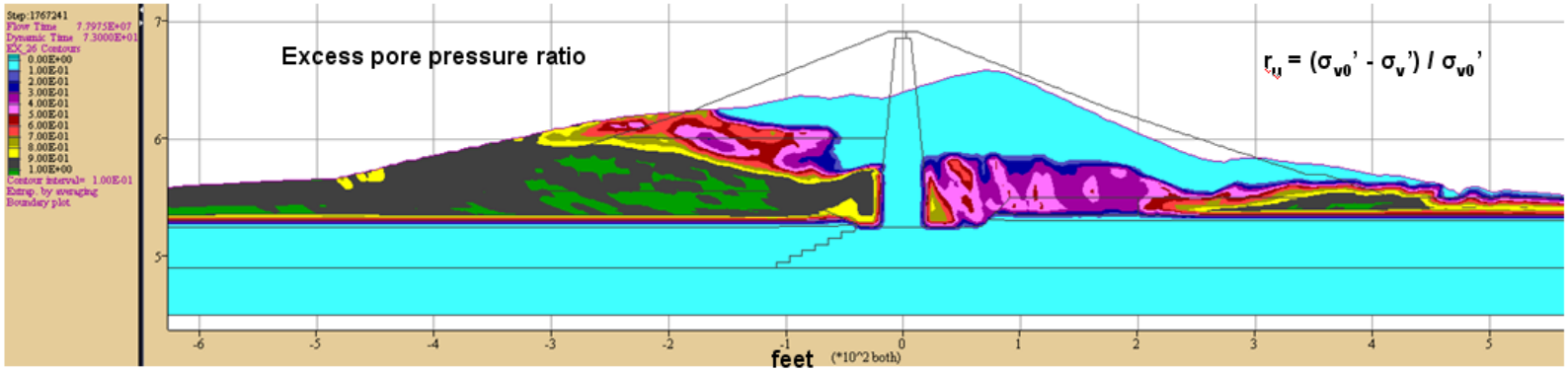

Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)

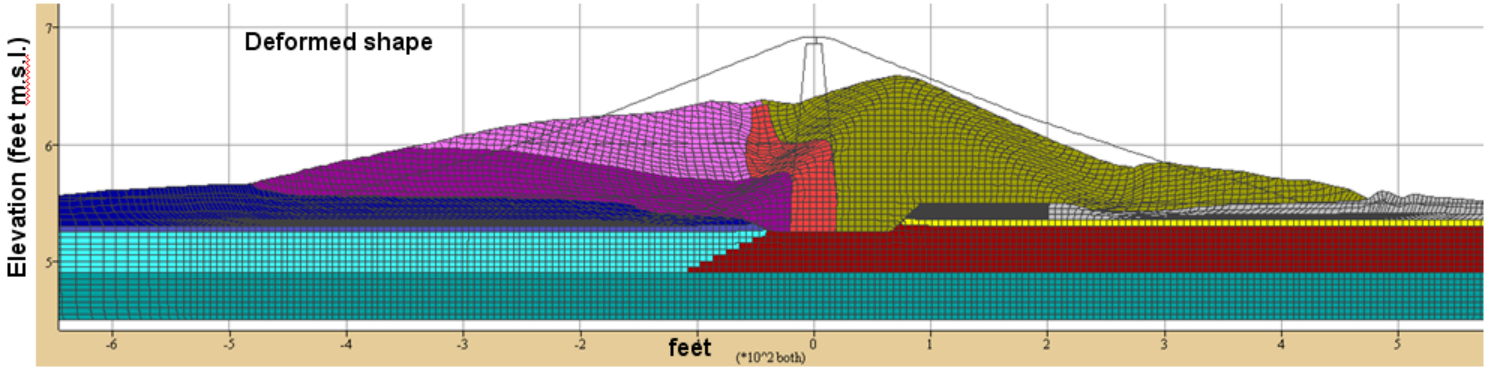

70
Velocity (cm/s)
Time (seconds)
(*10)

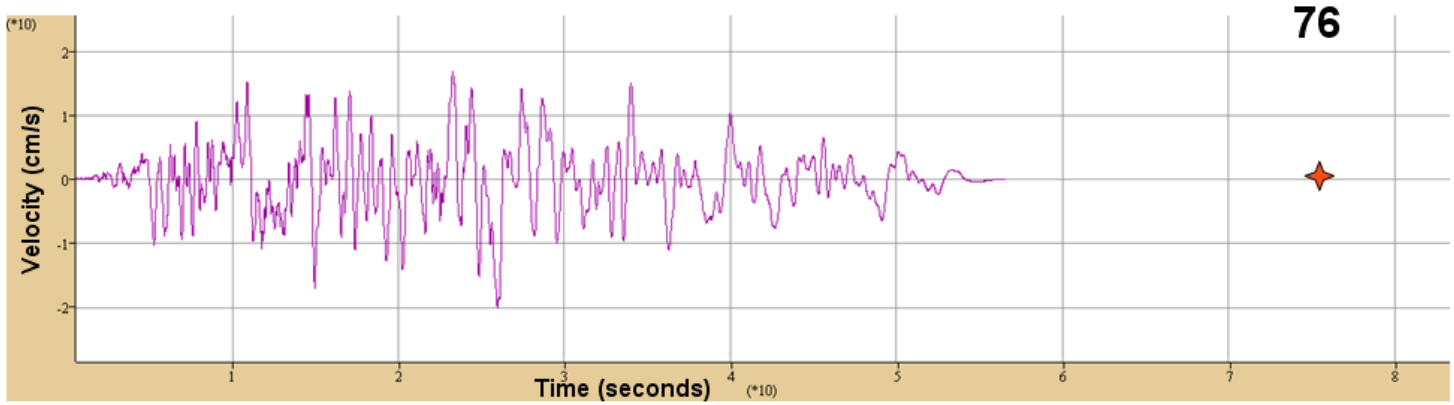

Excess pore pressure ratio
$r_u = (\sigma_{v0}' - \sigma_v') / \sigma_{v0}'$
feet
(*10^2 both)

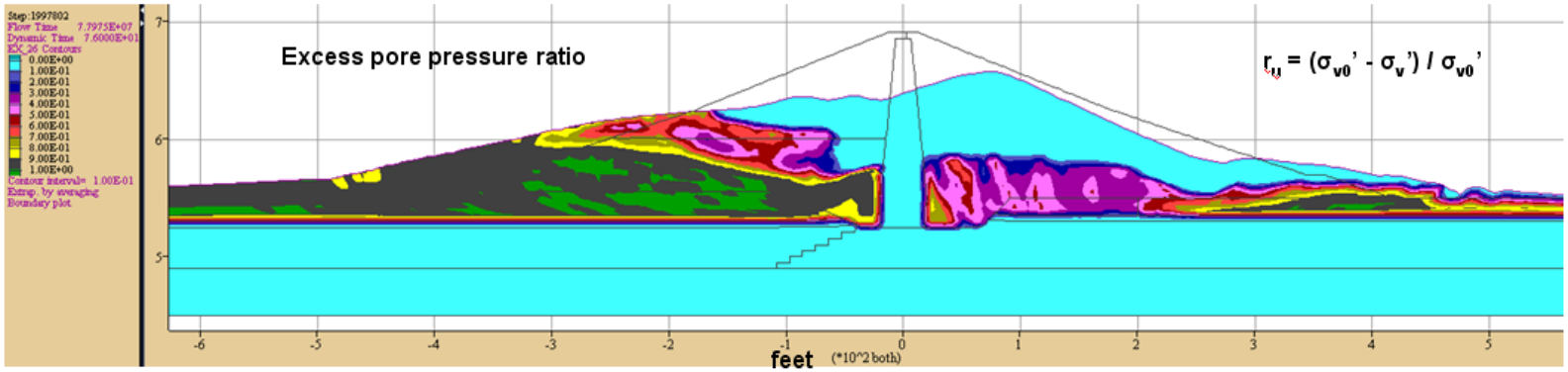

Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)

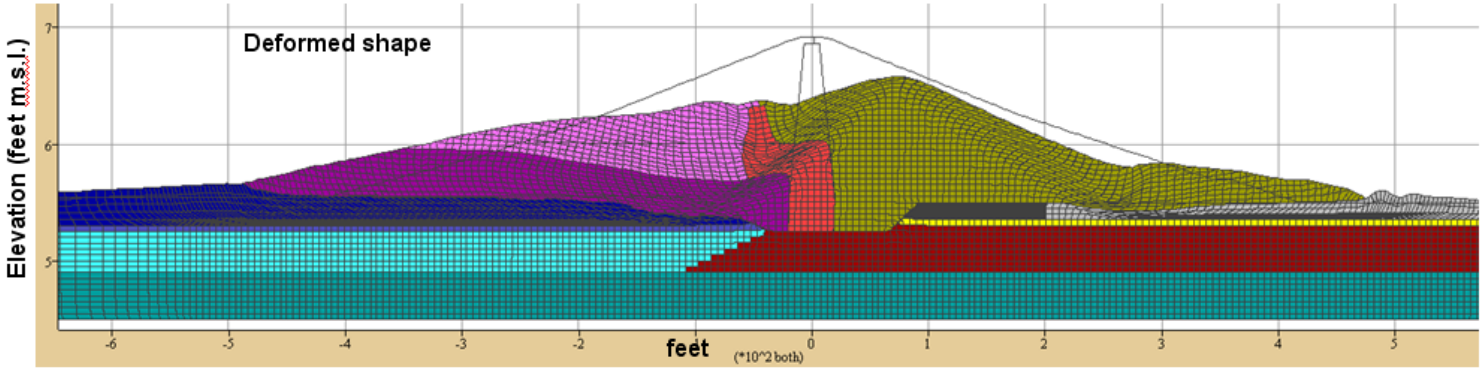

73
(*10)
Velocity (cm/s)
Time (seconds)
(*10)

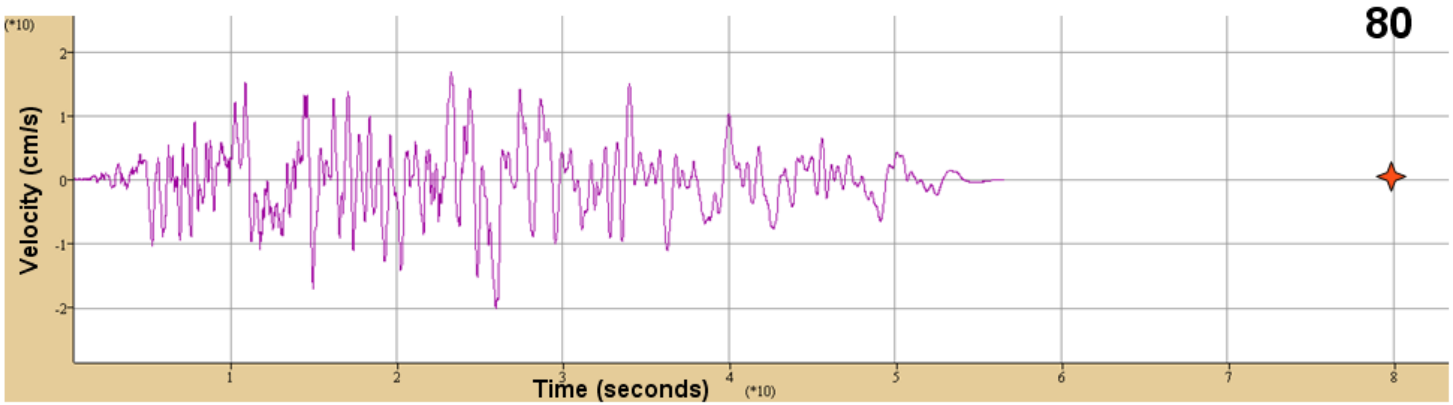

Excess pore pressure ratio
$r_u = (\sigma_{v0}' - \sigma_v') / \sigma_{v0}'$
feet
(*10^2 both)

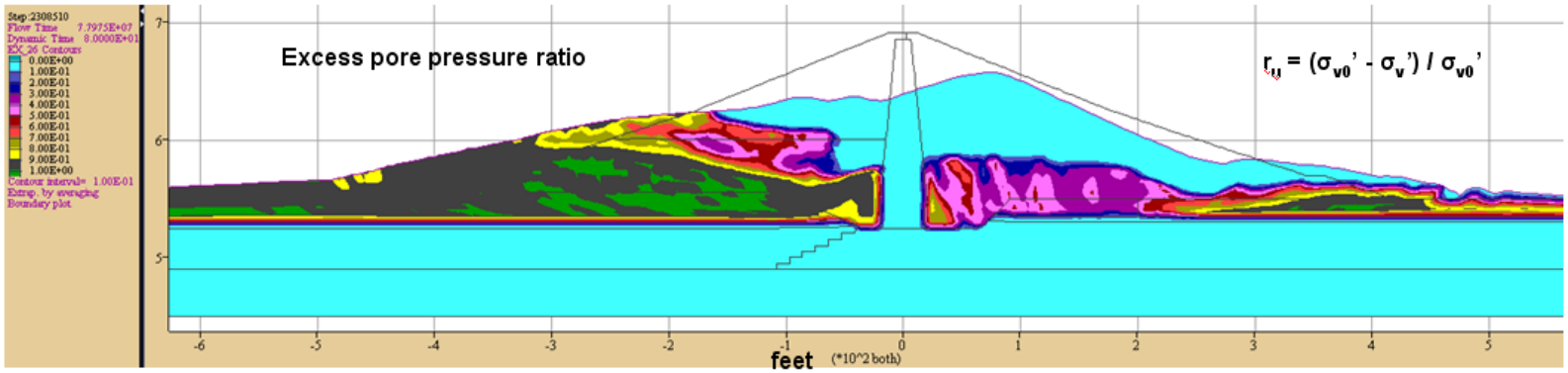

Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)

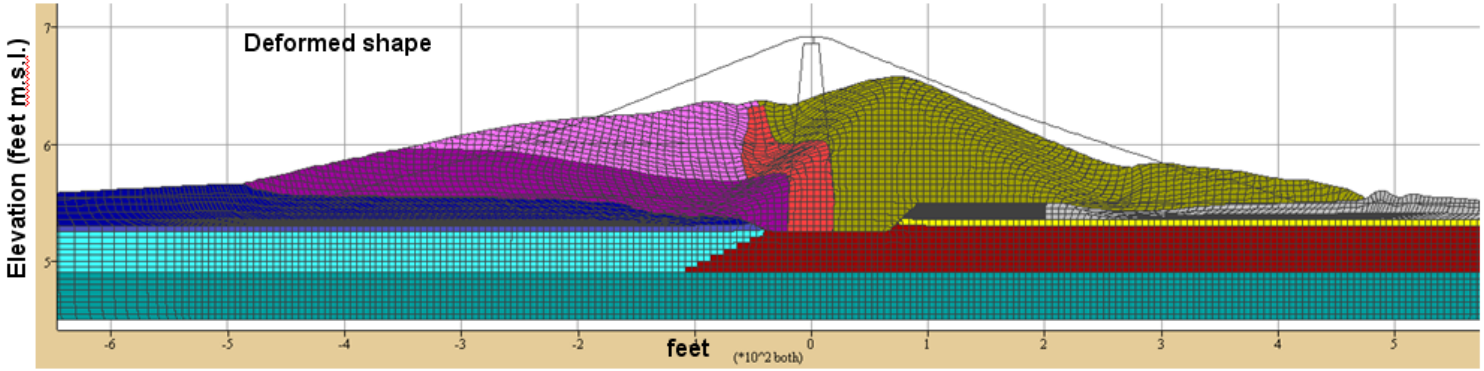

76
(*10)
Velocity (cm/s)
Time (seconds)
(*10)


Excess pore pressure ratio
$r_u = (\sigma_{v0}' - \sigma_v') / \sigma_{v0}'$
feet
(*10^2 both)


Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)

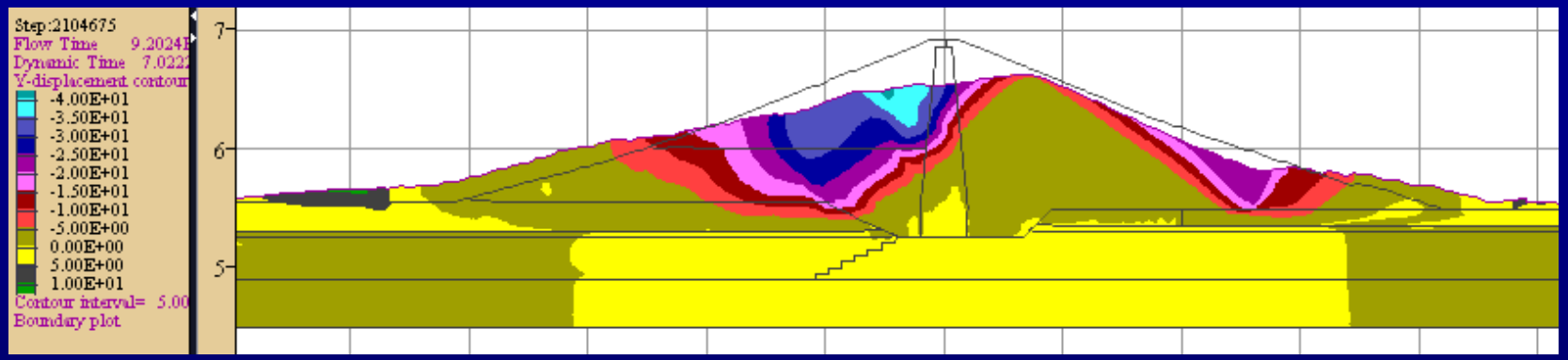

80
(*10)
Velocity (cm/s)
Time (seconds)
(*10)


Excess pore pressure ratio
$r_u = (\sigma_{v0}' - \sigma_v') / \sigma_{v0}'$
feet
(*10^2 both)

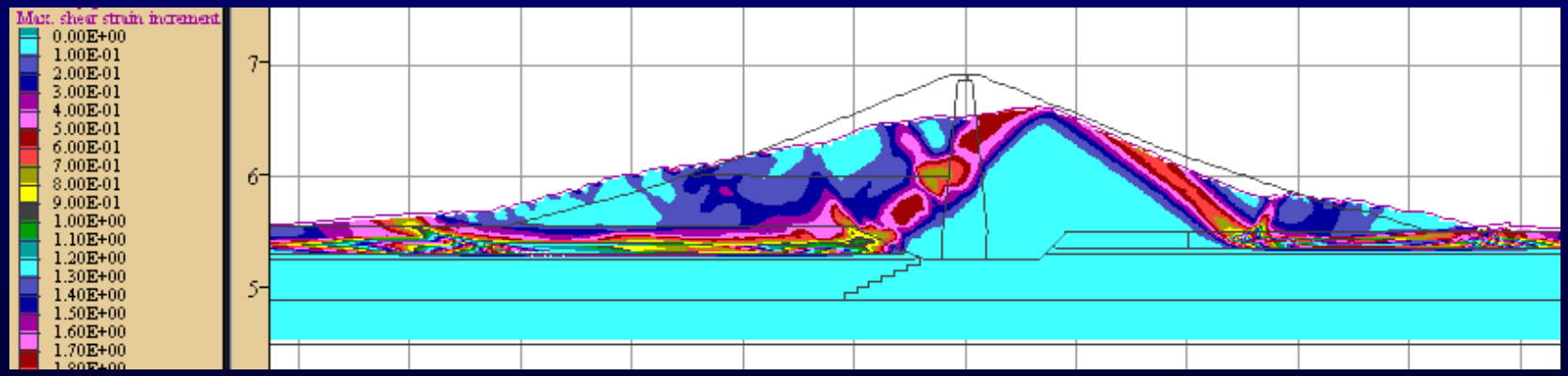

Deformed shape
Elevation (feet m.s.l.)
feet
(*10^2 both)

Existing Embankment Evaluation (MCE)

Vertical Displacement (Contours at 5-foot intervals)

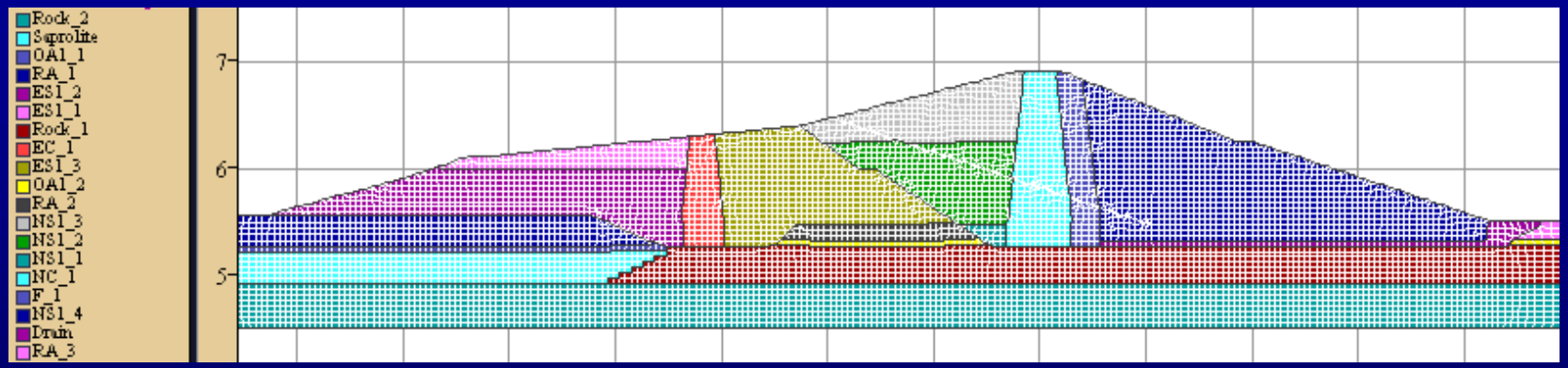


Maximum Shear Strain Increment

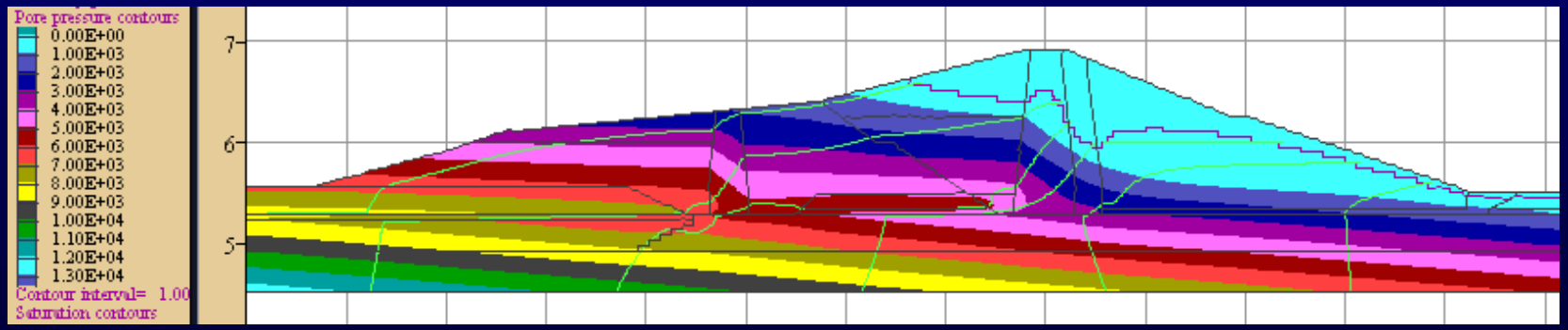


Remediation Alternatives: #1 - Downstream Modification (1)

Materials and FLAC Mesh

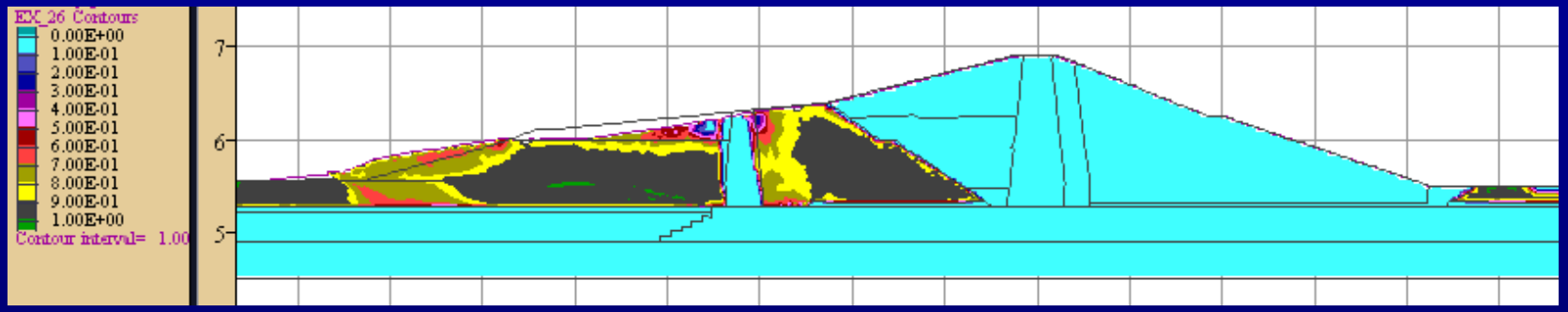


Steady State Seepage Condition



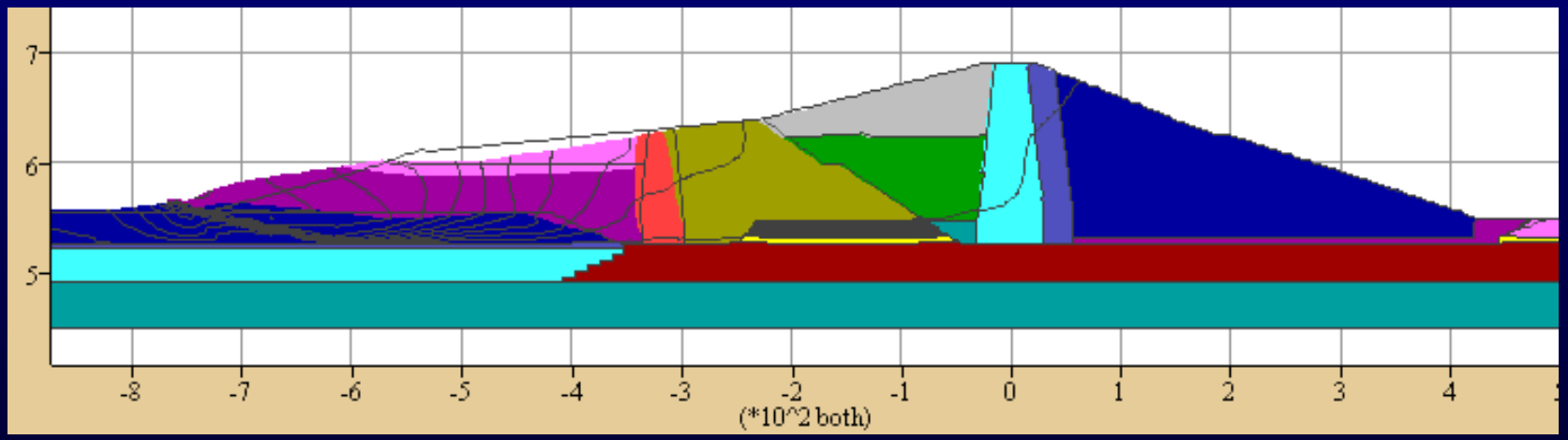
Downstream Modification (2)

Maximum Excess Pore Pressure Ratio



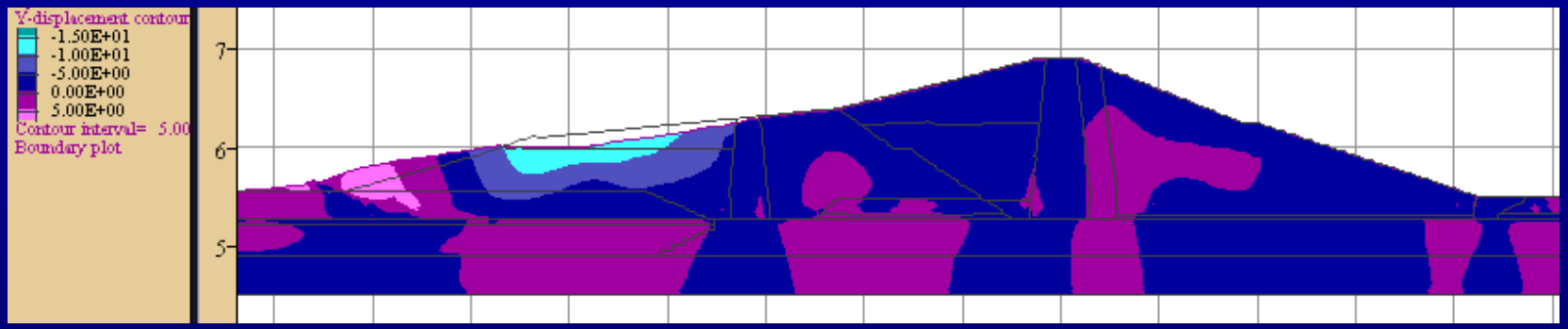
Horizontal Displacement Contours

(5-foot intervals)

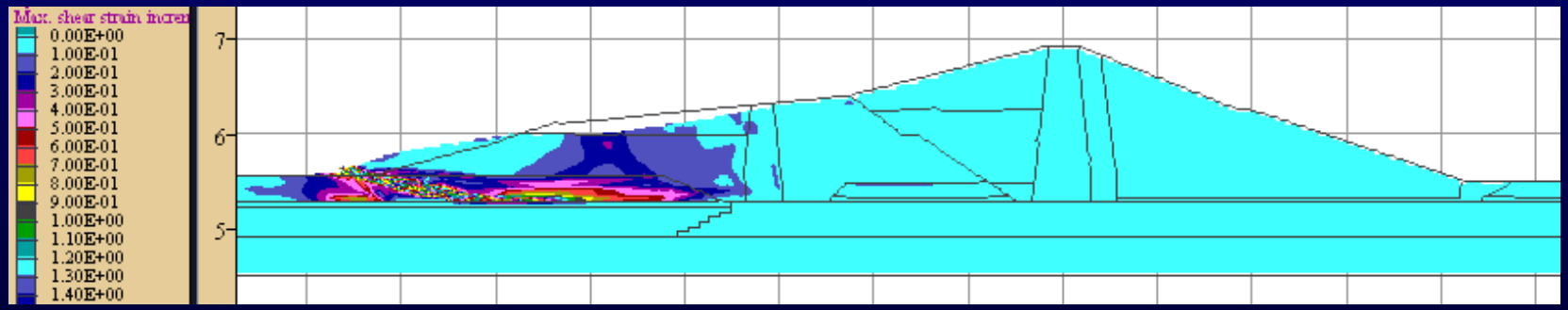


Downstream Modification (3)

Vertical Displacement (Contours at 5-foot intervals)



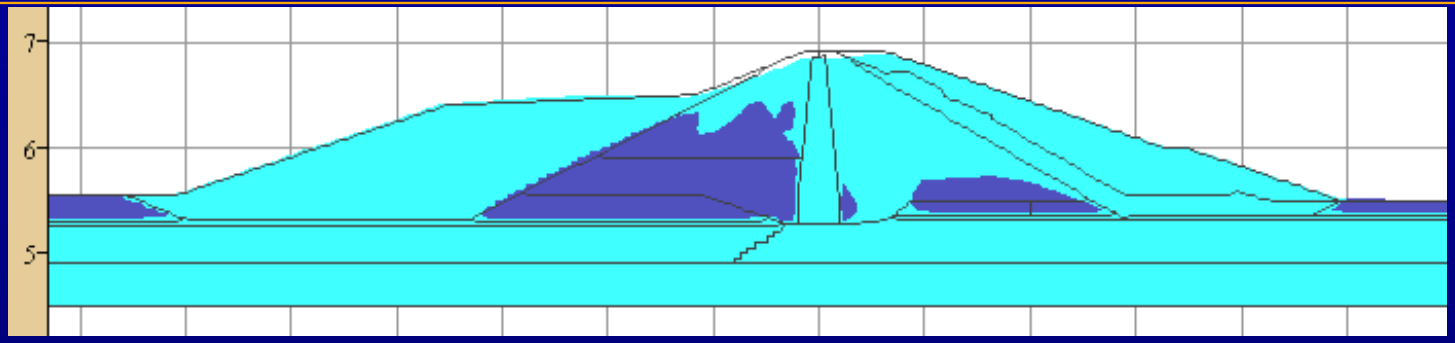
Maximum Shear Strain Increment



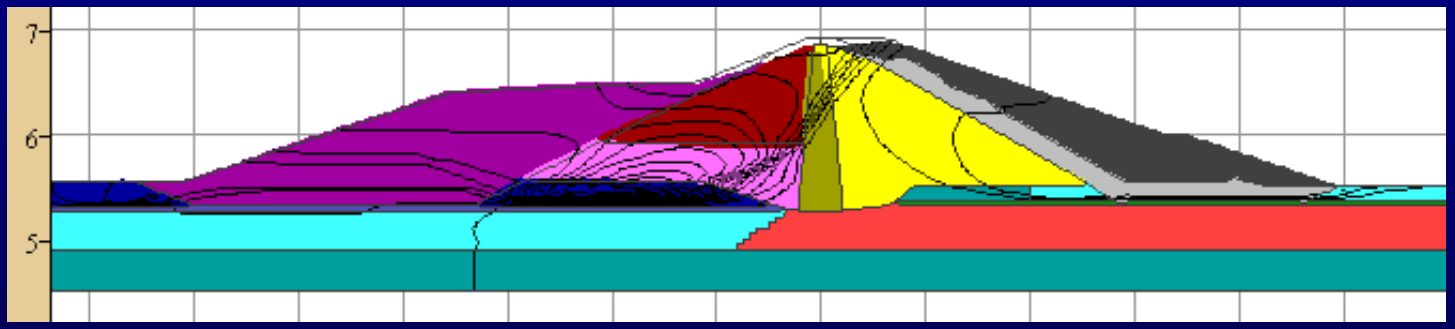
Remediation Alternatives: #2 – Upstream-Downstream Modification

Extent of liquefaction

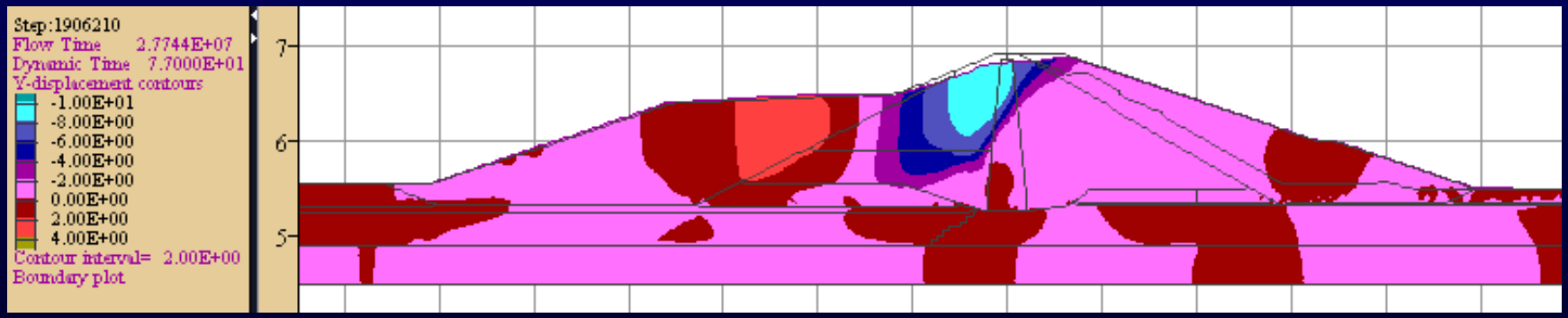
(r_u > 0.7)



Deformed shape and horizontal displacement contours (1 ft)



Vertical displa-cements (1 ft int.)



CONCLUSIONS

- FLAC, in conjunction with UBCSAND-Revised constitutive model provides both state of practice and state of art evaluation of the seismic deformations of the embankment dam, instrumental for both evaluation of the existing dam and the remediation design.
- Parameter uncertainty effect requires parametric analyses to evaluate the sensitivity of the model to input parameters and to develop a range of potential response over a likely range of input parameters.
- Parameters that have been identified as important include: site characterization with soil parameters, the earthquake time history, polarity of the time history, selection of the residual strength, and the reservoir level at the time of earthquake occurrence.
- Acceptable deformations are ensured by various remediation options. Selection of the preferred variant should also consider economic, constructability, and quality control aspects.