2008 Destabilizing Factors

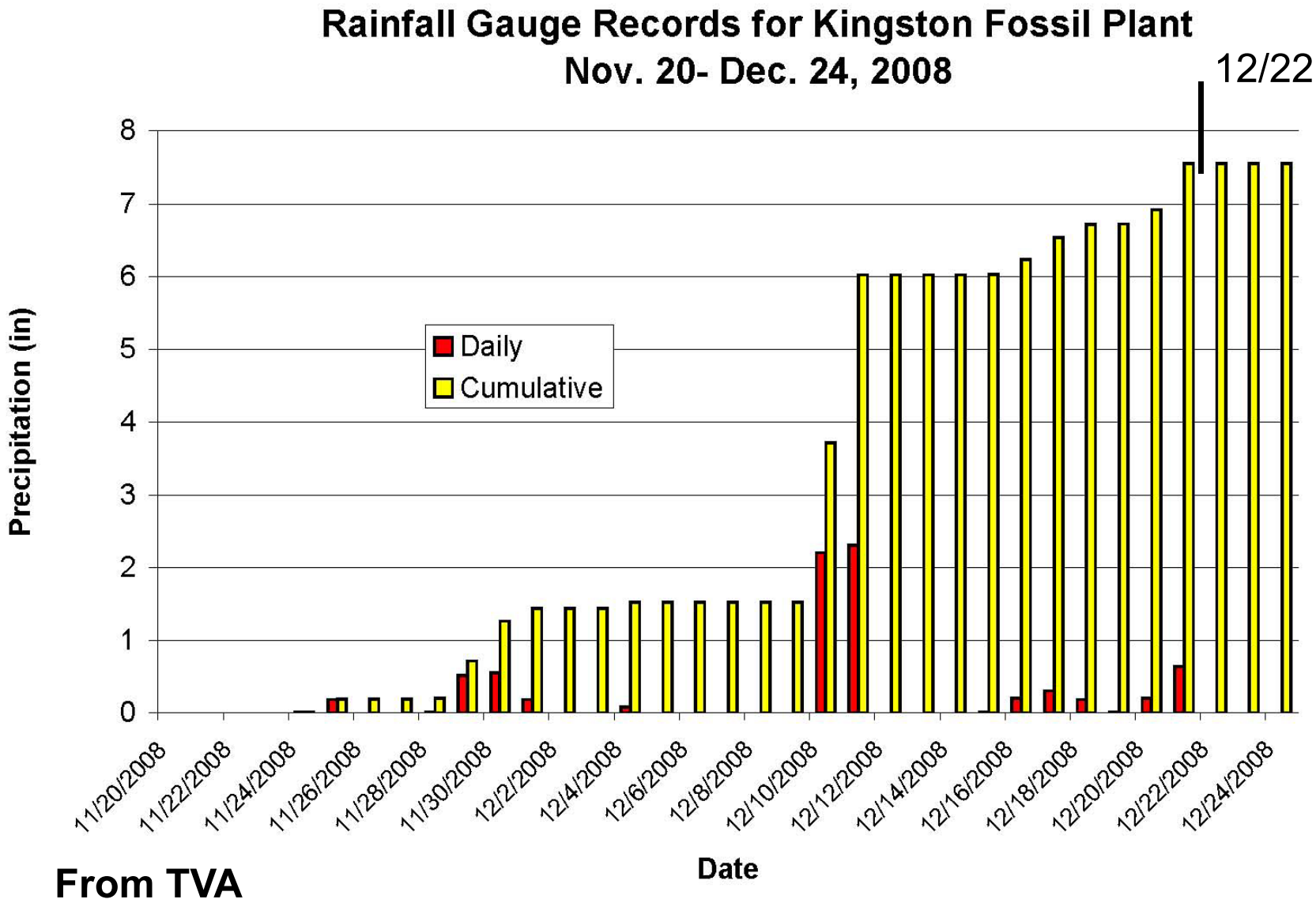
- Rainfall
- Reservoir Rapid Drawdown
- Rate of Loading due to Increased Height of Fill

Rainfall Impacts

- Nov. 20 to Dec. 21, 2008 Rainfall was 7.95 inches; higher than normal for one month
- Water levels concentrate in Cell 2 rim ditch just behind dike crest
- Excess Rain Water on Cell Ponds is absorbed or decanted off Cells 1 and 2 back to Ash Pond
- Rainfall on December 20 &21, 2008 was 1.28 inches

Minor Contributing Factor

TVA Rainfall at Kingston Fossil



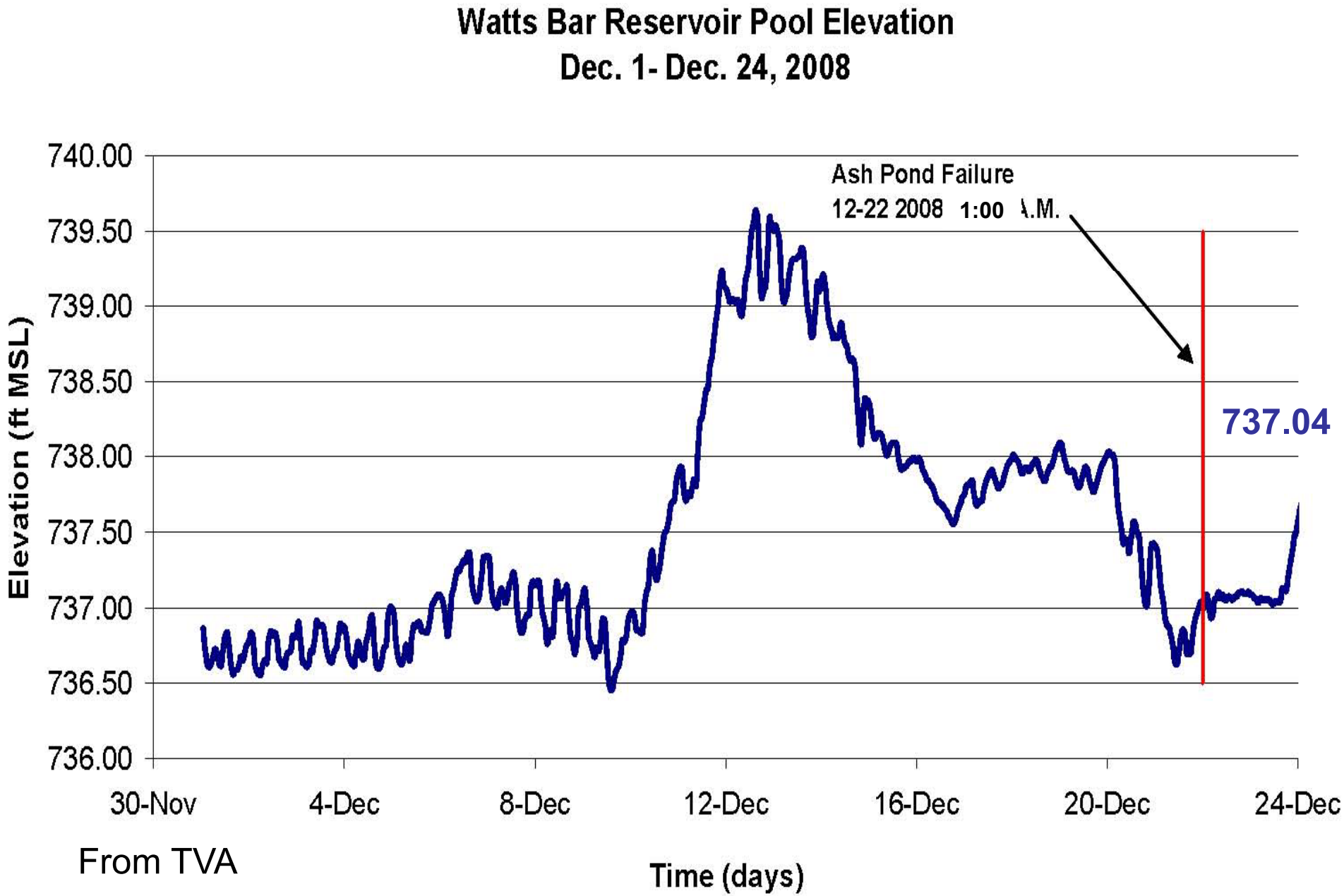
From TVA

Watts Bar Reservoir Rapid Drawdown

- Lowered reservoir at toe of Dike C reduces stability of perimeter dike fill
- Watts Bar Reservoir pool was lowered nearly 3 feet in 10 days after the December 10 and 11 rains, to get the pool back to Normal Winter water levels
- The Normal Winter Pool is El. 735
- Pool El. was 737.04 on 12/22/08, 0:00 am

Minor Contributing Factor

TVA Pool Elevation December 2008

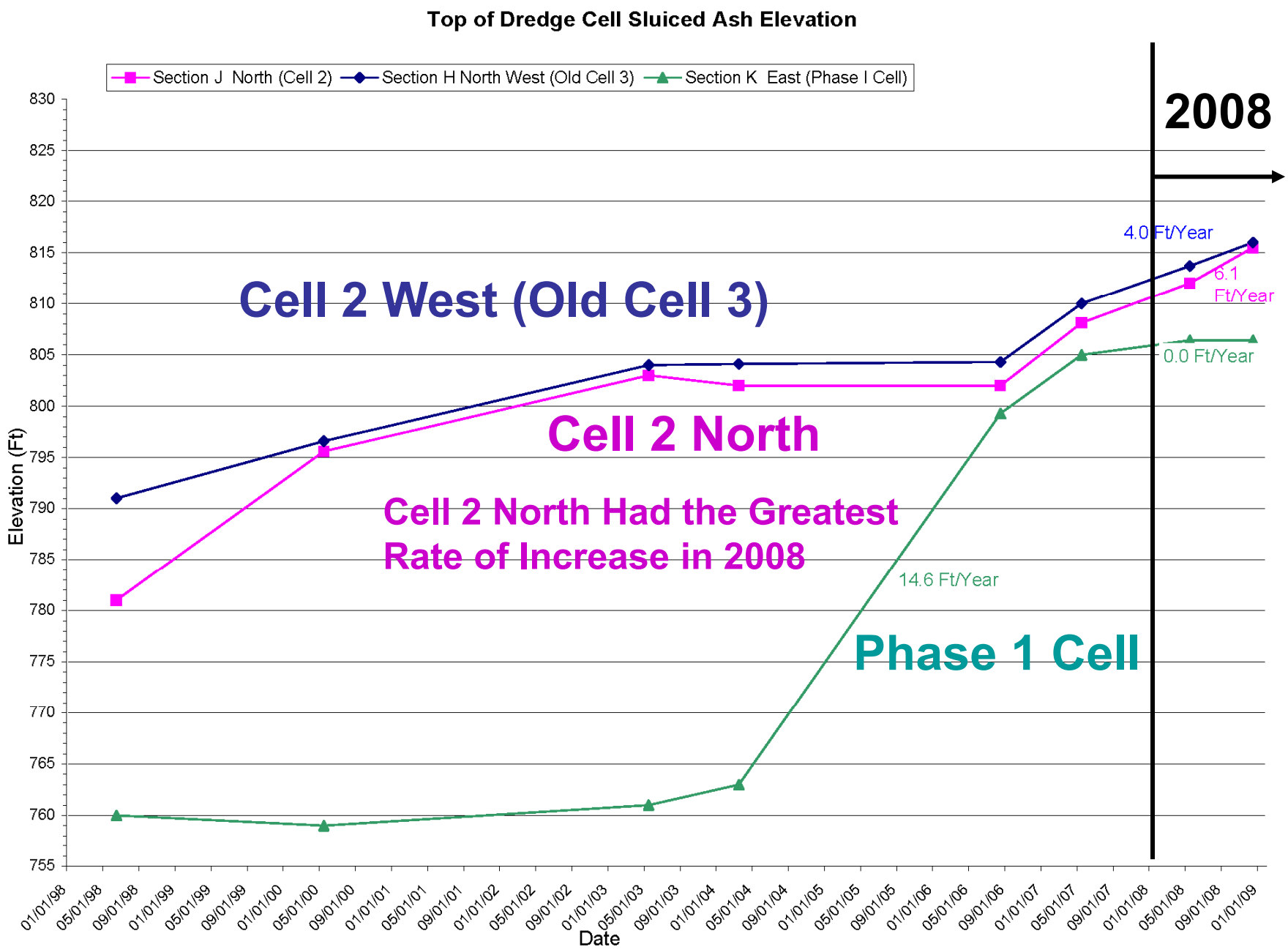


From TVA

Increased Rate of Cell 2 Loading in 2008

- Cell 2 Northwest Vertical Filling Rate - 6.1 ft/yr Was Highest Based on Surveys and TVA Observations
- Cell 2 Southwest Vertical Filling Rate – 4.0 ft/yr
- Phase 1 Cell Filling Rate – <1.0 ft/yr in 2008
- See attached Cell Elevation versus Time

Contributing Destabilizing Factor

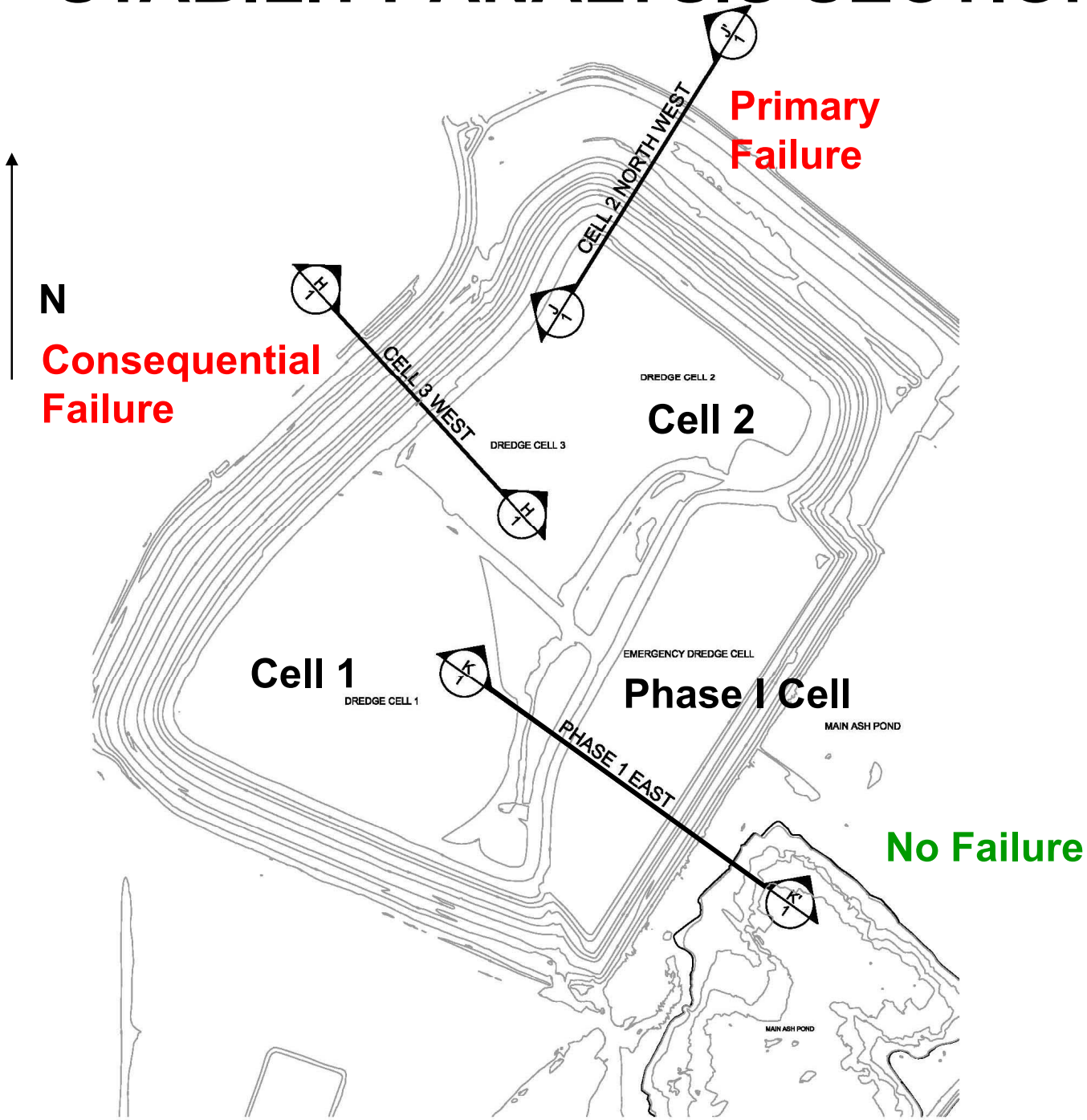

Top of Dredge Cell Sluiced Ash Elevation
Section J North (Cell 2)
Section H North West (Old Cell 3)
Section K East (Phase I Cell)
2008
Cell 2 West (Old Cell 3)
Cell 2 North
Cell 2 North Had the Greatest Rate of Increase in 2008
Phase 1 Cell
4.0 Ft/Year
6.1 Ft/Year
0.0 Ft/Year
14.6 Ft/Year
Elevation (Ft)
Date

Ash Generation

- 1995 Computations Show D Level Dikes to Store 394,000 Cubic Yards/Year (cy/yr)
- TVA Reported Generation Rates (cy/yr):
  - FYE 2006 416,000 to 471,000 (TVA HED)
  - FYE 2007 (TVA HED) 596,000
  - FYE 2008 (TVA HED) 462,000
  - FYE 2009 (TVA HED 2.5 months) 127,000
- TVA 3-year Future (cy/yr) 467,000

Dredge Cell Stability Analyses

STABILITY ANALYSIS SECTIONS



Stability Analysis Summary

- Shallow Slope Stability of Dikes Above El. 765
- Intermediate Stability Checks of Dikes
- Deep Foundation Stability Checks showing
  - Cell 2 Northwest – Section J-J, Failed North*
  - Cell 2 Southwest (old Cell 3) - Section H-H, Failed Toward North, Dikes A thru D2 flowed on top of ash
  - Phase 1 Emergency Cell East - Section K-K, Foundation Did Not Fail because of No Slimes

*** Primary Origin of Failure**

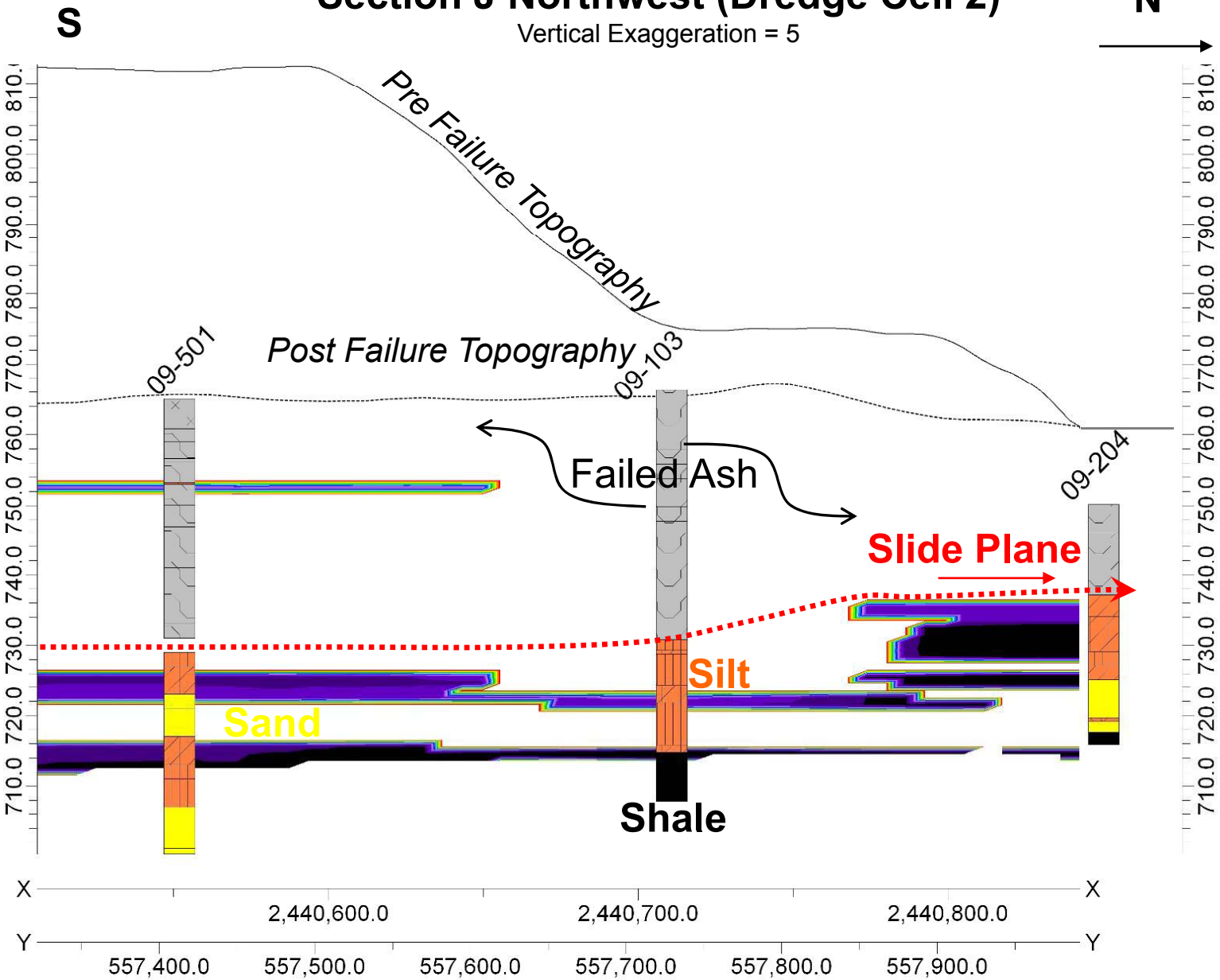
12-30-08

Failed Cell 2
"Y"
Dike D
Dike C
EMORY RIVER
Cell 1,
(Inactive)
Phase 1 Cell
MAIN ASH POND
200 feet

Section Looking West

Natural Soils ~ Estimated Undrained Shear Strength from CPT and Vanes
Section J Northwest (Dredge Cell 2)

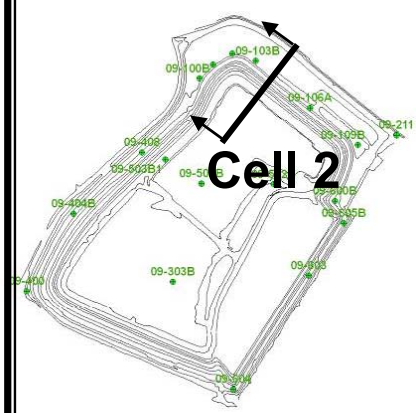
Vertical Exaggeration = 5

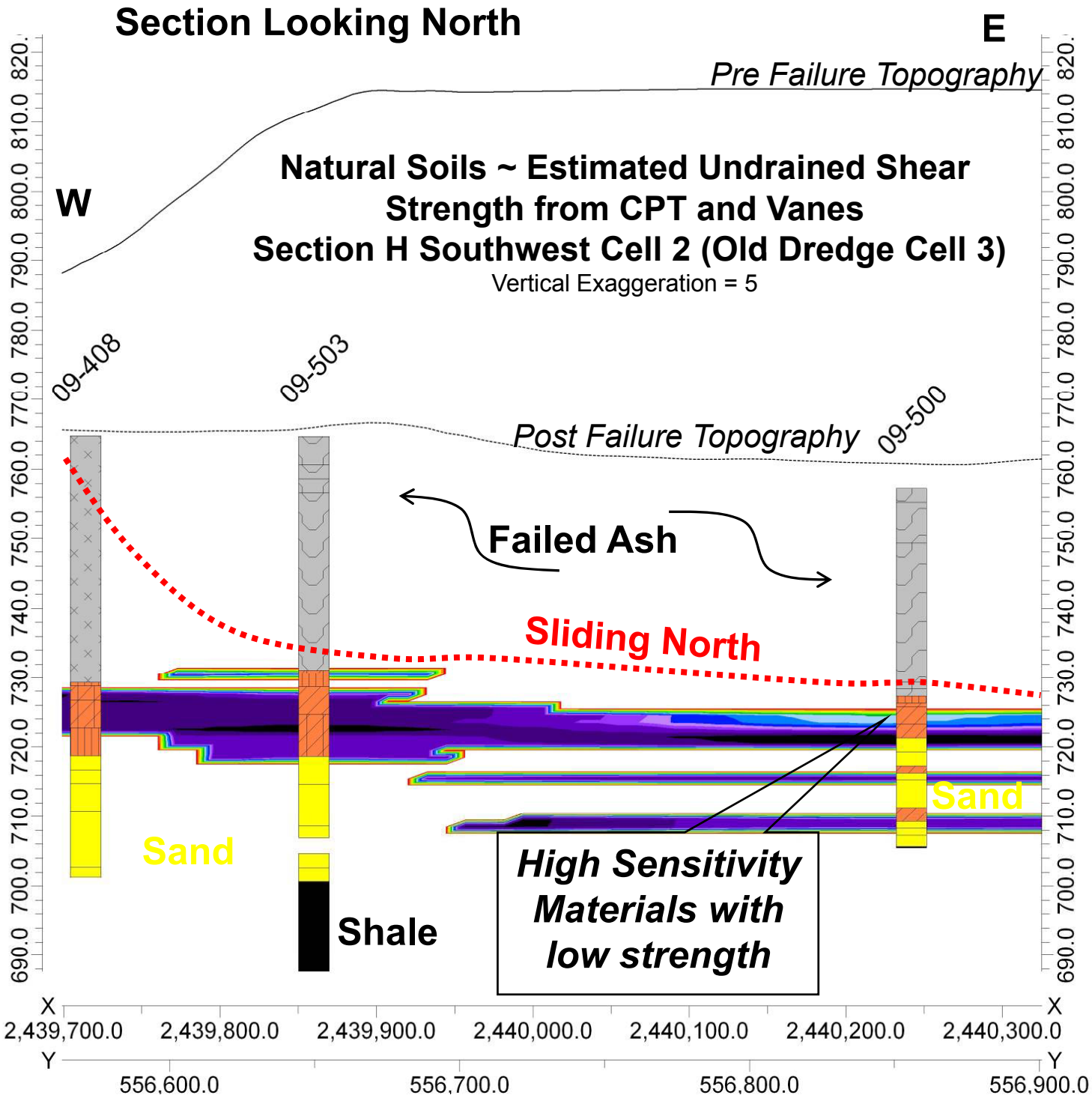


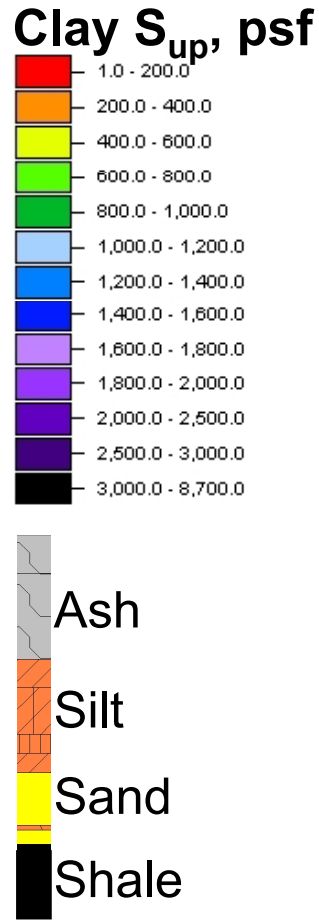
Clay S_{up}, psf

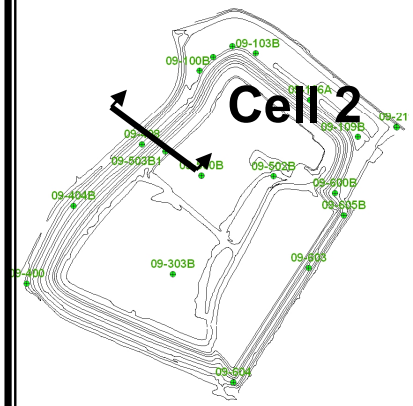
- 1.0 - 200.0
- 200.0 - 400.0
- 400.0 - 600.0
- 600.0 - 800.0
- 800.0 - 1,000.0
- 1,000.0 - 1,200.0
- 1,200.0 - 1,400.0
- 1,400.0 - 1,600.0
- 1,600.0 - 1,800.0
- 1,800.0 - 2,000.0
- 2,000.0 - 2,500.0
- 2,500.0 - 3,000.0
- 3,000.0 - 8,700.0

- Ash
- Silt
- Sand
- Shale




Section Looking North
E
W
Pre Failure Topography
Natural Soils ~ Estimated Undrained Shear Strength from CPT and Vanes
Section H Southwest Cell 2 (Old Dredge Cell 3)
Vertical Exaggeration = 5
09-408
09-503
09-500
Post Failure Topography
Failed Ash
Sliding North
Sand
Sand
Shale
High Sensitivity Materials with low strength
690.0
700.0
710.0
720.0
730.0
740.0
750.0
760.0
770.0
780.0
790.0
800.0
810.0
820.
X
2,439,700.0
2,439,800.0
2,439,900.0
2,440,000.0
2,440,100.0
2,440,200.0
2,440,300.0
Y
556,600.0
556,700.0
556,800.0
556,900.0


Clay S_{up}, psf
1.0 - 200.0
200.0 - 400.0
400.0 - 600.0
600.0 - 800.0
800.0 - 1,000.0
1,000.0 - 1,200.0
1,200.0 - 1,400.0
1,400.0 - 1,600.0
1,600.0 - 1,800.0
1,800.0 - 2,000.0
2,000.0 - 2,500.0
2,500.0 - 3,000.0
3,000.0 - 8,700.0
Ash
Silt
Sand
Shale


Cell 2

Air View of Swan Pond Road and RR Alignment

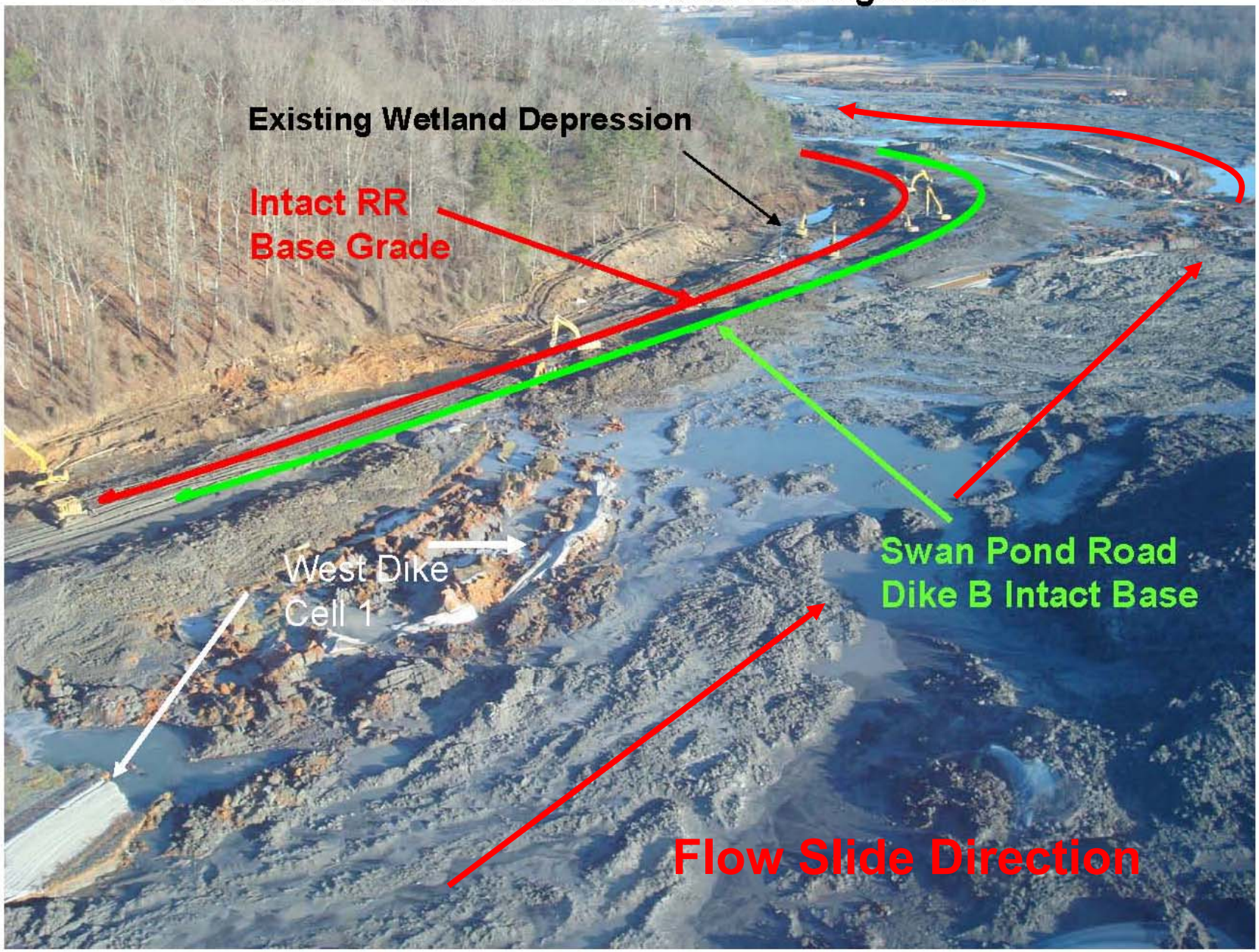
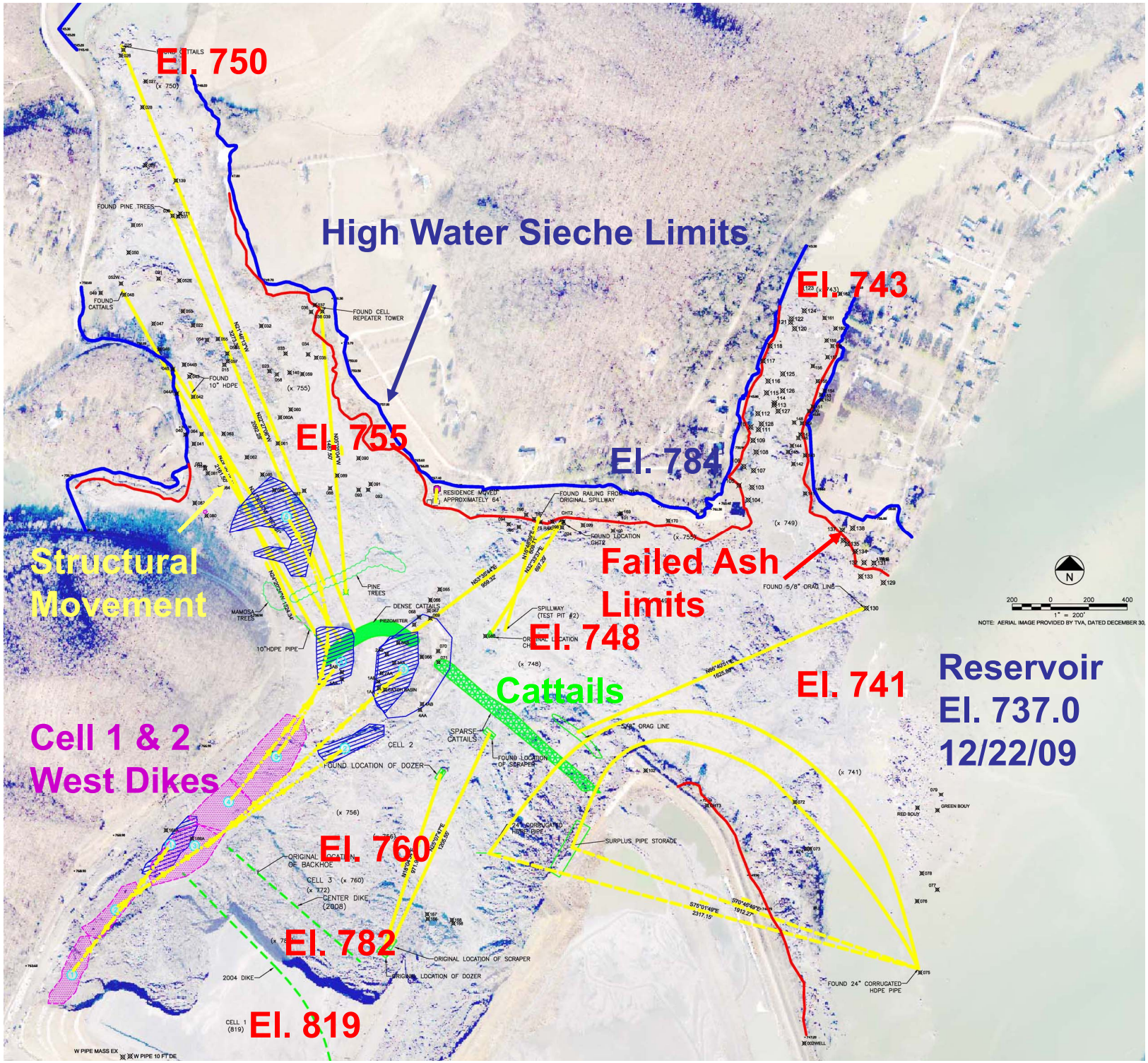


FIGURE 1.2.8_3

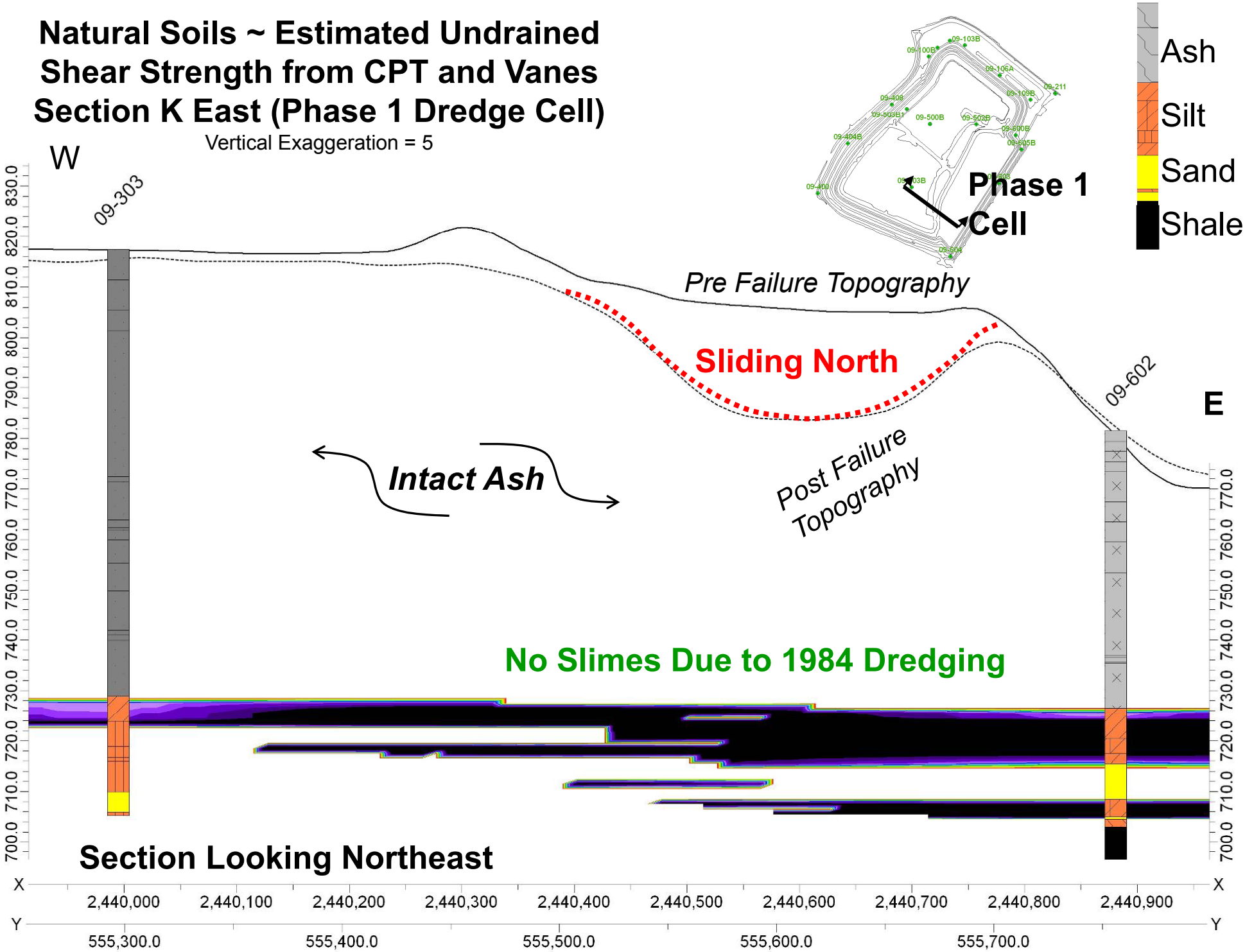
AECOM

AECOM Relic Survey



Natural Soils ~ Estimated Undrained Shear Strength from CPT and Vanes Section K East (Phase 1 Dredge Cell)

Vertical Exaggeration = 5



Factor of Safety (FS)

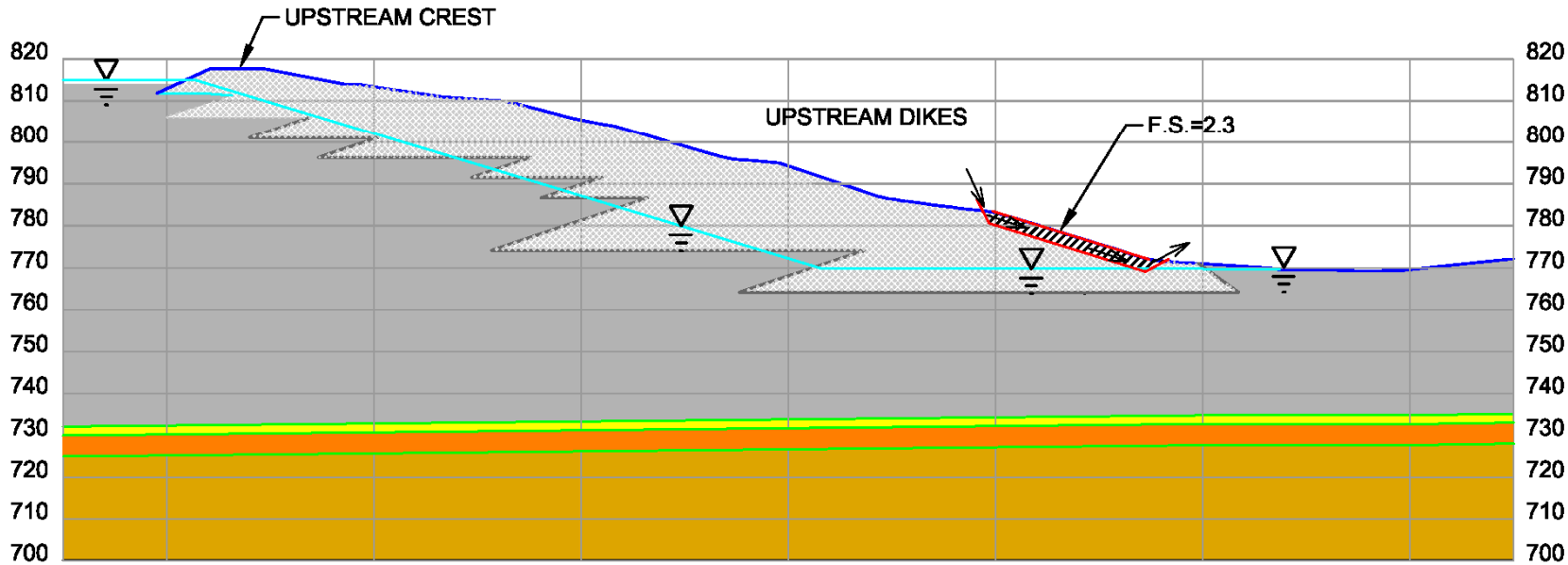
- Sum of Resisting Forces divided by Sum Driving Forces

$$\mathbf{FS} = \frac{\sum \mathbf{F\ resisting\ forces}}{\sum \mathbf{F\ driving\ forces}}$$

FS < 1.0 Failure
FS = 1.0 Failure Imminent

SLOPE STABILITY ANALYSIS
CASE I INFINITE SLOPE STABILITY
NO NEAR SURFACE SEEPAGE FORCES
SLOPE OF DIKE 3H:1V

FS=2.3

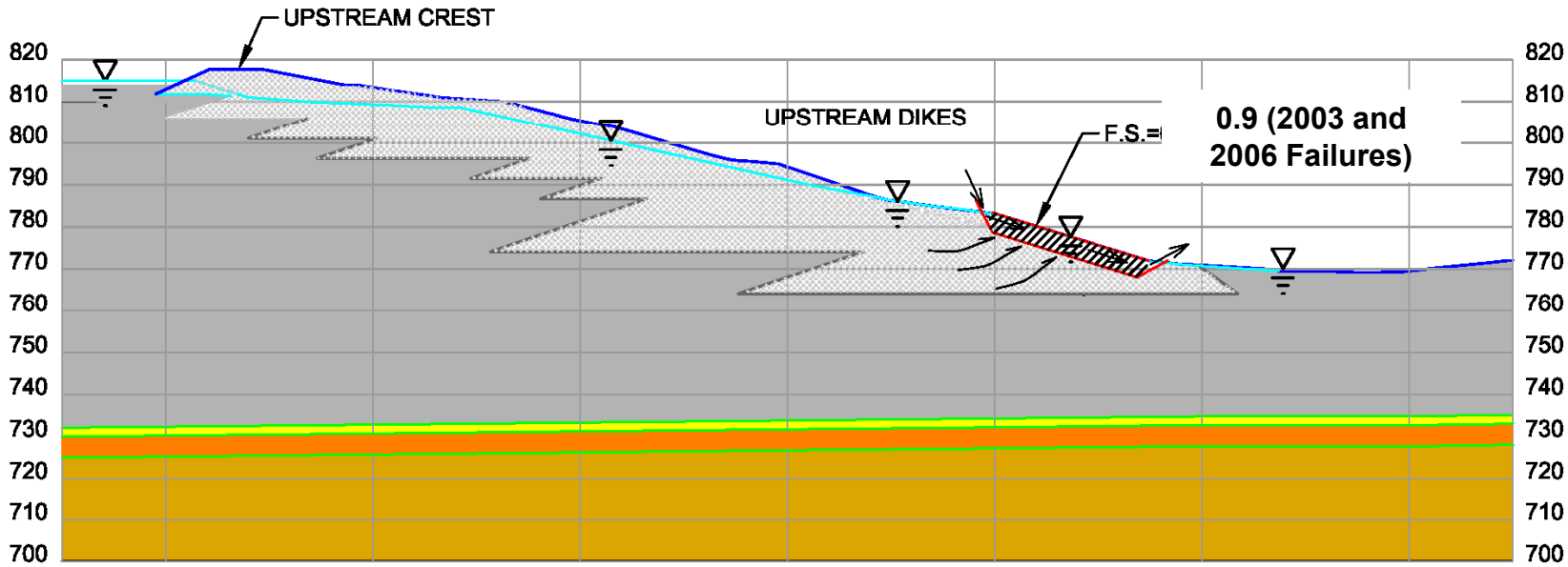


LEGEND:

- FAILURE SURFACE
- PHREATIC SURFACE
- DIKE ASH ϕ=37°
- SLUICED ASH ϕ=30°
- LAMINATED SENSITIVE SILTS AND ASH (SLIMES)
- ALLUVUIM CLAYS AND SILTS
- ALLUVUIM SANDS AND GRAVELS

SLOPE STABILITY ANALYSIS
CASE III SLOPE STABILITY
SEEPAGE WATER EMERGING FROM
3H:1V SLOPE

FS=0.9 < 1.0



LEGEND:

- FAILURE SURFACE
- PHREATIC SURFACE
- DIKE ASH ϕ=37°
- SLUICED ASH ϕ=30°
- LAMINATED SENSITIVE SILTS AND ASH (SLIMES)
- ALLUVUIM CLAYS AND SILTS
- ALLUVUIM SANDS AND GRAVELS

Dredge Cell 2 Intermediate Depth Stability

Stage 1: Flyash Drained Condition Phi (ø)=30˚

Case 2: Slimes Undrained Condition

Name: Ash - Dike
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Unit Wt. Above Water Table: 102 pcf
Cohesion: 0 psf
Phi: 37 °

Name: Dike - Compacted Clay Fill
Model: Mohr-Coulomb
Unit Weight: 120 pcf
Cohesion: 600 psf
Phi: 15 °

Name: Ash - Sluiced
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Cohesion: 0 psf
Phi: 30 °
Phi-B: 0 °

Name: Soft Clay
Model: Mohr-Coulomb
Unit Weight: 110 pcf
Cohesion: 600 psf
Phi: 0 °

Name: Alluvium - Clays and Silts
Model: Mohr-Coulomb
Unit Weight: 110 pcf
Cohesion: 1200 psf
Phi: 0 °

Name: Alluvium - Silty Sands and Silts
Model: Mohr-Coulomb
Unit Weight: 130 pcf
Cohesion: 600 psf
Phi: 30 °

Name: Laminated Sensitive Silts and Ash Slimes 1
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 700 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 2
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 800 psf
Phi: 0 °

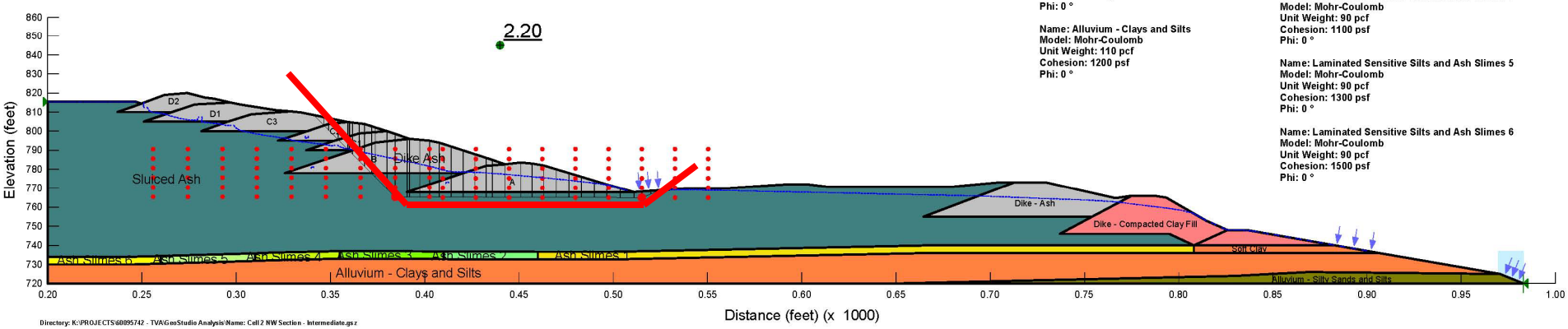
Name: Laminated Sensitive Silts and Ash Slimes 3
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 900 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 4
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1100 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 5
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1300 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 6
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1500 psf
Phi: 0 °

Factor of Safety = 2.2



Dredge Cell 2 Northwest Section

Stage 1: Flyash Drained Condition Phi (∅)=30˚

Case 2: Slimes Undrained Condition Lower Bound Su's

Factor of Safety = 1.2

Name: Ash - Dike
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Unit Wt. Above Water Table: 102 pcf
Cohesion: 0 psf
Phi: 37 °

Name: Dike - Compacted Clay Fill
Model: Mohr-Coulomb
Unit Weight: 120 pcf
Cohesion: 600 psf
Phi: 15 °

Name: Ash - Sluiced
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Cohesion: 0 psf
Phi: 30 °
Phi-B: 0 °

Name: Soft Clay
Model: Mohr-Coulomb
Unit Weight: 110 pcf
Cohesion: 600 psf
Phi: 0 °

Name: Alluvium - Clays and Silts
Model: Mohr-Coulomb
Unit Weight: 110 pcf
Cohesion: 1200 psf
Phi: 0 °

Name: Alluvium - Silty Sands and Silts
Model: Mohr-Coulomb
Unit Weight: 130 pcf
Cohesion: 600 psf
Phi: 30 °

Name: Laminated Sensitive Silts and Ash Slimes 1
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 600 psf
Phi: 0 °

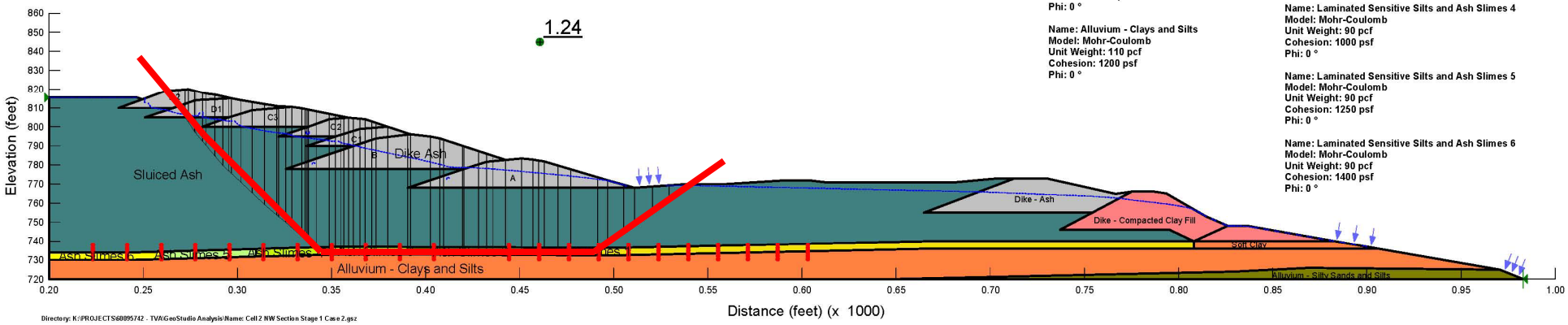
Name: Laminated Sensitive Silts and Ash Slimes 2
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 700 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 3
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 800 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 4
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1000 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 5
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1250 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 6
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1400 psf
Phi: 0 °



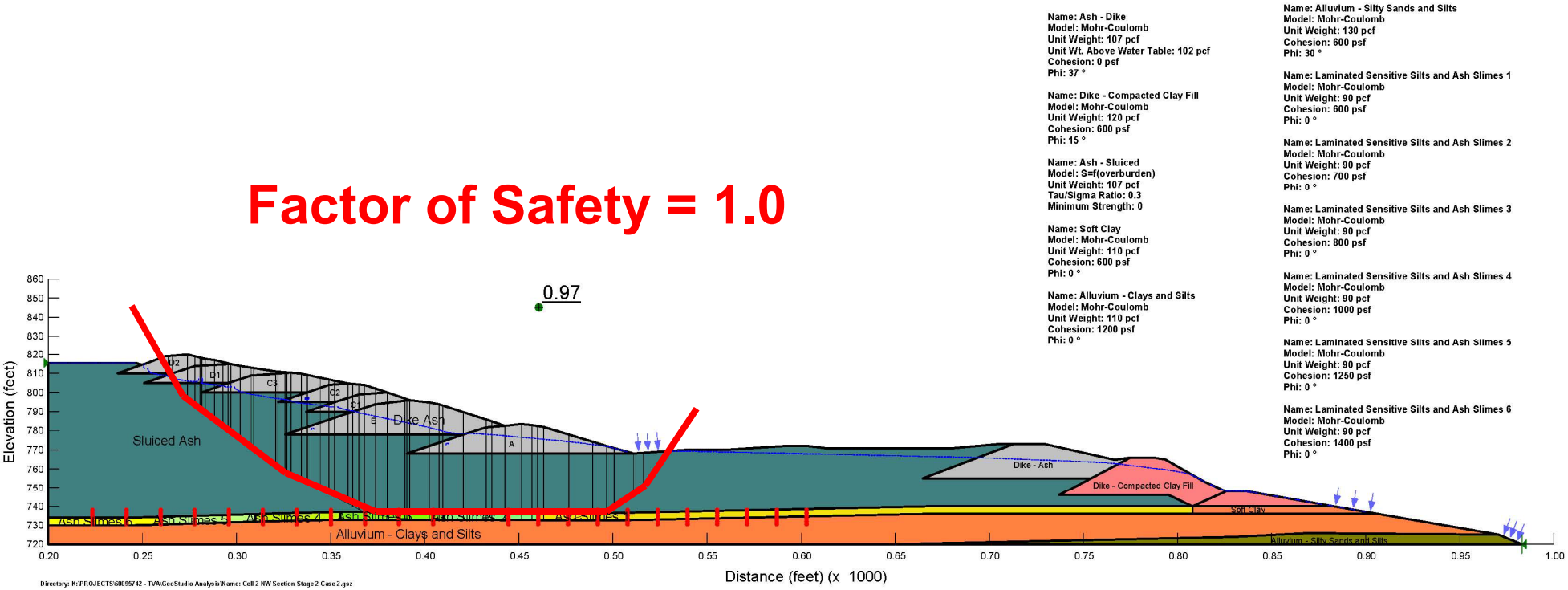
Directory: K:\PROJECTS\60095742 - TVA\GeoStudio Analysis\Name: Cell 2 NW Section Stage 1 Case 2.gsz

Dredge Cell 2 Northwest Section

Stage 2: Flyash Undrained Condition Su/p =0.3

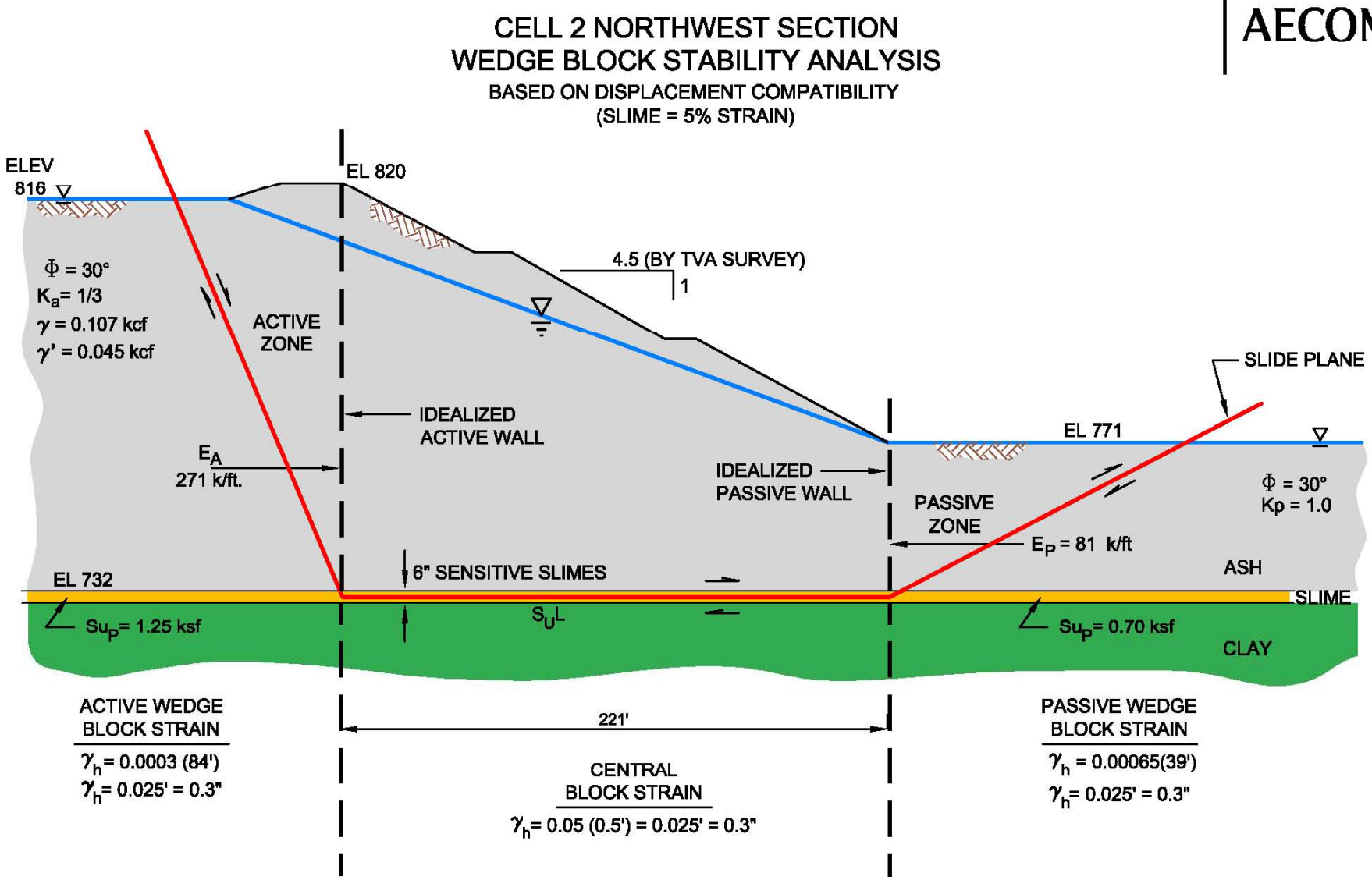
Case 2: Slimes Undrained Condition Lower Bound Su's

Factor of Safety = 1.0



Traditional Wedge Block Analysis for Weak Foundation

AECOM

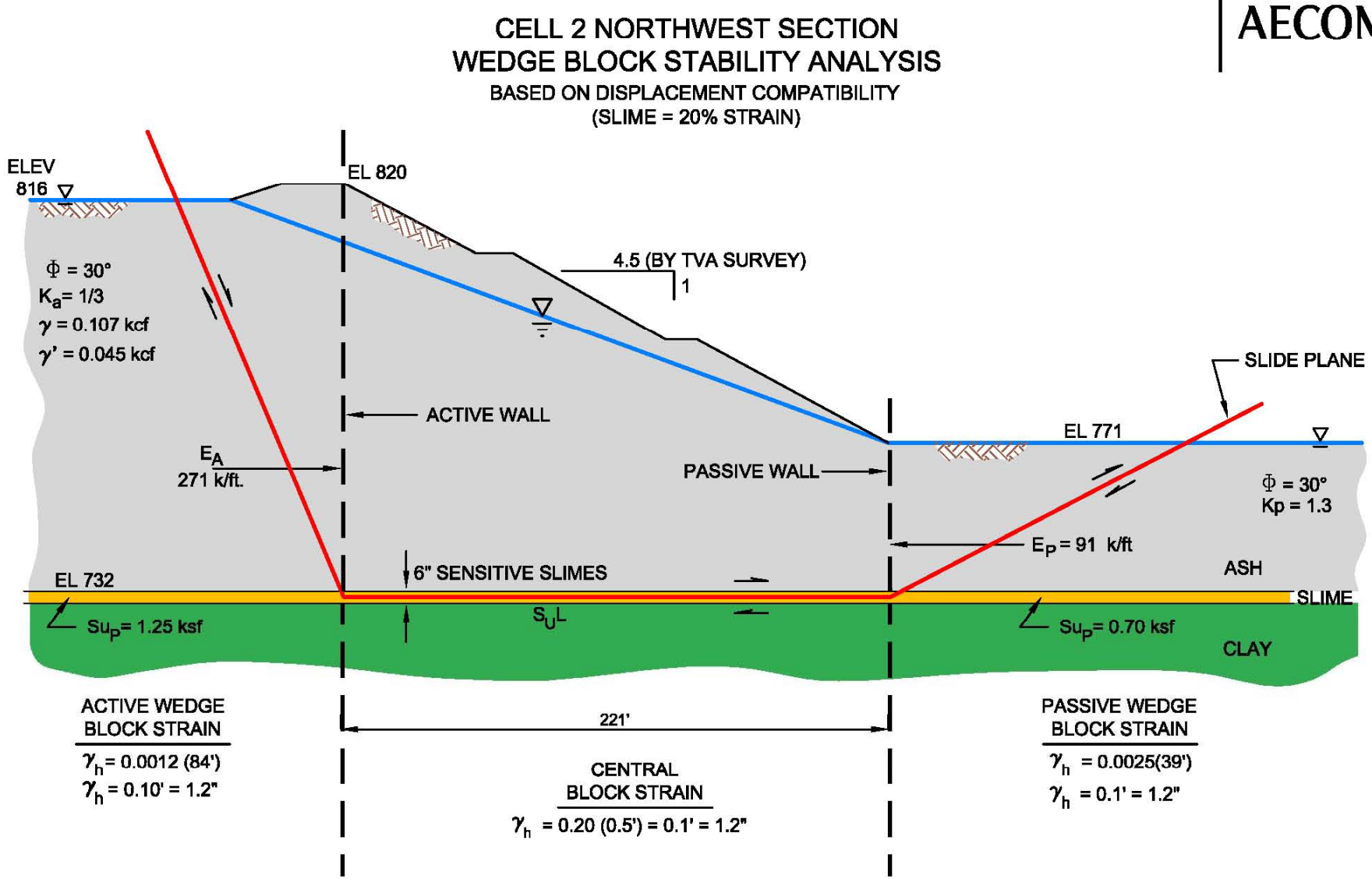


$$FS = \frac{S_u L}{E_A - E_P} = \frac{(1.25 + 0.7)/2\ (221')}{271 - 81} = \frac{215\ \text{k/ft.}}{190\ \text{k/ft.}} = 1.1,\ \textbf{FAILURE IMMINENT}$$

FS = 1.1

Traditional Wedge Block Analysis for Weak Foundation

AECOM



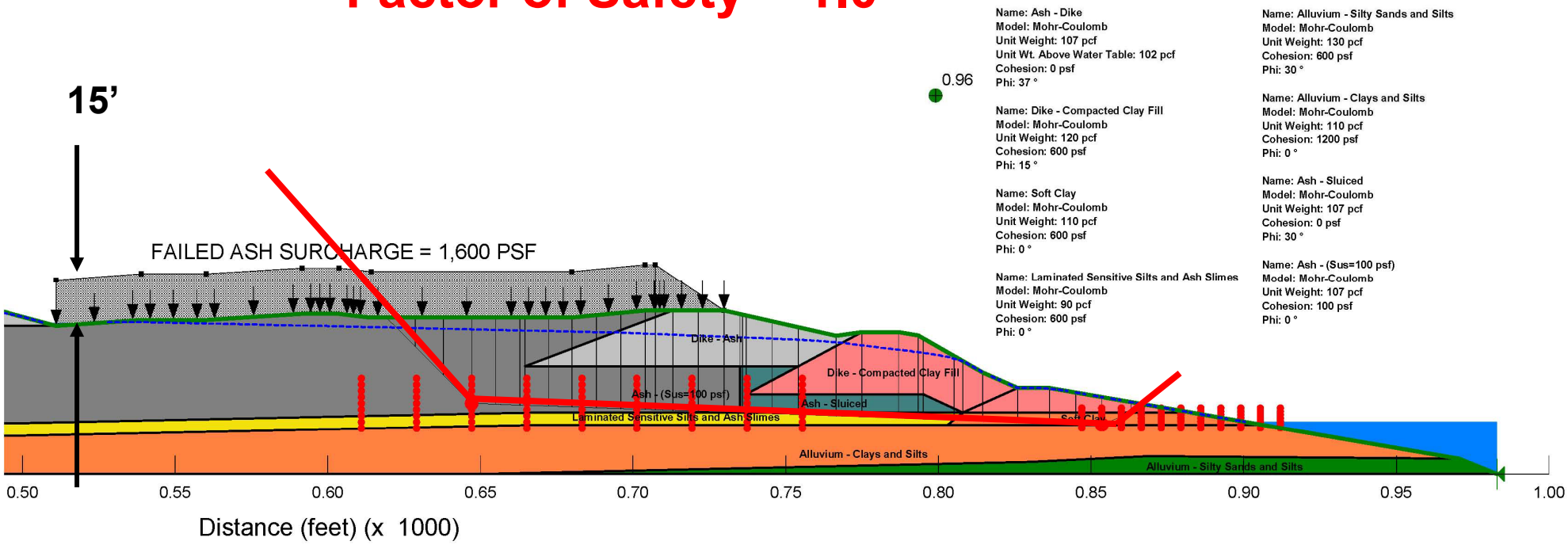
$$FS = \frac{S_u L}{E_A - E_P} = \frac{0.75\,(1.25 + 0.7)/2\,(221')}{271 - 91} = \frac{162\text{ k/ft.}}{180\text{ k/ft.}} = 0.9, \textbf{ FAILURE}$$

FS = 0.9

Dredge Cell 2 Northwest Section

Stage 3: 1600 psf Surcharge Moved to Crest of Dike C

Factor of Safety = 1.0



Name: Ash - Dike
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Unit Wt. Above Water Table: 102 pcf
Cohesion: 0 psf
Phi: 37 °

Name: Dike - Compacted Clay Fill
Model: Mohr-Coulomb
Unit Weight: 120 pcf
Cohesion: 600 psf
Phi: 15 °

Name: Soft Clay
Model: Mohr-Coulomb
Unit Weight: 110 pcf
Cohesion: 600 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 600 psf
Phi: 0 °

Name: Alluvium - Silty Sands and Silts
Model: Mohr-Coulomb
Unit Weight: 130 pcf
Cohesion: 600 psf
Phi: 30 °

Name: Alluvium - Clays and Silts
Model: Mohr-Coulomb
Unit Weight: 110 pcf
Cohesion: 1200 psf
Phi: 0 °

Name: Ash - Sluiced
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Cohesion: 0 psf
Phi: 30 °

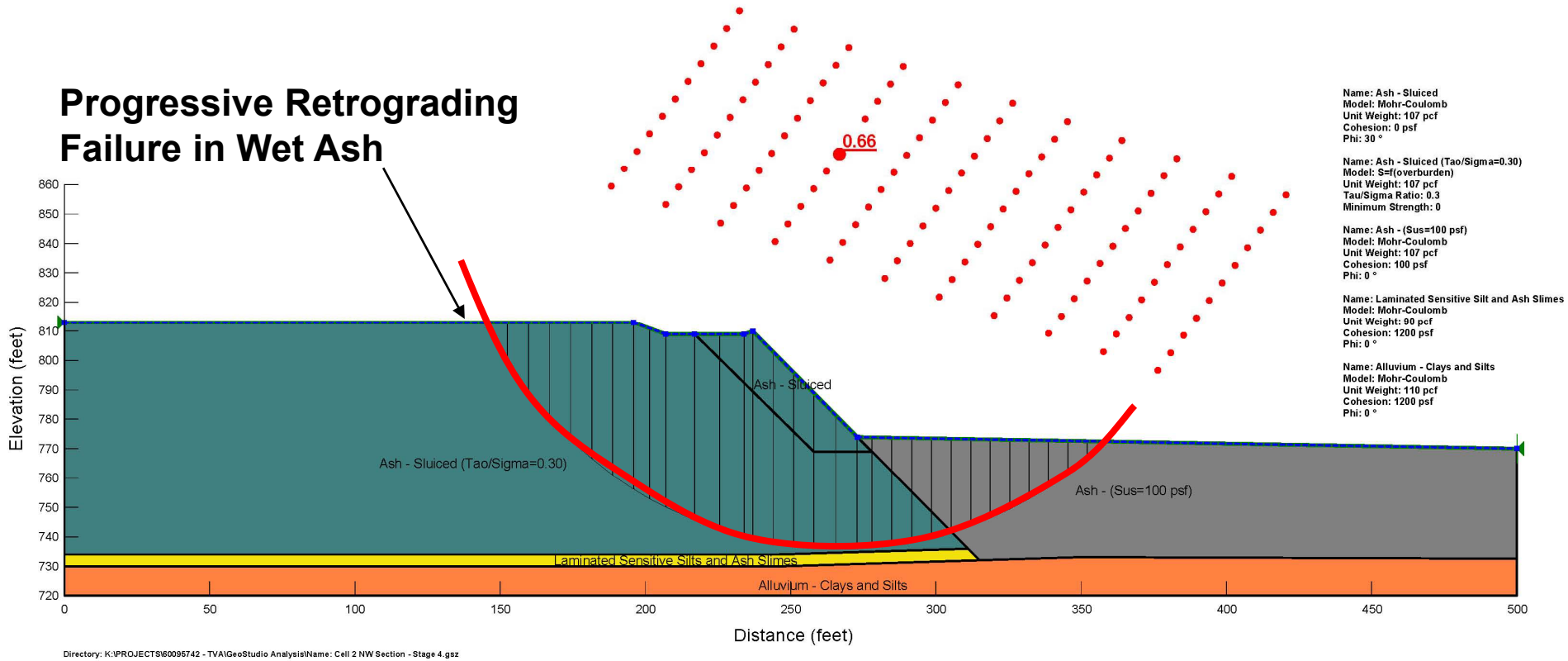
Name: Ash - (Sus=100 psf)
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Cohesion: 100 psf
Phi: 0 °

Directory: K:\PROJECTS\60095742 - TVA\GeoStudio Analysis\Name: Cell 2 NW Section - Stage 3 Post-Failure Case 2.gsz

Dredge Cell 2 Northwest Section

Stage 4: Progressive Failures of Remaining Cells 2 and 1

Factor of Safety = 0.7



Dredge Cell 2 Southwest Section

Case 1: Flyash Drained Condition Phi (Ø)=30˚

Name: Ash - Dike & Dike B2
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Unit Wt. Above Water Table: 102 pcf
Cohesion: 0 psf
Phi: 37 °

Name: Ash - Sluiced
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Cohesion: 0 psf
Phi: 30 °

Name: Dike B1 & Swan Pond Road
Model: Mohr-Coulomb
Unit Weight: 114 pcf
Cohesion: 0 psf
Phi: 37 °

Name: Railroad Shale Fill
Model: Mohr-Coulomb
Unit Weight: 120 pcf
Cohesion: 0 psf
Phi: 37 °

Name: Alluvium - Clays and Silts
Model: Mohr-Coulomb
Unit Weight: 110 pcf
Cohesion: 1200 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 1
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1100 psf
Phi: 0 °

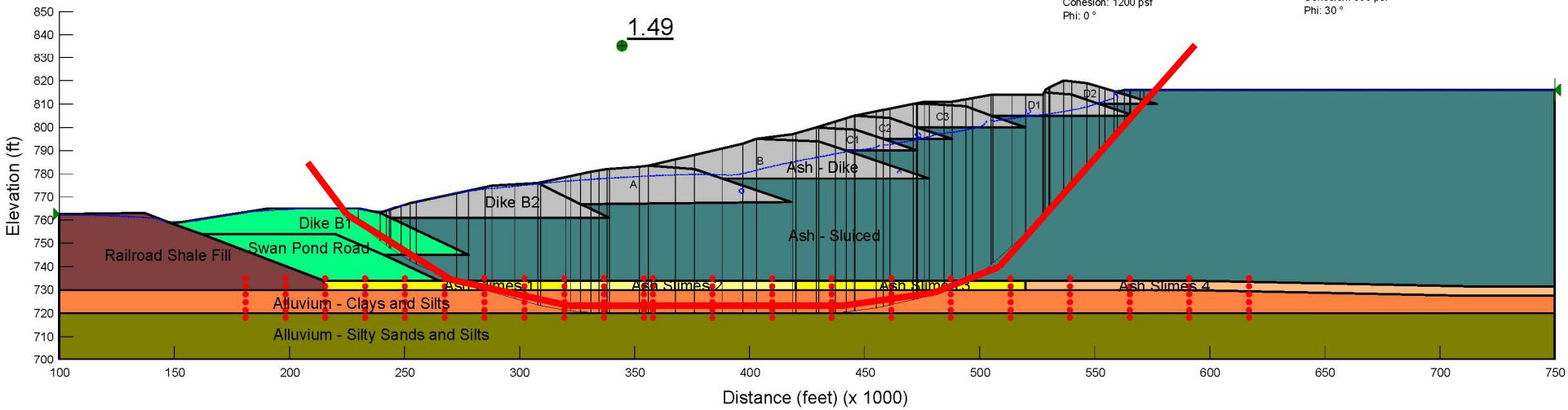
Name: Laminated Sensitive Silts and Ash Slimes 2
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1175 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 3
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1250 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 4
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1400 psf
Phi: 0 °

Name: Alluvium - Silty Sands and Silts
Model: Mohr-Coulomb
Unit Weight: 130 pcf
Cohesion: 600 psf
Phi: 30 °

Factor of Safety = 1.5



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Dredge Cell 2 Southwest Section

Case 2: Flyash Undrained Condition Su/p = 0.30

Name: Ash - Dike & Dike B2
Model: Mohr-Coulomb
Unit Weight: 107 pcf
Unit Wt. Above Water Table: 102 pcf
Cohesion: 0 psf
Phi: 37 °

Name: Ash - Sluiced
Model: S=f(overburden)
Unit Weight: 107 pcf
Tau/Sigma Ratio: 0.3
Minimum Strength: 0

Name: Dike B1 & Swan Pond Road
Model: Mohr-Coulomb
Unit Weight: 114 pcf
Cohesion: 0 psf
Phi: 37 °

Name: Railroad Shale Fill
Model: Mohr-Coulomb
Unit Weight: 120 pcf
Cohesion: 0 psf
Phi: 37 °

Name: Alluvium - Clays and Silts
Model: Mohr-Coulomb
Unit Weight: 110 pcf
Cohesion: 1200 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 1
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1100 psf
Phi: 0 °

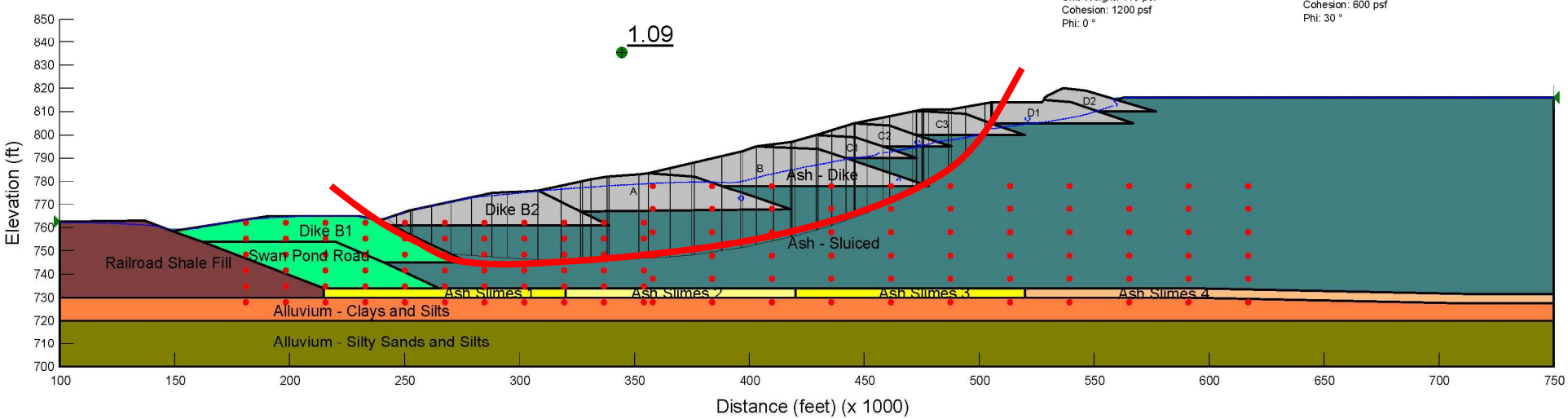
Name: Laminated Sensitive Silts and Ash Slimes 2
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1175 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 3
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1250 psf
Phi: 0 °

Name: Laminated Sensitive Silts and Ash Slimes 4
Model: Mohr-Coulomb
Unit Weight: 90 pcf
Cohesion: 1400 psf
Phi: 0 °

Name: Alluvium - Silty Sands and Silts
Model: Mohr-Coulomb
Unit Weight: 130 pcf
Cohesion: 600 psf
Phi: 30 °

Factor of Safety = 1.1

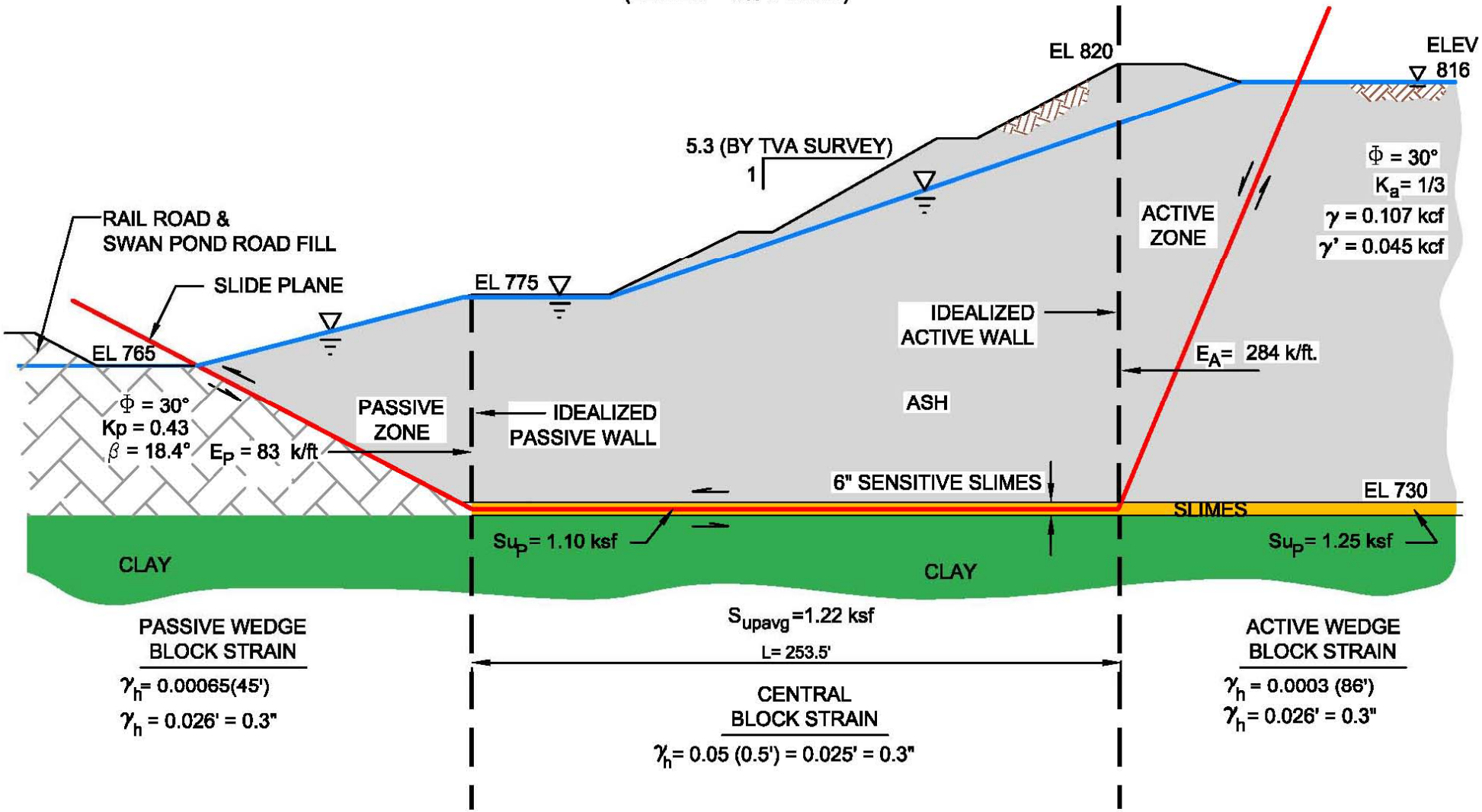


Directory: K:\PROJECTS\60095742 - TVA\GeoStudio Analysis\Name: Cell 2 SW Section Case 2.gsz

AECOM

CELL 2 SOUTHWEST SECTION
WEDGE BLOCK STABILITY ANALYSIS

BASED ON DISPLACEMENT COMPATIBILITY
(SLIMES = 5% STRAIN)



FS = 1.5

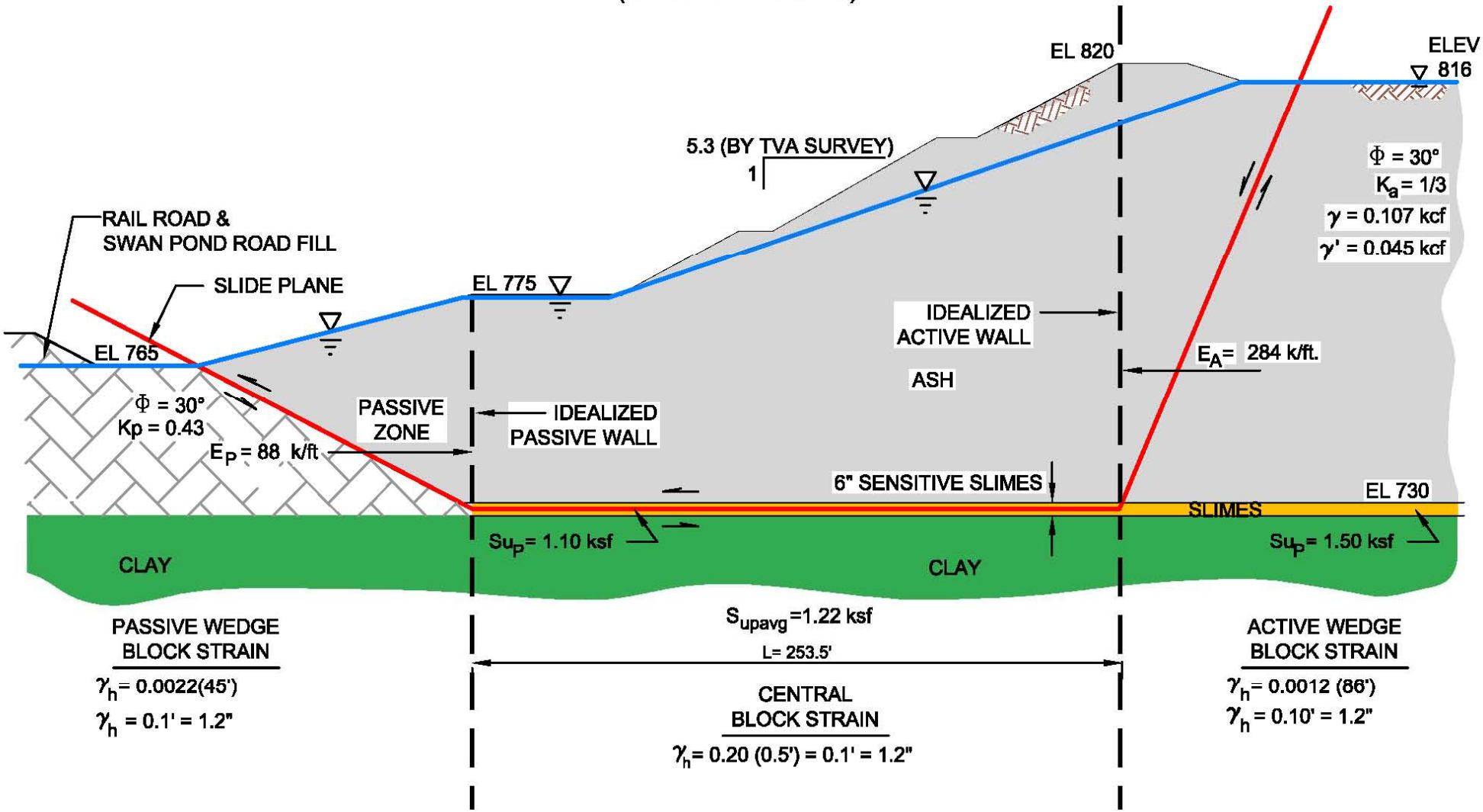
$$FS = \frac{S_{upavg}}{E_A - E_P} = \frac{1.22\ (253.5')}{284 - 83} = \frac{309\ k/ft.}{201\ k/ft.} = 1.5, \textbf{ STABLE}$$

FIG. 1.6.3_17

AECOM

CELL 2 SOUTHWEST SECTION
WEDGE BLOCK STABILITY ANALYSIS

BASED ON DISPLACEMENT COMPATIBILITY
(SLIMES = 20% STRAIN)



$$FS = \frac{S_{upavg}}{E_A - E_P} = \frac{0.75\,(1.22)\,(253.5')}{284 - 88} = \frac{232\text{ k/ft.}}{196\text{ k/ft.}} = 1.2,$$ **NO FAILURE** (INCLUDES CREEP)

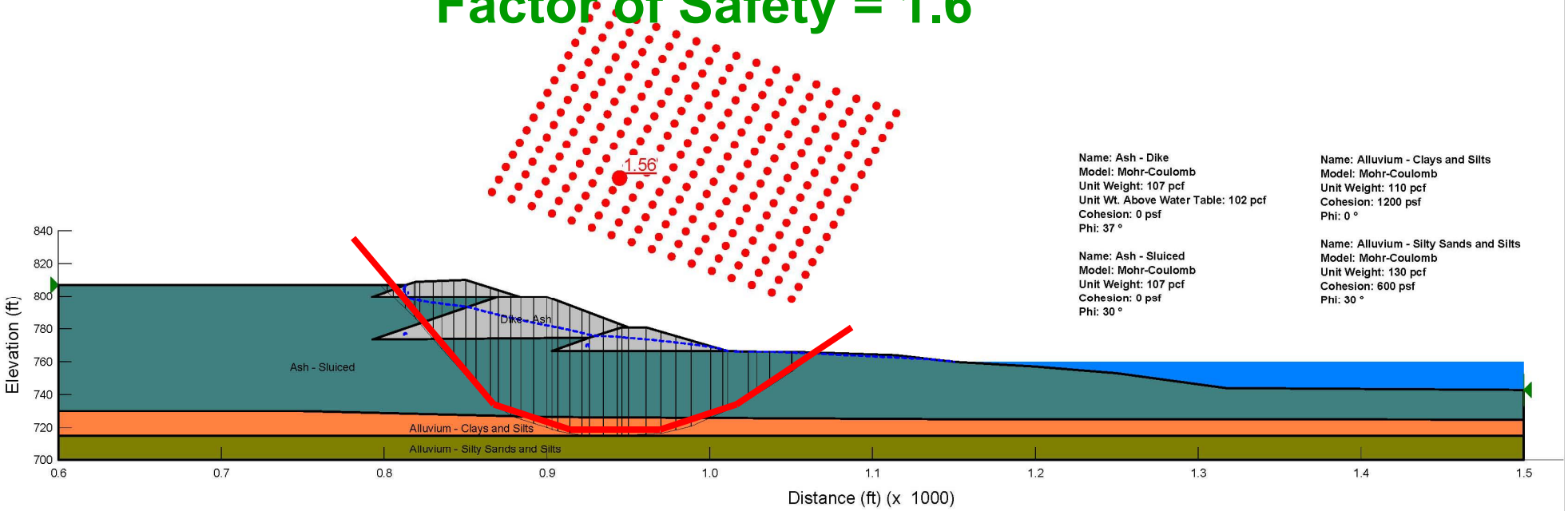
FS = 1.2

FIG. 1.6.3_18

Phase 1 Emergency Dredge Cell East Section

Case 1: Flyash Drained Condition Phi (Ø)=30˚

Factor of Safety = 1.6

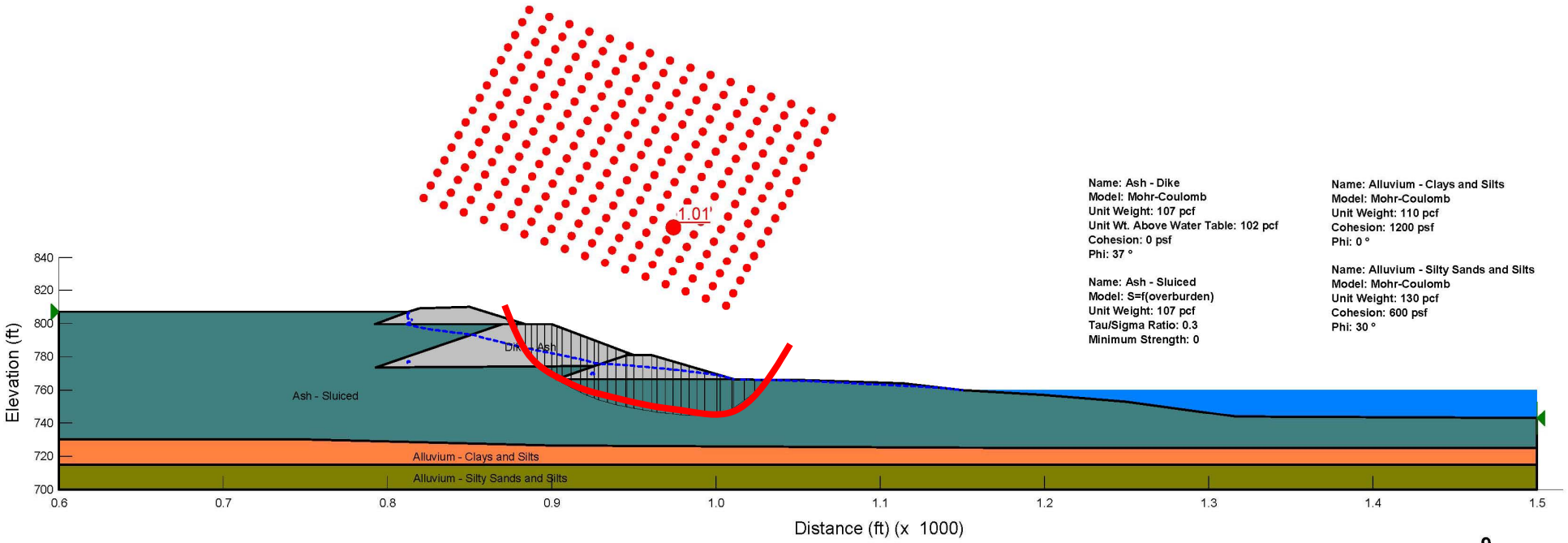


Directory: K:\PROJECTS\60095742 - TVA\GeoStudio Analysis\Name: Phase 1 East Section Case 1.gsz

Phase 1 Emergency Dredge Cell East Section

Case 2: Flyash Undrained Condition Su/p = 0.30

Factor of Safety = 1.0

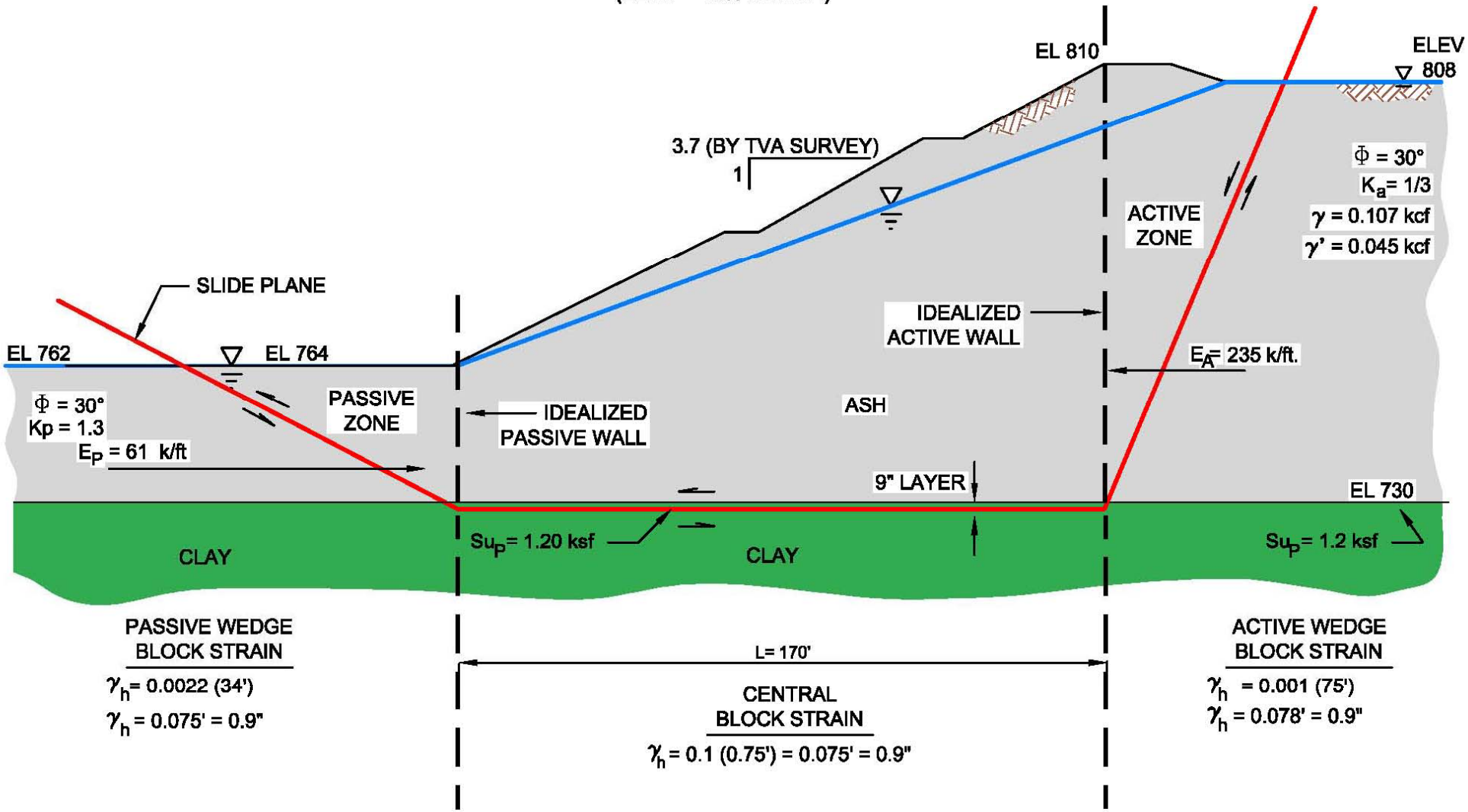


Directory: K:\PROJECTS\60095742 - TVA\GeoStudio Analysis\Name: Phase 1 East Section Case 2.gsz

PHASE 1 EAST EMERGENCY DREDGE CELL
WEDGE BLOCK STABILITY ANALYSIS

BASED ON DISPLACEMENT COMPATIBILITY
(CLAY = 10% STRAIN)

AECOM



FS = 1.2

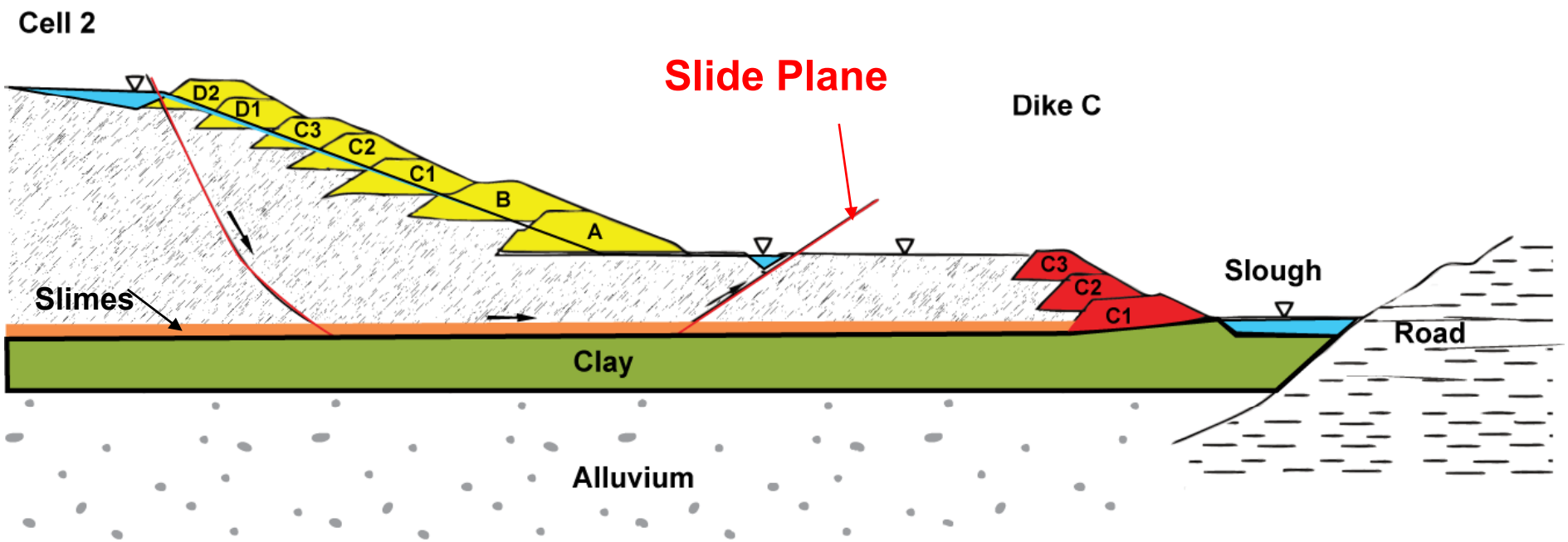
$$FS = \frac{S_{upavg}}{E_A - E_P} = \frac{(1.2)\,(170')}{235 - 61} = \frac{204\ \text{k/ft.}}{174\ \text{k/ft.}} = 1.2,\ \textbf{STABLE}$$

FIG. 1.6.3_19

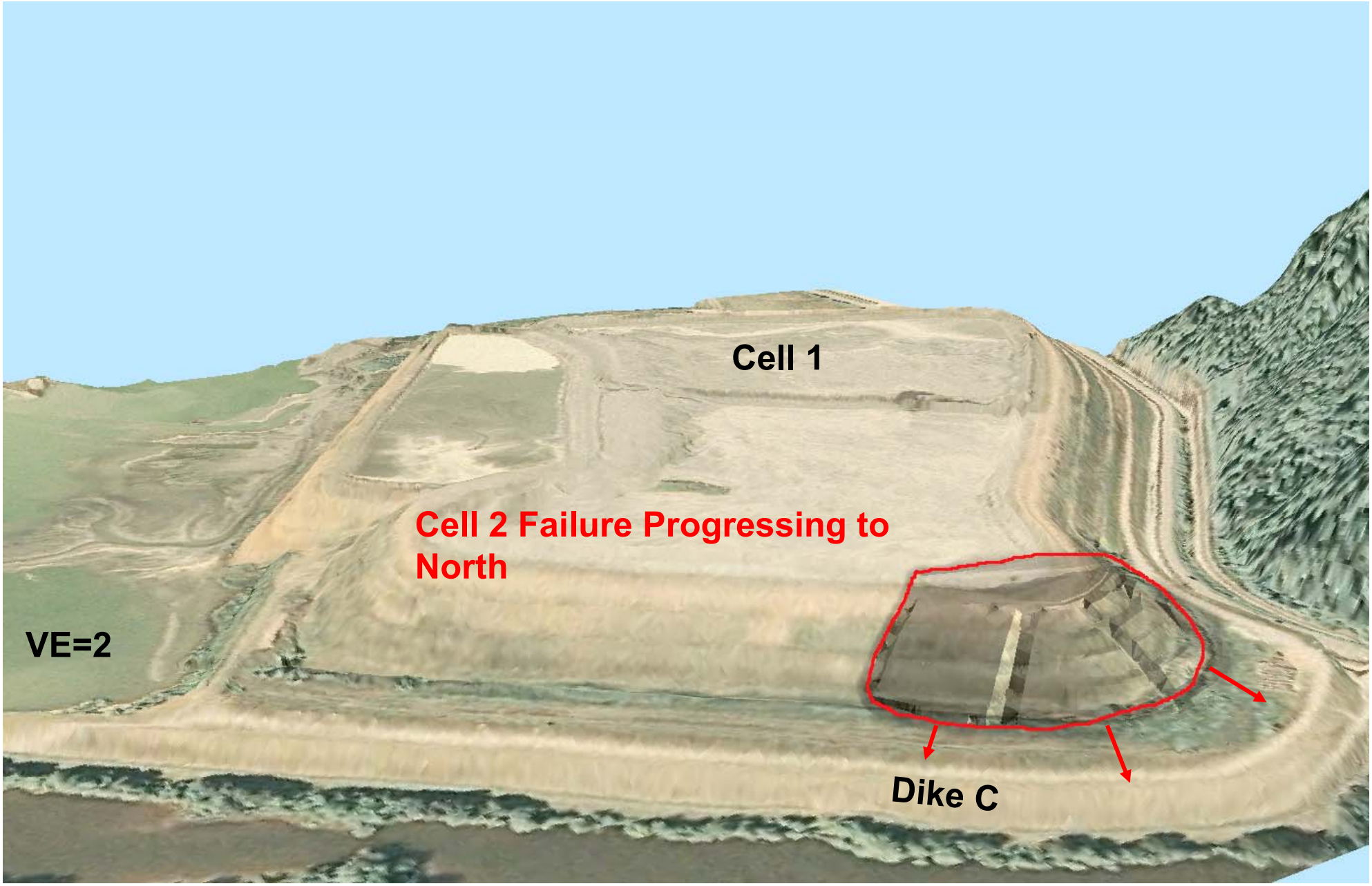
AECOM Slope Stability Analysis Summary

- **Computed FS for Cell 2 Northwest Shows Failure in Slimes**
- Computed FS for Cell 3 Southwest Shows No Failure in Slimes
- Computed FS for Phase 1 Emergency Cell Shows No Failure. No Slimes present
- West Dike Shallow Slope Stability above 1.0
- No evidence of 2008 Piping or Seepage Failure
- Failure event lasted approximately 1 hour

Stage 1 - Initiation of Failure at North Side of Dredge Cell 2

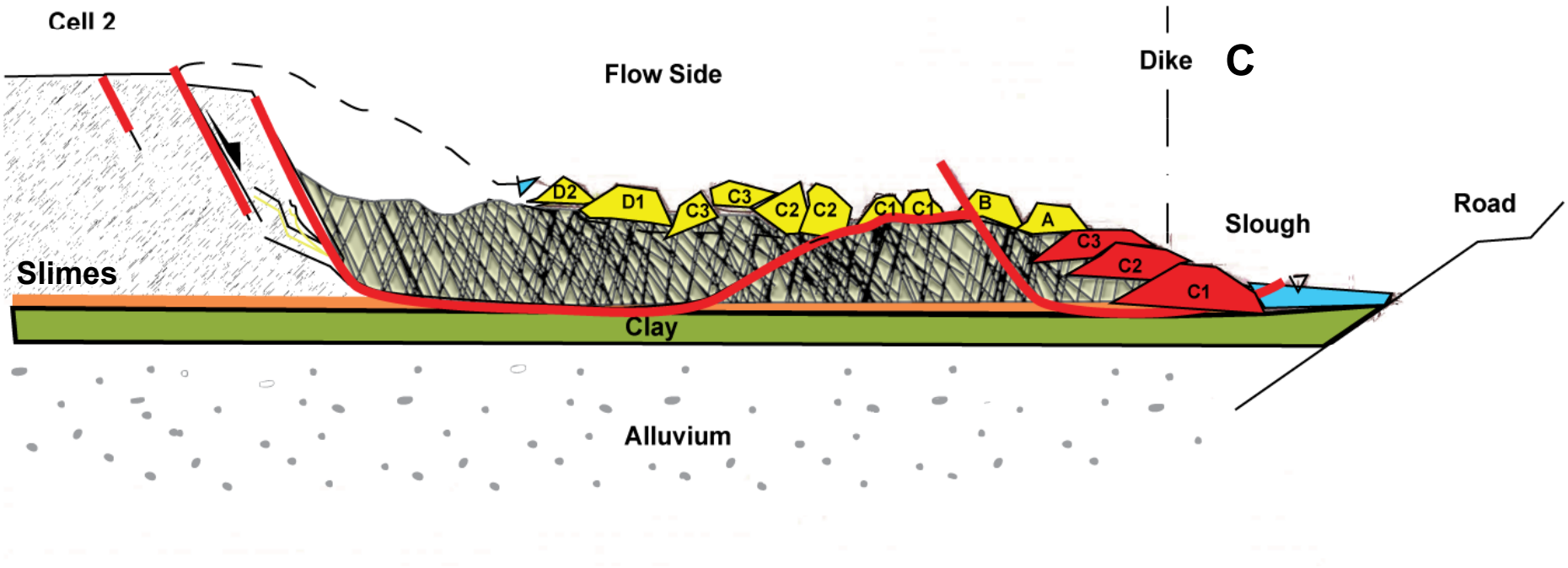


Looking West

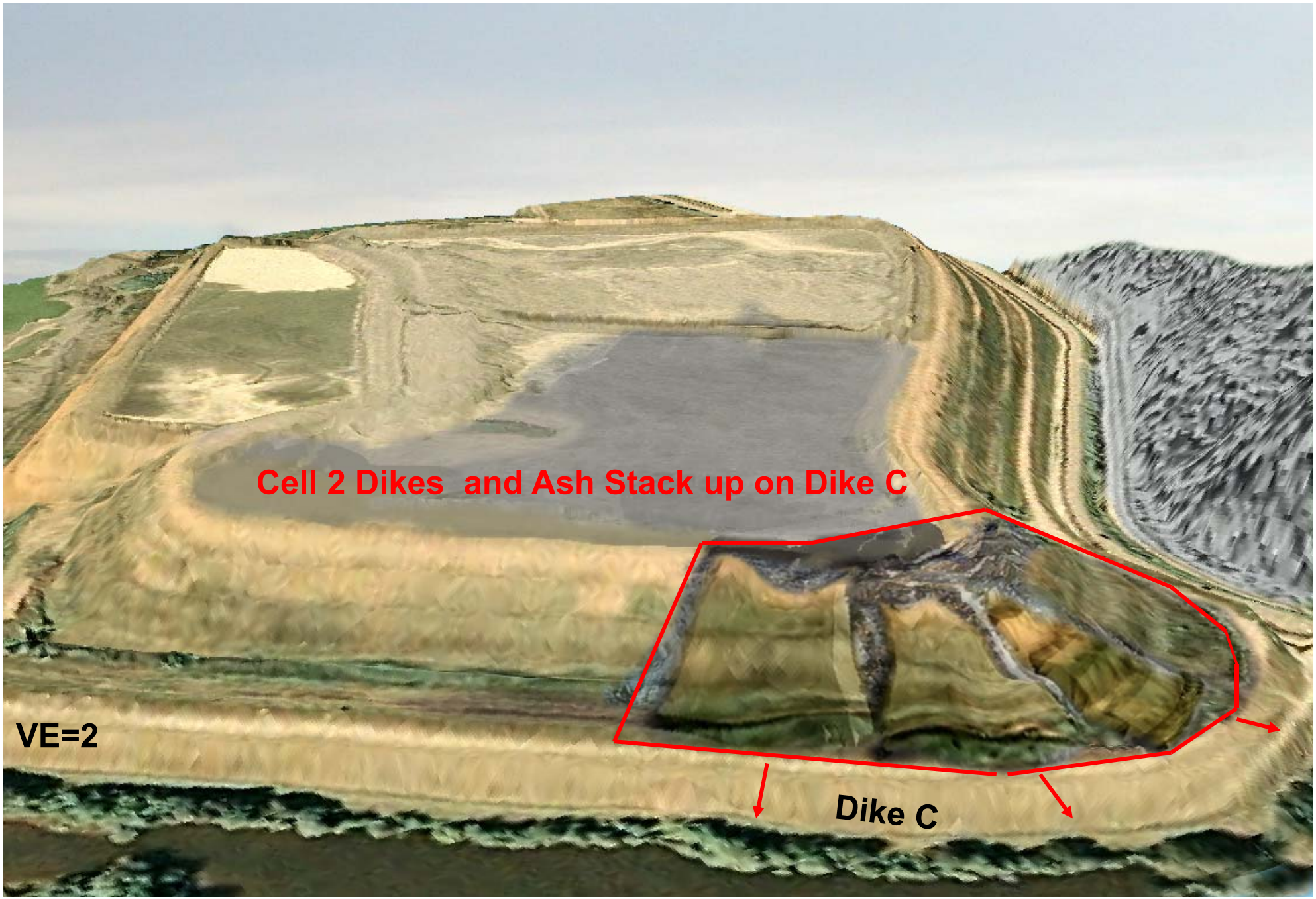


December 22, 2008 Expected Failure Mode at NW Corner of Cell 2

Stage 2 – Ash & Dikes A thru D2 Pile Up Against Dike C. This Surcharge and increased Ash Pressure Causes Dike C to Fail

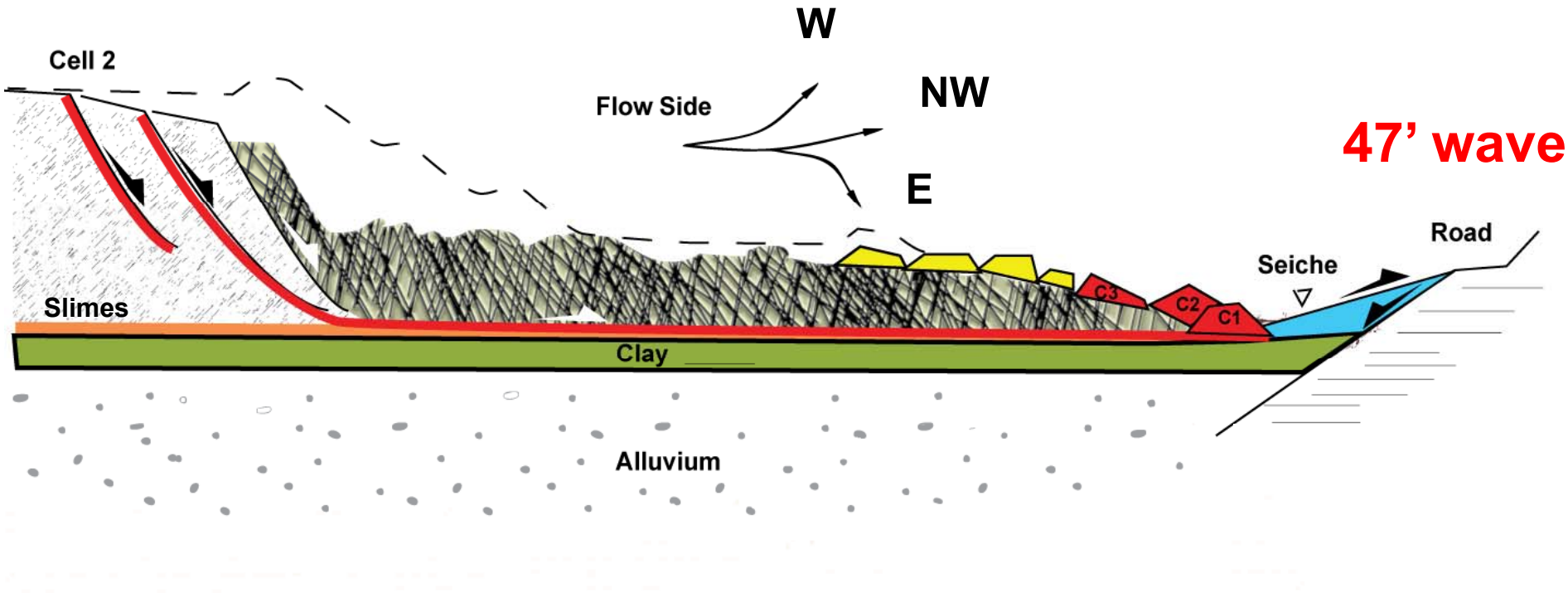


Looking West

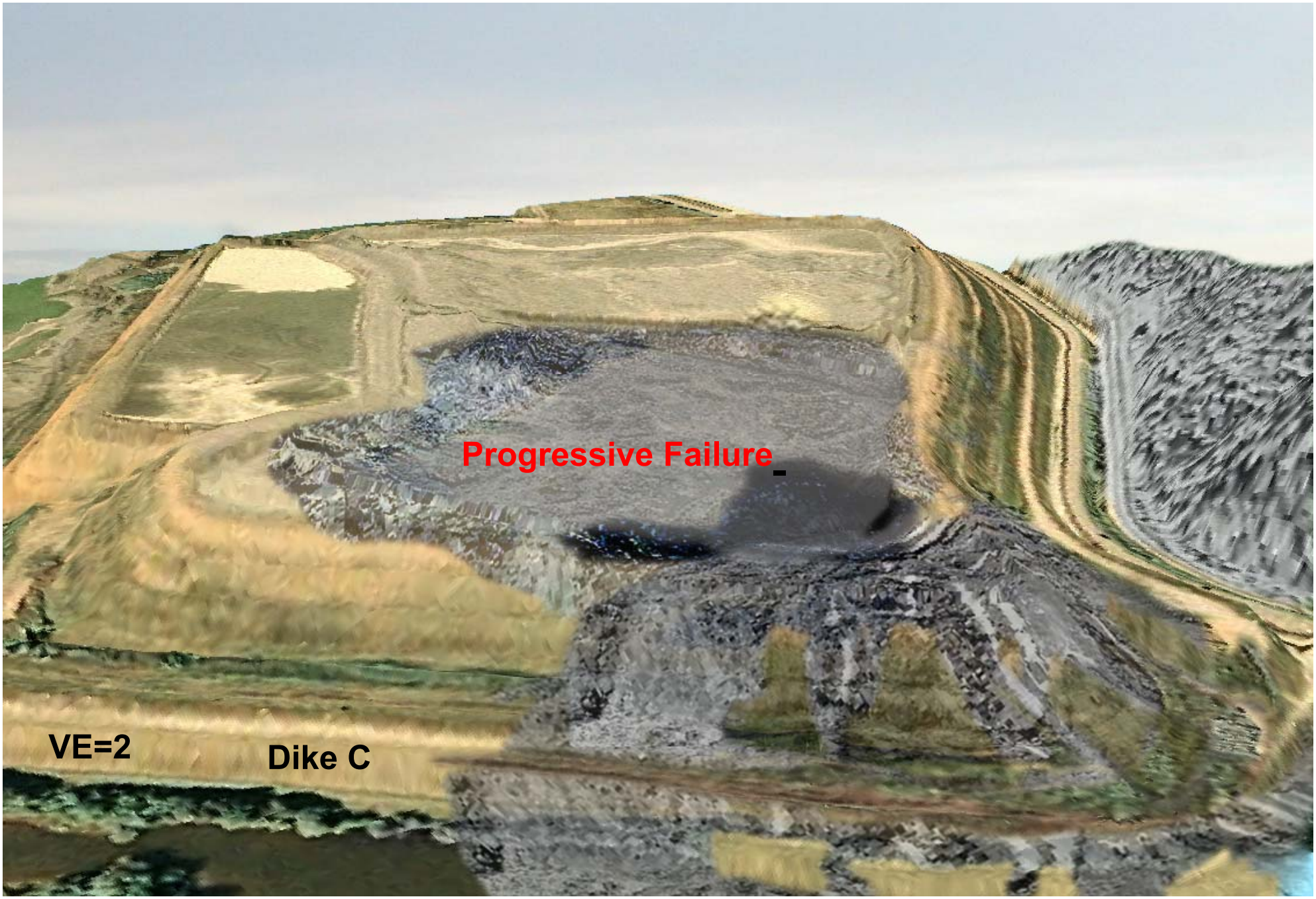


December 22, 2008 Expected Failure Mode at NW Corner of Cell 2

Stage 3 – Progressive Failure Southward that Fails North and West Dikes A thru D2 Back to Cell 1 D Dike. 5.4 Million CY Fill Sloughs and Reservoir



Looking West



December 22, 2008 Expected Failure Mode at NW Corner of Cell 2

December 23, 2008 Post Failure Photo Overlaid on TVA Surveys

Summary of Dredge Cell Failure

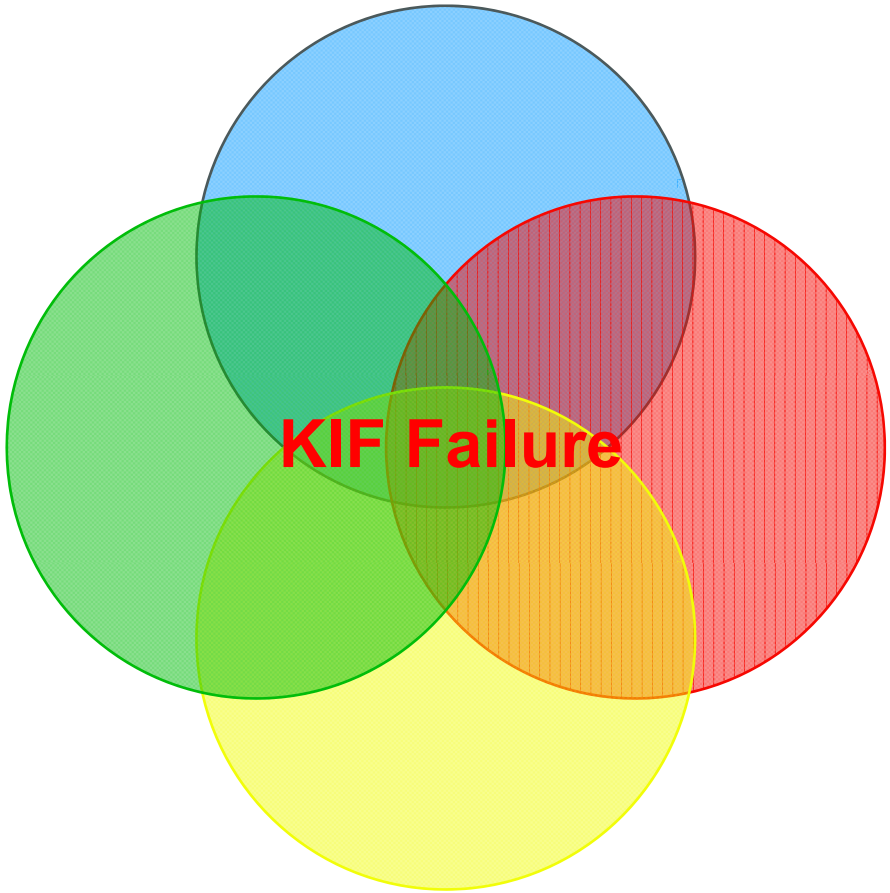
Dredge Cell 2 was on the verge of deep failure at north end of 85 to 90-foot high fill due to:

- Creep or progressive failure of the unusual loose silt mixed with ash slimes under the ash over the Swan Pond Creek Flood Plain
- Initial loose sluiced ash was placed under water and above the critical void ratio steady state line
- No consolidation or densification of sluiced ash occurred with depth even though fill was placed over older ash
- Dredge cells were maintained wet by sluicing
- Upward filling and 50-foot high dikes having 3H:1V slopes with benches. Geometry and added height of ash behind the upstream dike construction adds load to the silt/ash slimes and foundation soils
- The upstream dikes founded on wet loose sluiced ash with a 200-foot setback from perimeter Dike C

Kingston Dredge Cell Failure Conditions

Increased Loads Due to Higher Fill

Hydraulically Placed Loose Wet Ash



Fill Geometry & Setbacks

<u>Unusually</u> Weak Slimes Foundation

Dr. George Sower's 1979 quote on isolating the cause of slope failure reads:

"In most cases, several 'causes' exist simultaneously; therefore, attempting to decide which one finally produced failure is not only difficult but also technically incorrect. Often the final factor is nothing more than a trigger that sets a body in motion that was already on the verge of failure. Calling the final factor *the cause* is like calling the match that lit the fuse that detonated the dynamite that destroyed the building *the* cause of the disaster."

Late Prof. at Georgia Tech

QUESTIONS