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SEISMIC REMEDIATION OF THE CLEMSON UPPER AND LOWER DIVERSION DAMS; EVALUATION, CONCEPTUAL DESIGN AND DESIGN

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Site Location: Clemson, SC

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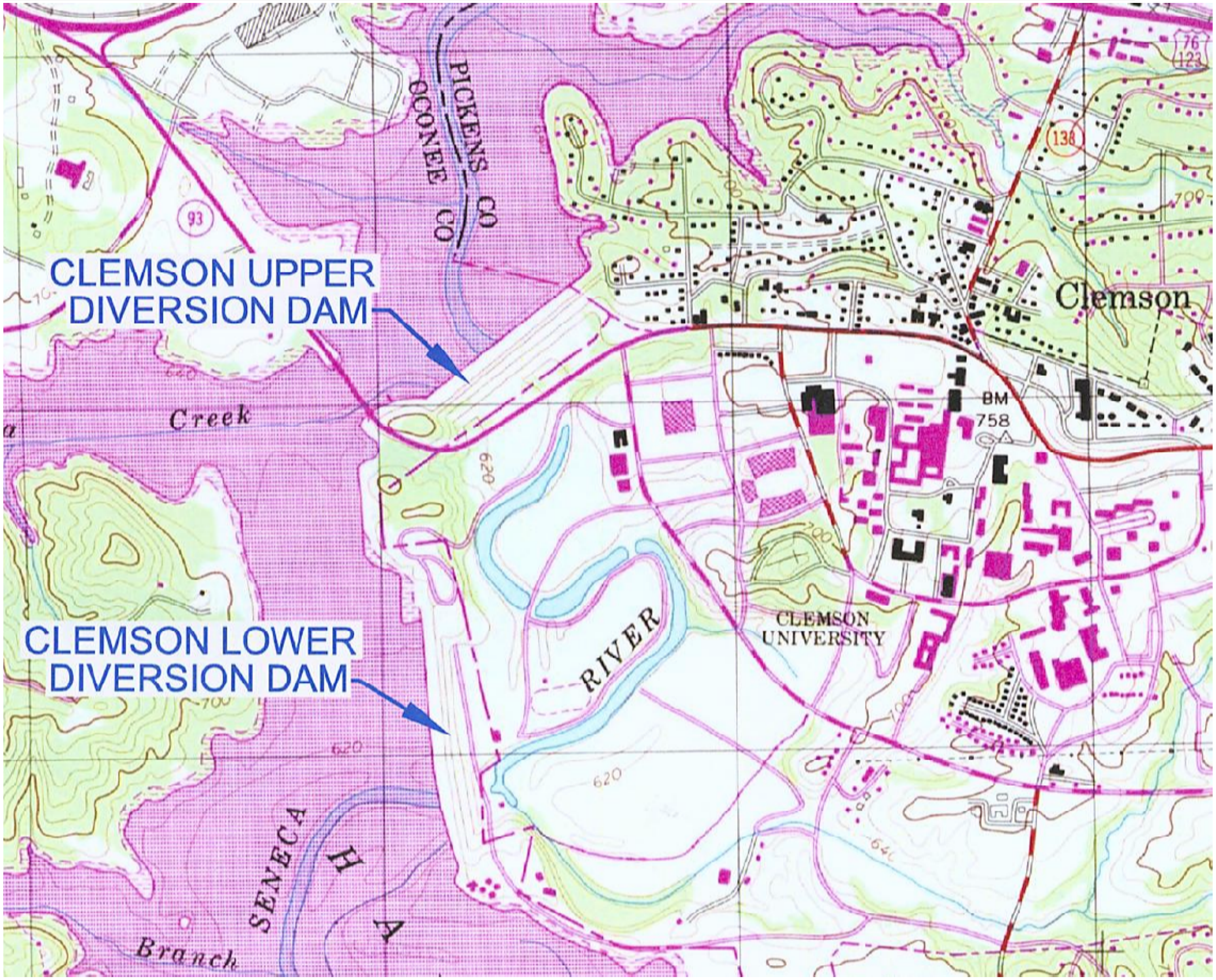

Site Location:
Death Valley (Clemson), SC

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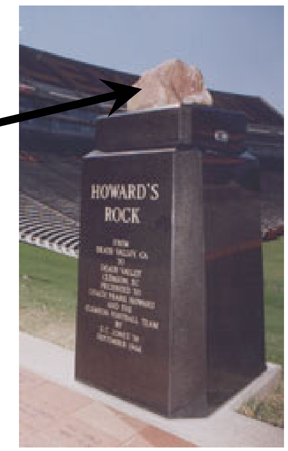
Lower Dam & Lake Hartwell

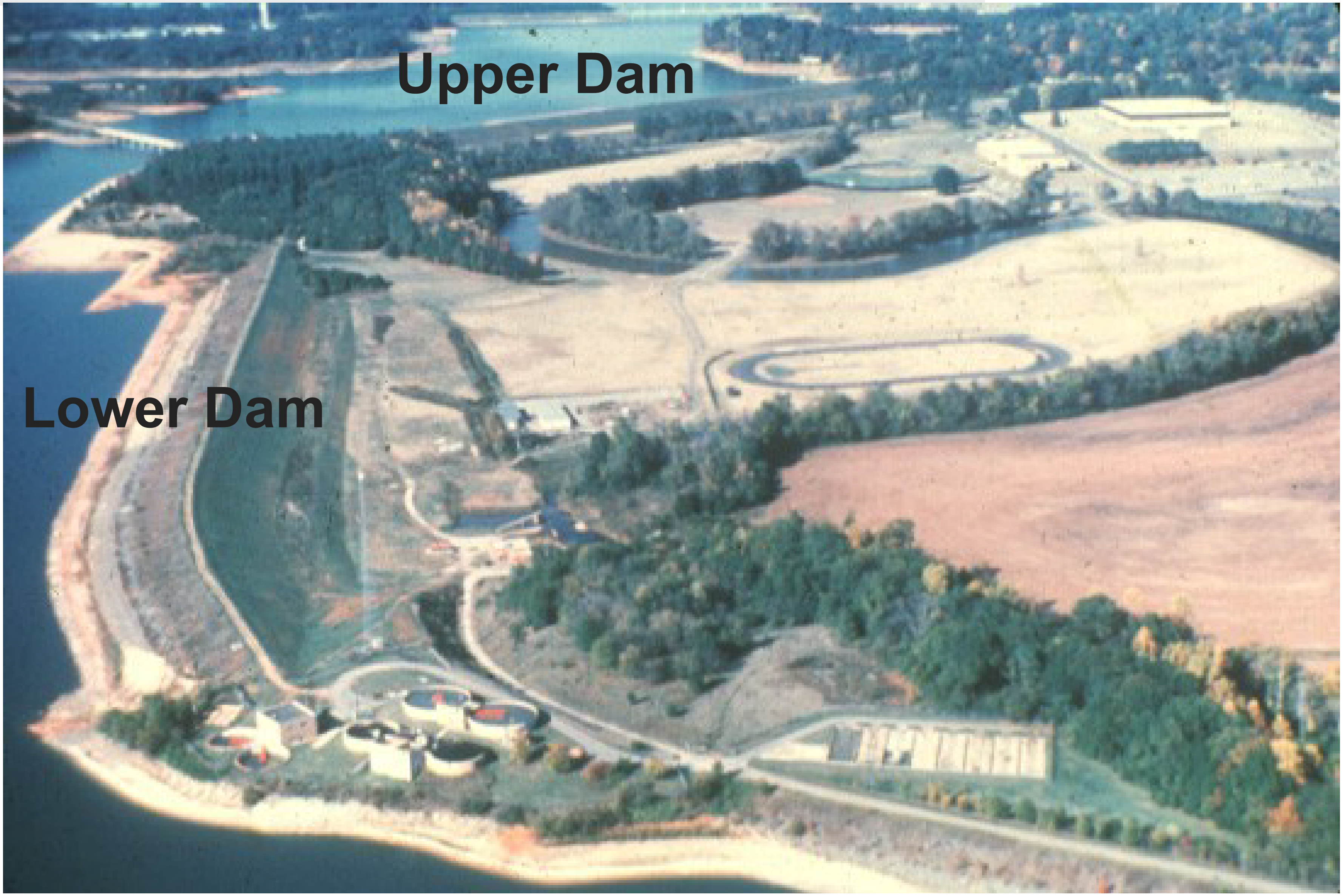
Icon



Saint

Clemson Saturday Religious Rituals

Aerial View of the Dams



Upper Diversion Dam

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Lower Diversion Dam

Simplified Cross Section of Clemson Diversion Dams

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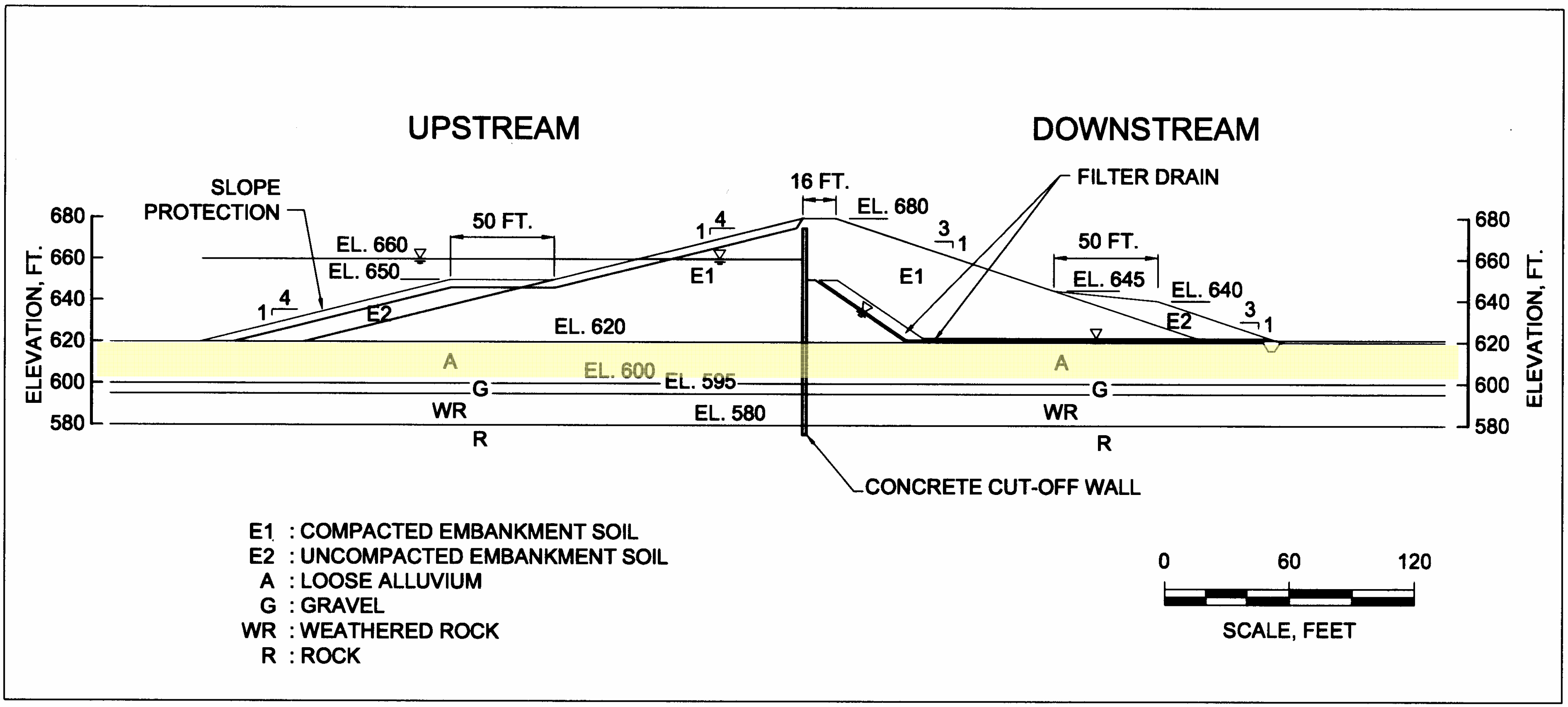

Installation of Cutoff Wall (1980s)

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Seepage Investigations

Early 1980's seepage investigations

- Documented loose silty sand / sandy silt layer within the foundation alluvium
  - Thickness from 7 to 28 feet
  - N-values = 3 to 30 blows per foot
- Reconnaissance report submitted to HQUSACE in 1986 recommending additional seismic stability investigations

Late 1980's and Early 1990's Data Collection & MCE Determination

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Data Collection

- 16 SPT borings
- 23 borings with undisturbed tube samples
- 15 CIUC (R') triaxial tests to large strains
- Laboratory vane shear, large strains
- Cross-hole seismic surveys (Vs profiles)

MCE Determination (WES)

- MCE: far field event with MM=VII in SC Seismic Zone (includes Charleston)
- a_{max} = 0.19 g
- Four EQ records, including 1971 San Fernando records

Conditions for Liquefaction Slope Failure

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Two Conditions for Occurrence of a Liquefaction Slope Failure

- **Potentially Unstable -** Slope must be unstable if soil strengths drop to Sus (Undrained Steady State Strength)
- **Triggering Strains Occurrence -** Soils must undergo strains that exceed triggering strains

Liquefaction Slope Failure Conditions

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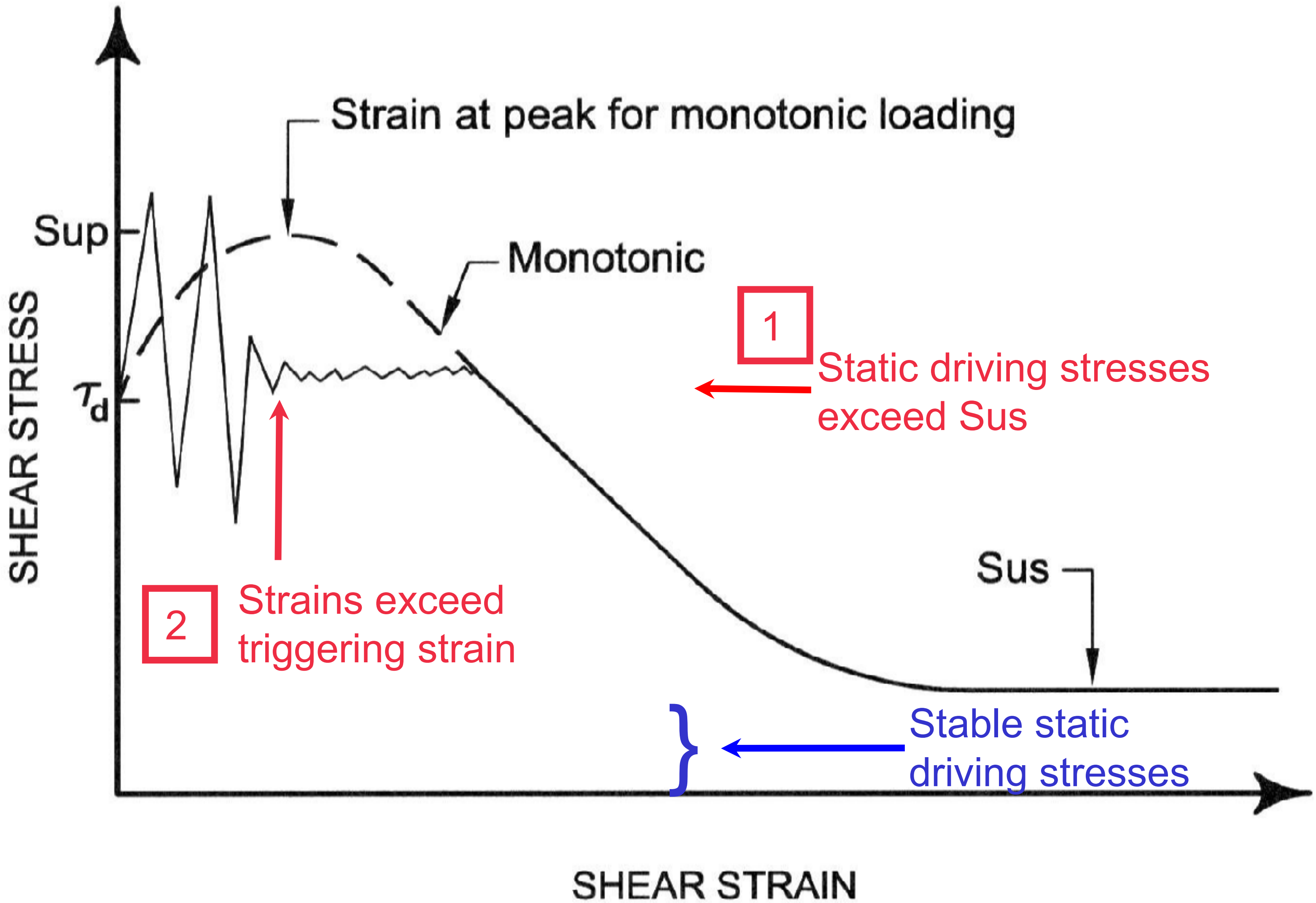

Seismic Stability Analyses for Clemson – 3 Levels

1. Steady-state-strength slope stability
2. One-dimensional triggering analysis; Newmark/SHAKE analysis beneath mid-slope berms
3. Two-dimensional dynamic finite element (FE) seismic model TARA, developed and applied by Prof. Liam Finn, UBC / Kagawa U.

1-D Triggering Analysis – Seismic Model

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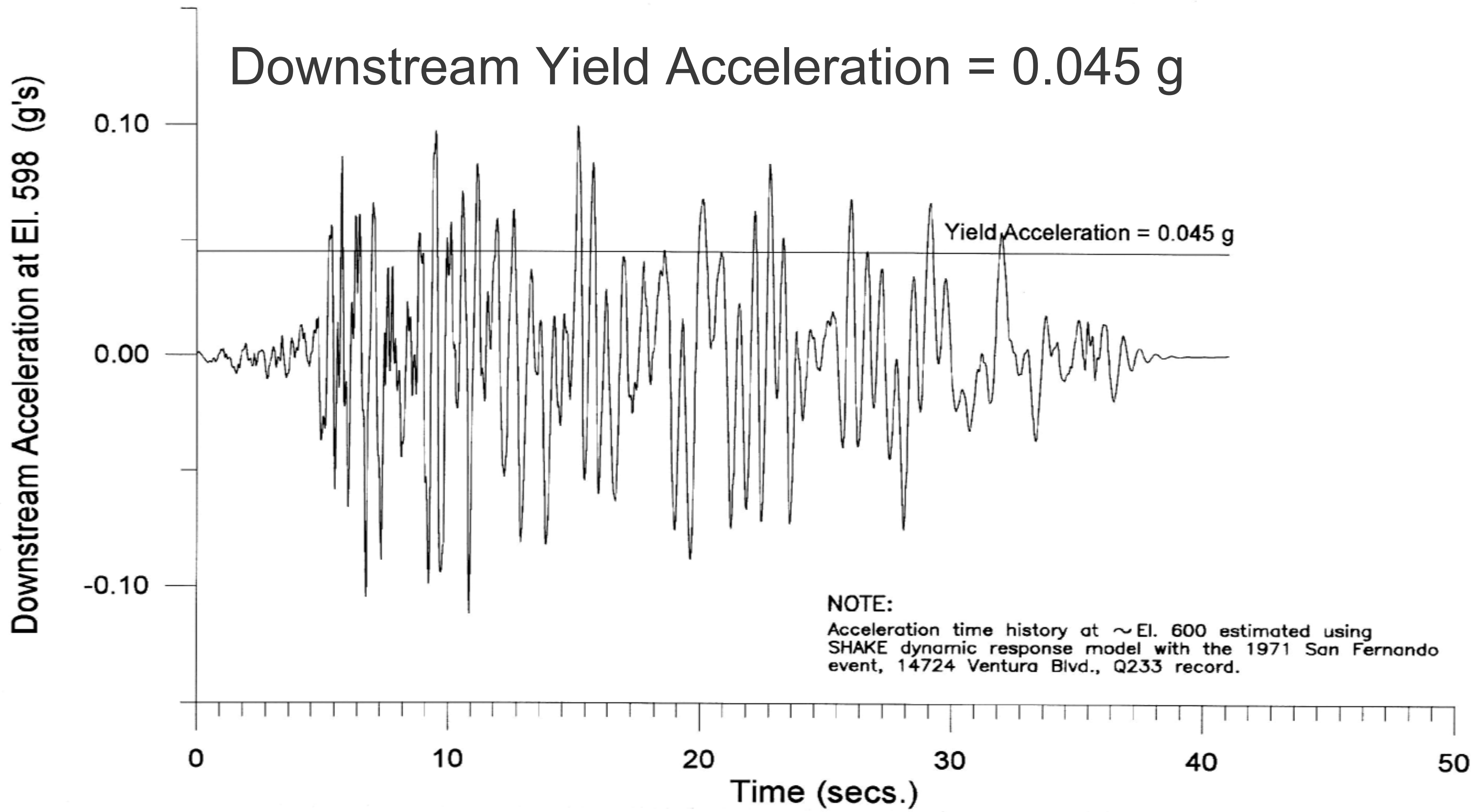
Downstream Slope – SHAKE Time History of Stress

Downstream Yield Acceleration = 0.045 g



1-D Triggering Analysis – Seismic Model

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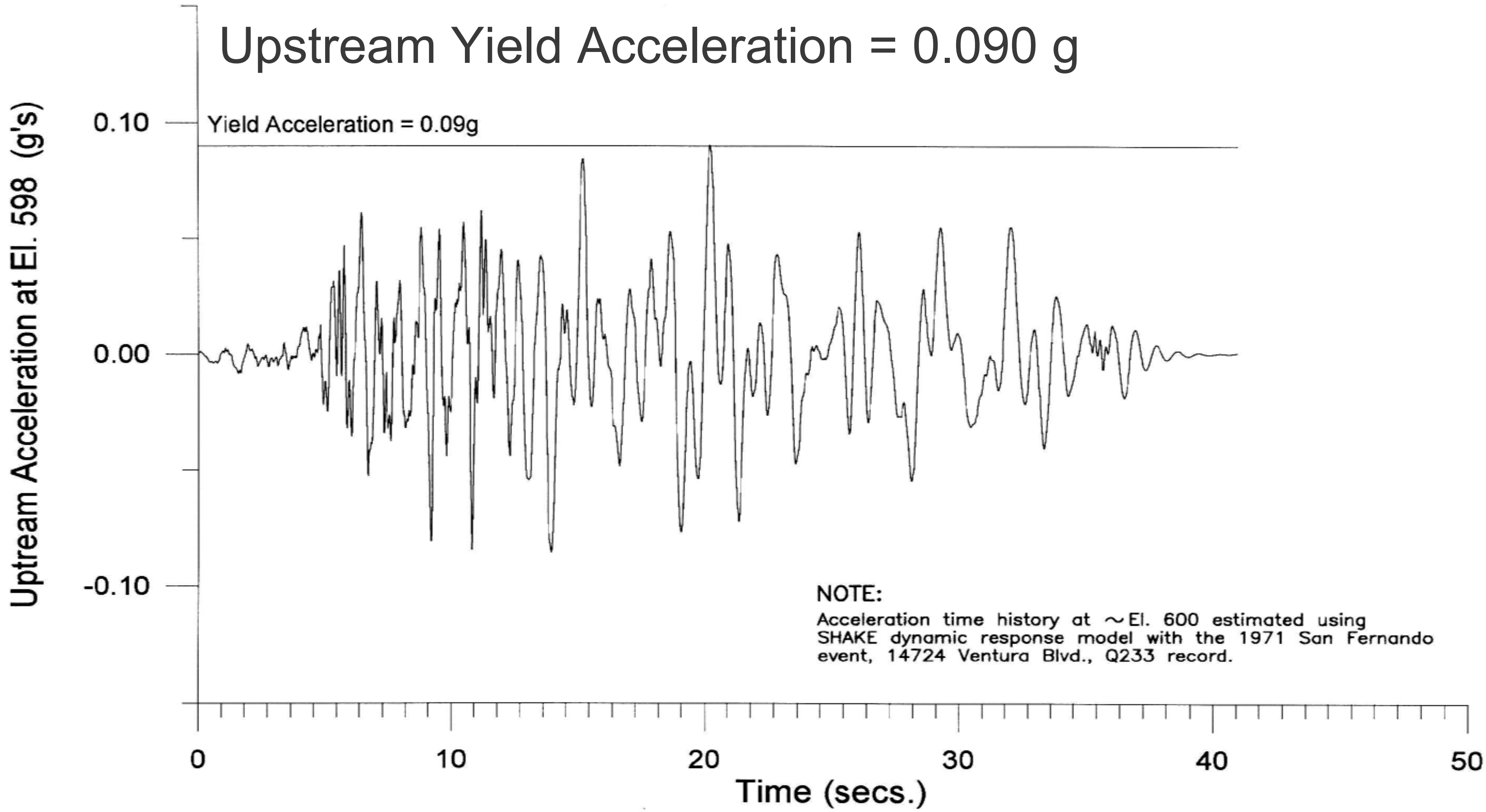
Upstream Slope – SHAKE Time History of Stress

Upstream Yield Acceleration = 0.090 g



2-D Dynamic FE Analysis – Seismic Strains FE Model

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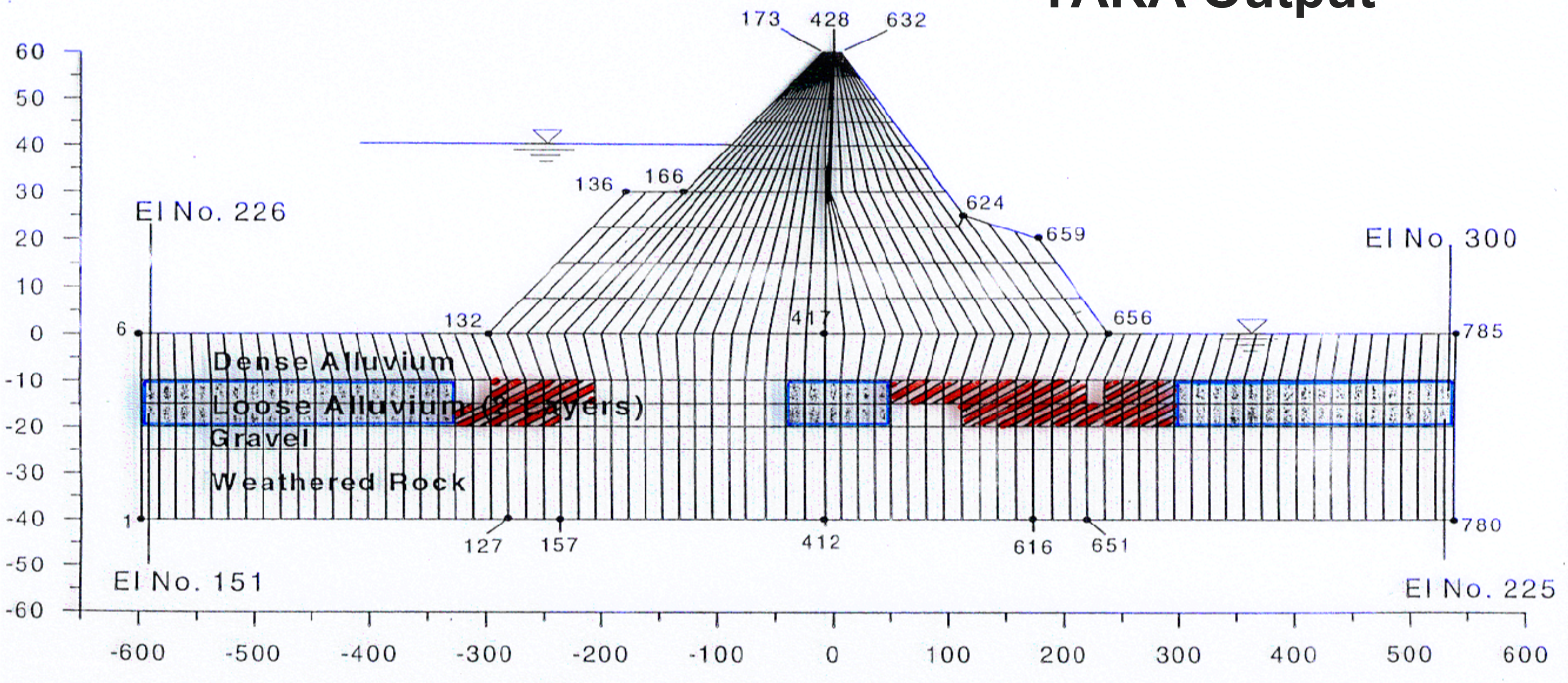
TARA Output



Triggered elements in red ($\gamma_{total} > 0.5\%$)

2-D Dynamic FE Analysis – Deformations FE Model

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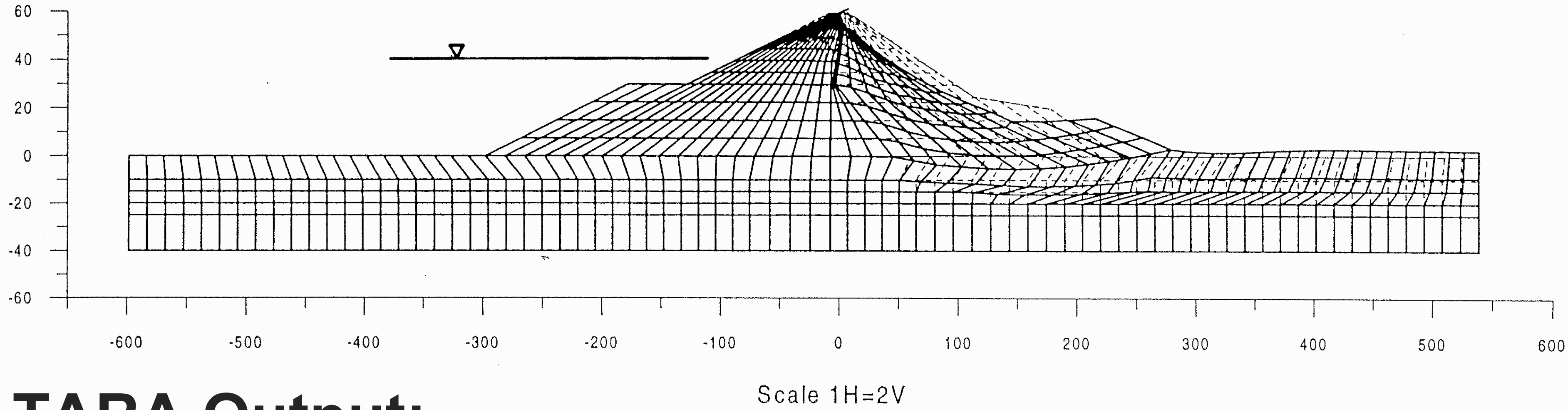

TARA Output:

<u>Horizontal Deformations:</u>

- Crest - **3.4 feet**
- Downstream Berm - **37.6 feet**
- Upstream Berm - **0.3 feet**

<u>Vertical Deformations:</u>

- Crest – **7.4 feet**

Stability Evaluation Conclusions

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Analyses using SHAKE/Newmark methods and TARA FE model indicate:

- **Downstream slope** will be **unstable** following MCE
- **Upstream slope** will be **stable** following MCE
- Dams would no longer be able to retain the normal reservoir
- Remediation of the downstream section of the dam is required
- No need to remediate the upstream section of the dam

Remedial Design

Goal:

Prevent a liquefaction failure and excessive deformations of the downstream sections of the Upper and Lower Clemson Diversion Dams during or following the Maximum Credible Earthquake (peak acceleration of 0.19 g)

Conceptual Designs

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1) Jet Grouting
2) Deep Soil Mixing
3) Stone Columns
4) Excavation and Replacement

Conceptual Designs

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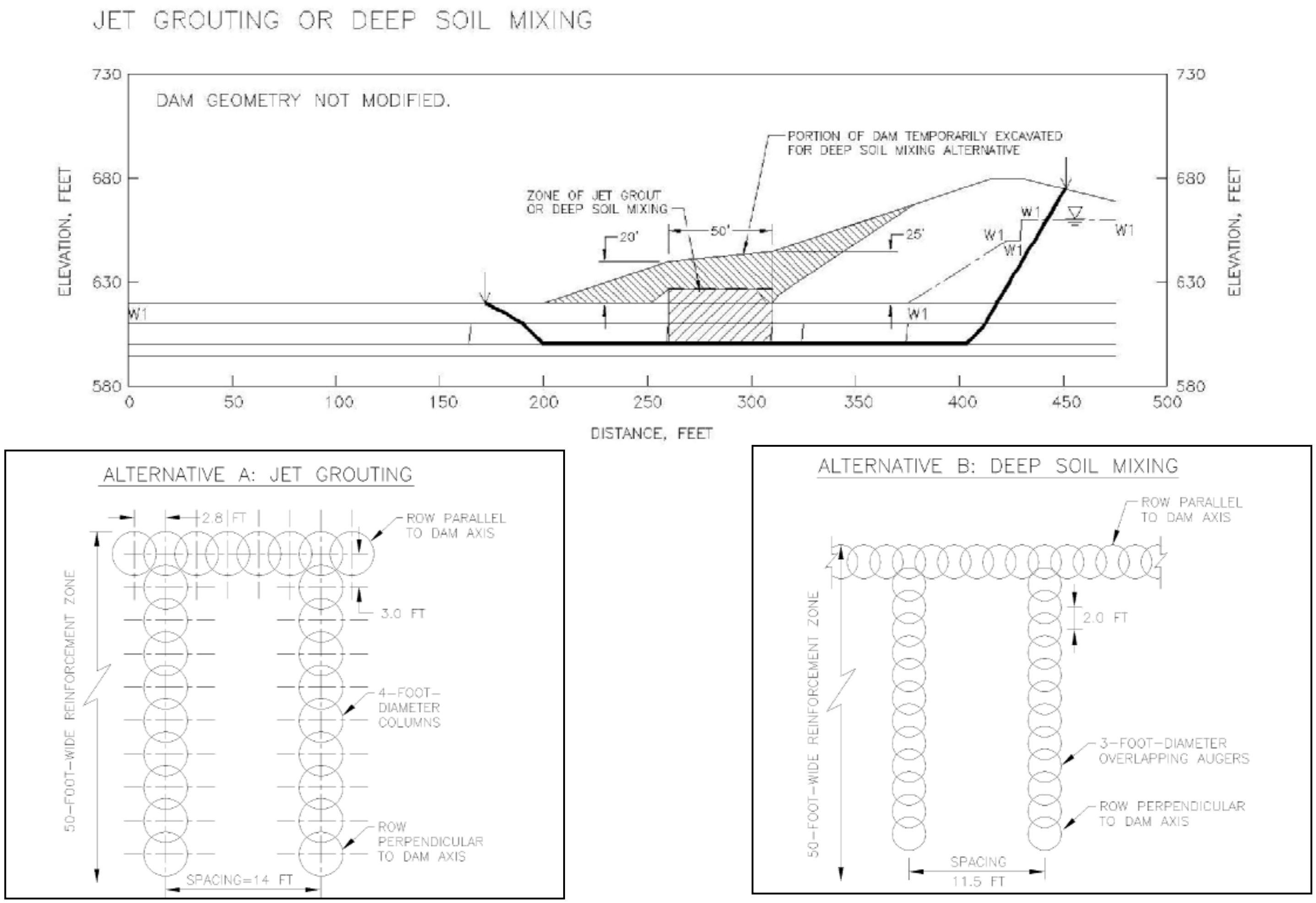
1) Jet Grouting or 2) Deep-Soil Mixing



Conceptual Designs

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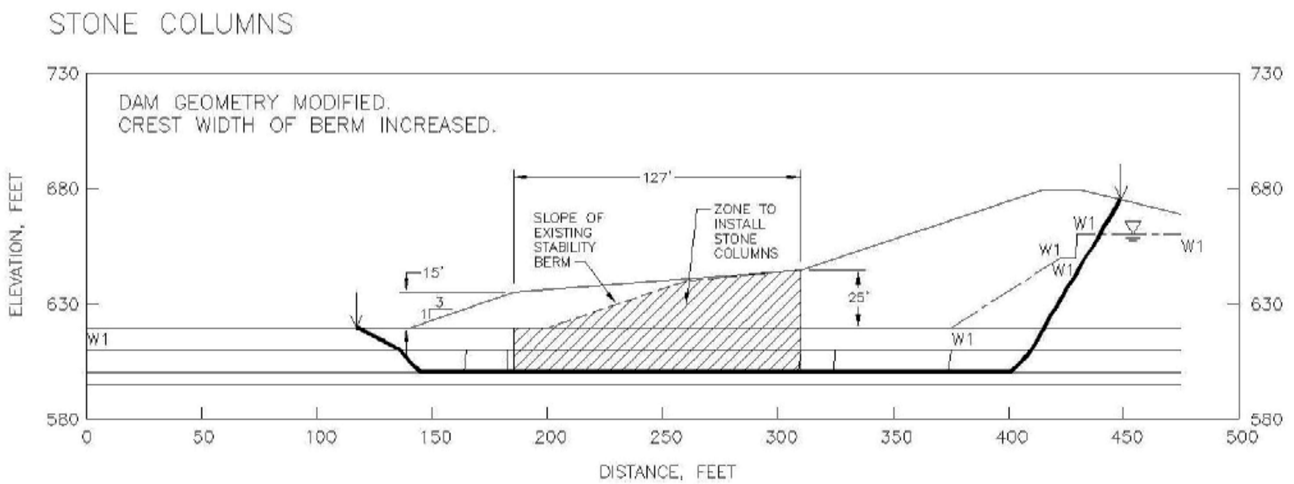
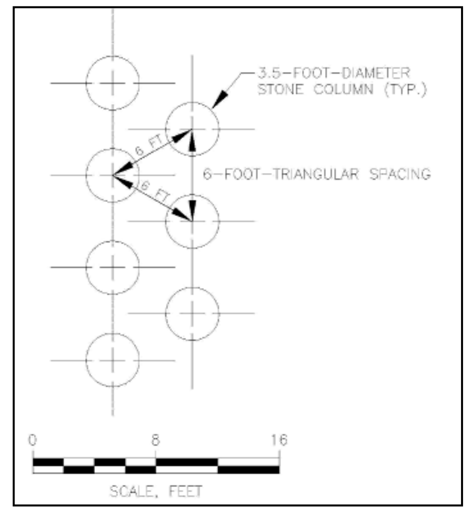
3) Stone Columns





Conceptual Designs

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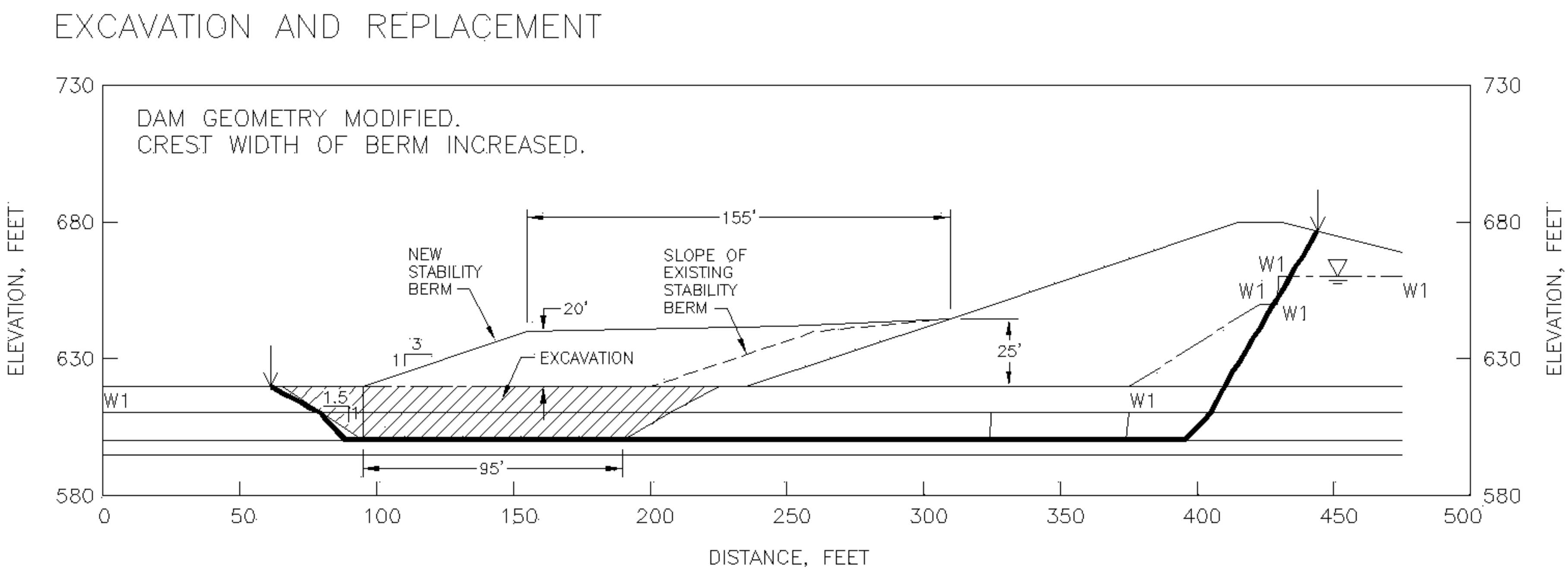
4) Excavation and Replacement



Conceptual Designs

Option	Estimated Cost
Jet Grouting	$10,700,000 to $14,100,000
Deep Soil Mixing	$8,200,000 to $9,800,000
Stone Columns	$14,200,000 to $14,700,000
Excavation and Replacement	$9,800,000 to $10,900,000

Conceptual Designs

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DESIGN SELECTION

Criteria:

- Cost
- Quality Assurance
- Confidence in Model
- Stability during construction
- Construction traffic
- Impact on adjacent structures
- Potential for weather delays
- Aesthetics

Selection:

Deep Soil Mixing

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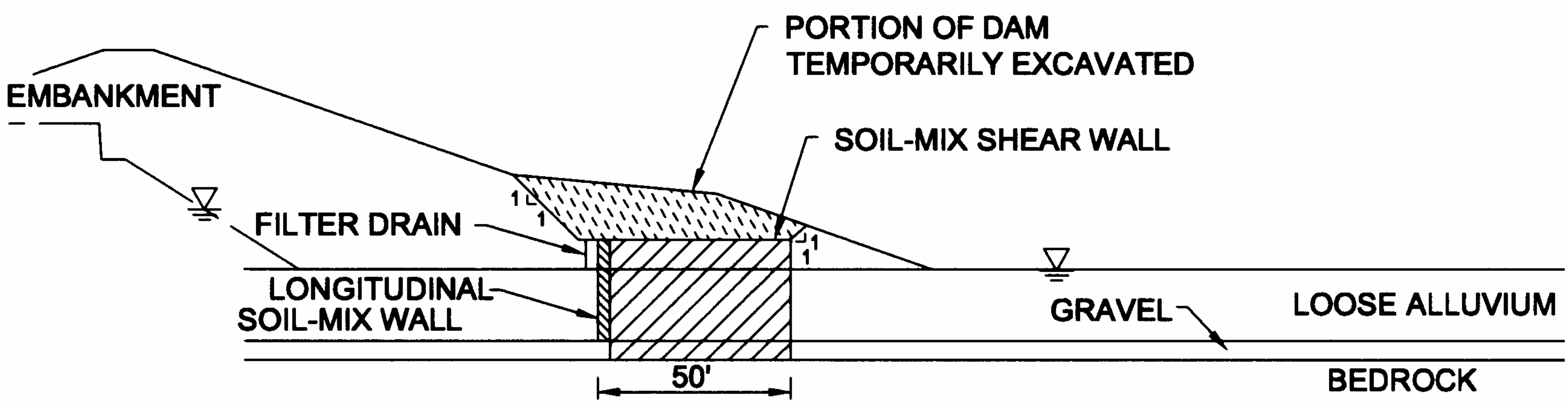
Final Design Details for Deep Soil Mix Remedial Measures

- 50-foot-long, 3-foot-wide transverse shear walls
- 15.5-foot wall spacing (center to center)
- Average shear strength of remediated zone = 2750 psf
- Soil-cement mix target strength ≈ 400 psi
- Wall embedments into upper berm material and into lower sand & gravel
- Longitudinal wall upstream of transverse walls
- Filtered drain upstream of longitudinal wall

Remedial Design



Final Design – Schematic Section

Remedial Design

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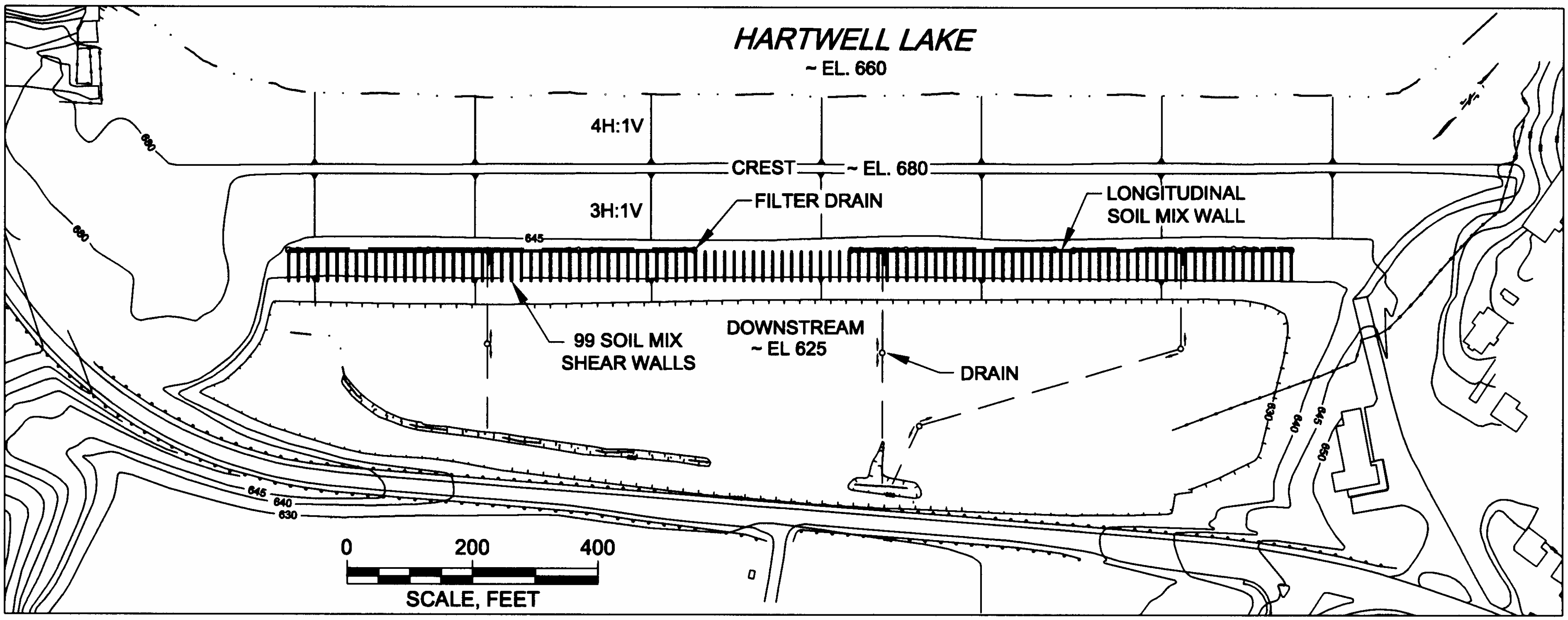

Final Design – Layout of Soil Mix Shear Walls Upper Diversion Dam

Remedial Design – Final Design Issues

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- What are the **Subsurface Conditions**?
  - Extent of Alluvium (top and bottom elevations)
  - Alluvium Soil Characteristics
  - Undrained Strength of Alluvium Clays & Silts for Excavation Stability
- What **soil cement shear strength** do we need?
- Can the Contractor produce a suitable **soil cement** with the Alluvium soils?
- **Where** should the soil mix walls be located to:
  - Provide seismic stability?
  - Minimize construction difficulties & costs?
- How should the design provide for **drainage of seepage**?
- How can we assure soil cement quality (**QA**)?

Remedial Design – Field Investigation

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- **Phase I Soil Borings (23)**
  - Thickness and depth of the alluvial layers requiring remediation
  - Characteristics of the alluvial layers
  - Thickness and depth of the blanket drain layer
  - Depth of the underlying dense sand, sand and gravel, or bedrock
- **Phase II Soil Borings (15)**
  - Bulk samples for soil-cement mix testing
  - Undisturbed samples of clay & silt alluvial soils for undrained strength testing
- **Groundwater Sampling** (for chloride & sulfate levels)
- **Local Cement Sampling**

Remedial Design

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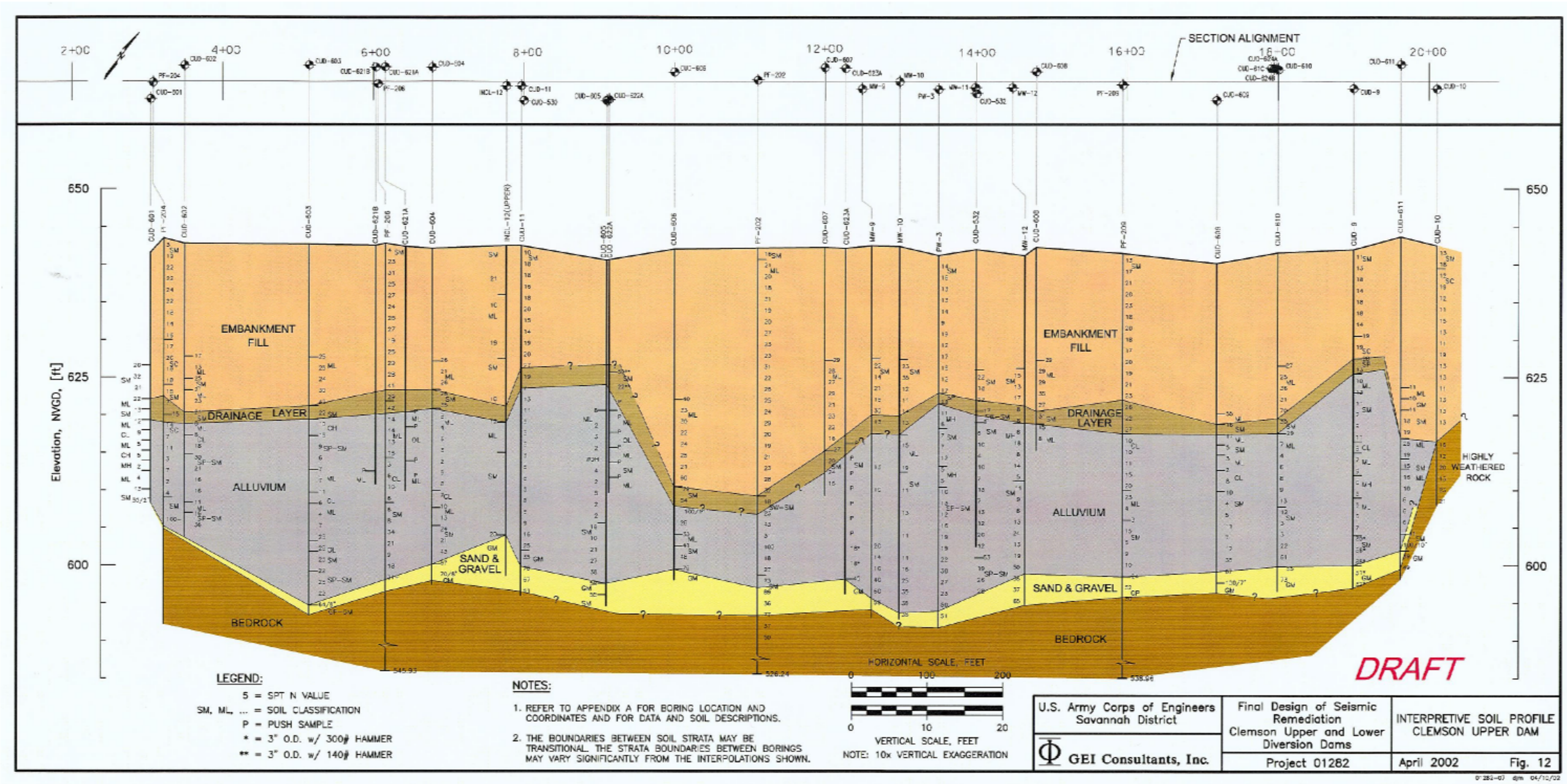

Interpretive Soil Profile – Upper Dam

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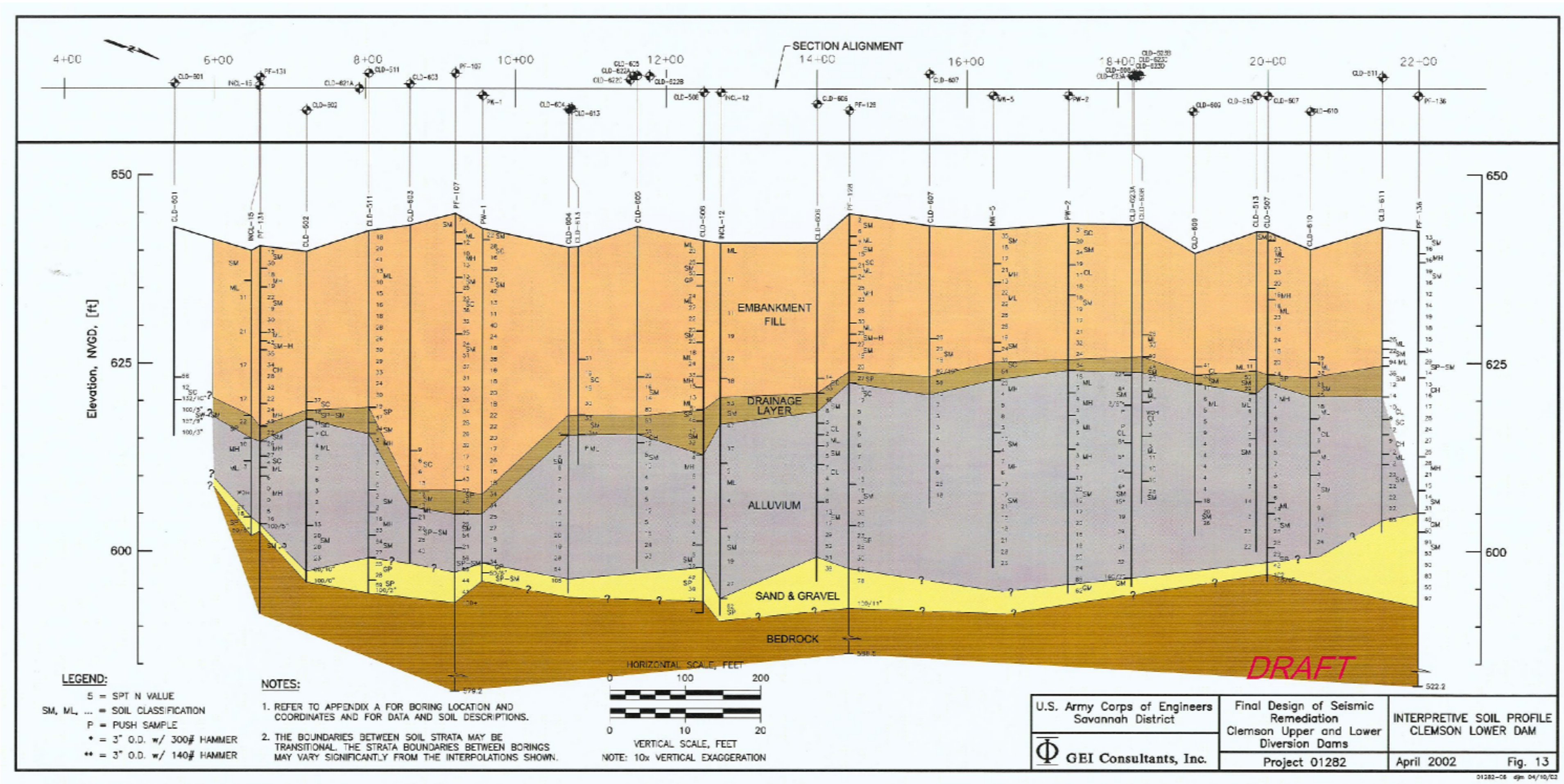
Remedial Design



Interpretive Soil Profile – Lower Dam

Remedial Design

Design of Soil-Mix Remediation – Design Approach

- Use of **Models**
  - **Steady-State Stability** (post seismic event) – limit equilibrium
    - Assumes liquefaction
  - **Dynamic Stresses & Strains** - Finite Element (TARA, 2D)
    - Evaluates Triggering
    - Provides Peak Stresses and Accumulated Strains during Seismic Event
  - **Peak Strength Stability** (post seismic event) – limit equilibrium
    - Assumes no liquefaction because triggering strains were not reached

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Design of Soil-Mix – Estimated Shear Stresses

Condition	Soil-Mix Wall Shear Stress
Static - alluvium strength drops to Sus	**82 psi**
Static - alluvium does not lose strength, but soil-mix walls take all stress within remediated zone	**60 psi**
Dynamic - alluvium does not lose strength and load is shared with soil	**55 psi**

Remedial Design

Factors of Safety

- FS > **1.2** for average alluvial zone remedial strength (2750 psf) and Sus values elsewhere (**liquefaction**)
- FS > **1.65** for average alluvial zone remedial strength (2750 psf) and Sup values elsewhere (**no liquefaction**)
- FS > **~2.5** for **soil-mix** shear wall strengths (≈400 psi)
- FS > **1.1** for **embedment** of shear wall resistance to peak seismic forces

Remedial Design – Construction Requirements

Soil-Cement in Soil Mix Shear Walls:

f'sc > 77.4 psi x (S / Wa) where:

f'sc = average **compressive strength** of soil-cement

S = soil-cement shear **wall spacing** (center to center), not to exceed 12.5 feet + maximum wall width

Wa = **average wall width**

Remedial Design - Laboratory Investigation

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- Index Testing / Alluvial Soil Characterization
- Soil-Cement Mix Testing
  - Batching
  - Strength Testing
- Undrained Strength Testing of Undisturbed Samples
- Groundwater Testing (for chloride & sulfate levels)

Remedial Design – Lab Testing

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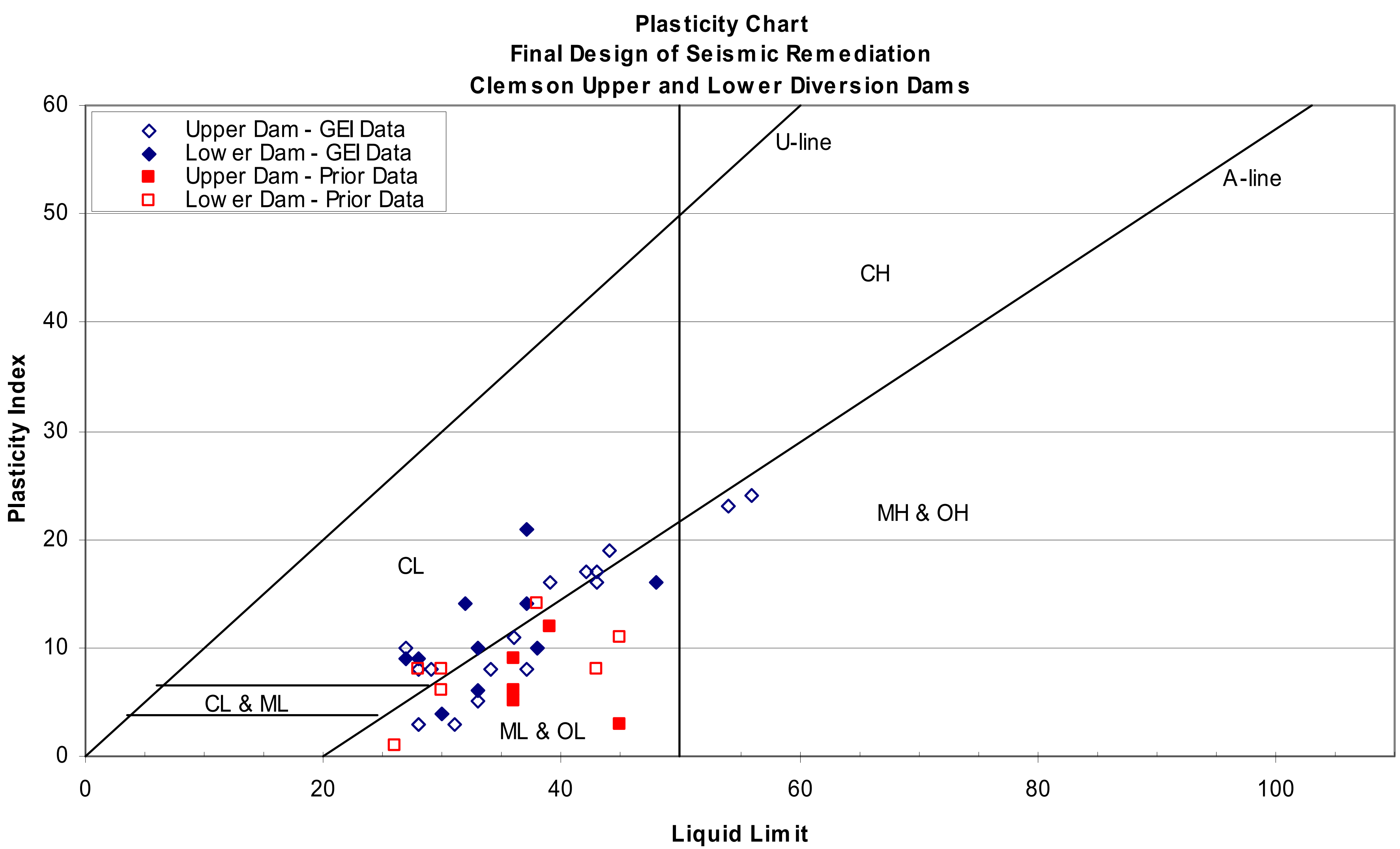
Alluvial Soil Types

- Silty Sand (SM)
- Silty Sand/Sandy Silt (SM/ML)
- Low to Medium Plasticity Silt (ML/MH)
- Clay (CL)
- Silty Sand/Sandy Silt with Organics (SM/ML-O)

Remedial Design – Plasticity Tests Summary Plot



Remedial Design – Lab Testing

Mixing soil and grout

Remedial Design – Lab Testing

Silty sand specimen at failure

Remedial Design – Lab Testing

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Batch #	Description	Cement Content for w/c = 0.7		
		300 lbs/cy	450 lbs/cy	600 lbs/cy
1	Silty Sand	X	X	
2	Silty Sand/Sandy Silt		X	X
3	Low to Medium Plasticity Silt		X(1)	X
4	Clay		X	X
5	Silty Sand/Sandy Silt with Organics			X

Soil-Cement Test Program

Remedial Design – Lab Testing

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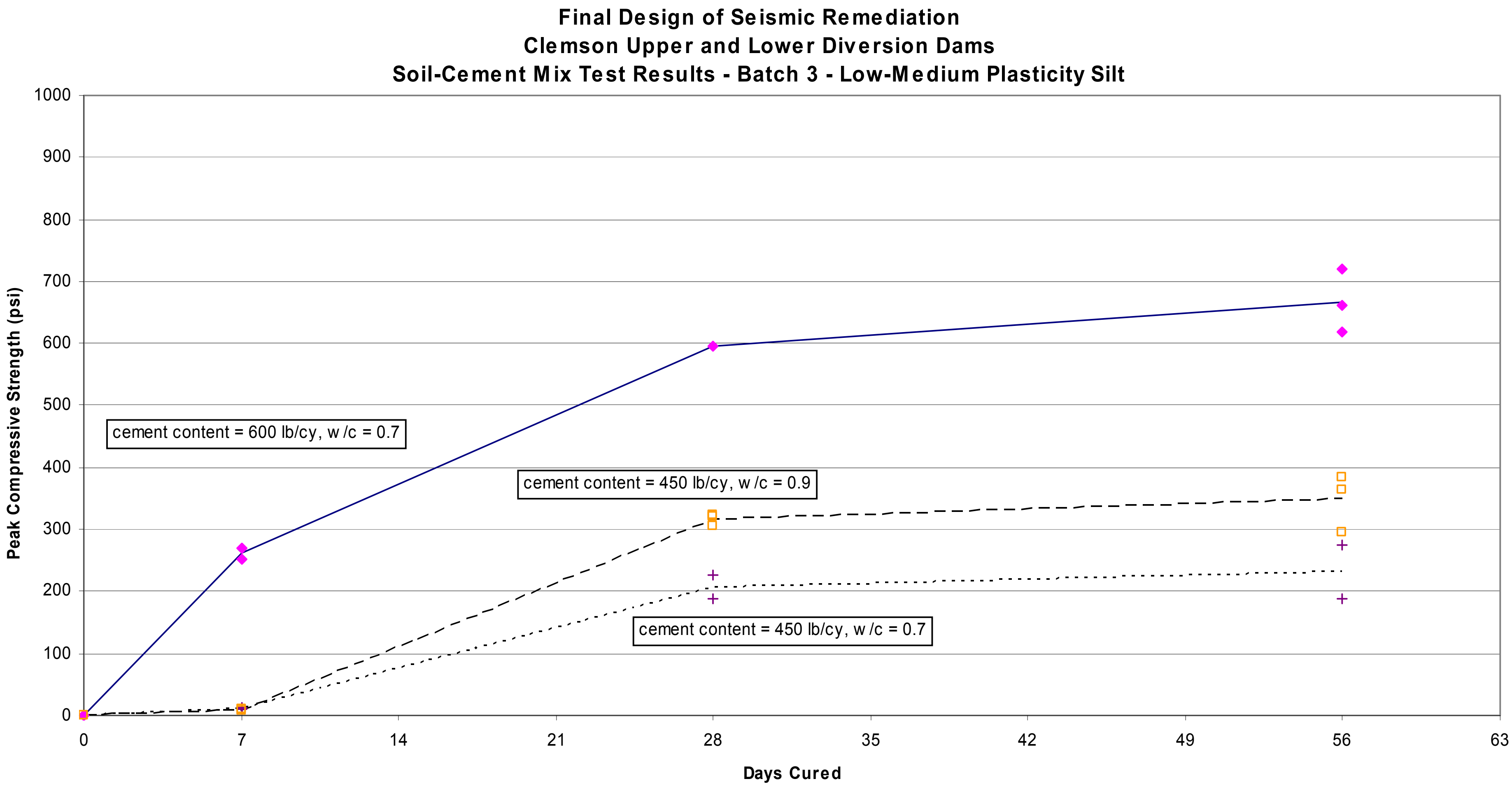

Strength Test Summary Low-Medium Plasticity Silt

Remedial Design – Position of Soil Mix Shear Walls

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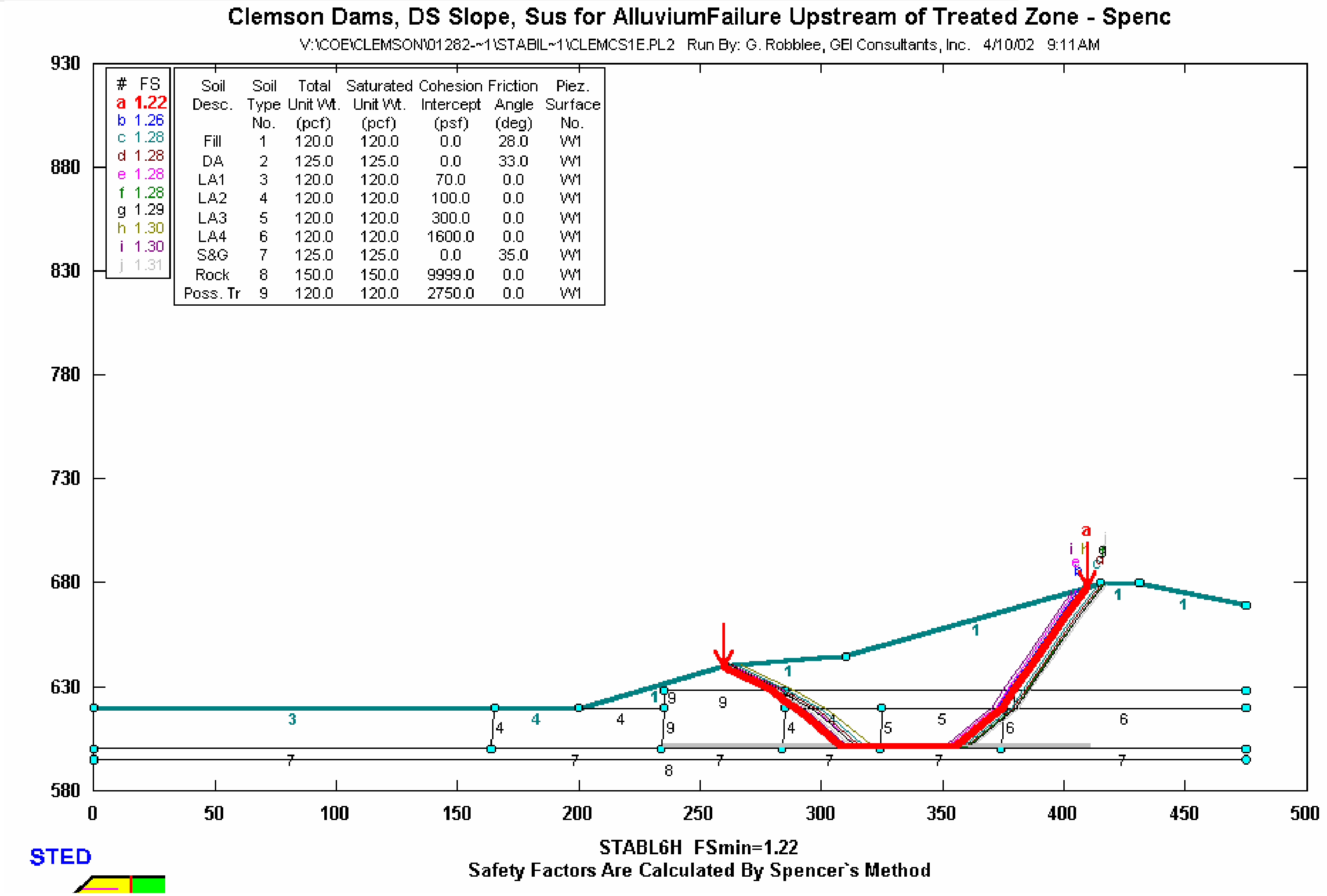

#	FS
a	1.22
b	1.26
c	1.28
d	1.28
e	1.28
f	1.28
g	1.29
h	1.30
i	1.30
j	1.31

Soil Desc.	Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Piez. Surface No.
Fill	1	120.0	120.0	0.0	28.0	W1
DA	2	125.0	125.0	0.0	33.0	W1
LA1	3	120.0	120.0	70.0	0.0	W1
LA2	4	120.0	120.0	100.0	0.0	W1
LA3	5	120.0	120.0	300.0	0.0	W1
LA4	6	120.0	120.0	1600.0	0.0	W1
S&G	7	125.0	125.0	0.0	35.0	W1
Rock	8	150.0	150.0	9999.0	0.0	W1
Poss. Tr	9	120.0	120.0	2750.0	0.0	W1

Sus FS = 1.2, Failure Upstream of Shear Walls

Remedial Design – Shear Wall Embedment

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- **Purposes:**
  - Prevent potential interface failures
  - Transmit seismic stresses between these strata and the walls without excessive movement
- **FS > 1.1** for resistance to **peak seismic forces**
- **Design embedment** of the soil-cement walls into
  - Overlying berm is **8 feet**
  - Underlying sand and gravel is **4 feet**

Remedial Design – Longitudinal Wall

- **Purpose:** Reduce movement potential of soil between transverse walls
- **Notes:**
  - Shear strength (Sup) of soil between shear walls sufficient to prevent relative slippage between soil and walls
  - Longitudinal walls decrease soil strains, and thus make it even less likely that the soil strength would decrease to Sus
  - Design does not include longitudinal walls in dense alluvium areas of former river channel

Remedial Design – Drainage System

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- **Purpose:** Prevent buildup of pore pressures upstream of longitudinal wall
- **Filtered seepage collection system** upstream of the longitudinal wall:
  - **Slotted pipes surrounded by gravel and geotextile**
  - **Elevations of system selected to intercept blanket drain**
  - **Discharge piping to ditches and ponds beyond toes of dams**

Remedial Design-
Drain Details

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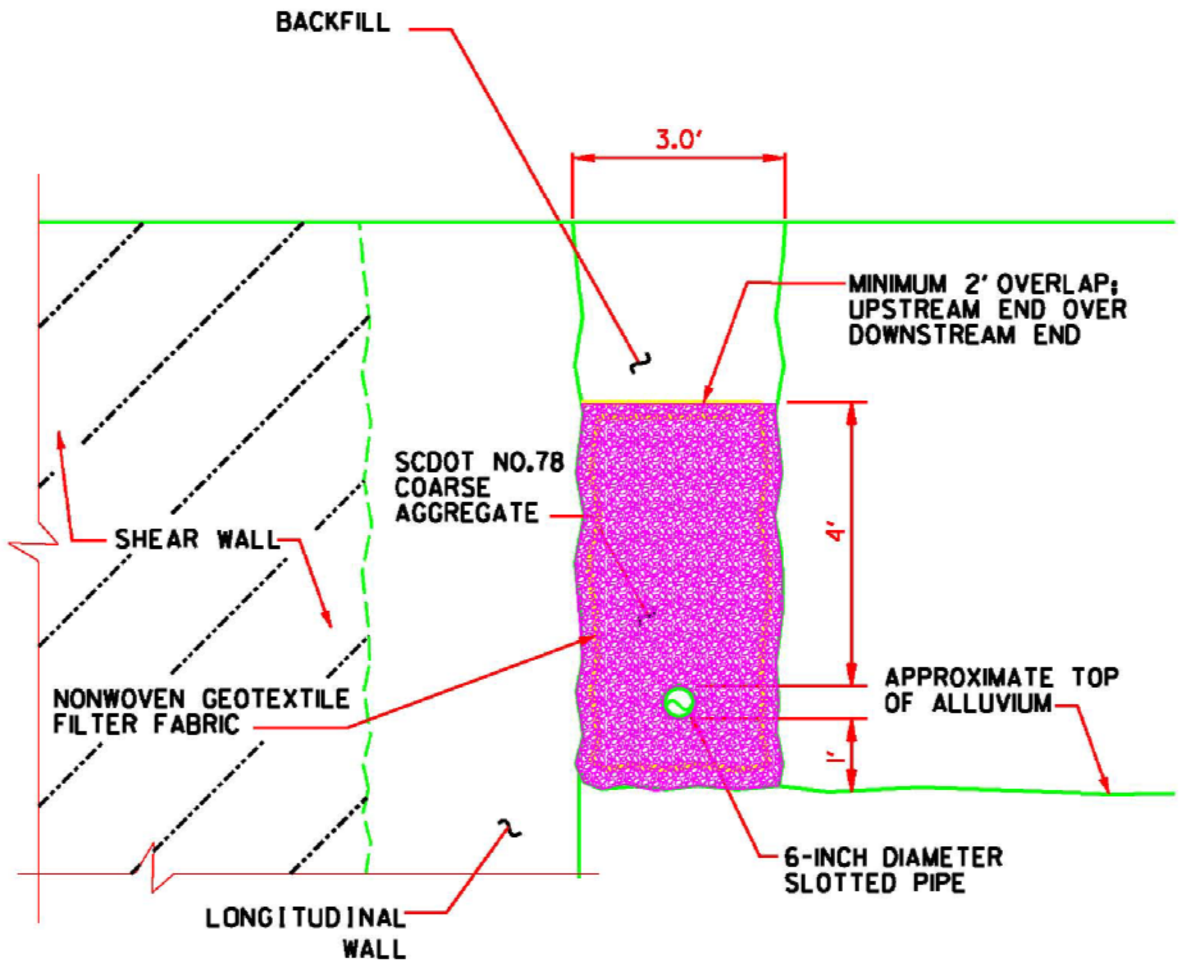

Remedial Design – Lower Dam Plan

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