Characterization and Three-Dimensional Modeling of Soil Variability for Evaluating Safety of Dam Infrastructure

Geo-Omaha 2024

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trwd
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DEPARTMENT OF DEFENSE · UNITED STATES OF AMERICA

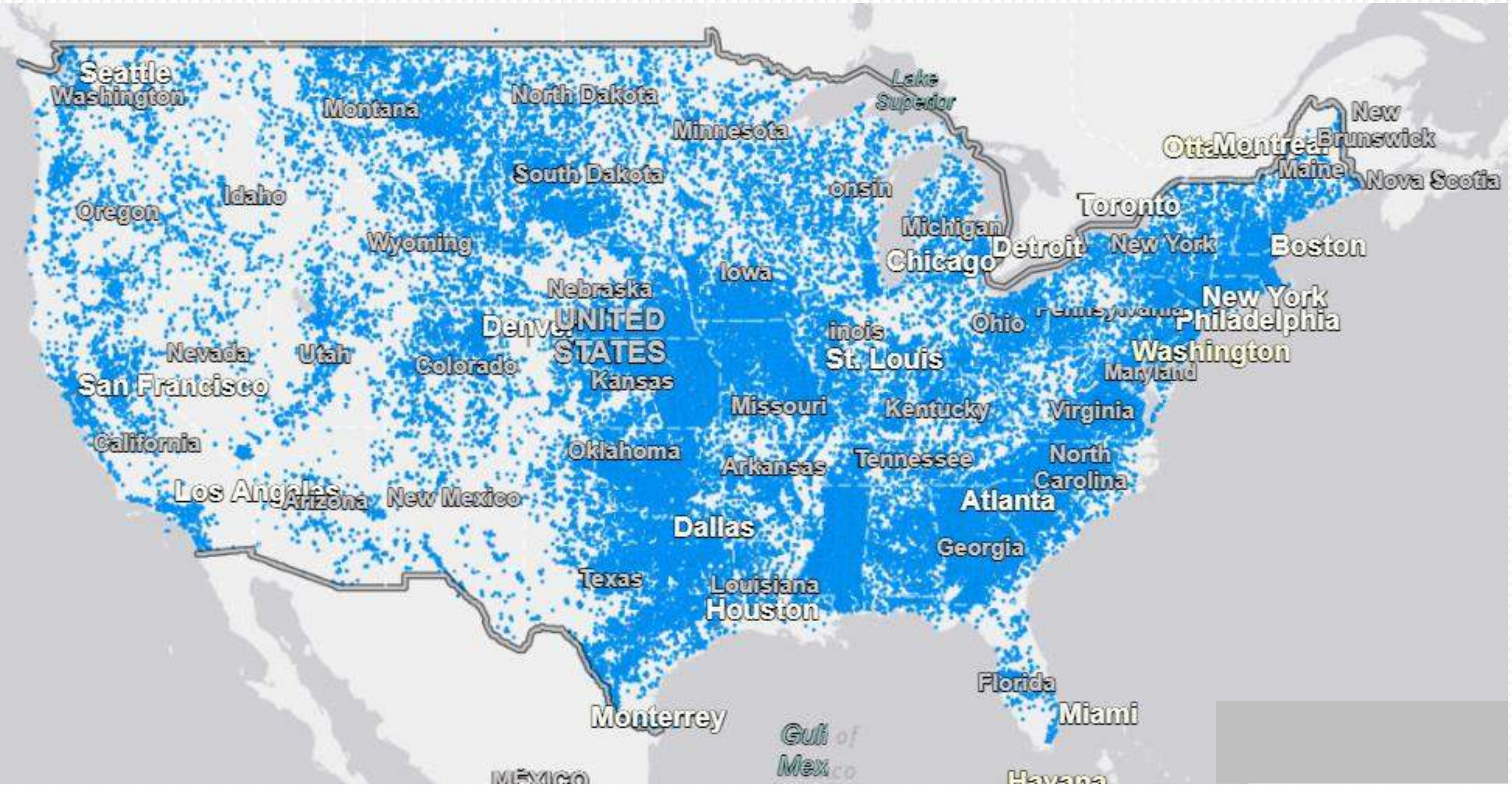
NRCS
Natural Resources Conservation Service

Presentation Outline

1. Introduction and Background
2. Development of Framework for ch
3. Geotechnical Studies – Eagle Mou
   - Hazard Quantification
   - Soil Vulnerabilities and Critical Zo
   - Slope Stability and Liquefaction As
4. Summary and Conclusions

Introduction

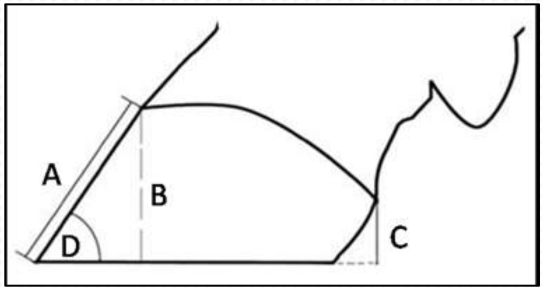
- Dams are one of the most critical infrastructures with a complex interplay among different disciplines.
- More than 90,000 dams in the nation, with an average of 62 years.



Source: National Inventory of Dams

Introduction

- Several factors play a key role in the performance of an earthen infrastructure.



Introduction

Hydraulic Fill Dams: Extensive hydraulic mining in the United States, followed by the discovery of gold in California in 1849, led to the utilization of the hydraulic fill procedure for the construction of dams

Fort Peck Dam

Lower San Fernando Dam

Introduction

Hydraulic Fill Dam Failures are major catastrophic failures that result in property damage, lives, and the environment.

Samarco Fundao TSF Failure, Brazil, 2015

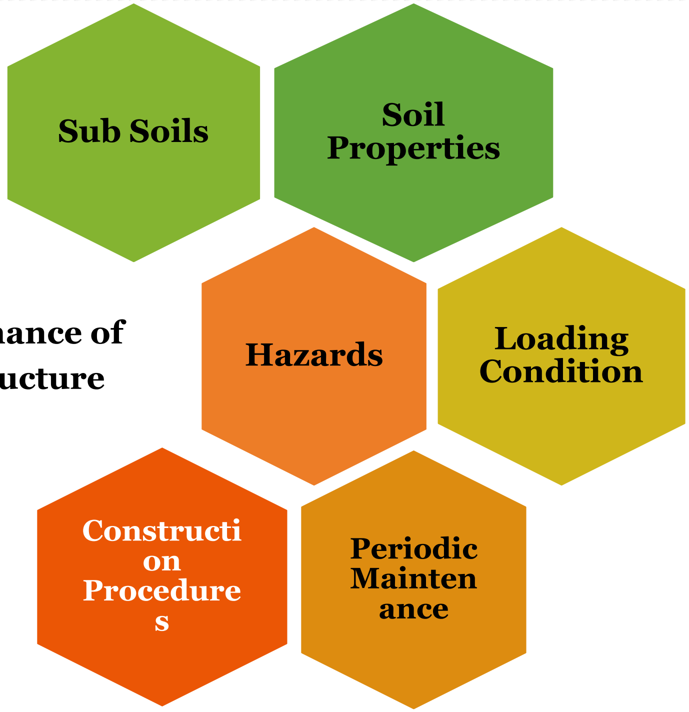
Mount Polley TSF Failure, Canada, 2014

Cadia TSF Failure, Australia, 2018

Brumadinho TSF Failure, Brazil, 2019

Merriespruit TSF Failure, South Africa, 1994

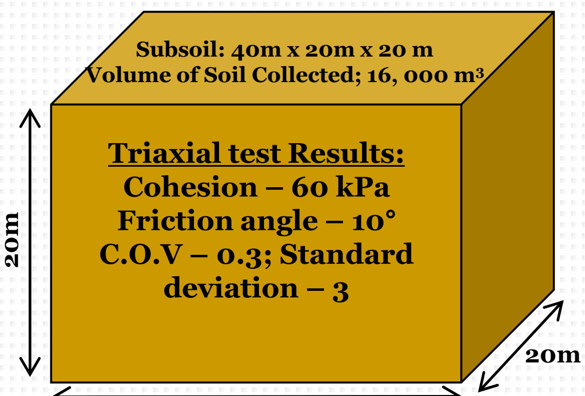
Introduction



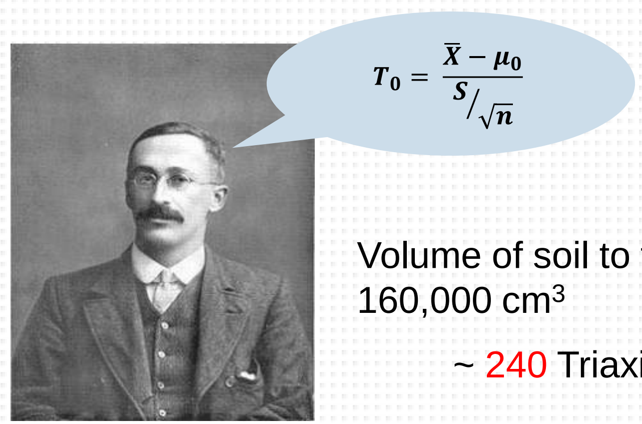
Performance of Infrastructure

Uncertainties with current practices

- **Constrained Soil Investigation Works – Limited Characterization**



Required volume of soil to be tested for having 98% confidence on soil properties?

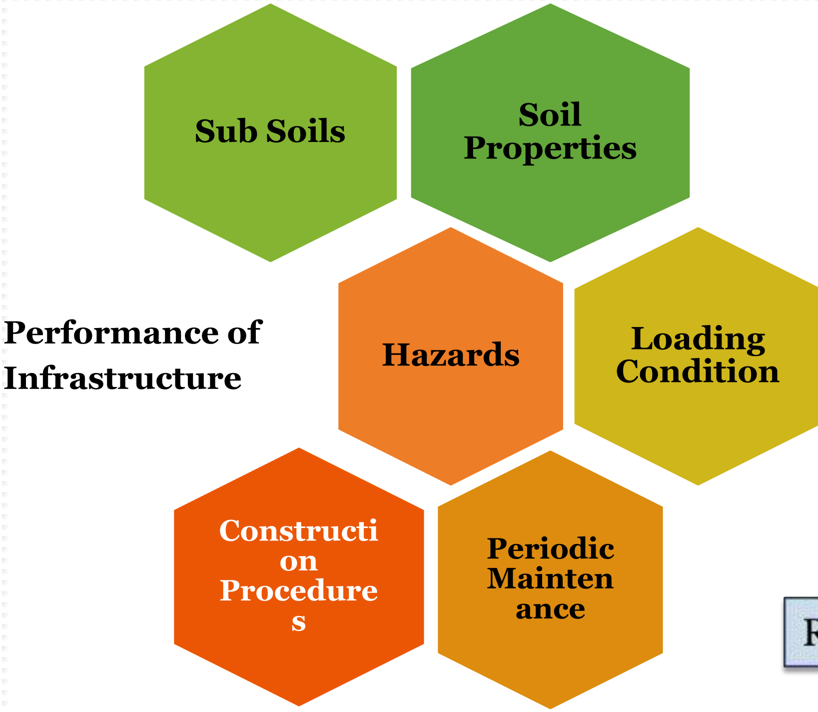


Gosset (1876-1937)

Volume of soil to test: 160,000 cm^3

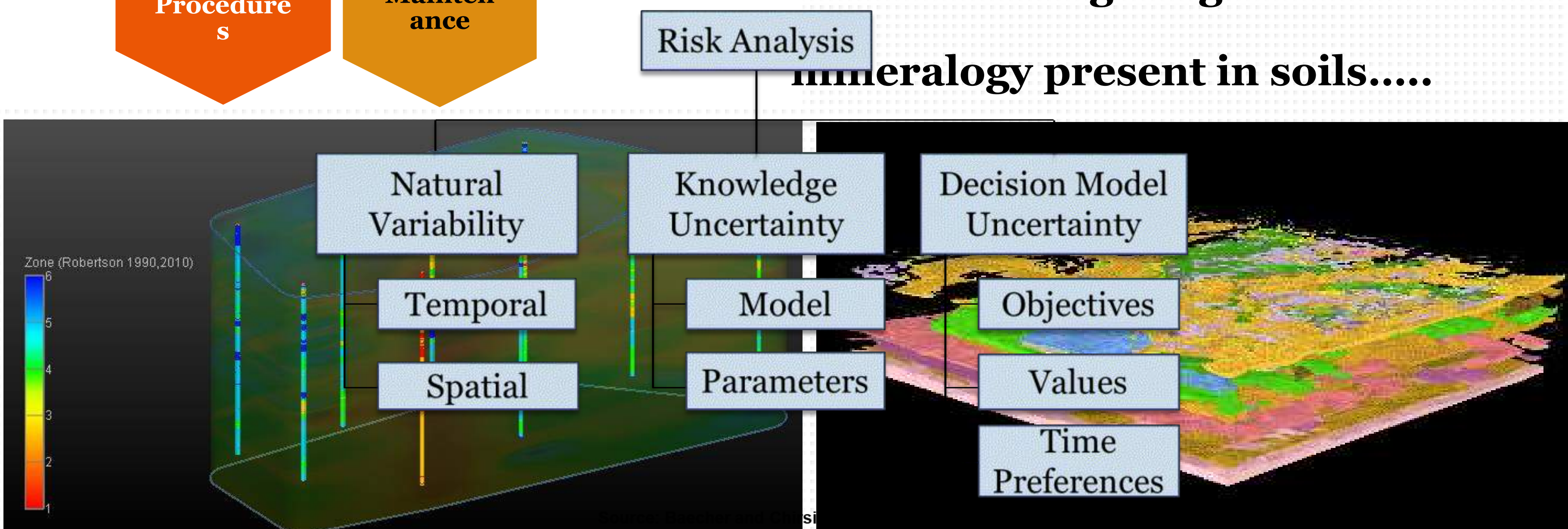
~ 240 Triaxial tests

Introduction



Uncertainties with current practices

- **Constrained Soil Investigation Works – Limited Characterization**
- **Assessments based on 2D Models**
- **Models and Hazards Uncertainty**
- **Not accounting for geochemical and mineralogy present in soils.....**

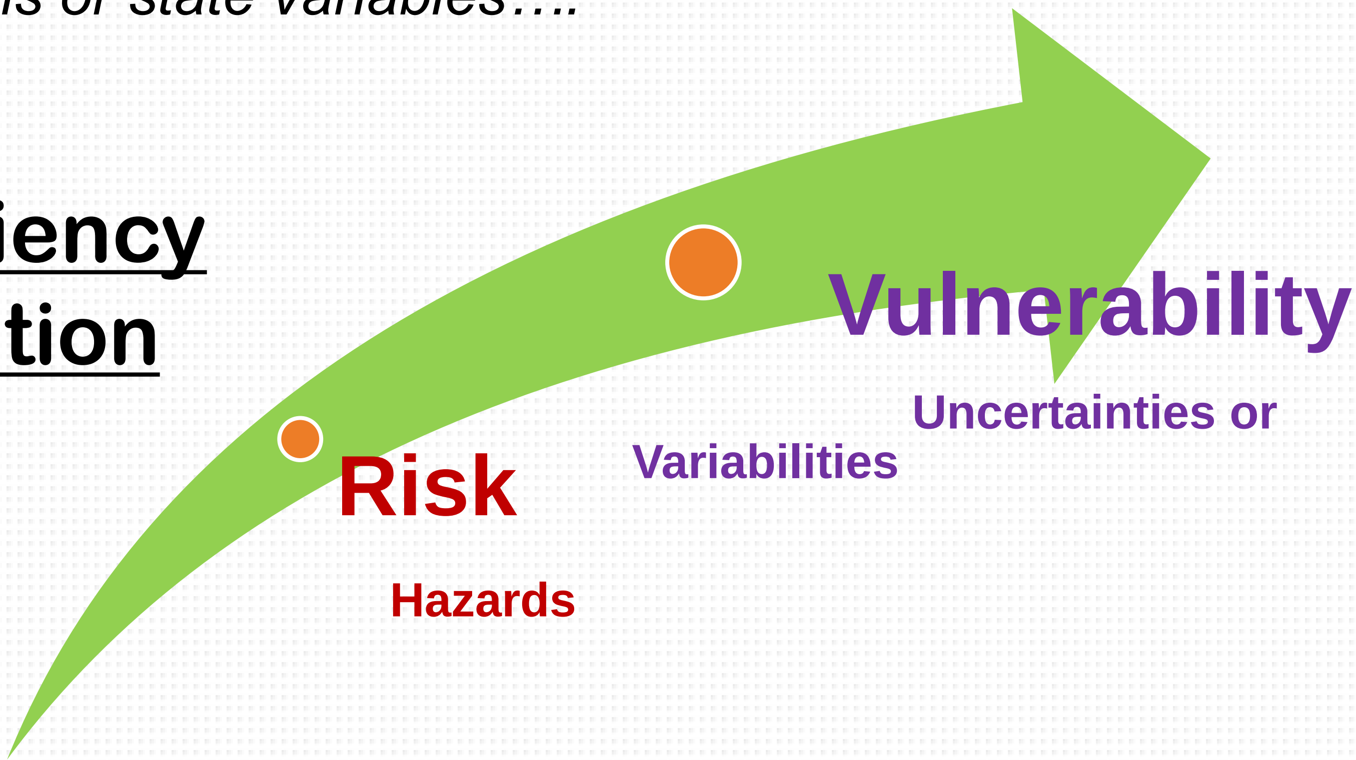


Introduction

Resiliency Definition

Holling (1973) has first described resiliency as a "measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables….

Resiliency solution



Introduction and Risk Framework

In geotechnical engineering, the resiliency metric can be addressed using Factor of Safety or Probability of Failure….

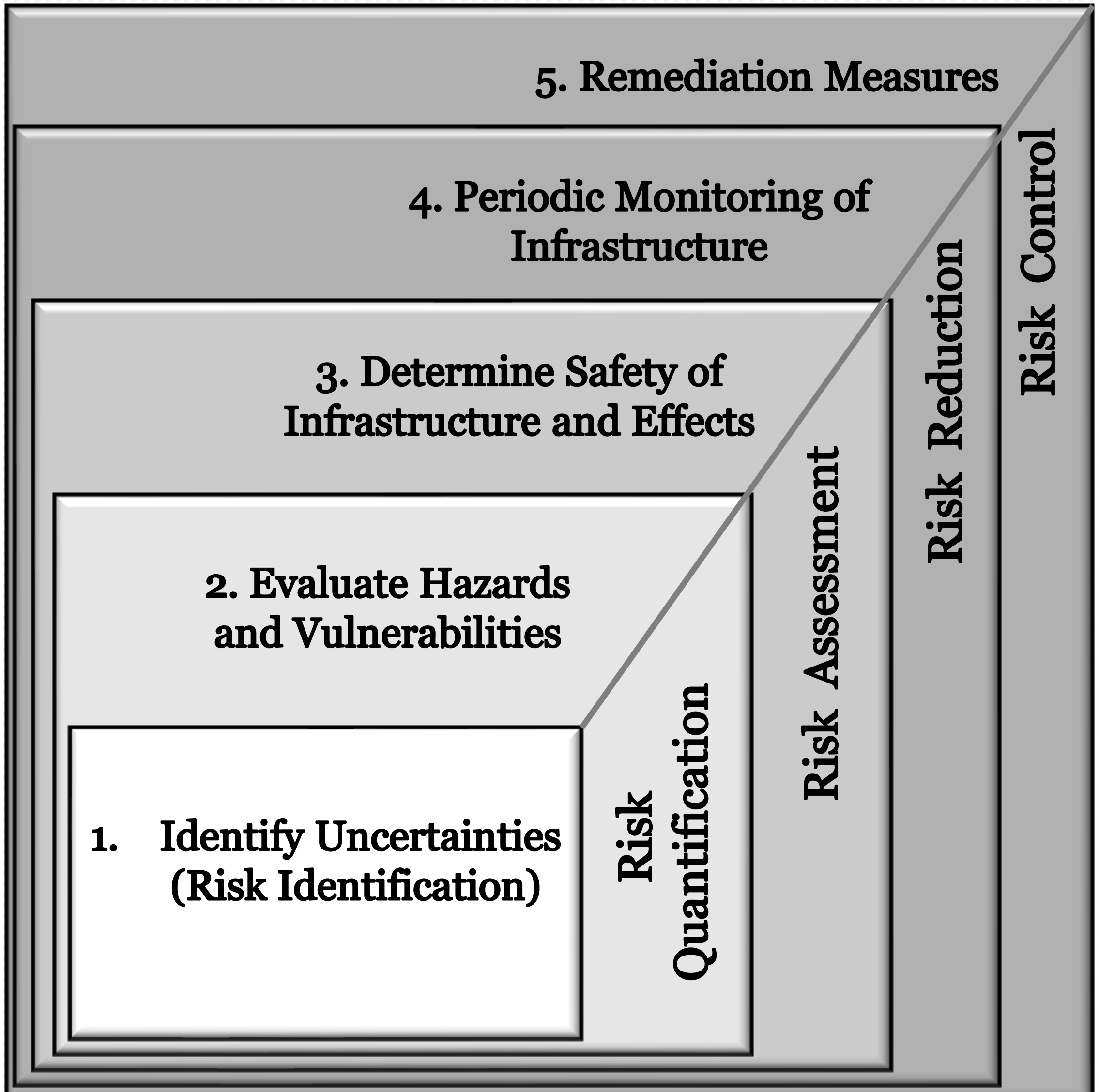
Risk

- **Natural hazards**: Earthquakes, Tornadoes, Climatic Effects, Flooding, Drought, and others
- **Man-made hazards**: Induced Seismicity (Fracking, Blasting), Measurement errors, Model errors, Poor QA/QC practices, Design limitations and others

Vulnerability

- **Variabilities** and **Uncertainties** in soil properties
- Identifying **localized critical zones** compared to global
- **Assessing** condition of the Infrastructure

Risk-Based Framework



Geotechnical Data (Material Characterization and Performance Evaluation)

↓

Check for Data Stationarity and Normal Distribution

↓

Detrending/ Transformations*(Box-Cox)*

↓

Geostatistical Analysis

↓

Variogram Modeling *(Model correlation)*

↓

Kriging Analysis *(Perform predictions)*

Introduction and Risk Framework

Geostatistical Theory

Prof. Danie G. Krige
(1919 – 2013)

- Mining Engineer and Geostatiscian
- University of Witwatersrand, SA
- Developed empirical work for locating Ores in 1950's.

Prof. Georges Matheron
(1930 – 2000)

- French Mathematician and Geologist
- Centre de Geostatistique
- Developed mathematical formulation of empirical work in 1970's.

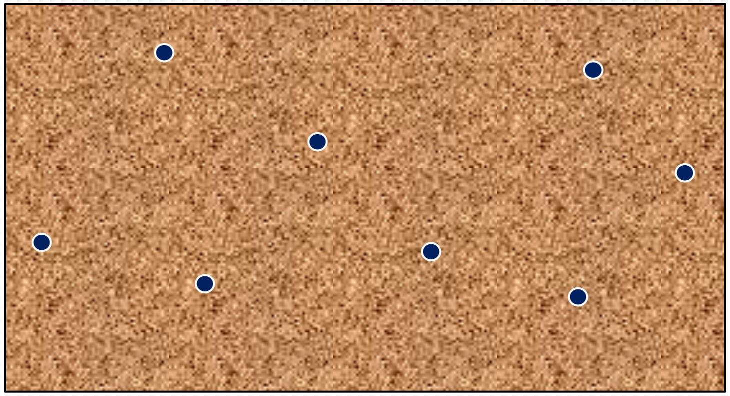
Geostatistical Theory

Geostatistical Analysis

- Developed from theory of **Regionalized random variables**

  Regionalized variable:
  $z(x_i)$; x_i ε D ; i = 1…n

  Random function model:
  $Z = (Z(x))_{x \, \varepsilon \, D}$

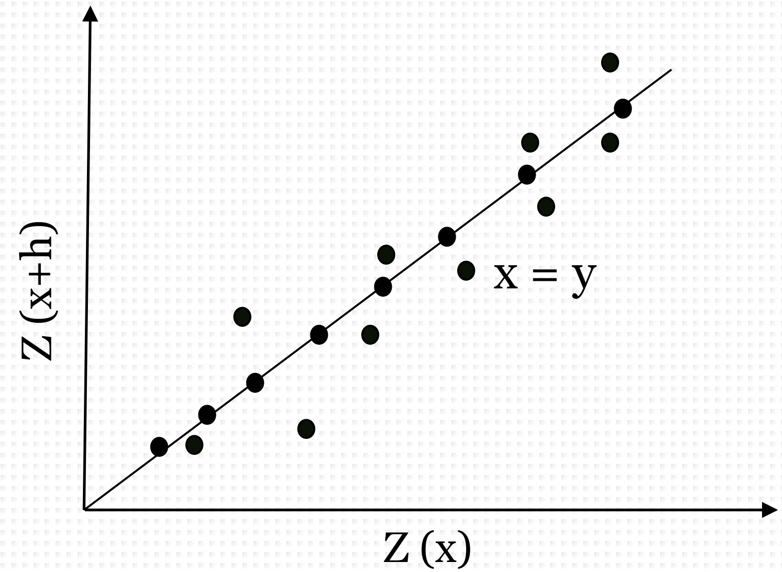


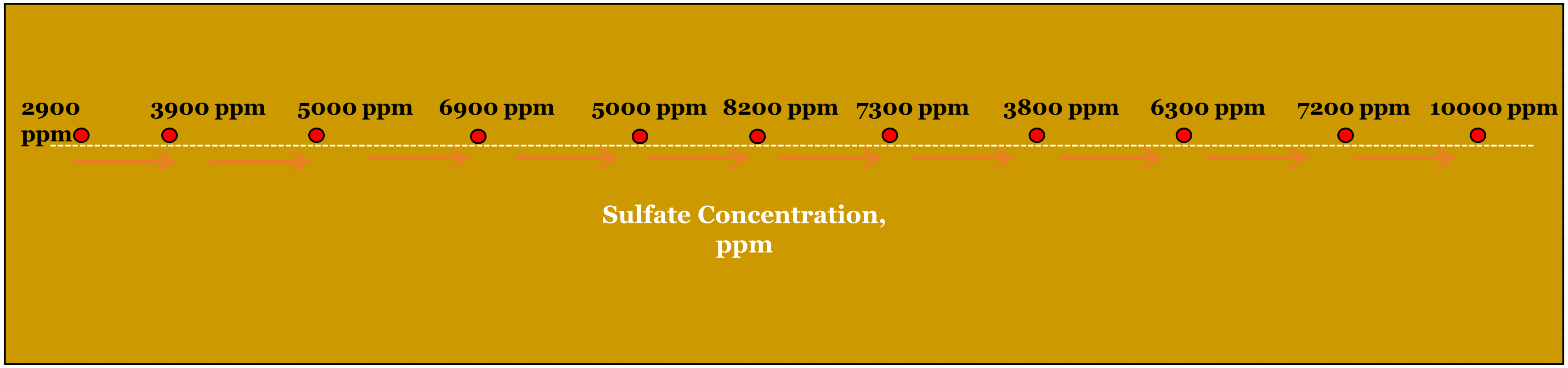
- Explains **spatial variability** of the random variable
- **Spatial continuity** is an essential feature in understanding spatial description of a random variable or any earth science materials
- **h-scatter plots**

Geostatistical Theory

Geostatistical Analysis: h-scatter plots

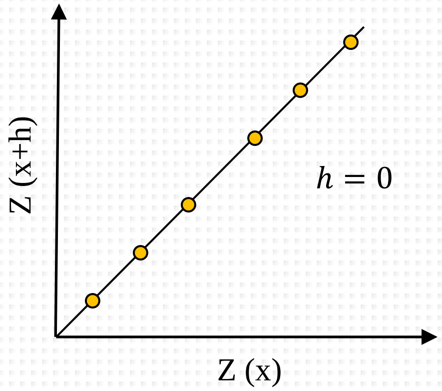
- Plot of Z (x) vs Z (x+h)
  - x : Random variable
  - h : lag distance
- h = 0; (Z (x), Z (x))
- h = 2m; (Z (x), Z (x+2))

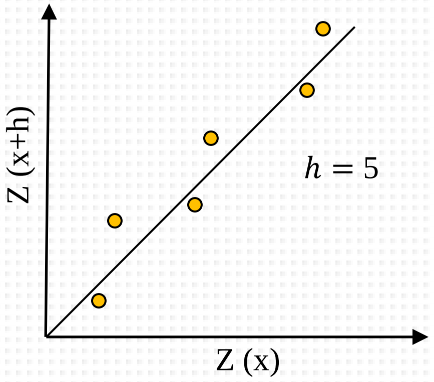


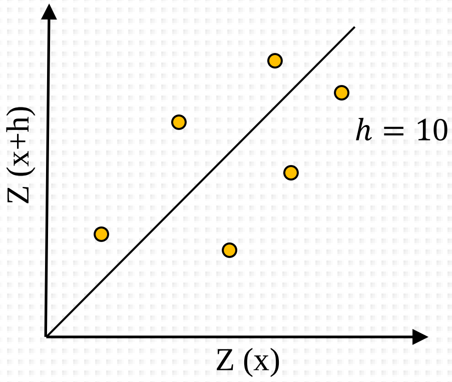


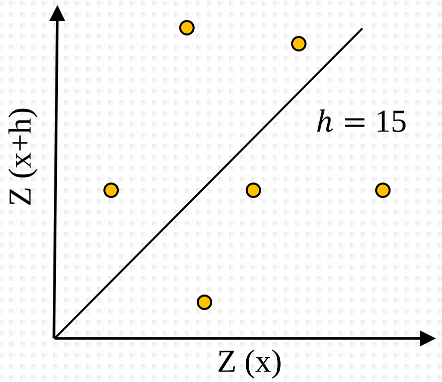
Geostatistical Theory

Geostatistical Analysis: h-scatter plots









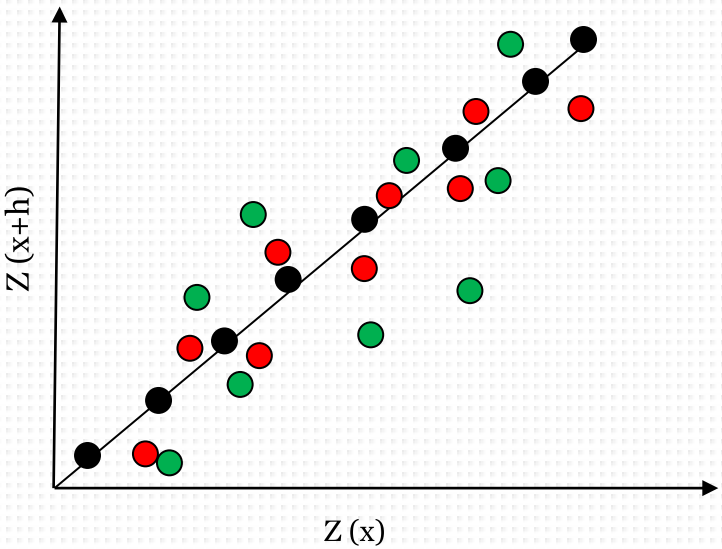
Summary of h- scatter plots:

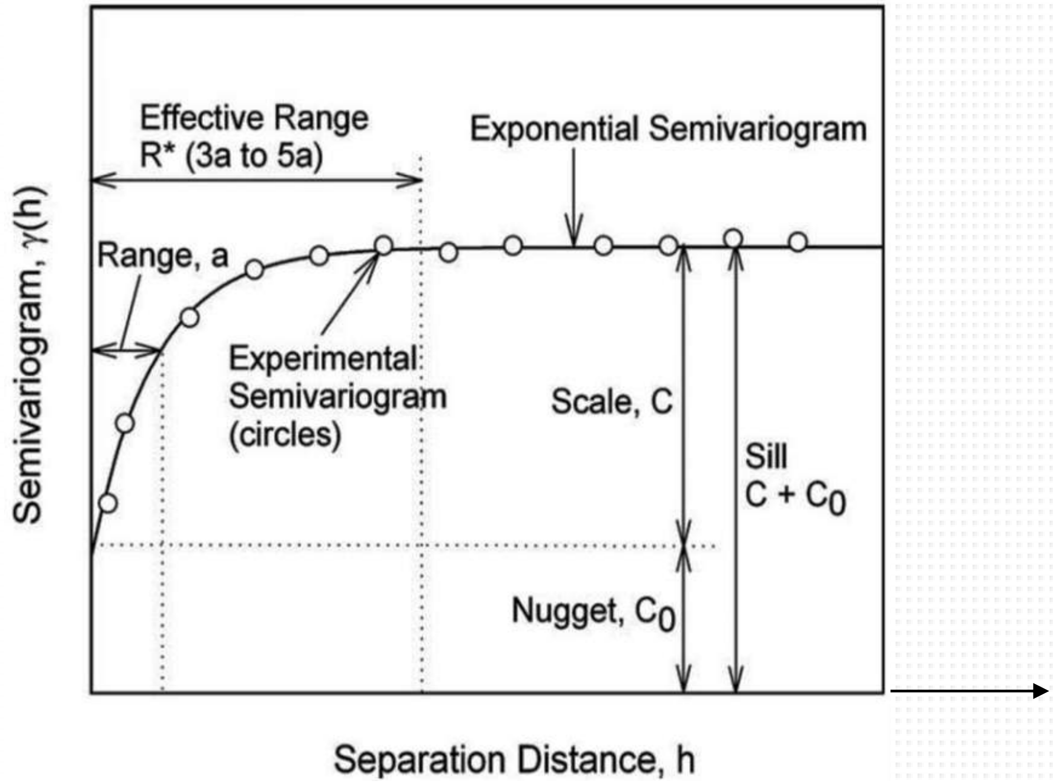
- Correlation function, ρ(h)
- Covariance function, C(h)
- **Variogram, γ(h)**

Geostatistical Theory

Geostatistical Analysis: Plot of Variogram

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z(x_i + h) - z(x_i)]^2$$





h = 0 m; $\gamma(h_1)$

h = 2 m; $\gamma(h_2)$

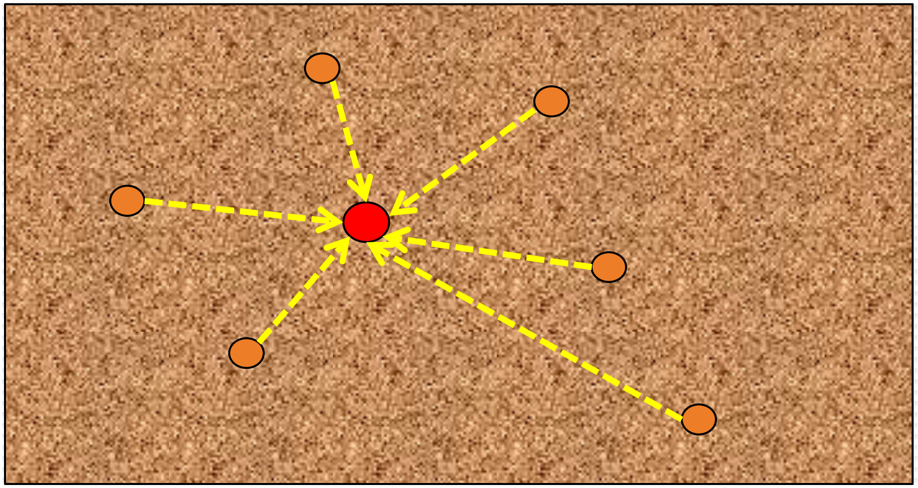
h = 4 m; $\gamma(h_3)$

h = n m; $\gamma(h_n)$

Geostatistical Analysis

Geostatistical Analysis: Interpolation

- Different estimation procedures exists in statistics: Polygon estimation, Triangulation, Inverse distance methods, Cell declustering, Kriging.



- Kriging predicts the value of the random variable $z(x_0)$ as a weighted average of the observed data that is spatially correlated.

$$\begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} & 1 \\ \vdots & \vdots & \ddots & \vdots & 1 \\ C_{n1} & C_{n2} & \cdots & C_{nn} & 1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_n \\ \lambda \end{bmatrix} = \begin{bmatrix} C_{x1} \\ \vdots \\ C_{xn} \\ 1 \end{bmatrix}$$

Development of 3D Model

Eagle Mountain Structures

Main Dam

- Main Dam Crest (41)
- Main Dam Downstream Toe (29)
- Main Dam Far Downstream (11)

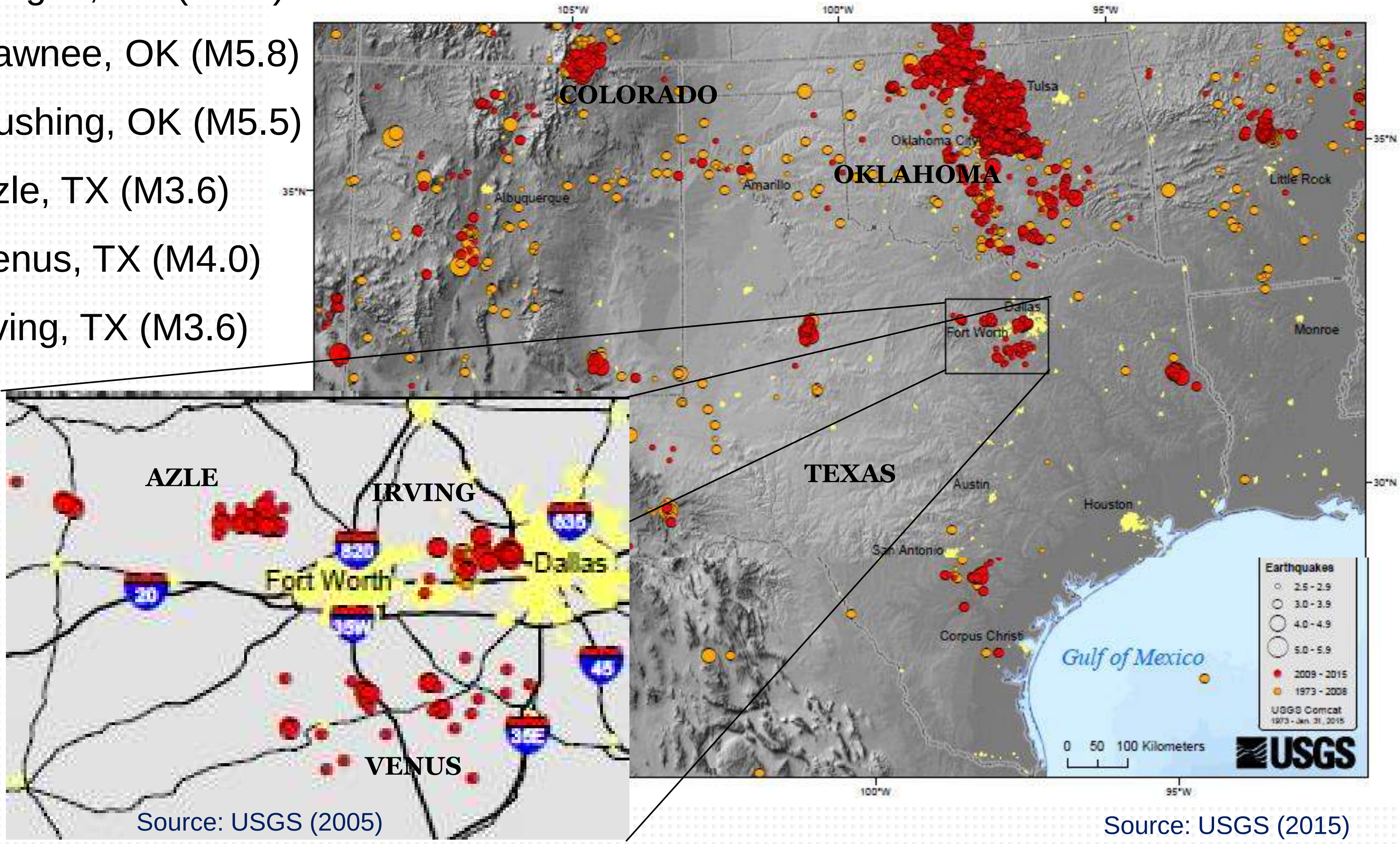
Levee

- Levee Crest (17)
- Levee Upstream (3)
- Levee Downstream Toe (9)
- Levee Far Downstream (4)

* (Number) indicate total SCPT's performed

HAZARD Quantification

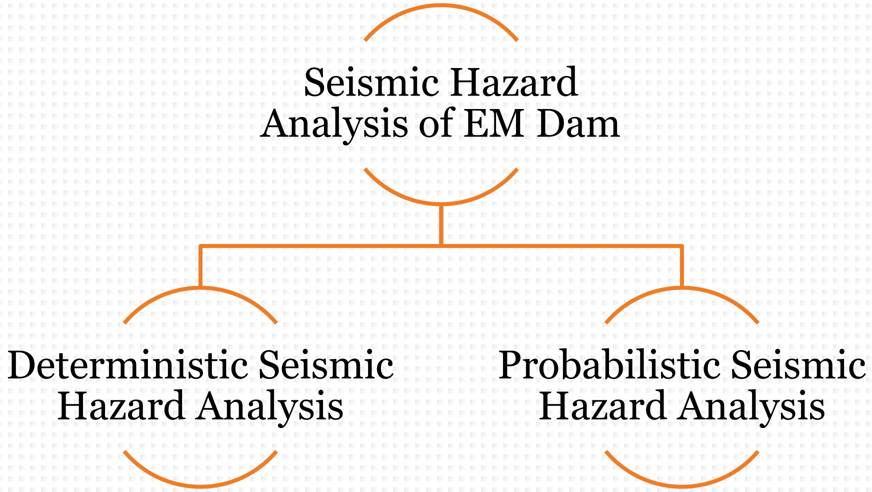
- Prague, OK (M5.6)
- Pawnee, OK (M5.8)
- Cushing, OK (M5.5)
- Azle, TX (M3.6)
- Venus, TX (M4.0)
- Irving, TX (M3.6)

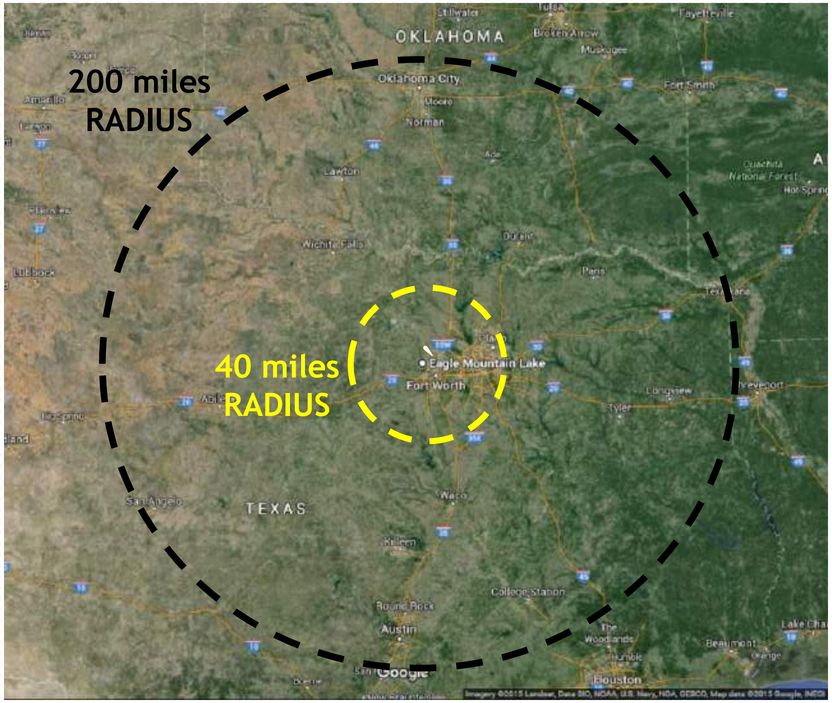


Source: USGS (2005)

Source: USGS (2015)

• Evaluation of Seismic Parameters

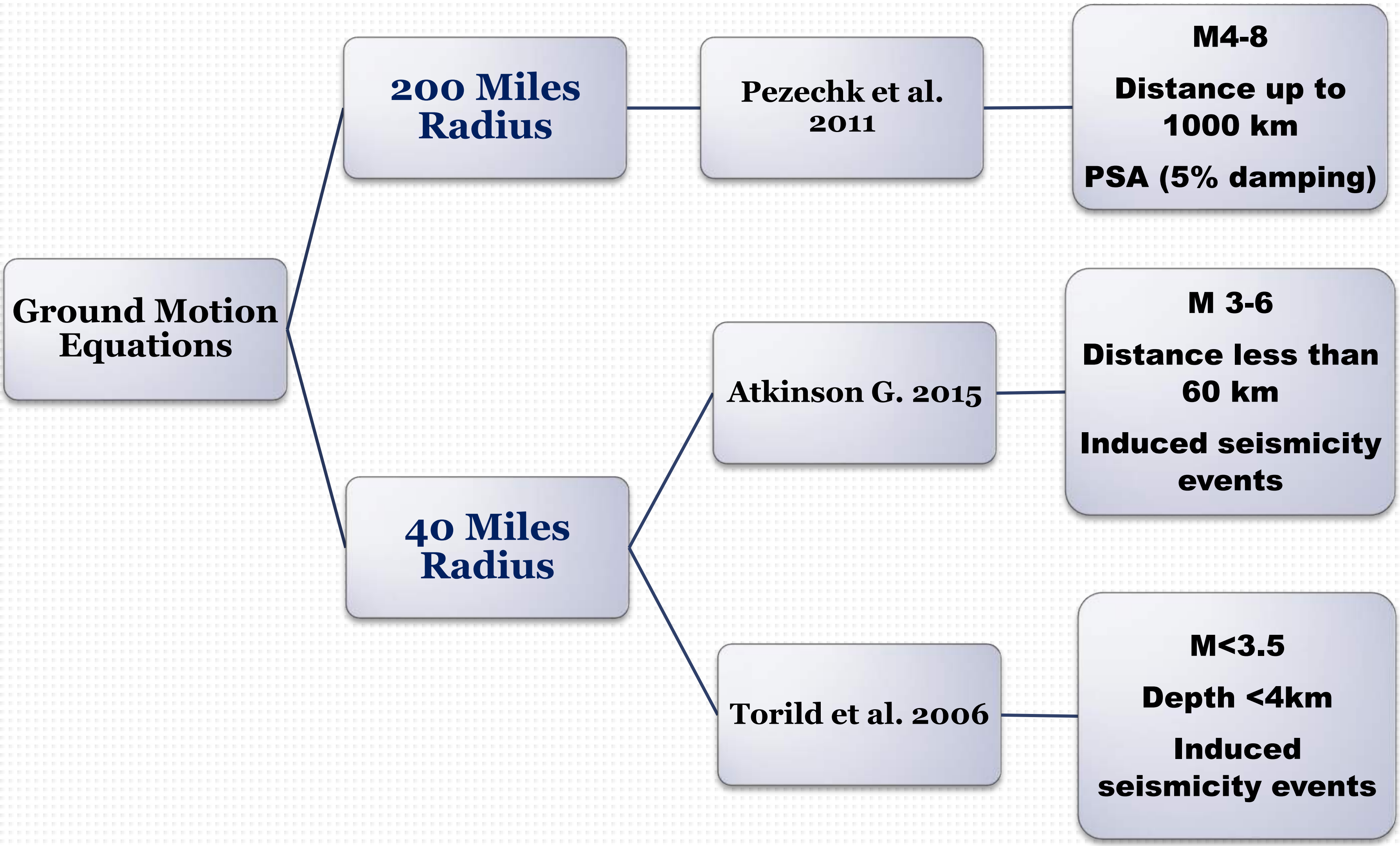




- Selection of earthquakes sources up to 200 miles radius (USGS, 2007-2015)
- Seismic analysis using data up to 200 miles radius and 40 miles radius

Seismic Hazard Analysis

GROUND MOTION PREDICTING EQUATIONS FOR EAGLE MOUNTAIN DAM



PSH TASKS PERFORMED

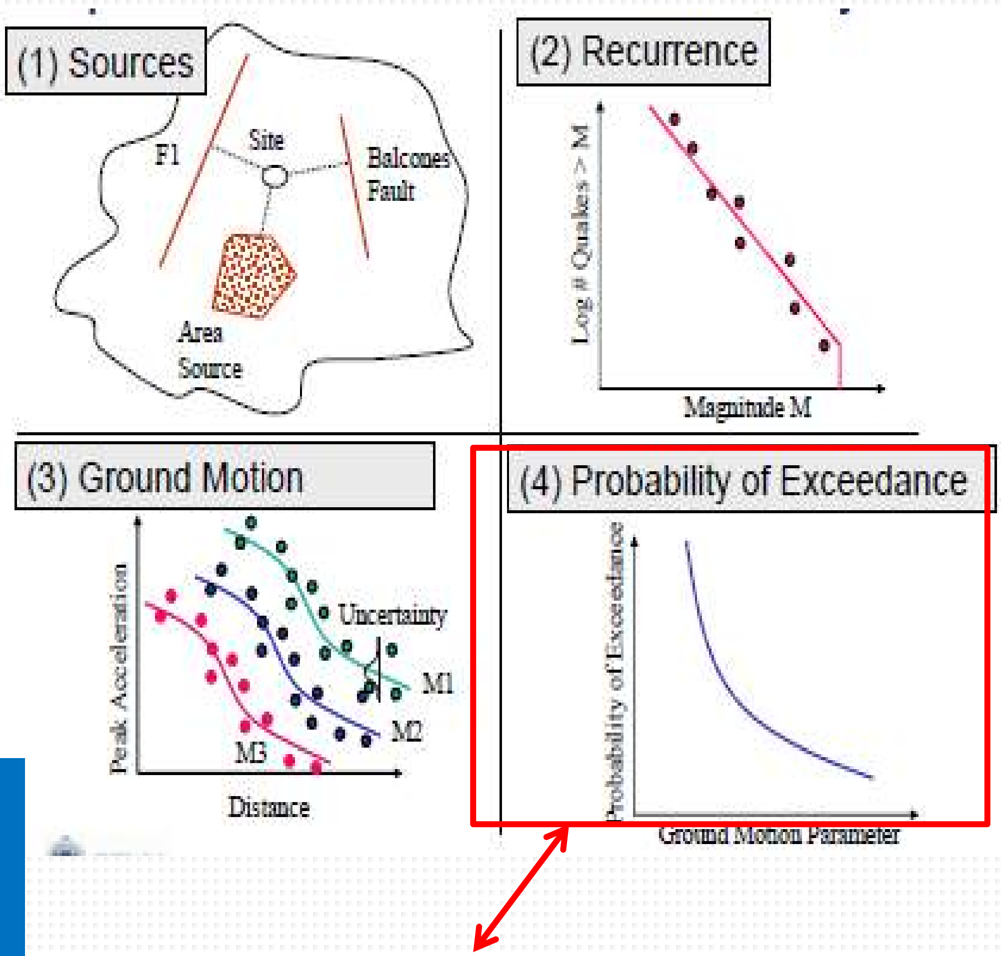
For Each Approach:

200-40 miles radius

Consists of four primary steps:

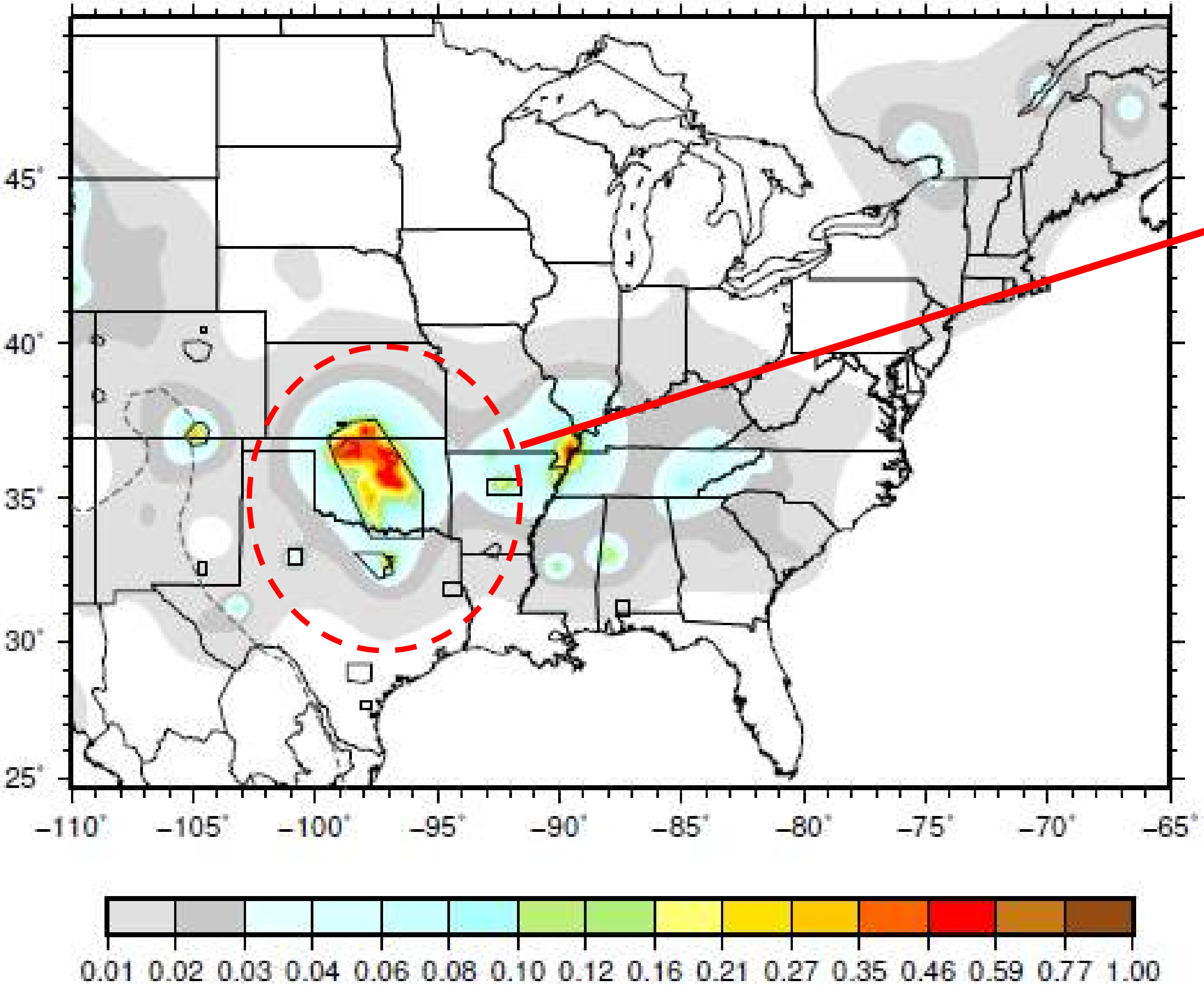
1. Identification and characterization of all sources
2. Characterization of seismicity of each source
3. Determination of motions from each source
4. Probabilistic calculations

PSHA characterizes uncertainty in location, size, frequency, and effects of earthquakes, and combines all of them to compute probabilities of different levels of ground shaking

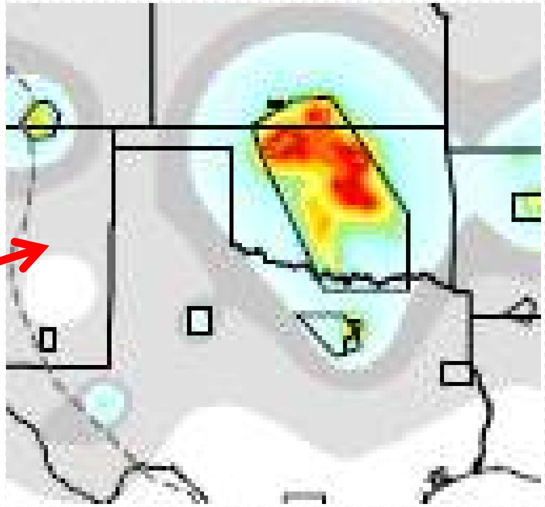


The earthquake hazard for the site is a PGA=0.28g with a 2% probability of being exceeded in a 50-year period.

VALIDATION OF PSHA



pga for 1% probability of exceedance in one year

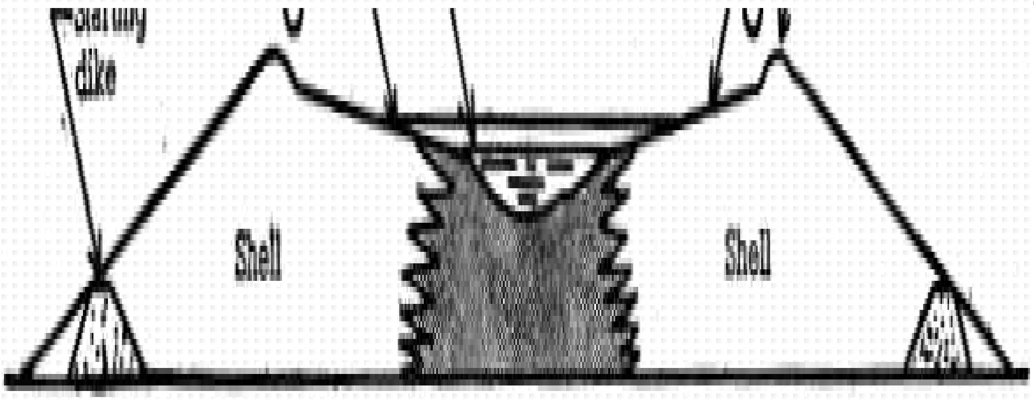


The earthquake hazard at EGM is 0.2g of 1% probability of exceedance in one year (USGS, 2016)

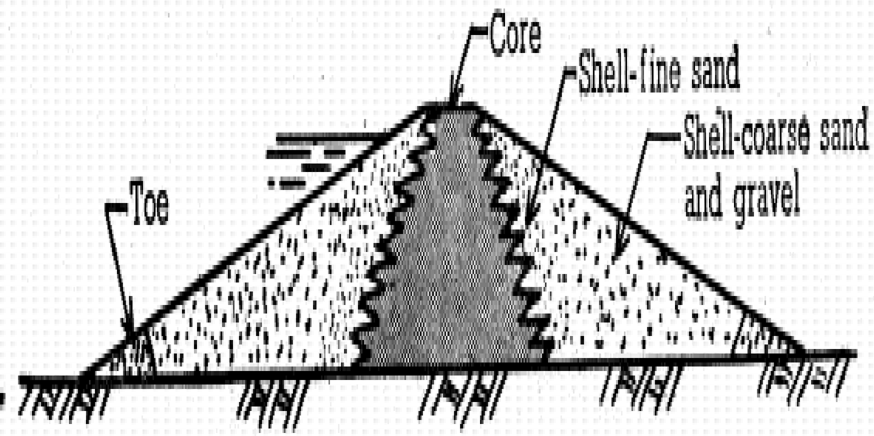
Source: USGS, 2016

Vulnerability of EM Structures

- Aging infrastructure- Constructed in 1930's
- Construction process – **Hydraulic technique**
- Uncertainties in deposited material and **high variability**



Source: Hsu 1988



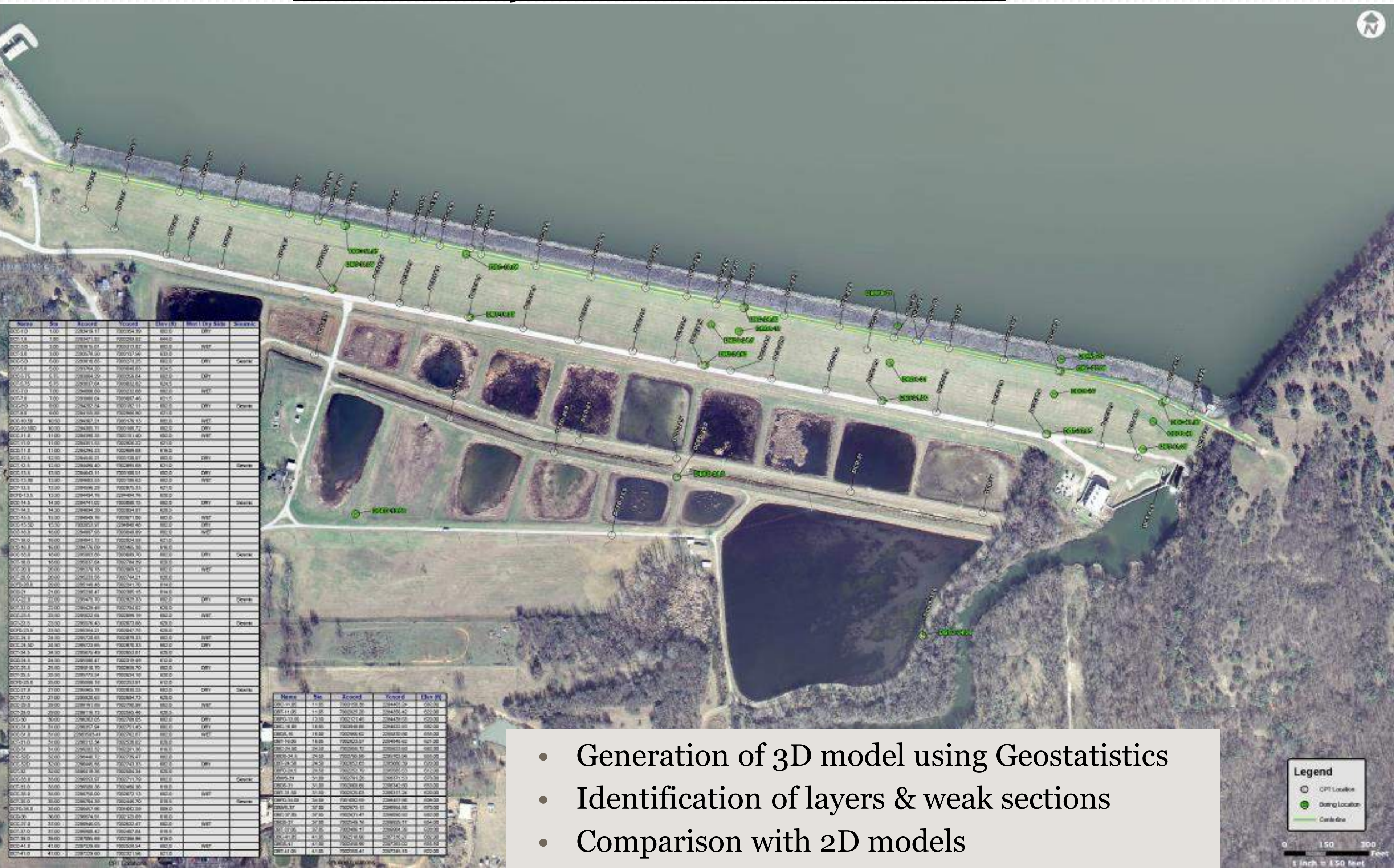
Source: Hsu 1988

Dikes at Toe (PIPES) Sedimentation → Raise the core up to the level of shells) → Coarse soil settles squeezing the core → As soon as the shell raises, core narrows and deepens → CORE ZONE WITH JAGGED EDGES

Hydraulic Fill Process

Soil Variability encountered in HF dams is HIGH (Sands, Silts and Clays)

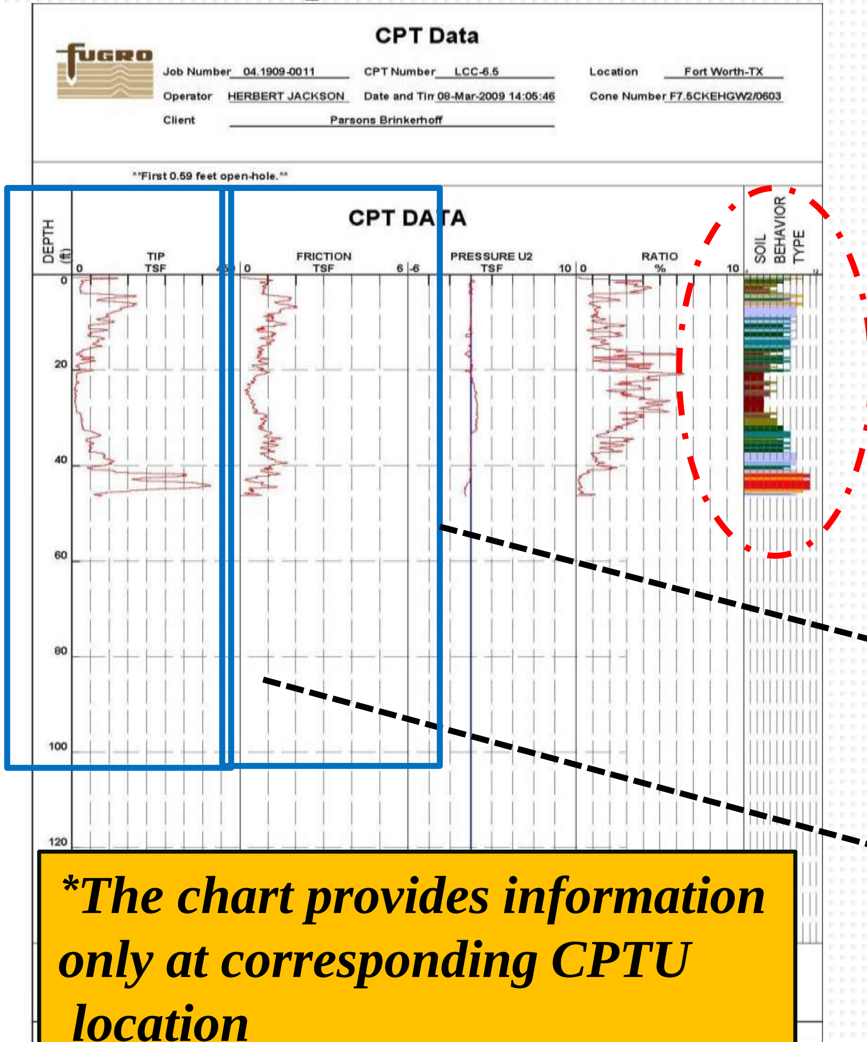
CPT Layout on EM Dam



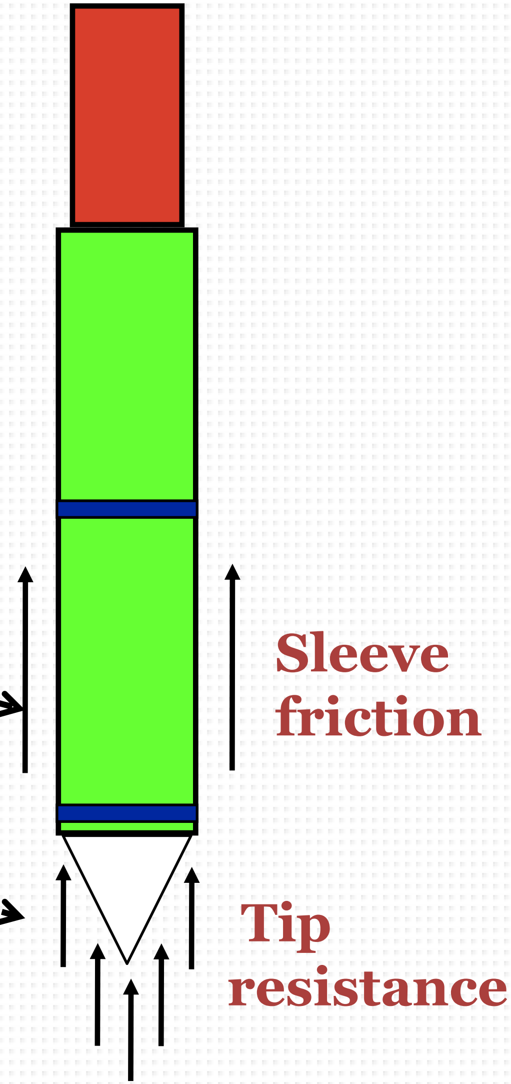
- Generation of 3D model using Geostatistics
- Identification of layers & weak sections
- Comparison with 2D models

Hydraulic Fill Structures- CPT Data

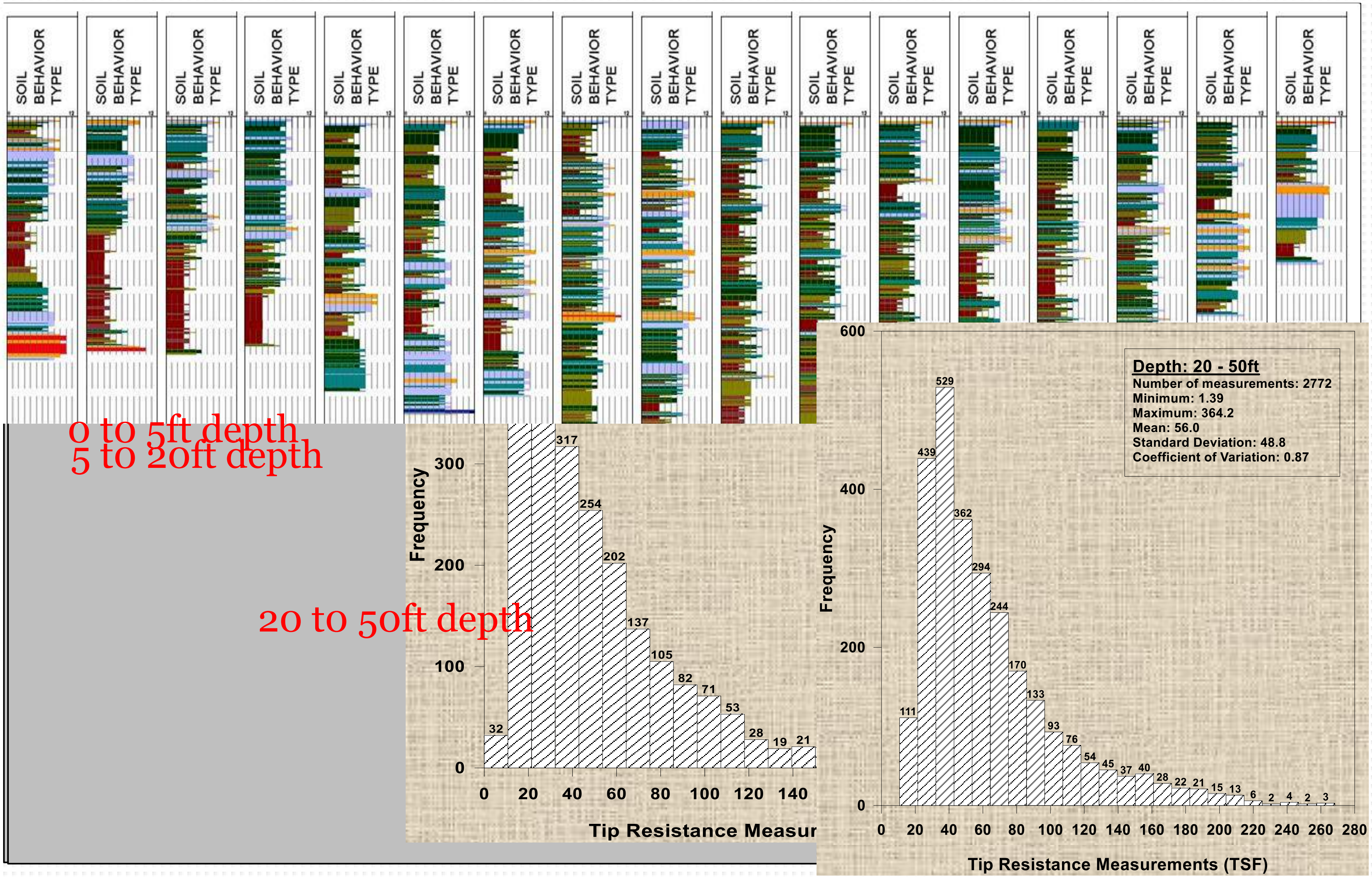
CPT Record performed on Crest



***The chart provides information only at corresponding CPTU location**



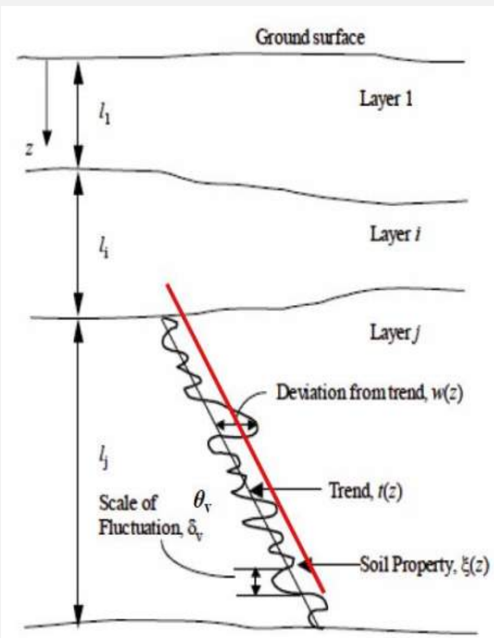
Hydraulic Fill Structures- CPT Profiles



Spatial Variability Analysis

Geostatistical Approach – Data evaluation, Stationarity, Variogram, Kriging Analysis, Validation

Data Evaluation



Spatial variation of soil properties (Davidovic et al., 2010)

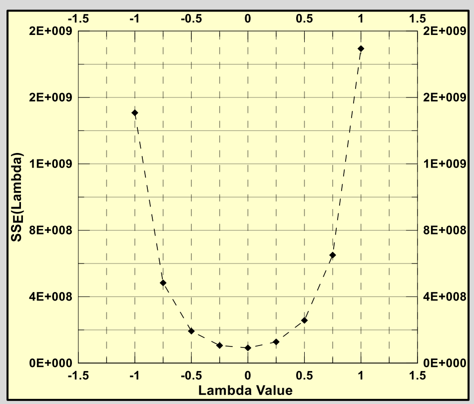
Stationarity

Constant mean and variance in data

- Analysis of Variance – constant mean
- Bartlett's test – constant variance
- Joint probability distribution – histograms & Shapiro wilk test

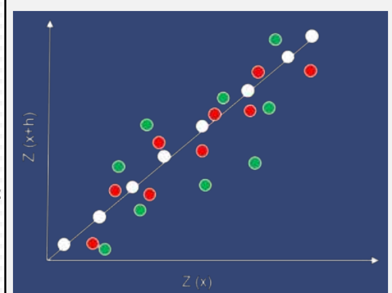
$$g_i = b_0 + b_1X_i + b_2Y_i + \varepsilon_i$$

$$g_i = b_0 + b_1X_i + b_2Y_i + b_3X_i^2 + b_4X_iY_i + b_5Y_i^2$$

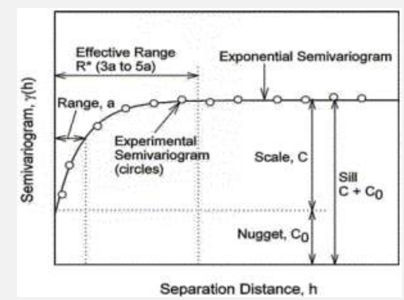


Variogram, Kriging, & Validation

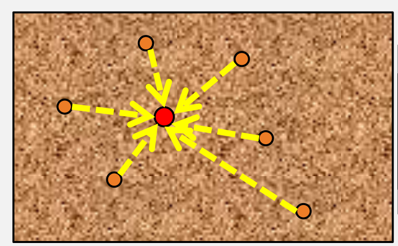
$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z(x_i + h) - z(x_i)]^2$$



h-scatter plot



Variogram



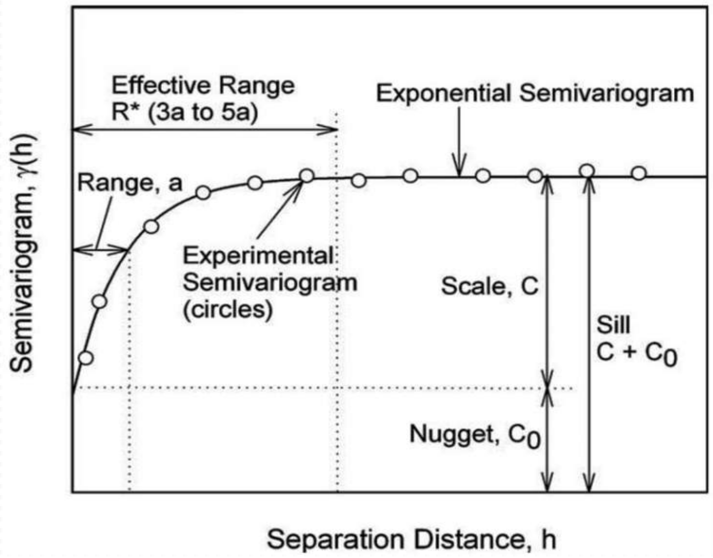
$$\begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} & 1 \\ \vdots & \vdots & \ddots & \vdots & 1 \\ C_{n1} & C_{n2} & \cdots & C_{nn} & 1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_n \\ \lambda \end{bmatrix} = \begin{bmatrix} C_{x1} \\ \vdots \\ C_{xn} \\ 1 \end{bmatrix}$$

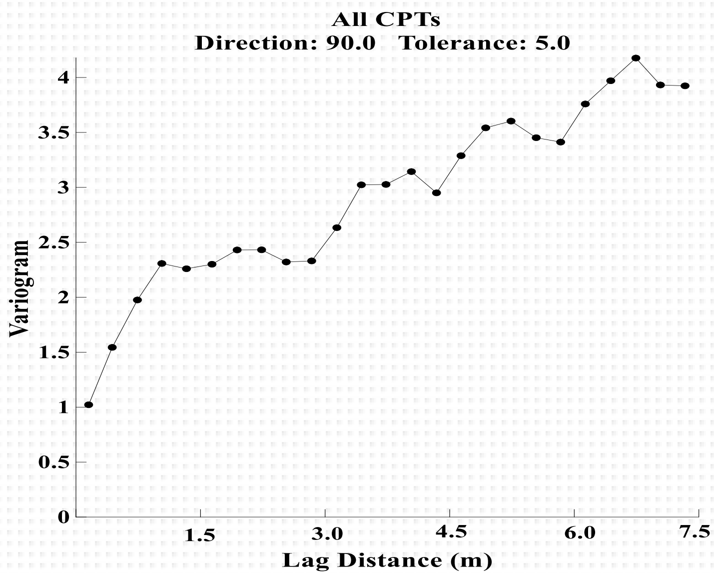
Ordinary Kriging

Bheemasetti, T., Puppala, A., Pedarla, A., Acharya, A., Caballero, S. (2015) Evaluation of Stationarity and Selection of Appropriate Transformation for Geostatistical Modeling of Geotechnical Projects. *GSP*. doi:10.3233/978-1-61499-601-9-559

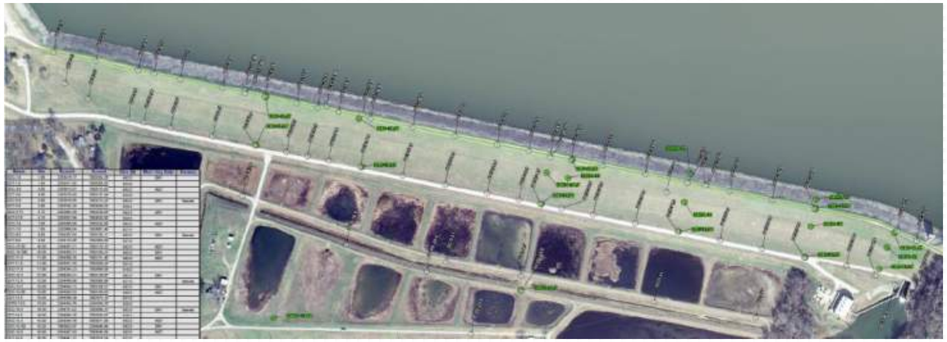
Eagle Mountain Structures- CPT Profiles

CPT No	Distance	Depth (m)	Spatial Variability Models				Variance
			Nugget	Range	Scale	Sill	
1	0.0	22.9	0.8	0.9	2.0	2.7	4.6
2	61.0	24.1	1.2	0.9	1.6	2.7	3.3
3	121.9	26.7	1.5	1.7	2.1	3.6	3.6
4	144.8	27.2	0.6	0.9	1.8	2.4	2.9
5	182.9	27.9	0.7	1.4	2.4	3.0	3.6
6	243.8	27.3	1.3	2.7	2.2	3.5	4.0
7	276.0	27.2	0.5	0.8	1.3	1.8	2.1
8	304.0	27.0	0.6	0.5	1.3	1.9	2.3
9	350.9	27.4	0.7	2.7	2.0	2.6	3.0
10	381.4	27.8	1.8	4.1	3.9	5.8	4.9
11	393.9	28.0	0.7	1.4	2.9	3.5	3.8
12	413.2	23.3	1.5	0.5	2.0	3.5	4.0
13	446.4	29.4	1.0	1.9	2.8	3.7	4.3
14	459.7	29.5	0.3	0.7	2.8	3.1	3.6
15	520.7	27.2	1.5	6.4	3.1	4.6	3.8
16	581.6	26.4	0.9	2.4	2.1	3.0	3.4
17	642.6	28.2	1.5	2.9	3.4	4.9	4.6
18	688.3	29.4	0.8	3.9	3.4	4.2	3.7
19	718.8	25.8	1.0	0.5	10.5	11.5	3.3
20	749.3	25.8	1.2	3.6	1.8	3.0	2.8
21	795.0	26.5	2.3	4.8	3.6	5.9	4.4
22	855.9	35.3	0.7	4.5	2.5	3.2	3.3
23	892.5	40.5	1.0	5.2	3.3	4.3	3.6
24	919.9	40.1	0.9	5.2	2.4	3.3	2.8
25	945.4	34.5	0.8	4.9	3.2	4.0	3.0
26	981.0	35.3	1.1	4.7	1.7	2.8	3.0
27	1041.9	37.7	0.9	5.3	2.3	3.2	2.6
28	1102.9	36.5	0.5	1.1	1.8	2.3	2.8
29	1224.1	31.1	0.3	0.4	1.6	1.9	2.2

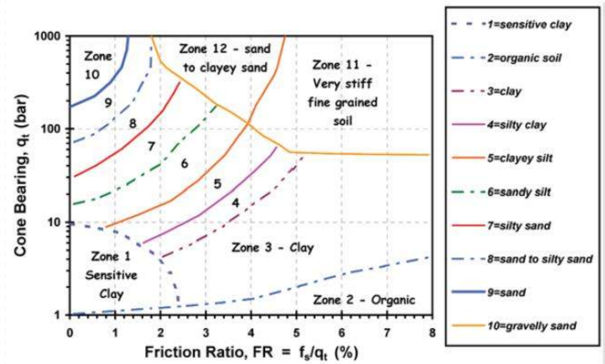




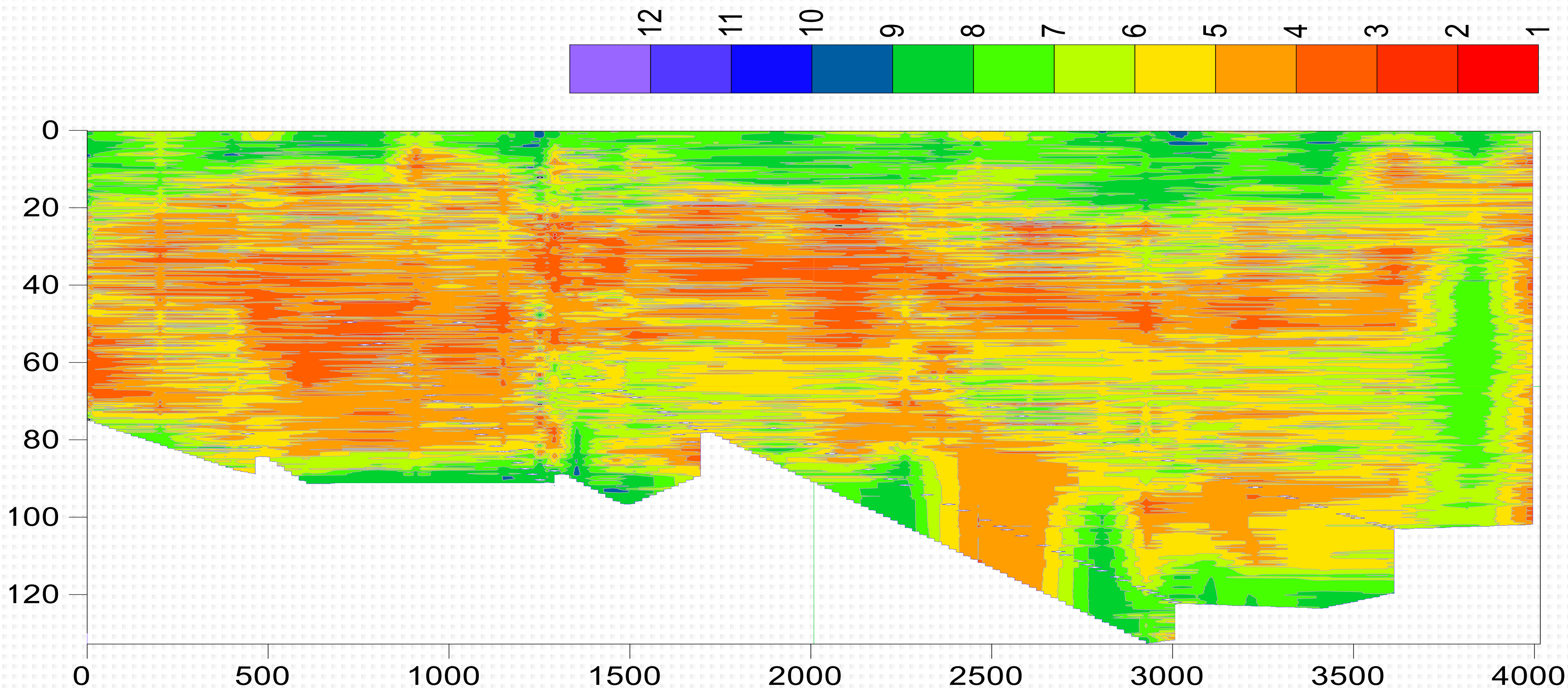
Main Dam Crest- SBT Profile



Main Dam CPT Layout



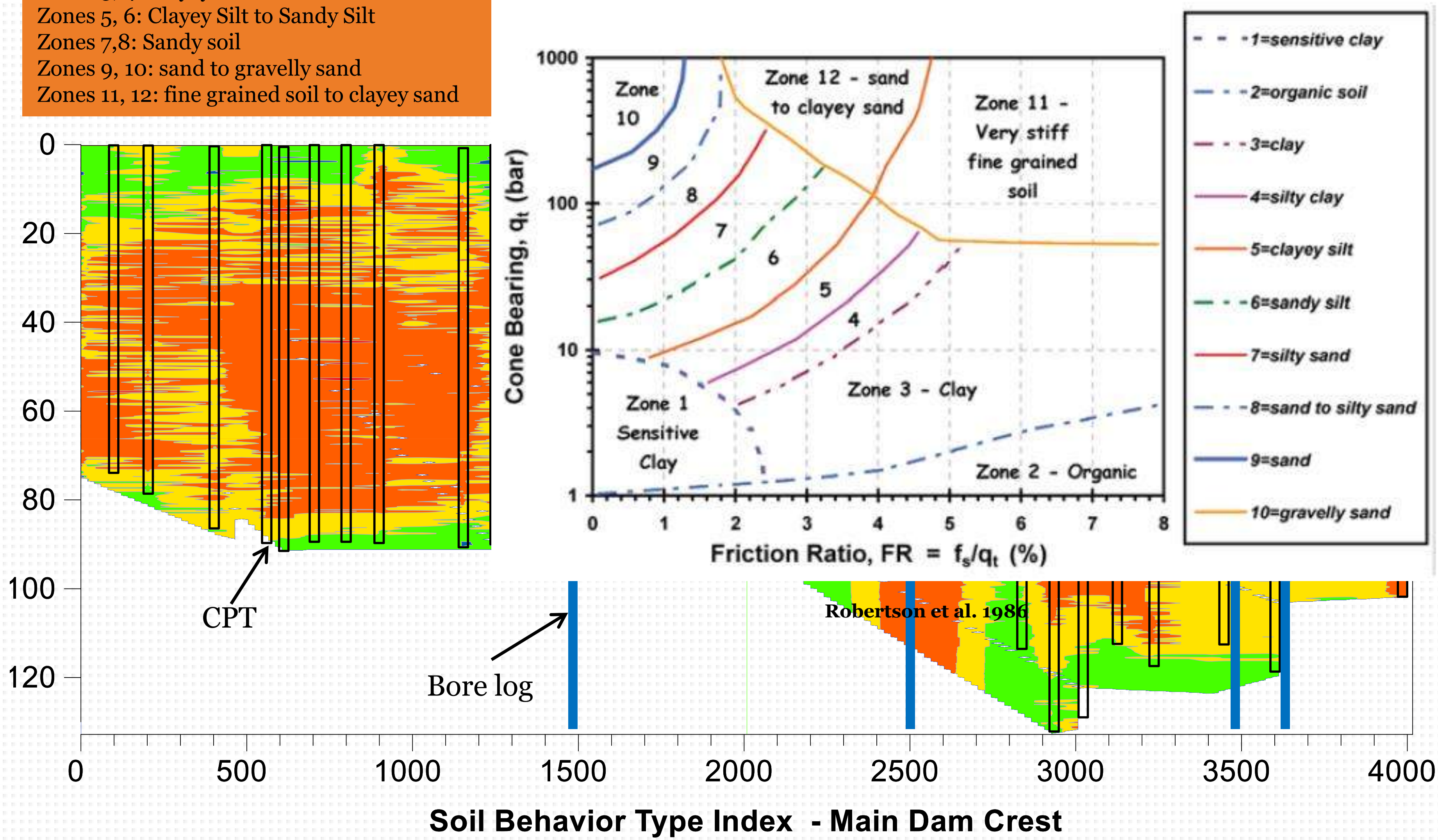
Robertson et al. 1986



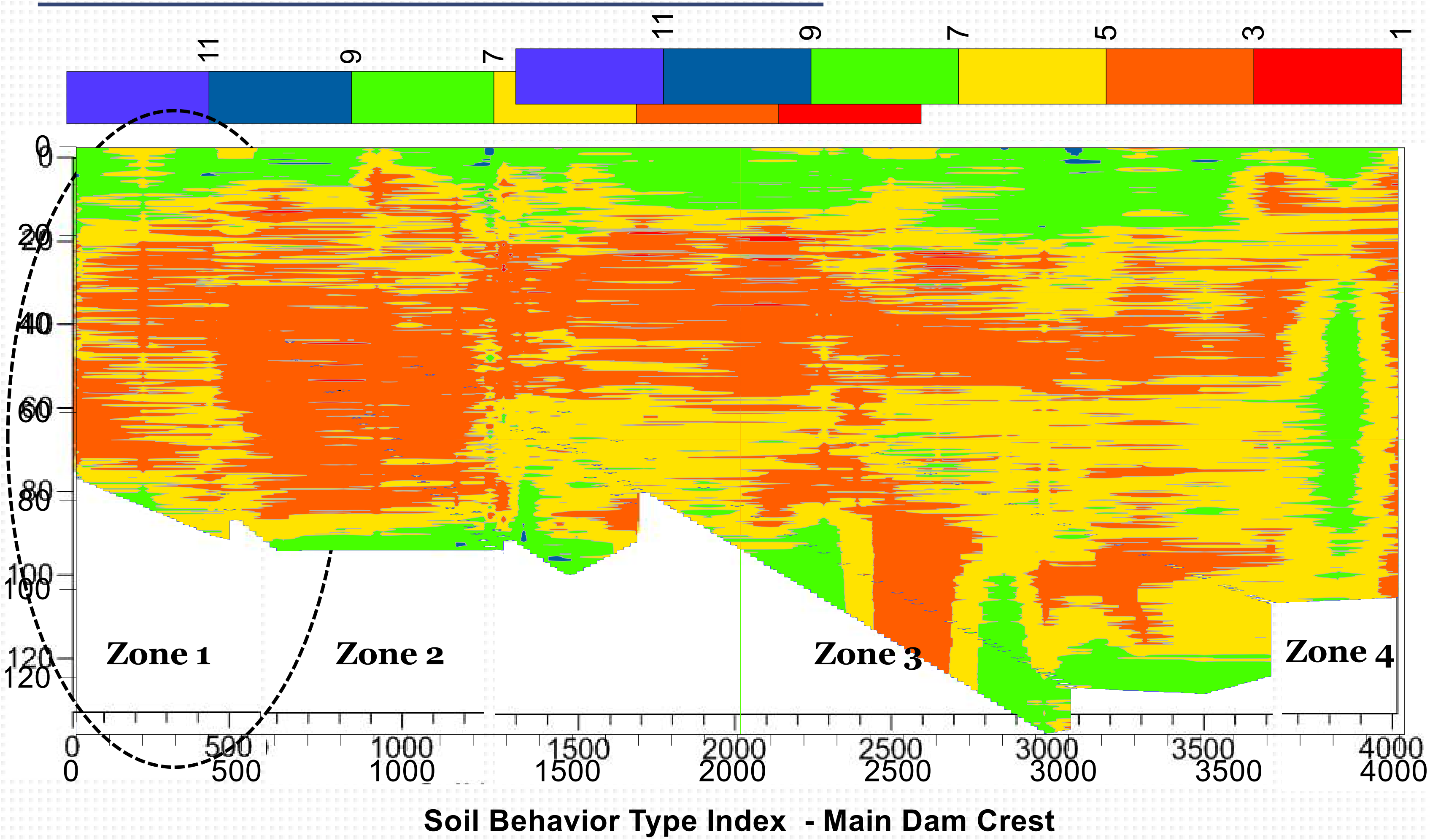
Soil Behavior Type Index - Main Dam Crest

Main Dam Crest- SBT Profile

Zones 1, 2: Sensitive Clays
Zones 3, 4: Clayey soil
Zones 5, 6: Clayey Silt to Sandy Silt
Zones 7,8: Sandy soil
Zones 9, 10: sand to gravelly sand
Zones 11, 12: fine grained soil to clayey sand



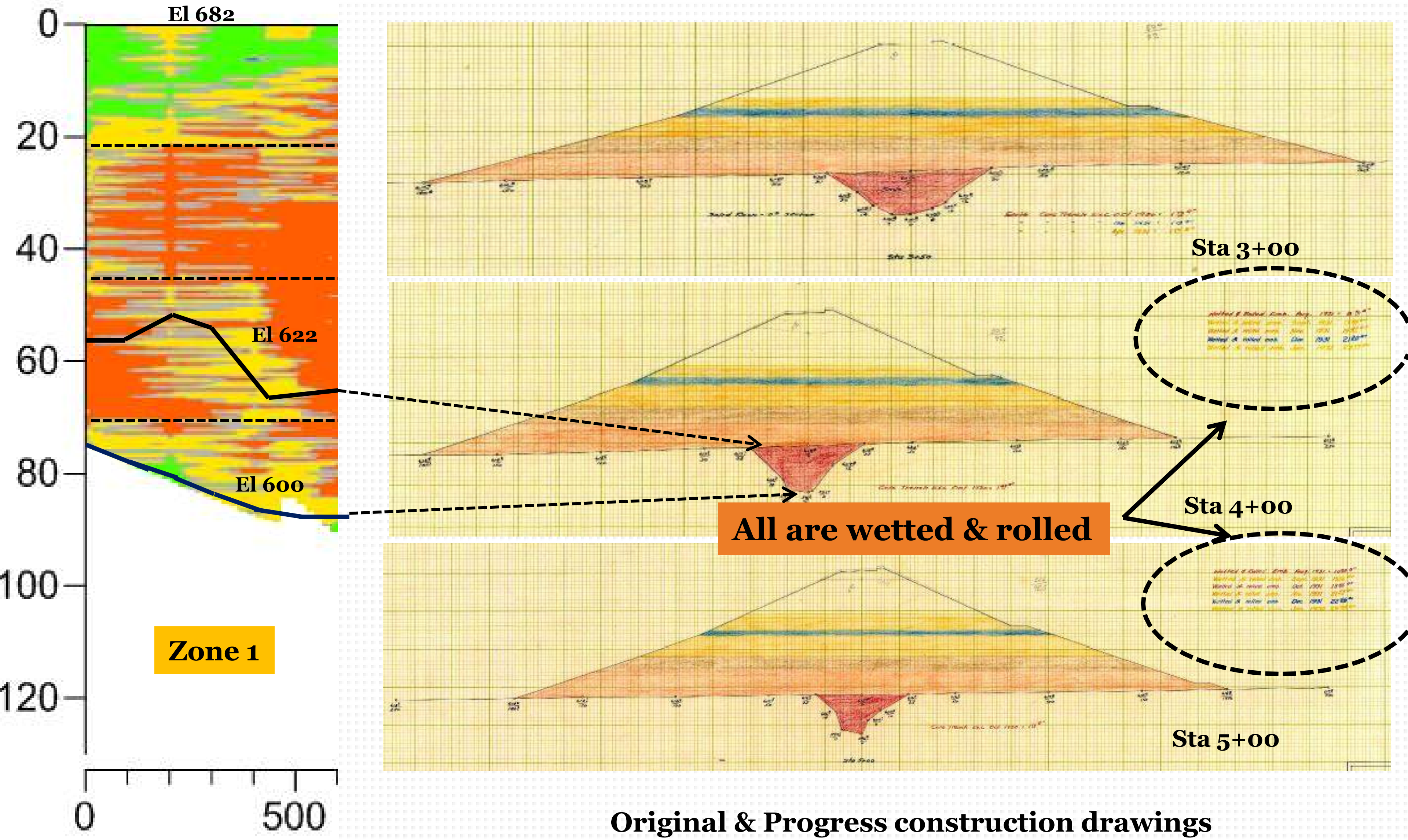
Main Dam Crest- SBT Profile



Key Observations: 4 zones

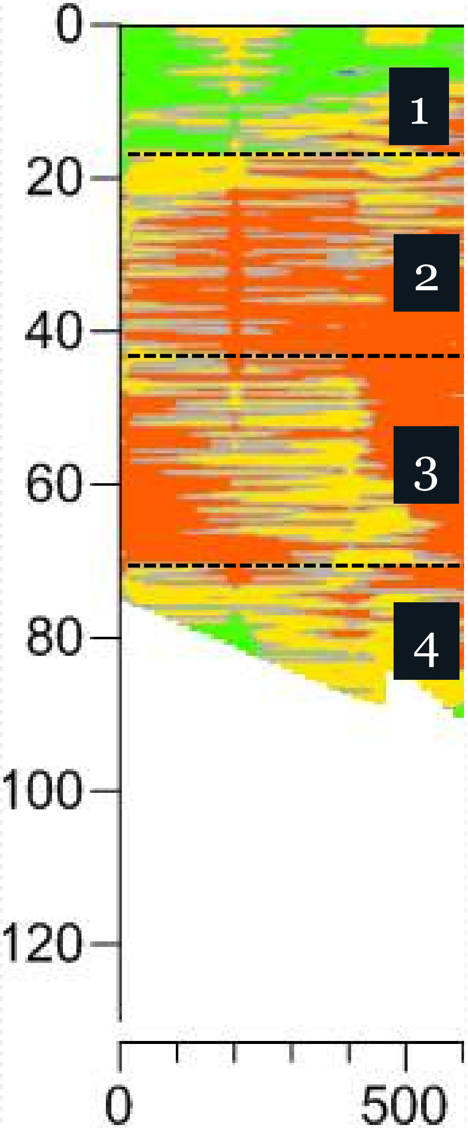
0 to 500ft ; 500 to 1200ft; 1200 to 3800ft; 3800 to 4000ft

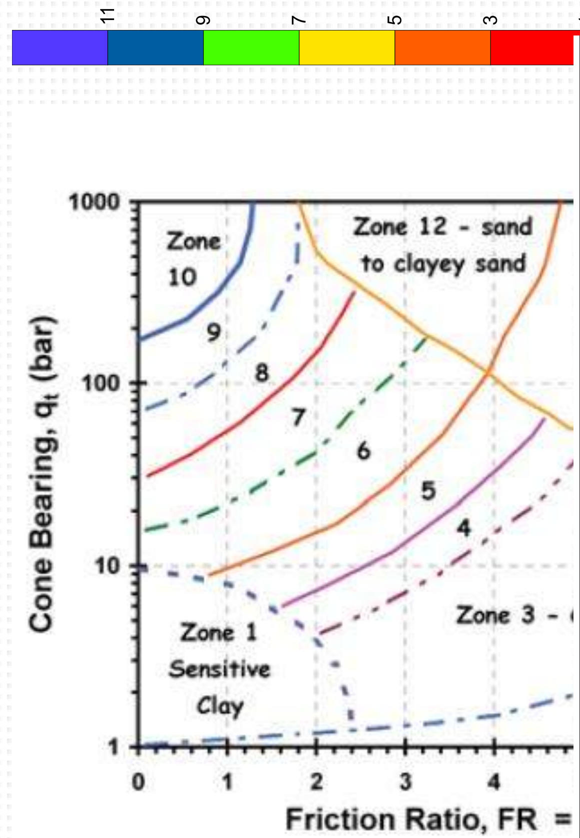
Main Dam Crest- SBT Profile

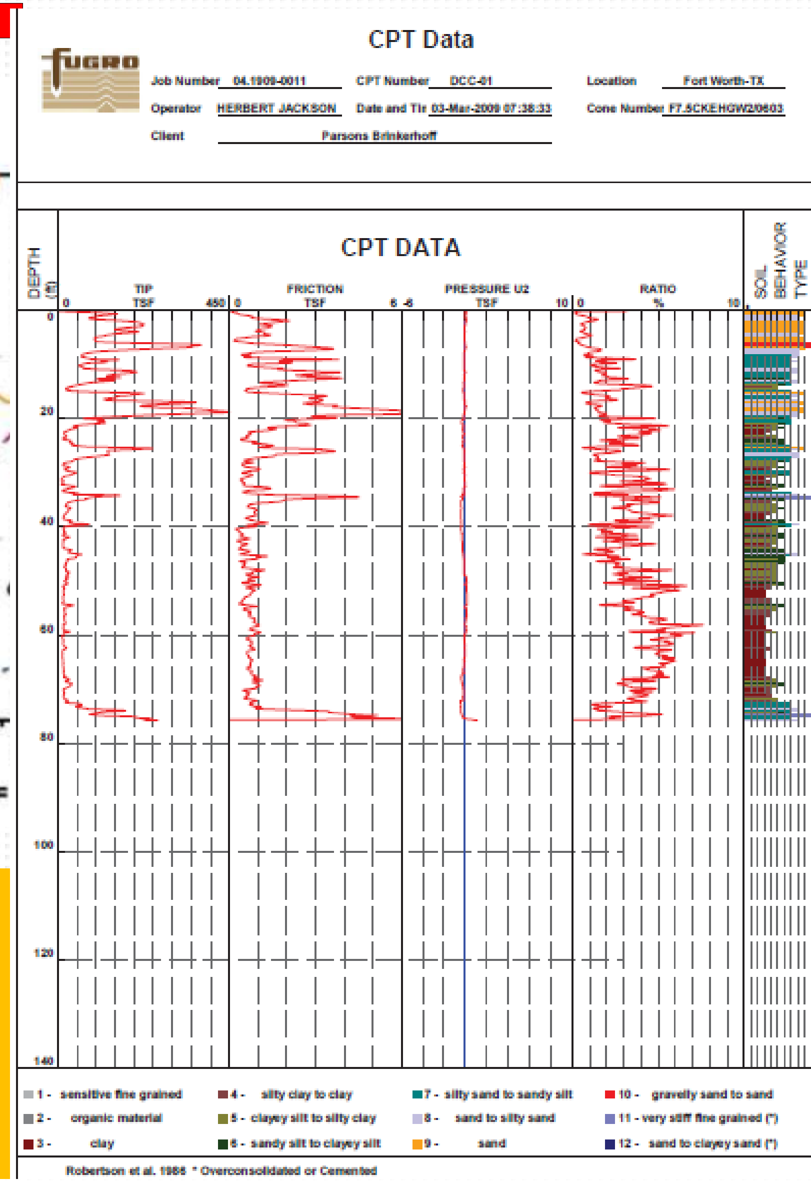


Original & Progress construction drawings

Main Dam Crest- SBT Profile



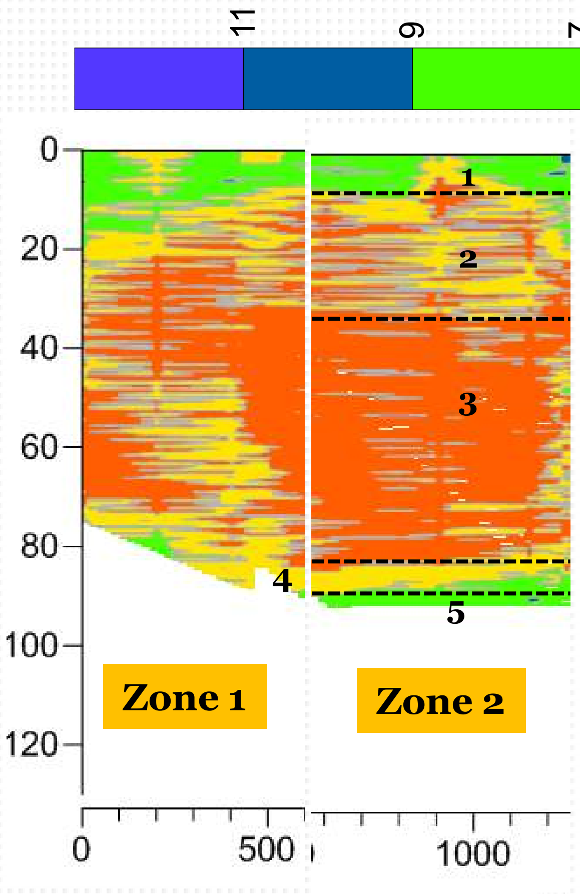


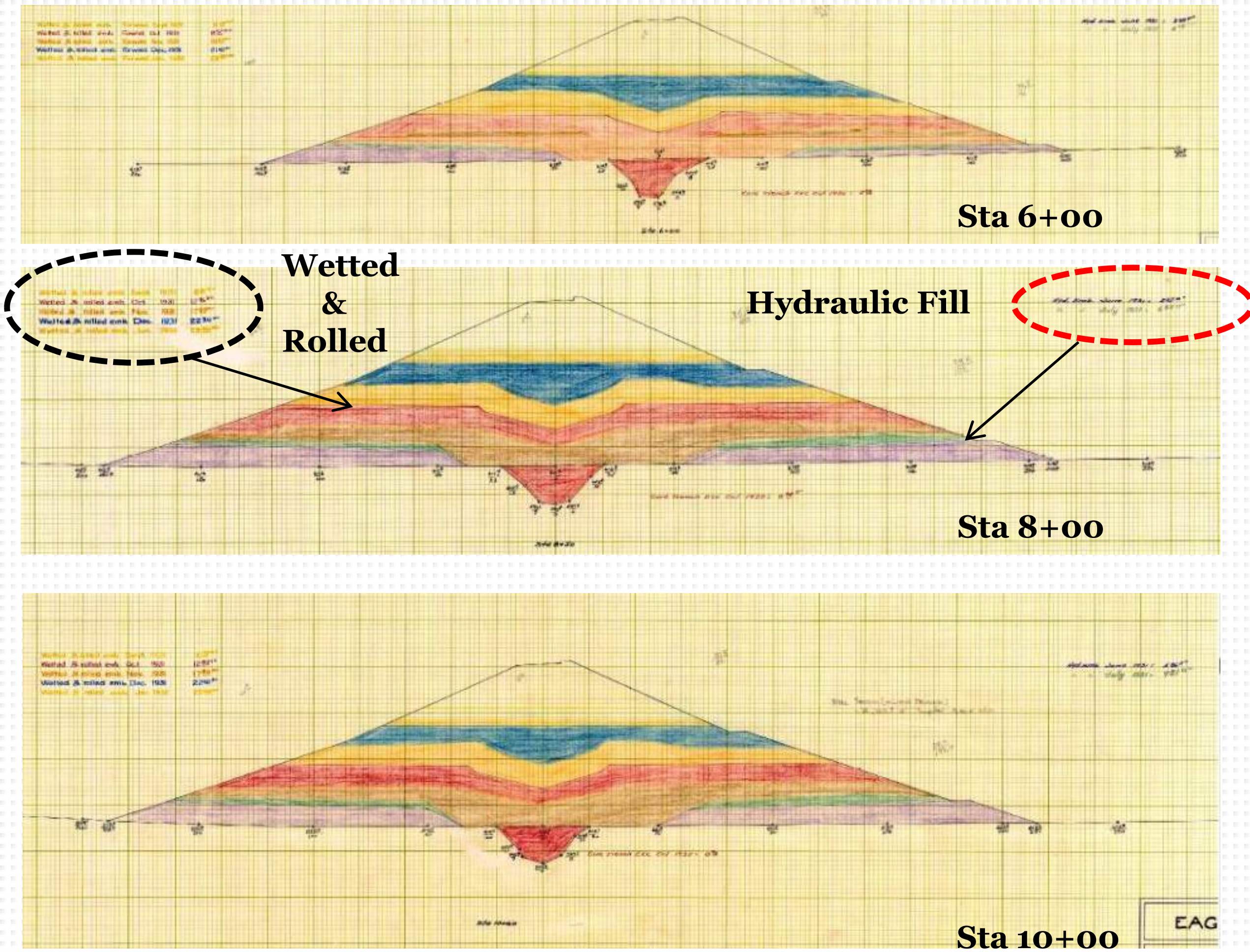


Classification

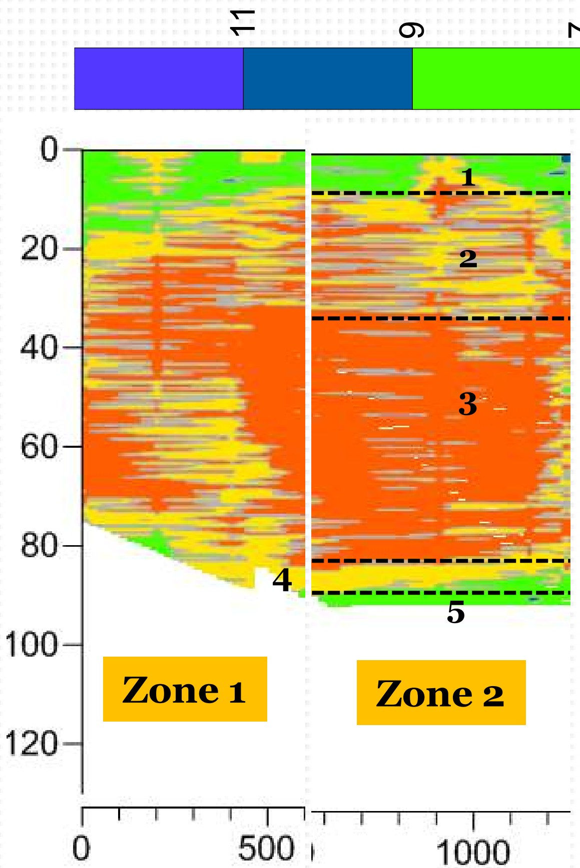
1. Mixtures of sand & silt
2. Mixtures of silt & clay
3. Mixture of clay & silt
4. Mixture of silt & sand

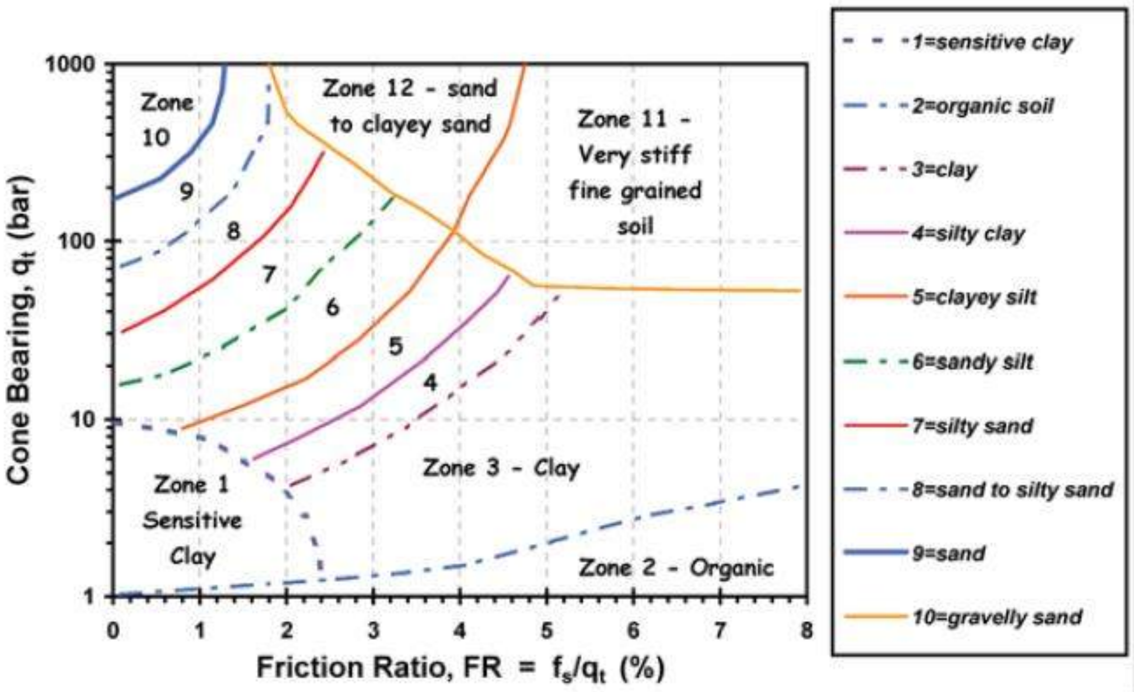
Main Dam Crest- SBT Profile





Main Dam Crest- SBT Profile

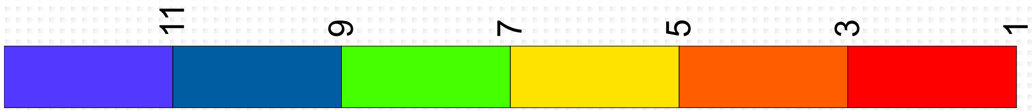


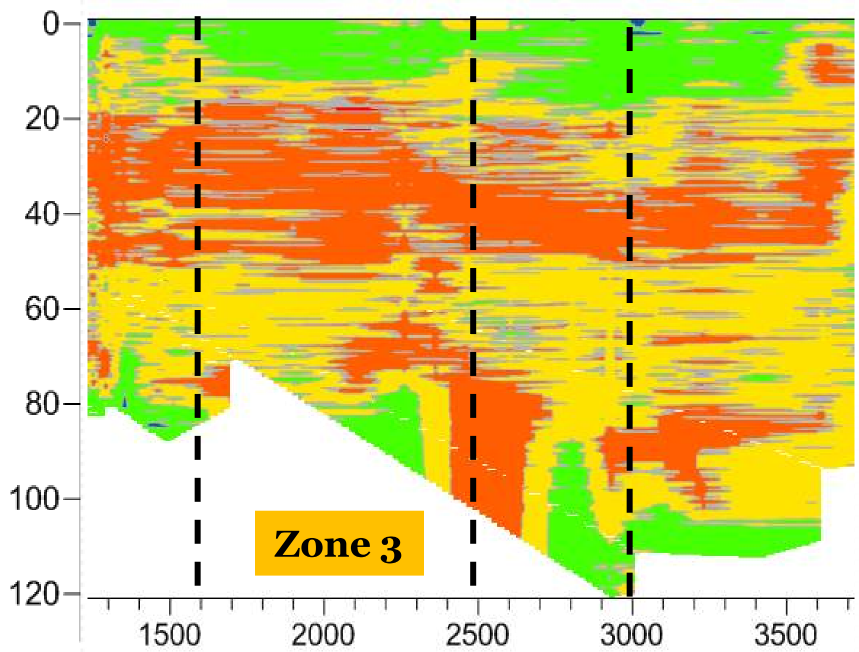


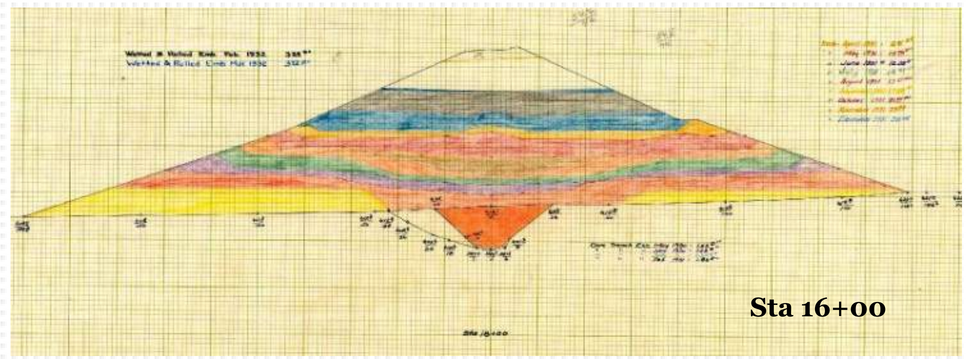
Classification

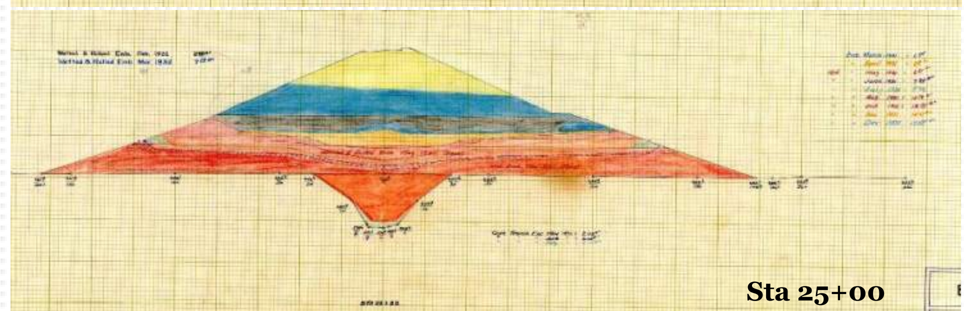
1. Mixtures of silt & sand
2. Mixtures of silt & clay
3. Mostly clay with silt lenses
4. Mixture of silt & sand layers

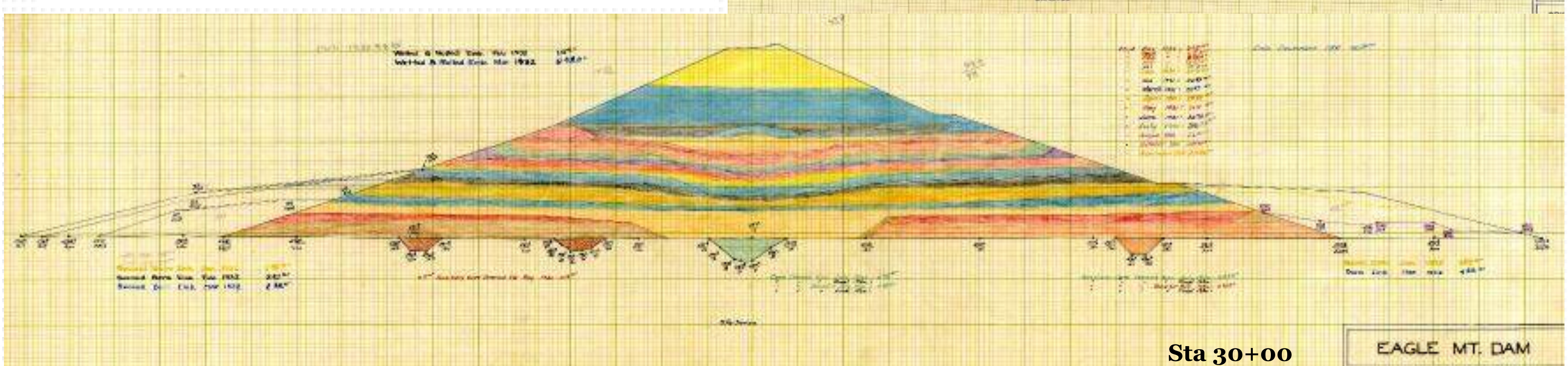
Main Dam Crest- SBT Profile



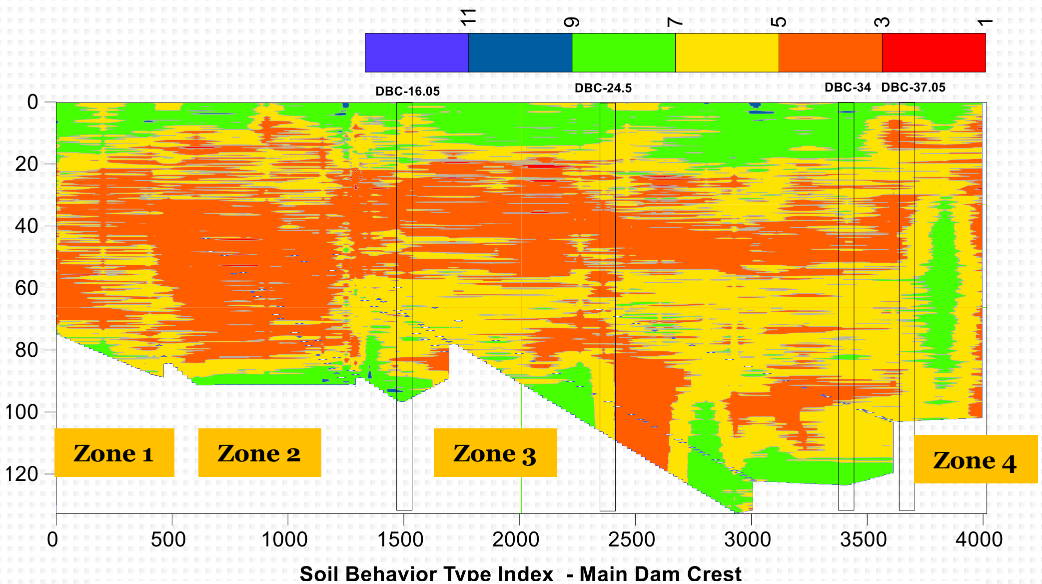


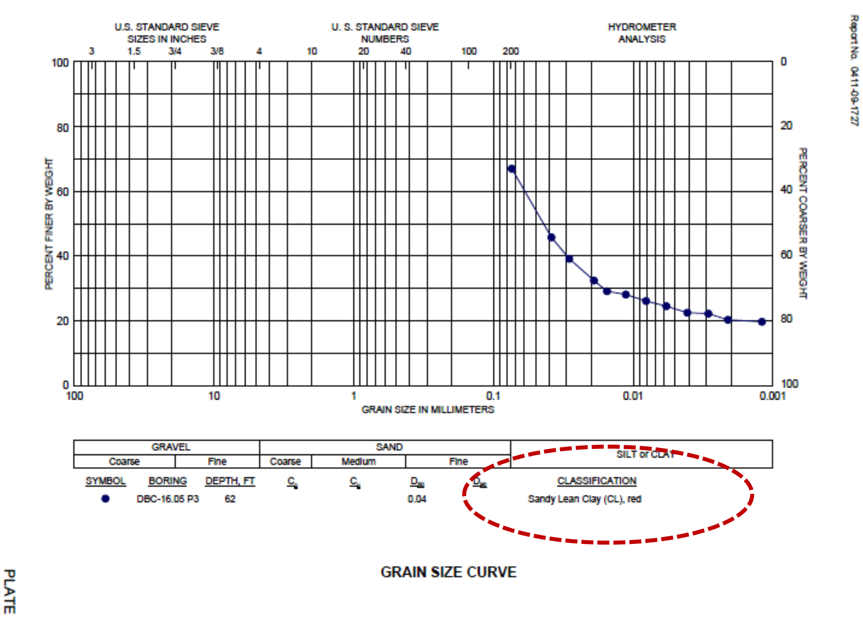


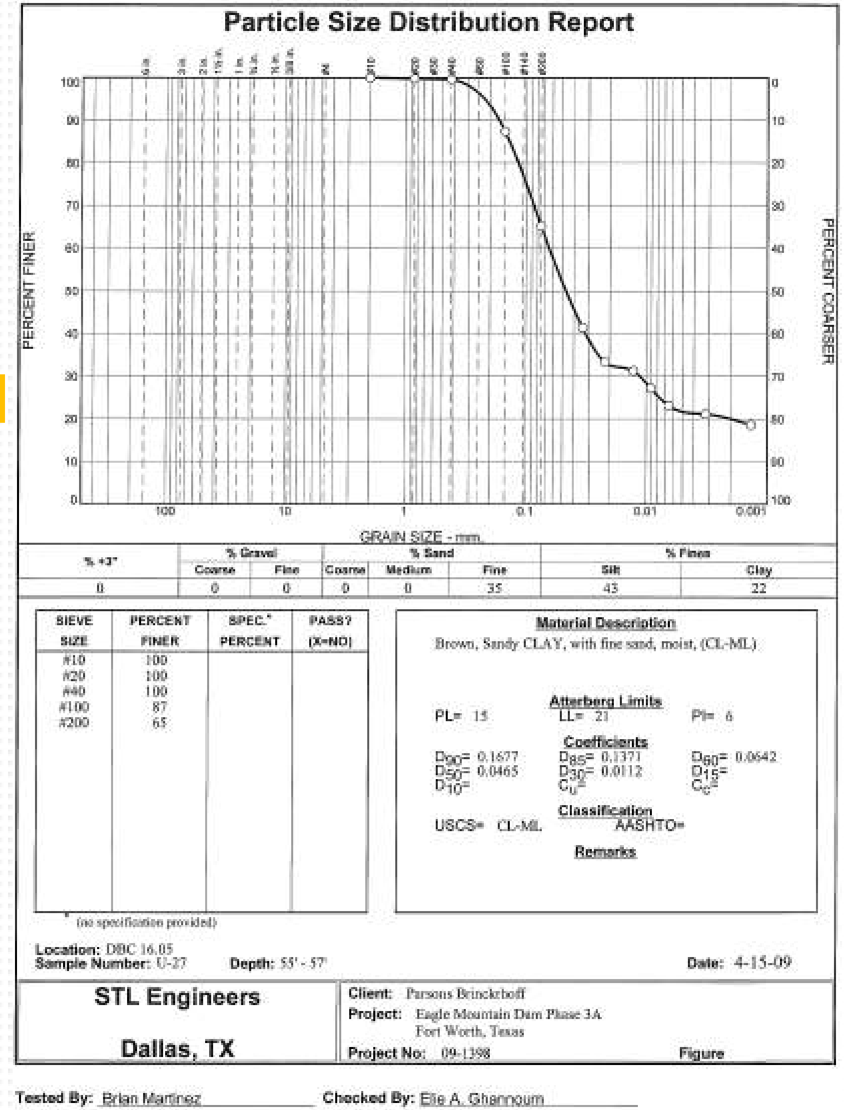




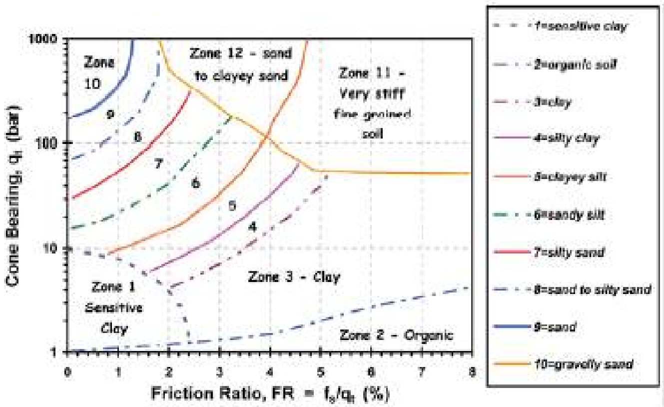
Main Dam Crest- SBT Profile

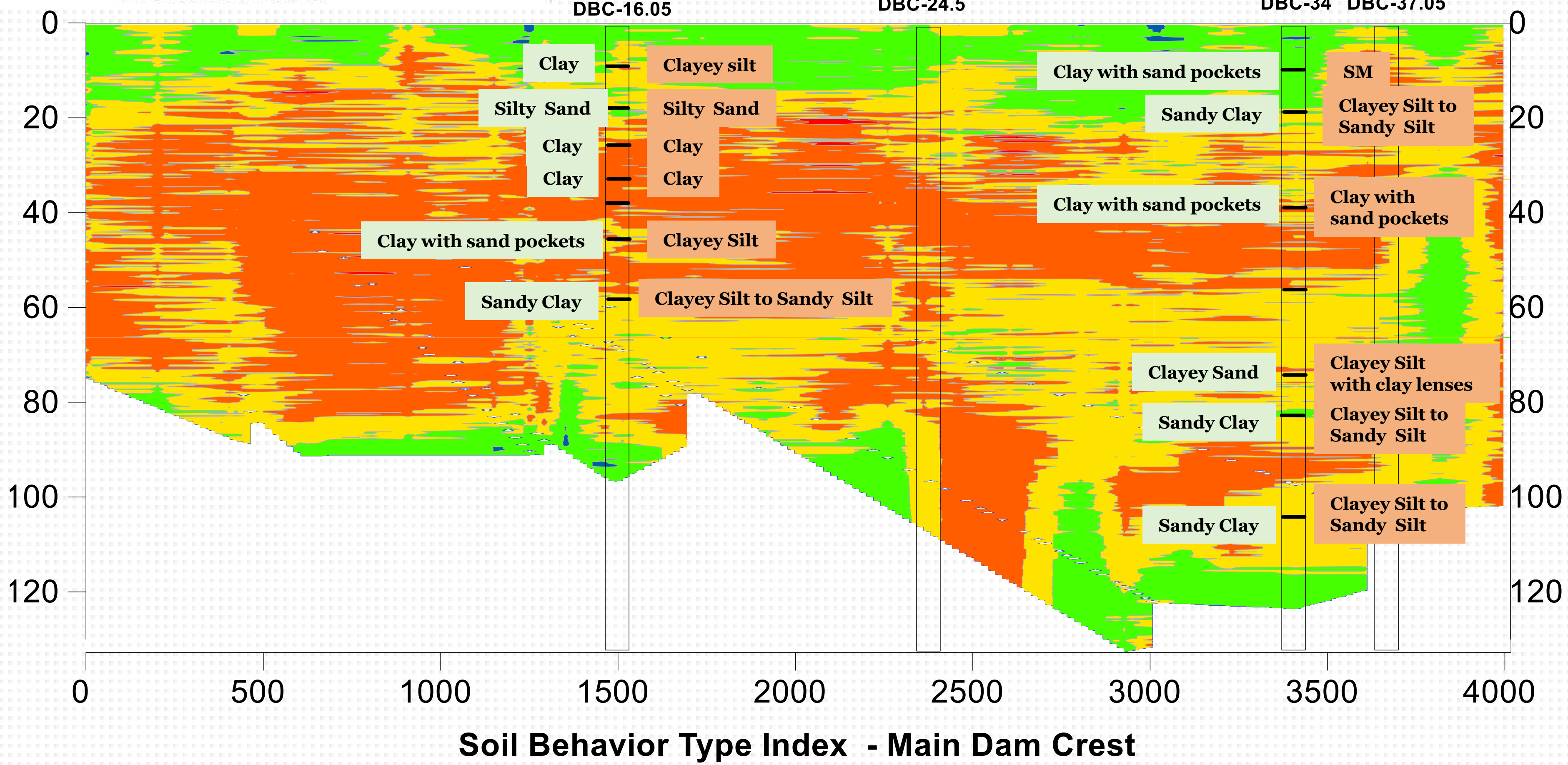




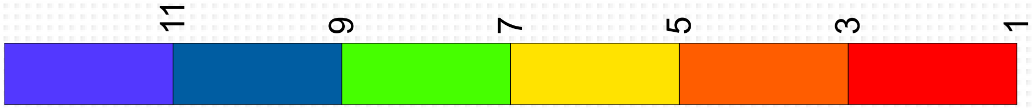


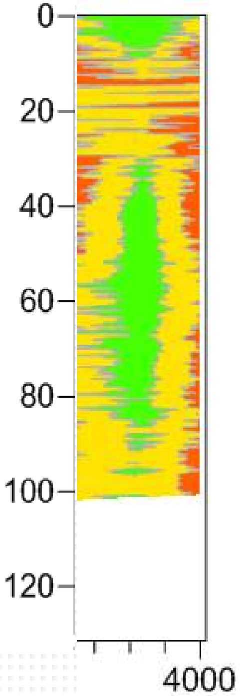
Main Dam Crest- SBT Profile

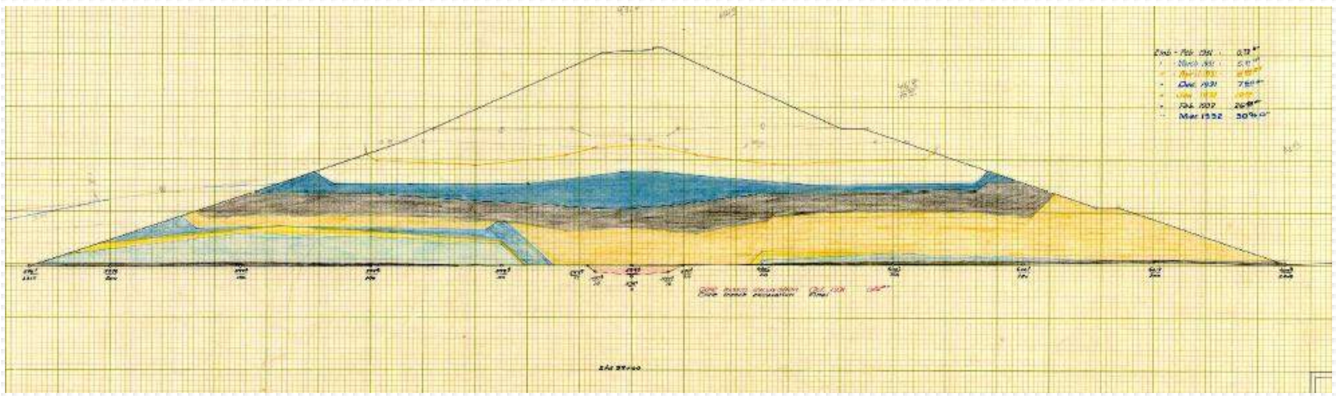




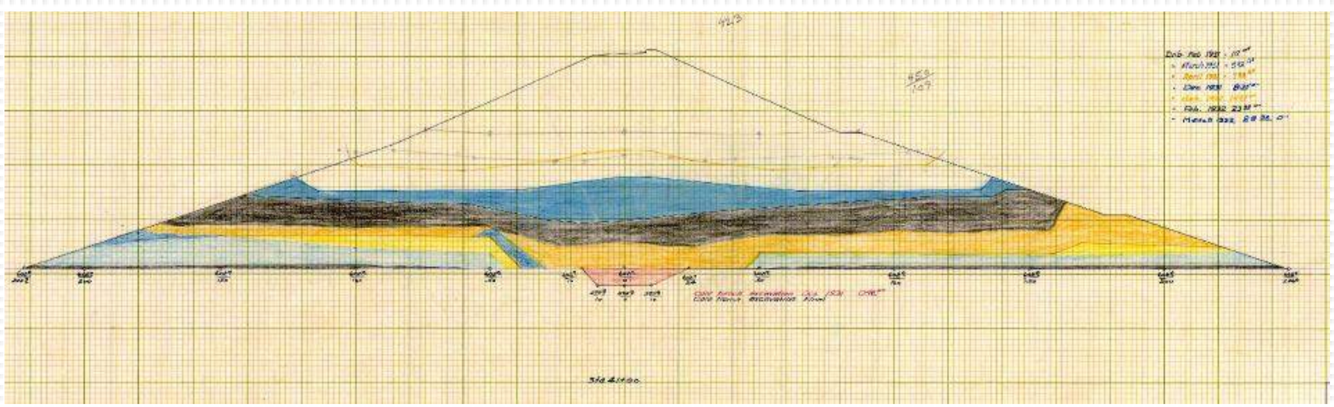
Main Dam Crest- SBT Profile





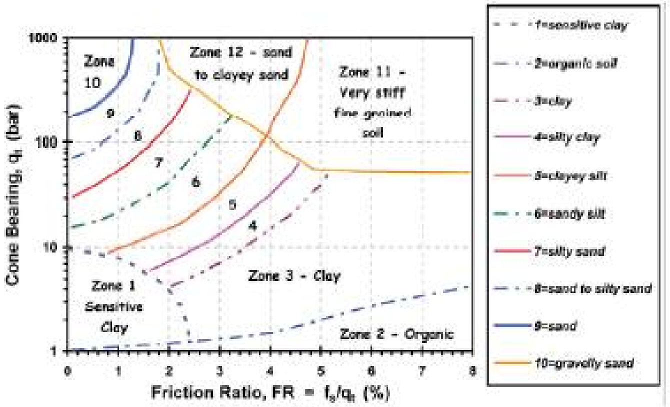


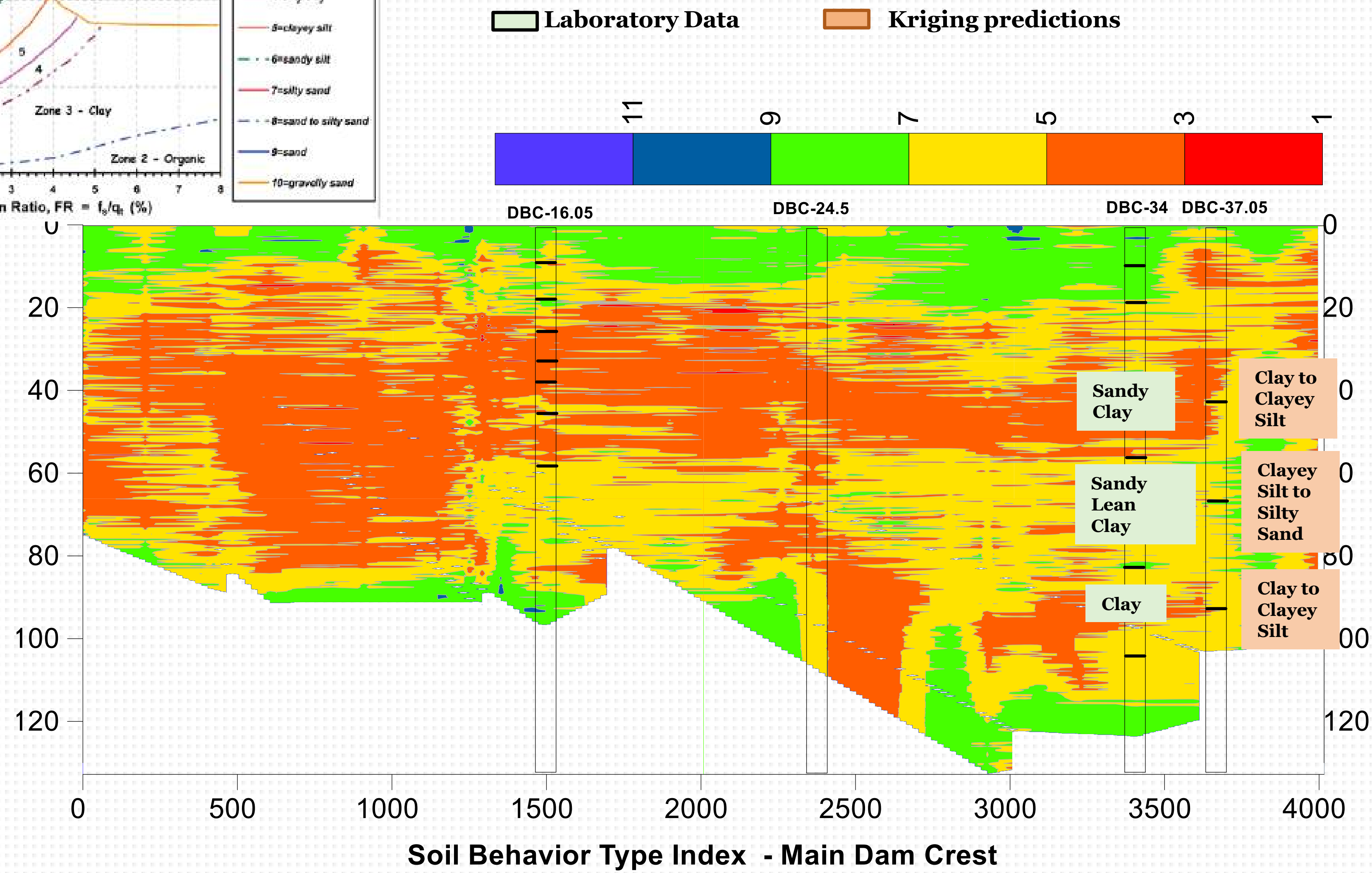
Sta 39+00



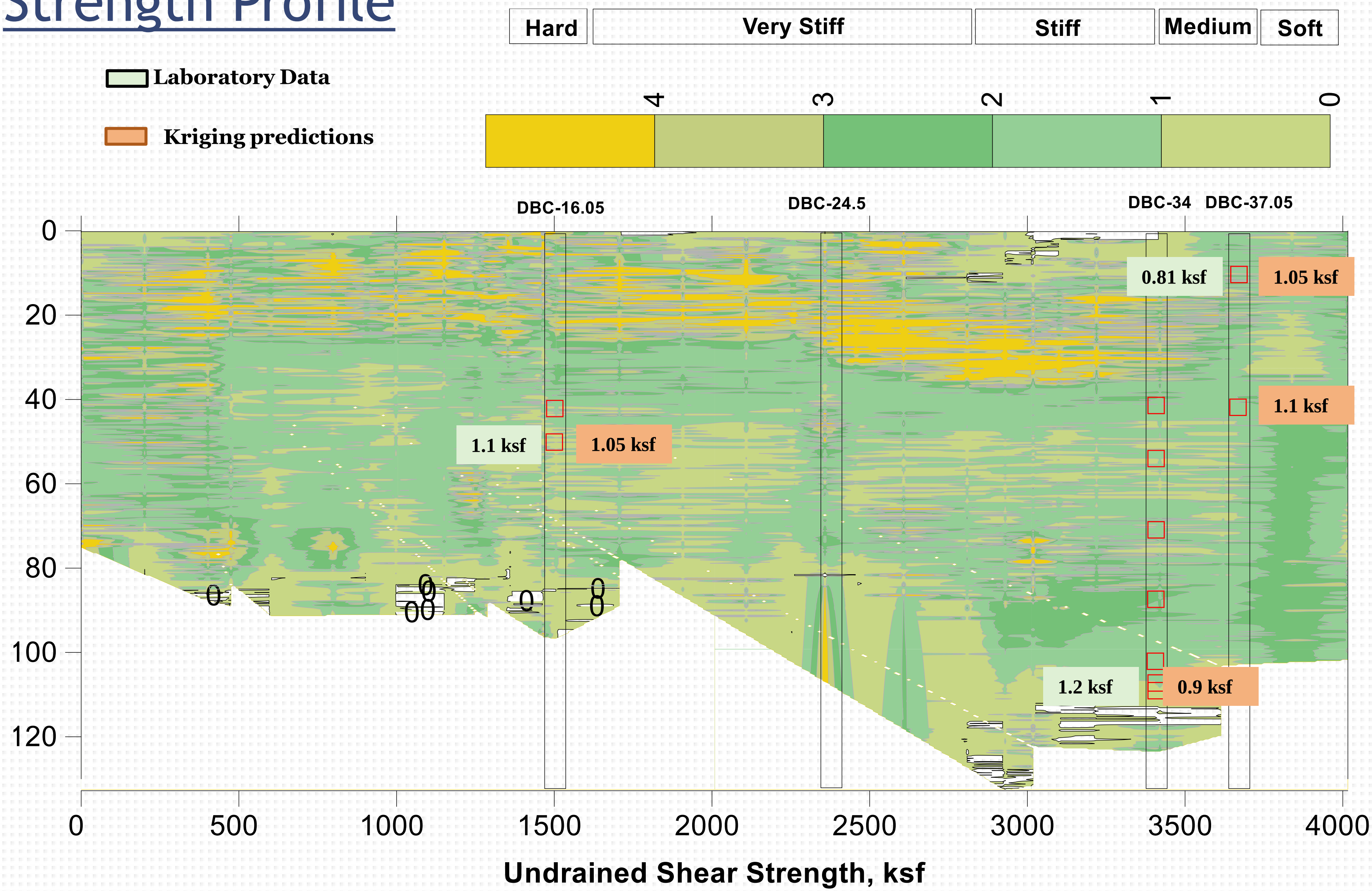
Sta 41+00

Main Dam Crest- SBT Profile

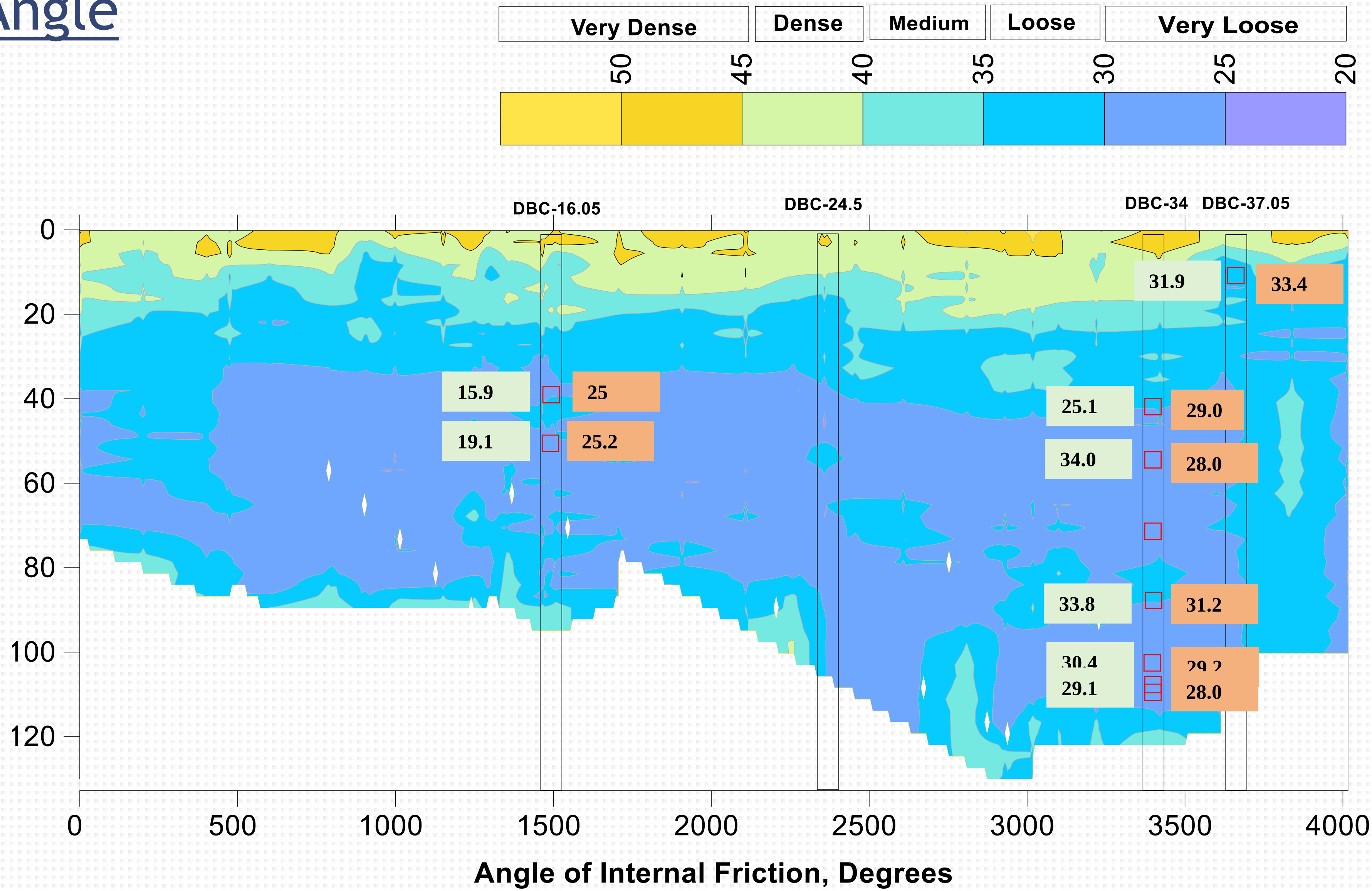




Main Dam Crest- Undrained Shear Strength Profile



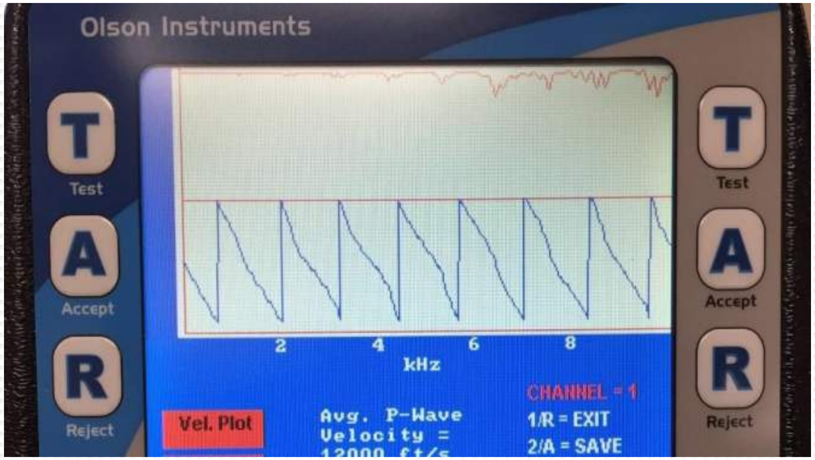
Main Dam Crest- Effective Friction Angle



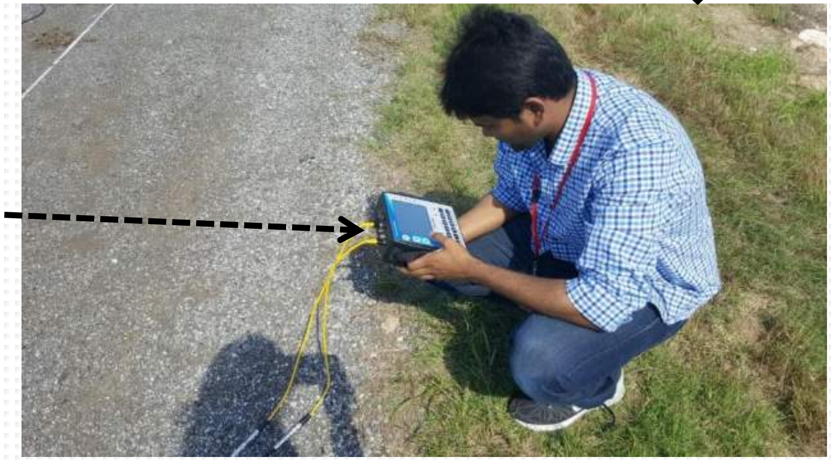
Geophysical Tests on Dam

Acoustic coupling

Constant energy impact

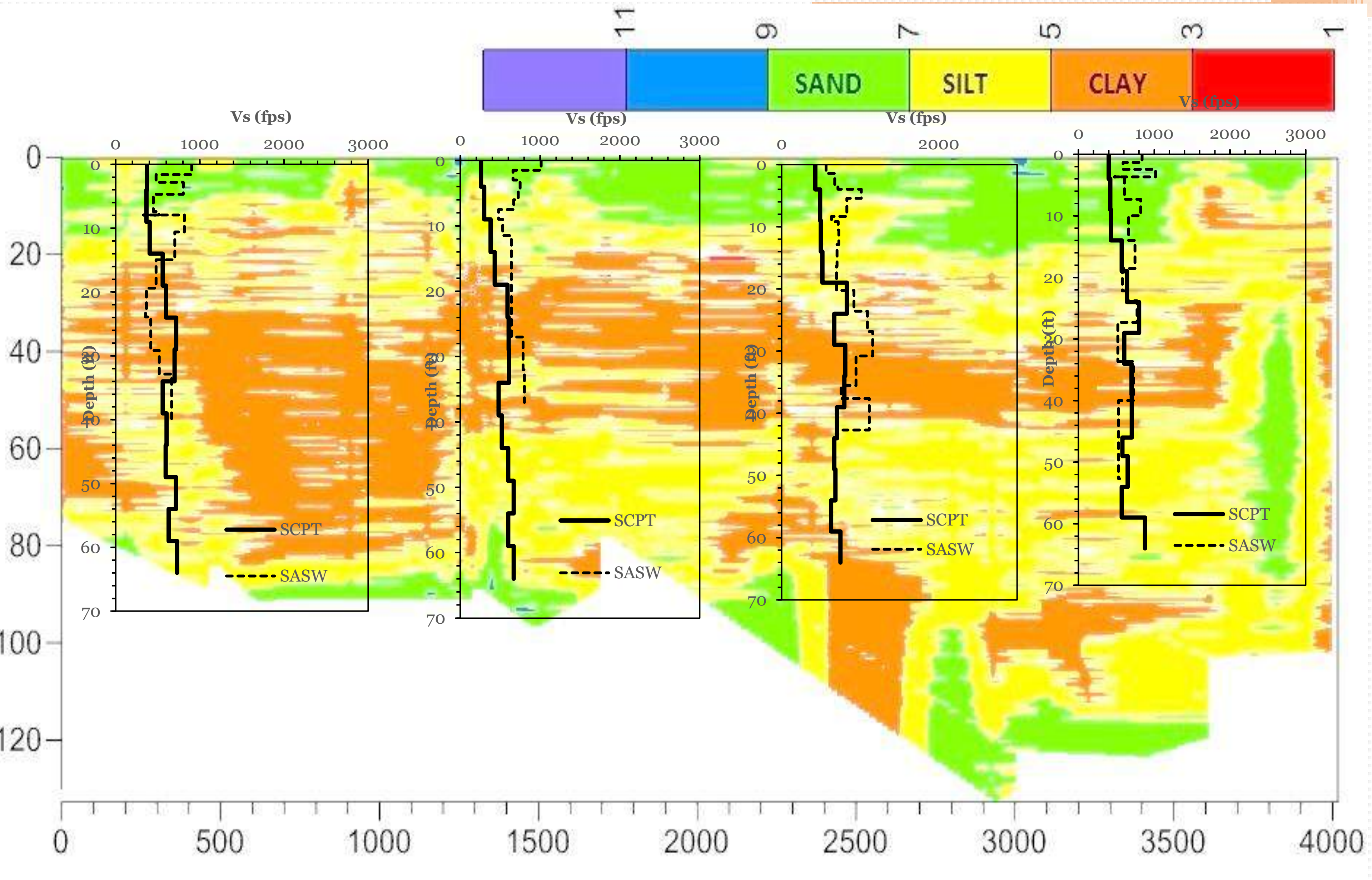


Phase and Coherence Data

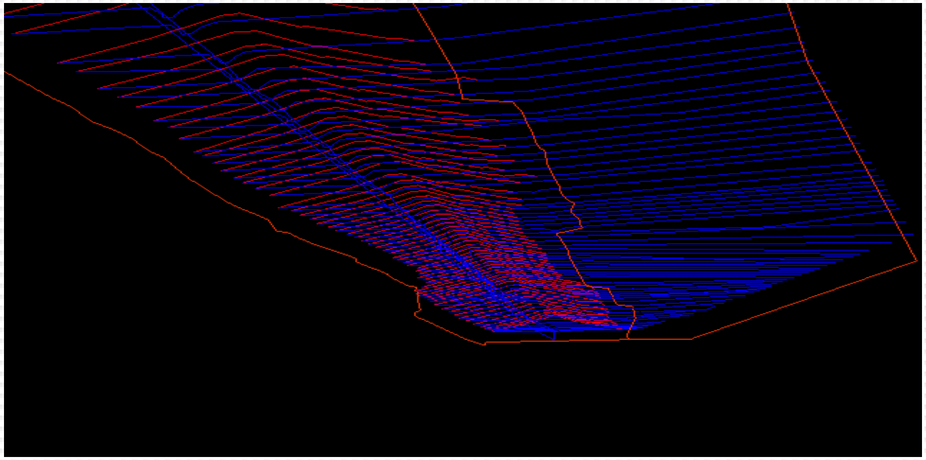


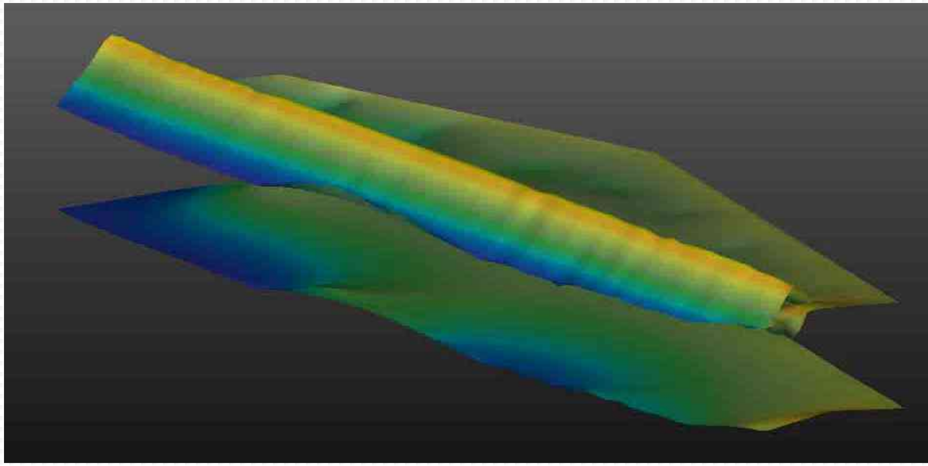
Accept/ Reject Test

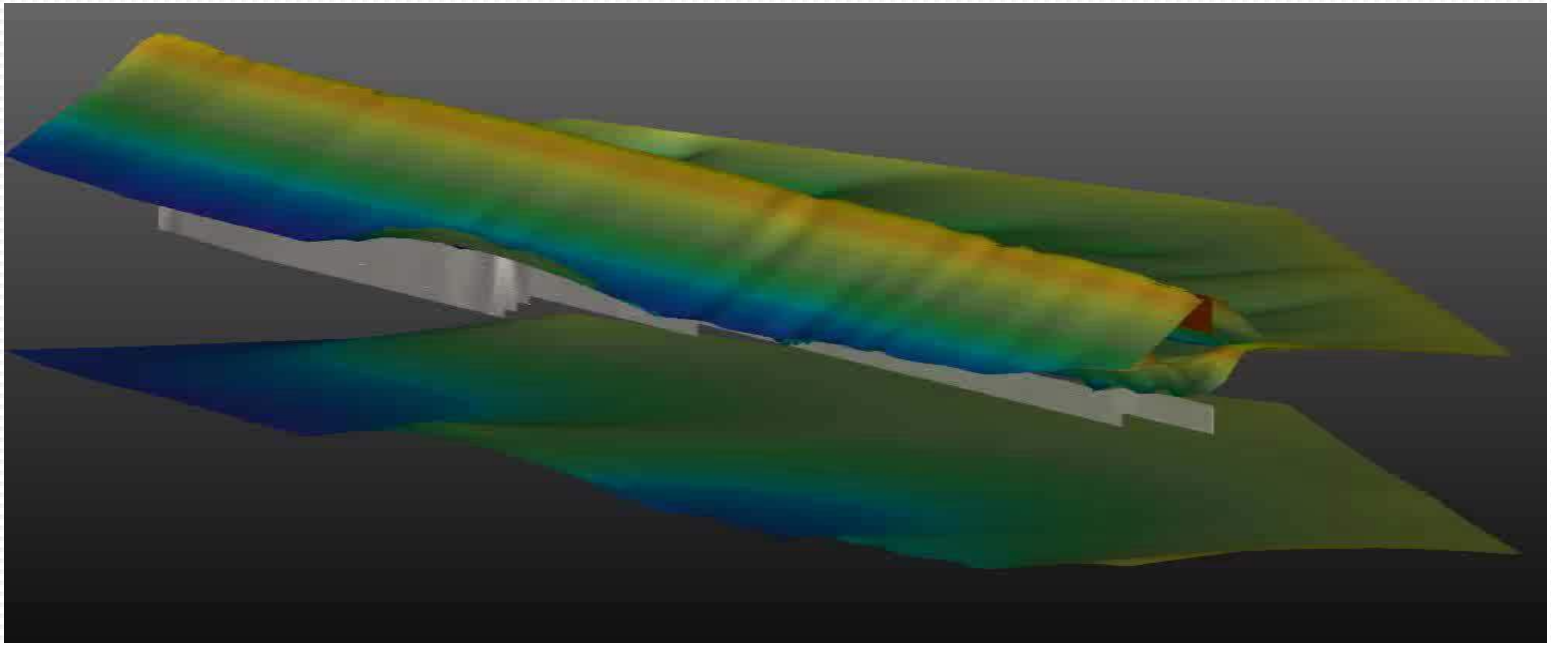
- Each SASW test for each receiver spacing was repeated for 4 times.
- For 1 location (2 ft, 4 ft, 8 ft): 12 SASW tests


11
9
7
5
3
1
SAND
SILT
CLAY
Vs (fps)
Depth (ft)
SCPT
SASW
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
3000
3500
4000

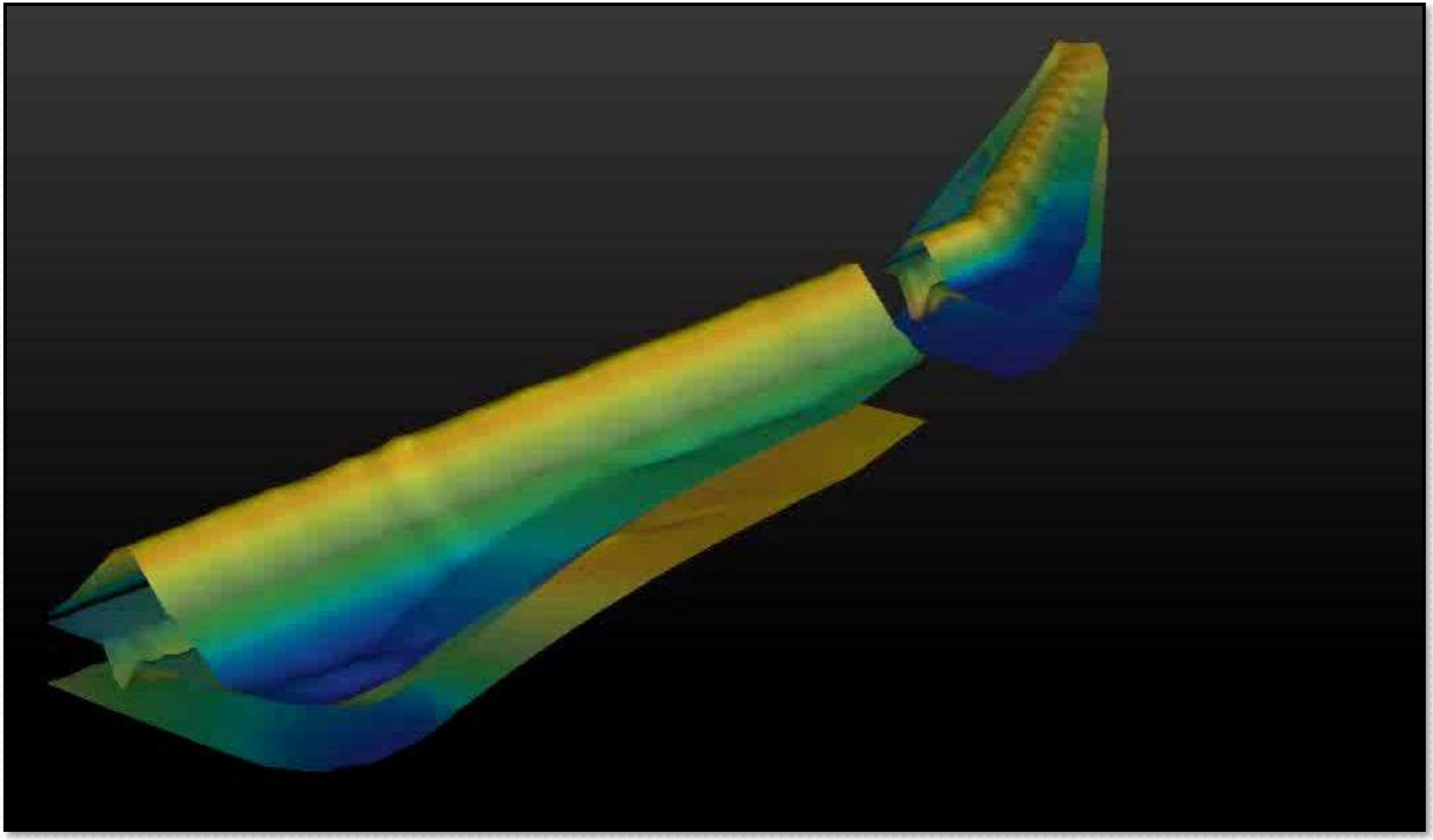
3D Model Generation





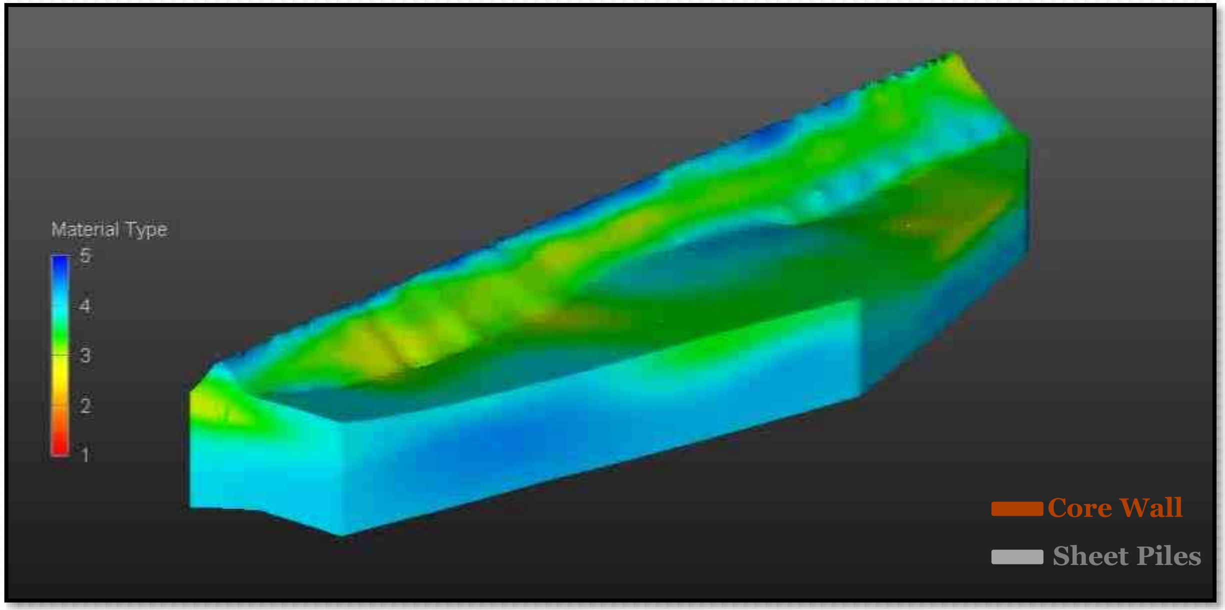


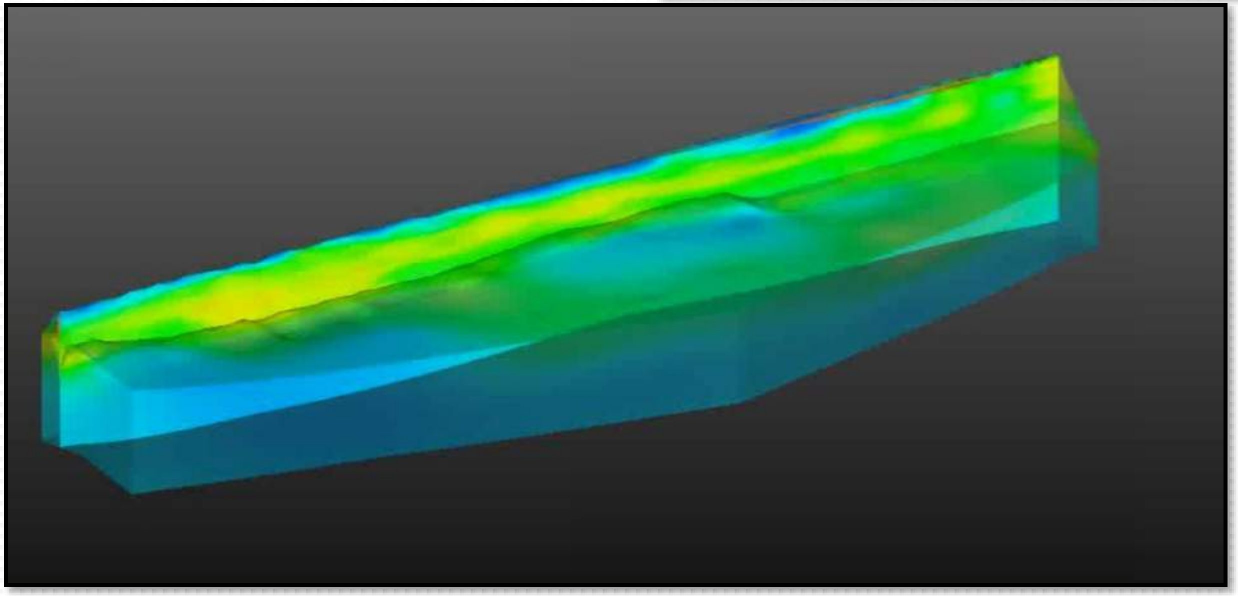
3D Model Generation



Spatial Variability of Soils in EM Dam

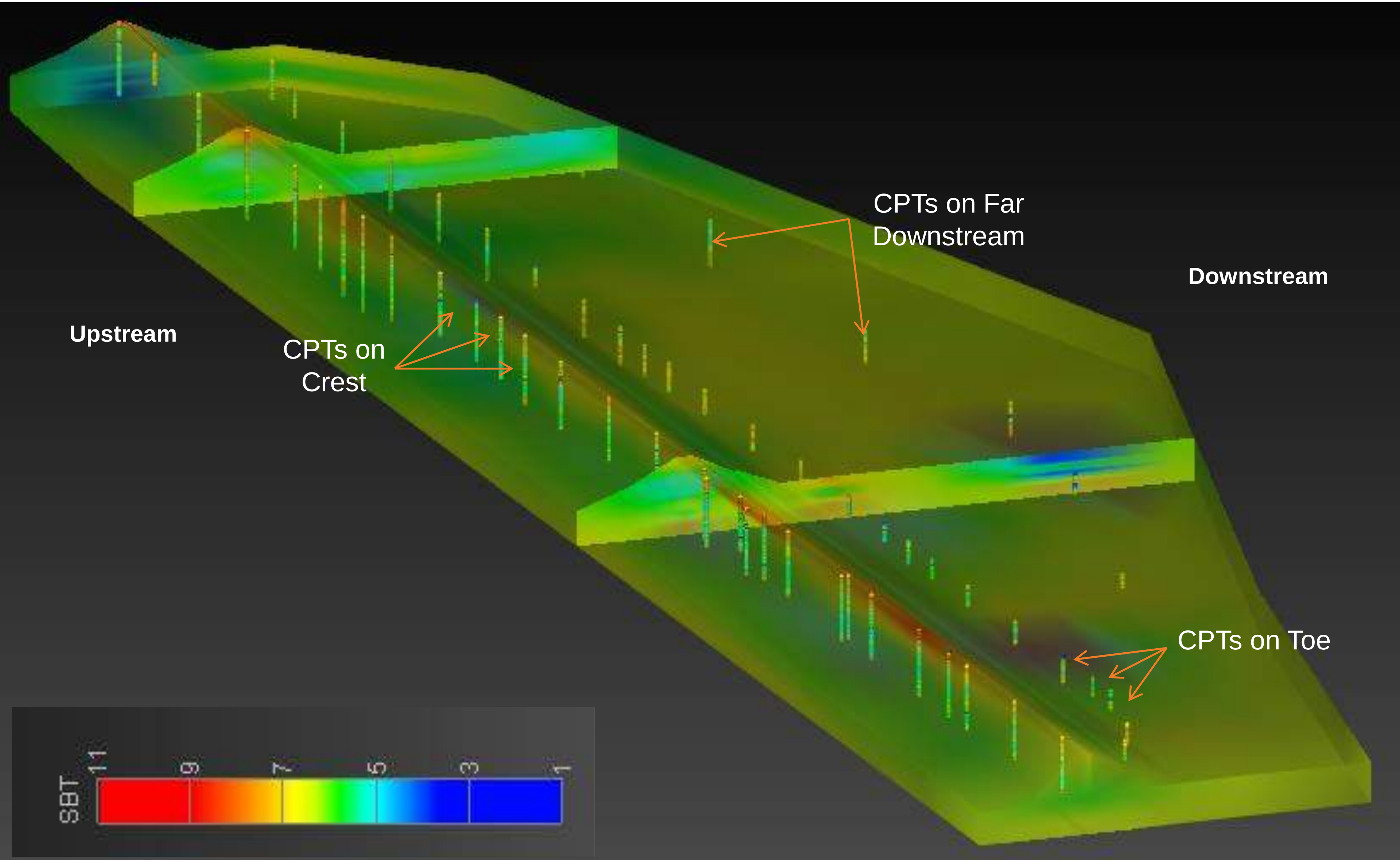
Material Type	Soil Behavior Type
1	Sensitive, fine grained
2	Organic soils - clay; Clays - Silty clay to clay
3	Silt mixtures - clayey silt to silty clay; Sand mixtures - silty sand to sandy
4	Sands - clean sand to silty sand; Gravelly sand to dense sand; Very
5	Very stiff fine grained *



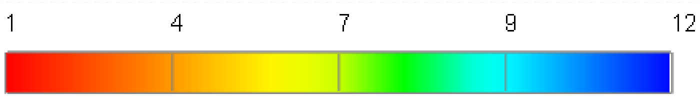


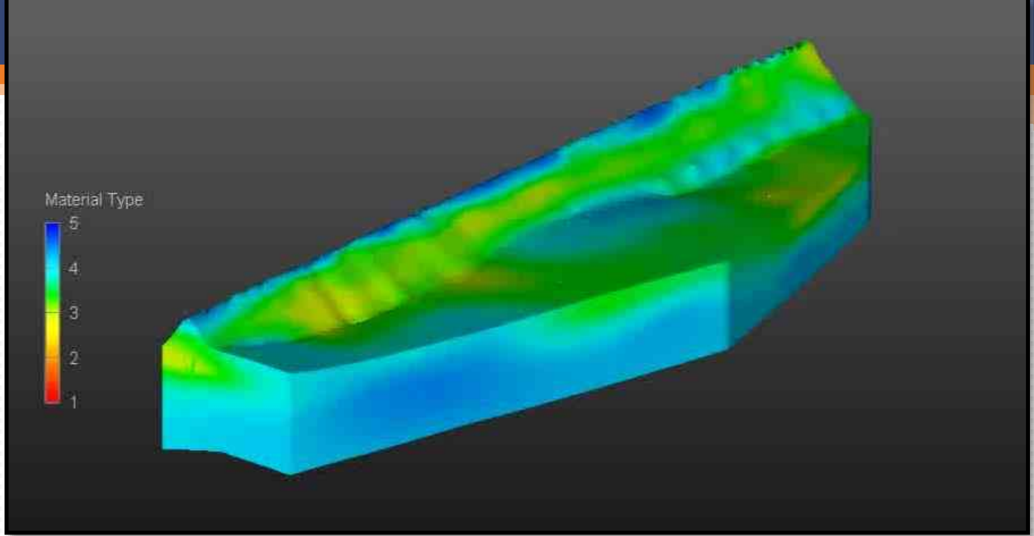
- Four construction stages identified due to the change of soil type along the dam
- Puddled Clay Core is identified after the interpolation
- Highest amount of hydraulic fill is located in Zone 3 (Information verified on PB Report, 2009, Sta. 30+00 & 37+00)
- Identification of clean sands present in the core section (Zone 3). They can cause seepage problems or can be liquefied.

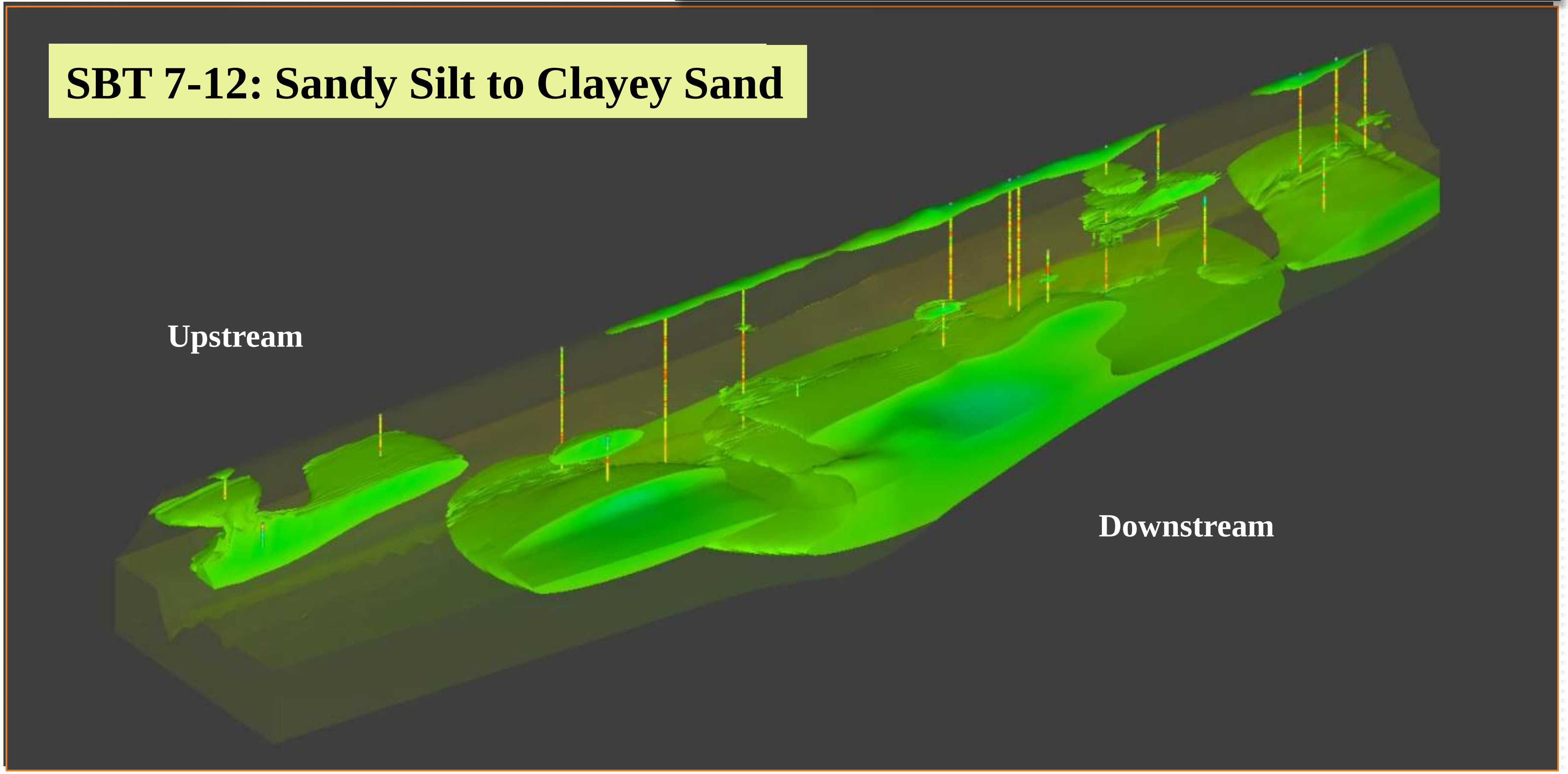
3D Model Results-Main Dam



Identification of critical Zones in EM Dam

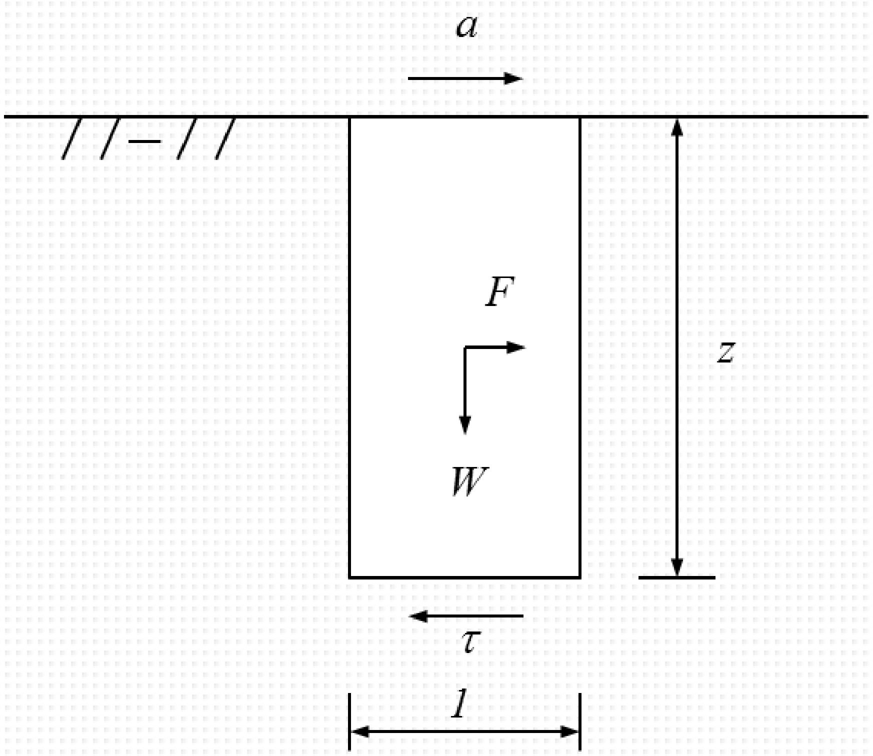






Liquefaction Analysis

Maximum Shear Stress at Base of Rigid Soil Column



F = earthquake-induced force

A = cross-sectional area of the rigid soil column (A = 1)

m = mass of the soil column

W = weight of the soil column

γ = total unit weight of the soil column

z = height of the soil column

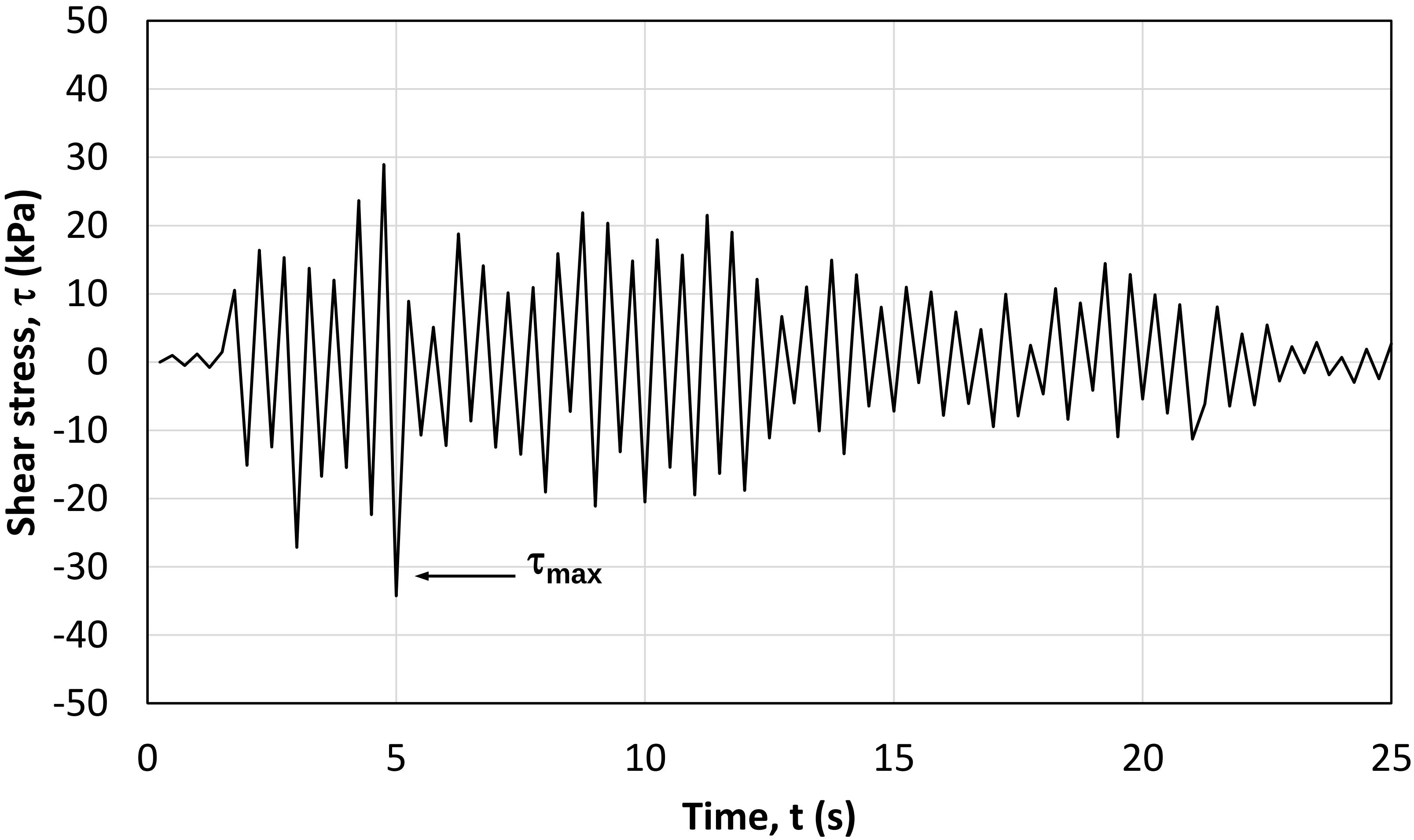
σ_{z0} = total overburden stress

a = ground acceleration

g = gravitational acceleration

$$\tau = \frac{F}{A} = \frac{ma}{1} = \frac{W}{g}a = \frac{\gamma z}{g}a = \sigma_{z0}\frac{a}{g}$$

Shear Stress Variation with Time



Cyclic Stress Ratio

Seed and Idriss (1971) converted the maximum shear stress with a non-uniform shear stress variation to a uniform cyclic shear stress:

$$\tau_{cyc} = 0.65\tau_{max}$$

Cyclic stress ratio is

$$CSR = \frac{\tau_{cyc}}{\sigma'_{z0}} = 0.65 r_d \left(\frac{\sigma_{z0}}{\sigma'_{z0}}\right)\left(\frac{a_{max}}{g}\right)$$

σ'_{z0} = effective overburden stress at a depth of z

a_{max} = maximum ground acceleration

r_d= stress reduction factor

Stress Reduction Factor

The stress reduction factor was introduced by Seed and Idriss (1971) to account for the fact that the soil is not a rigid body and the shear stress decreases with depth.

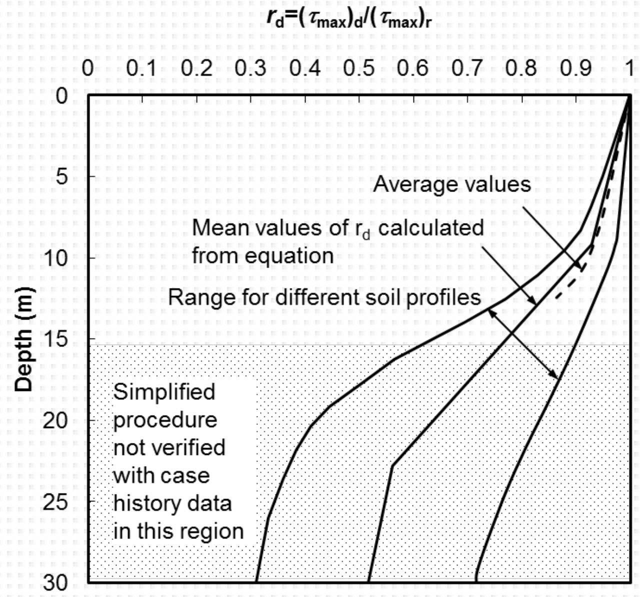
For noncritical projects, the following equations may be used to estimate the mean value of r_d:

$$r_d = 1.0 - 0.00765z \quad \text{for } z \leq 9.15 \text{ m}$$

$$r_d = 1.174 - 0.0267z \quad \text{for } 9.15 \text{ m} < z \leq 23 \text{ m}$$

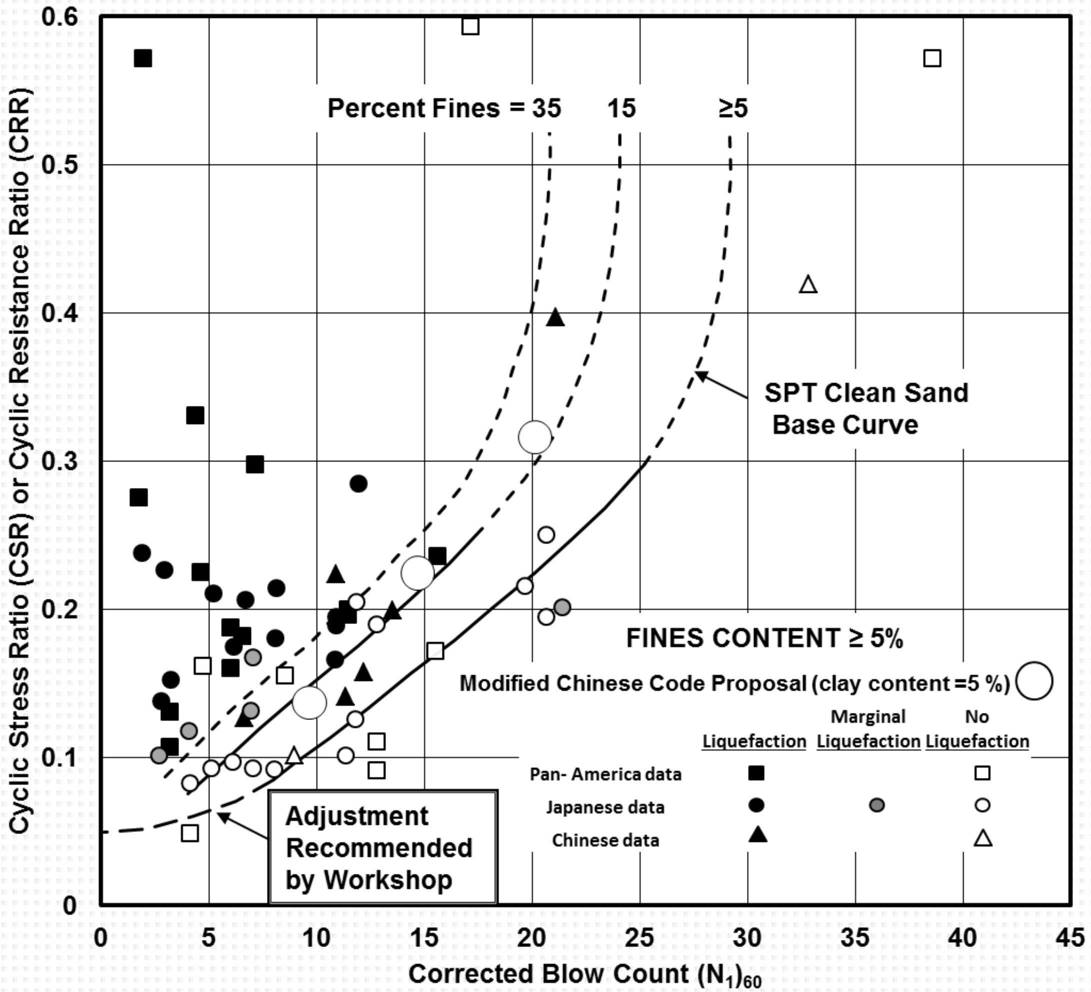
$$r_d = 0.744 - 0.008z \quad \text{for } 23 \text{ m} < z \quad 30 \text{ m}$$

$$r_d = 0.50 \quad \text{for } z > 30 \text{ m}$$



Youd and Idriss (1997)

CRR for Clean and Silty Sand at Earthquake Magnitude of 7.5



Youd and Idriss (1997)

Factor of Safety against Liquefaction

$$FS = \frac{CRR_M}{CSR} = \frac{MSF \cdot CRR_{M=7.5}}{CSR}$$

CRR_M = cyclic resistance ratio at a specific magnitude of earthquake

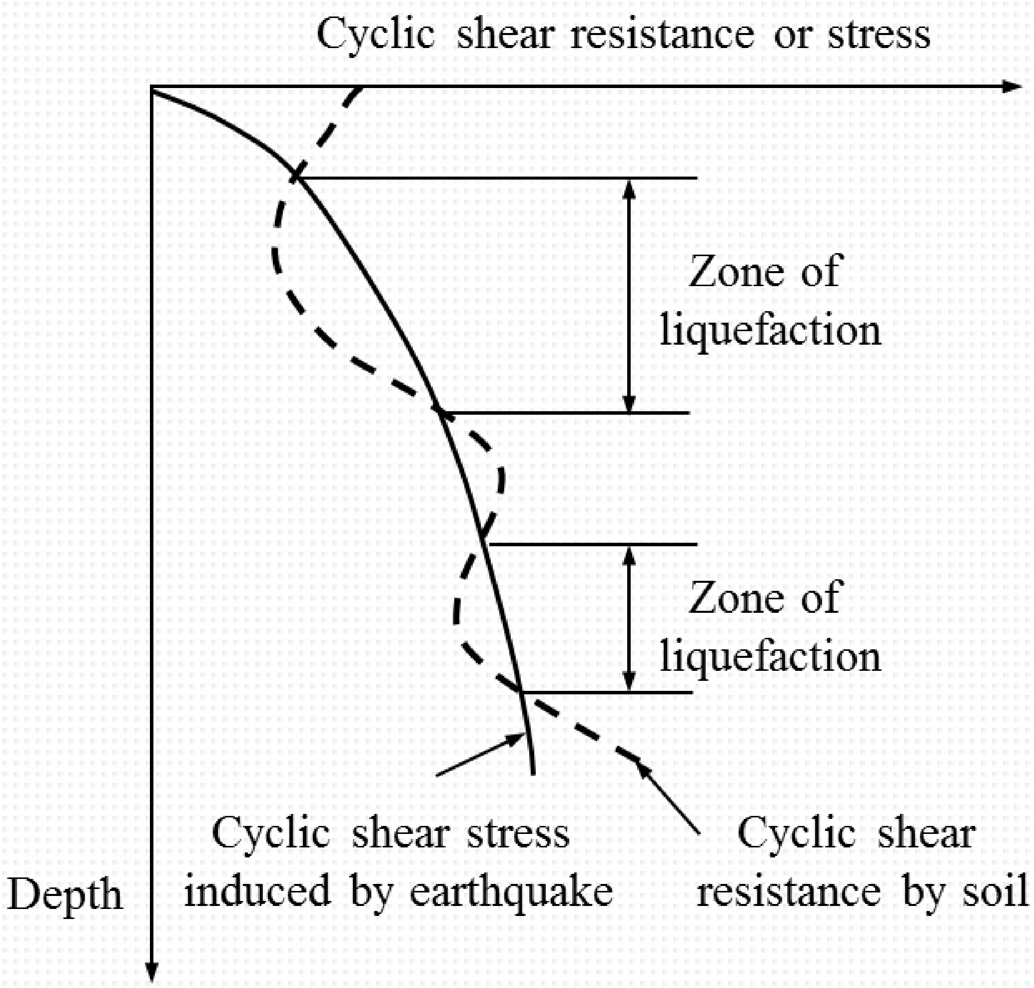
Magnitude scaling factor (*MSF*) (Idriss, 1999)

$$MSF = 6.9\,exp\left(-\frac{M_w}{4}\right) - 0.06 \qquad \text{for Mw} > 5.2$$

$$MSF = 1.82 \qquad \text{for Mw} \leq 5.2$$

M_w = moment magnitude of earthquake

Zone of Liquefaction



LIQUEFACTION

CYCLIC STRESS APPROACH

Characterization of Earthquake Loading (External Force)

Cyclic Stress Ratio (CSR)

⇩

Seismic Hazard Analysis

- DSHA
- PSHA
- Hypothetical Scenarios

Characterization of Liquefaction Resistance (Soil Strength)

Cyclic Resistance Ratio (CRR)

⇩

Obtained by correlation to In-Situ Test Results

- Standard Penetration Test – $(N_1)_{60}$
- Cone Penetration Test – q_{c1}
- Shear Wave Velocity – V_{s1}

$$F.S. = \frac{CRR}{CSR}$$

Liquefaction Framework:

Identification of Soil liquefaction Susceptibility (3D Visualization) → **CRR (Based on CPT, Shear Wave Velocity) Kriging Interpolation**

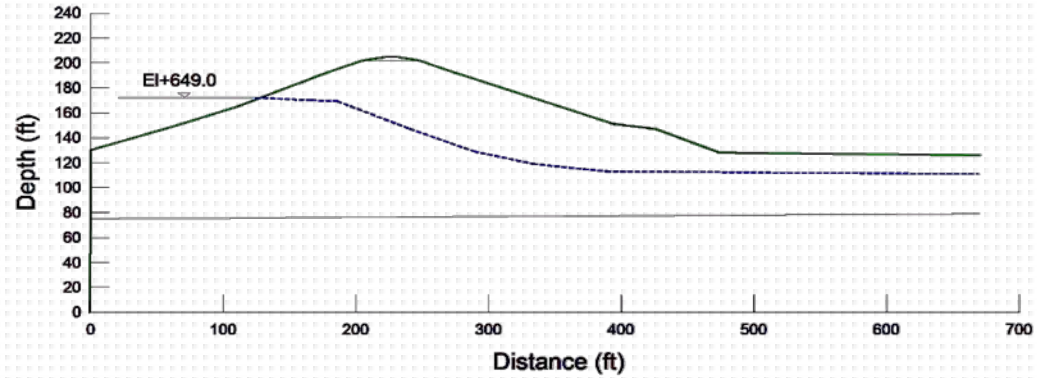
Characterization of Earthquake Loading (Enough to cause liquefaction?) DSHA, PSHA, Hypothetical Scenarios → **CSR**

→ **Interpolation of FS within the Structures** → **Will Liquefaction cause a significant Damage? (Reliability and Risk Analysis)**

Liquefaction Assessments

a. Actual Field Conditions

- Lake Level (LL): El+649.0
- a_{max}=0.3g
- M4.0



b. HYPOTHETICAL SCENARIOS

Scenario I

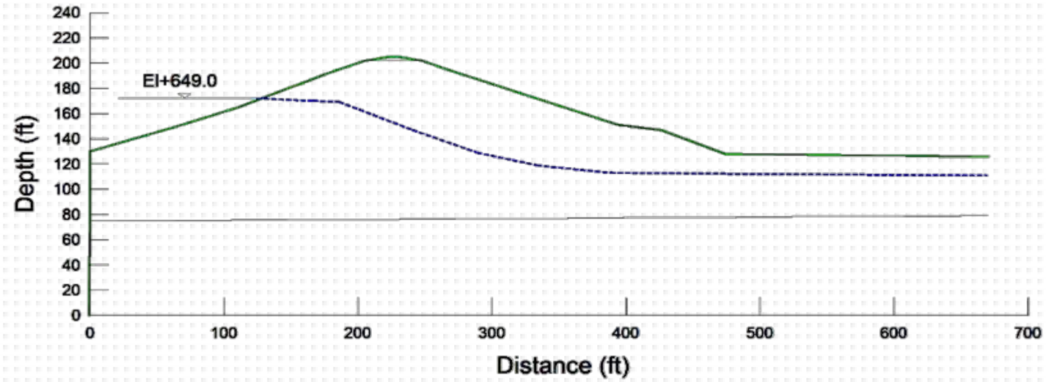
- Lake Level (LL): El+649.0
- a_{max}=0.3g
- M4.5, M5.5, M6.5

Scenario II

- Lake Level (LL): El+649.0
- a_{max}=0.4g
- M4.5, M5.5, M6.5

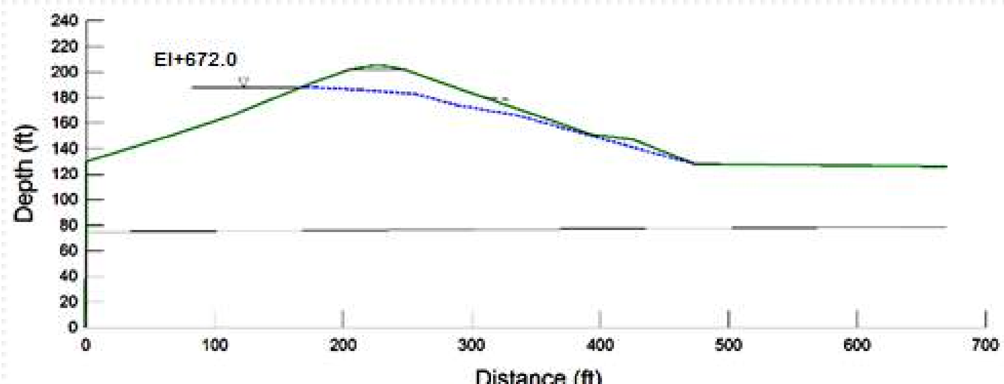
Scenario III

- Lake Leve (LL): El+649.0
- a_{max}=0.5g
- M4.5, M5.5, M6.5

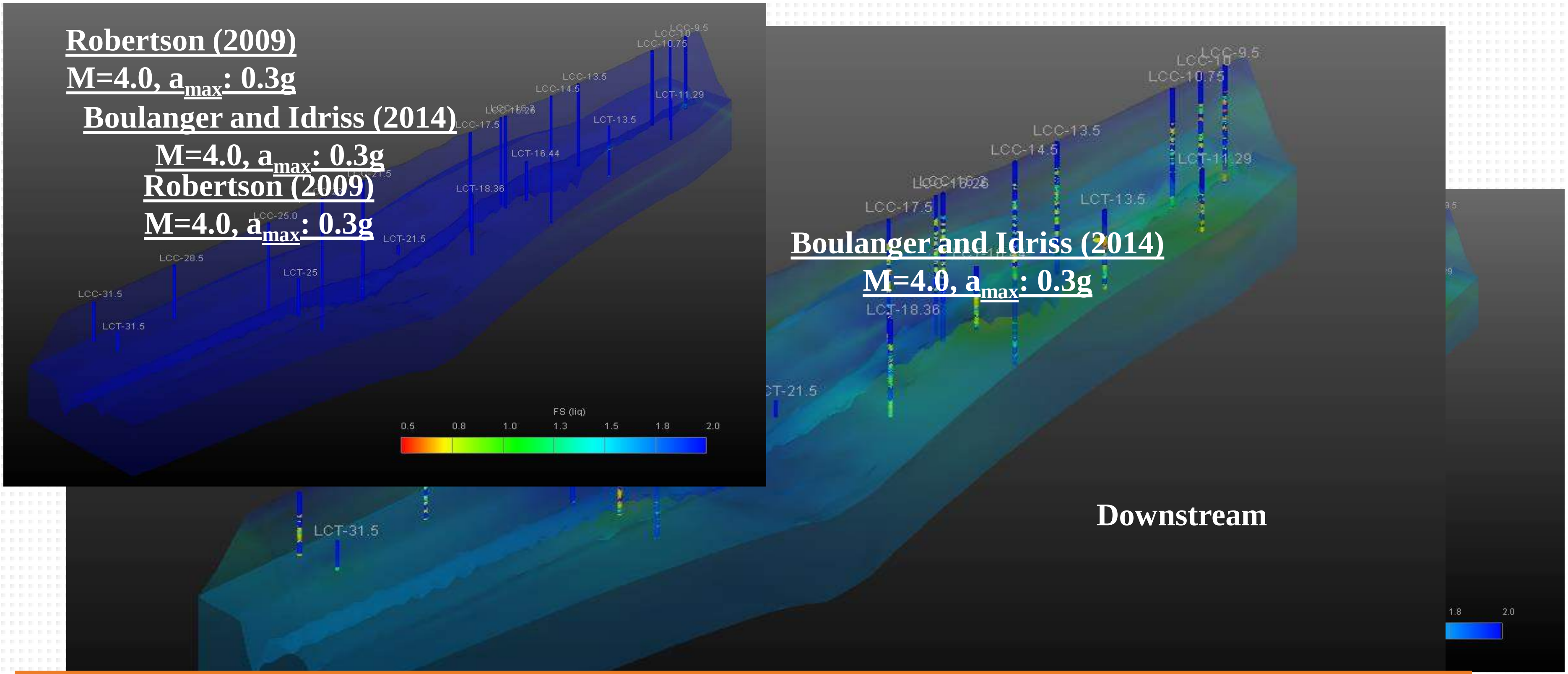


Scenario IV

- Lake Level (LL): El+672.0
- a_{max}=0.3g
- M4.5, M5.5, M6.5



Actual field condition:0.3g, M4; LL: El+649.0

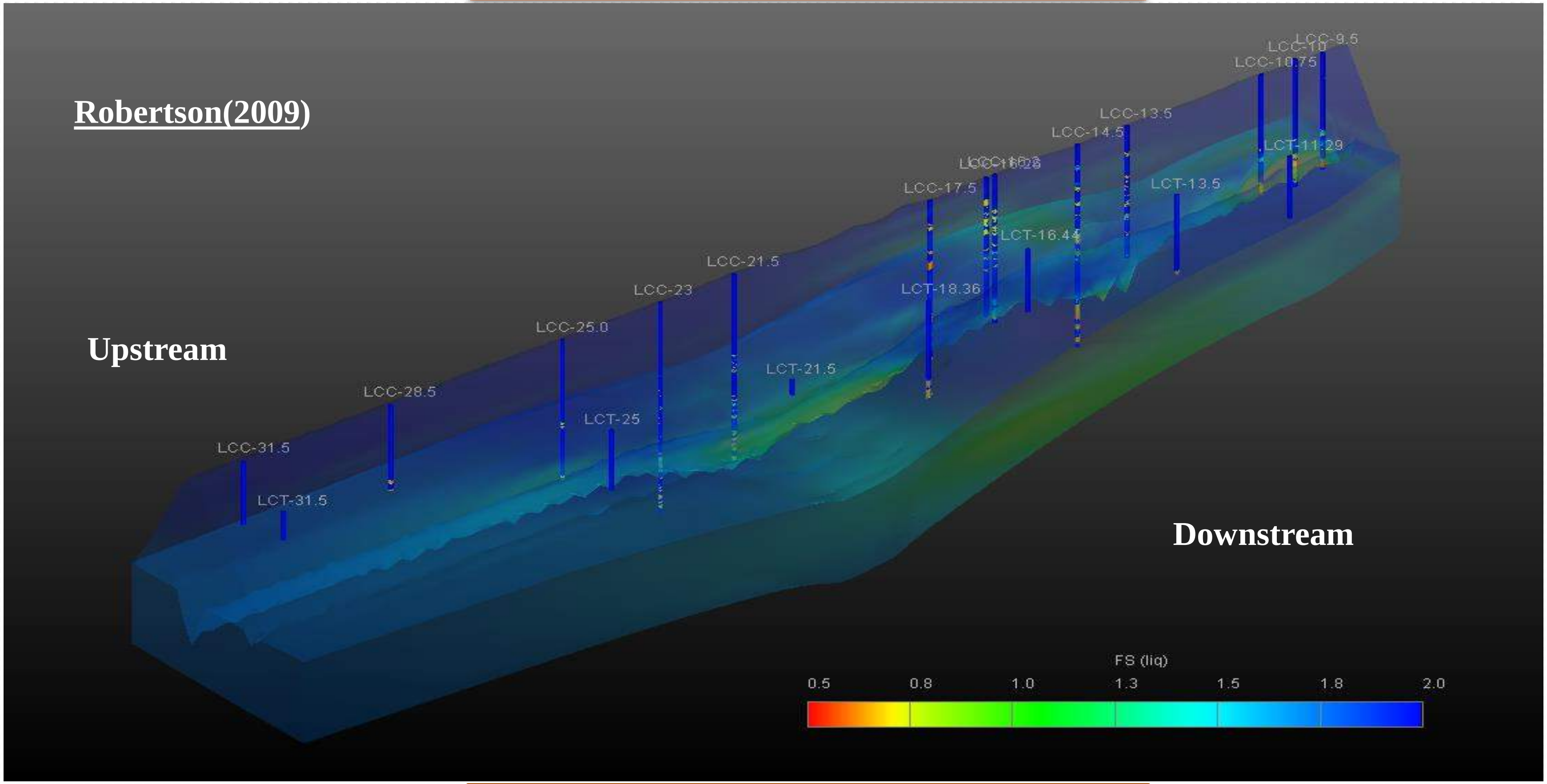


INSIGHTS FROM TWO METHODOLOGIES

- FOS values are higher than 1.5
- Levee is safe for actual field seismic conditions

Scenario I: 0.3g, M4.5, M5.5, M6.5; LL: El+649.0

a=0.3g; M4.5 → M5.5 → M6.5

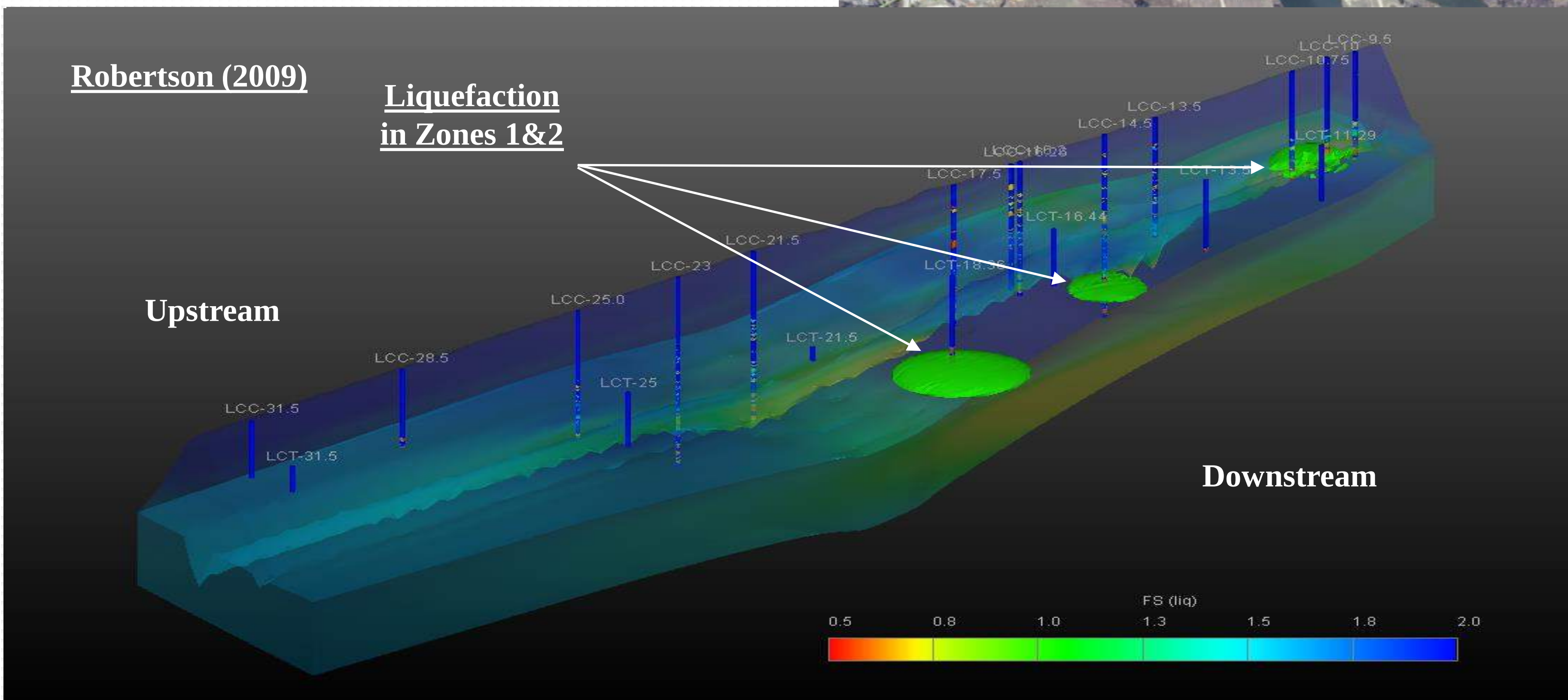


Major findings:

- No liquefaction has been observed.

Scenario II: 0.4g, M4.5, M5.5, M6.5; LL: El+649.0

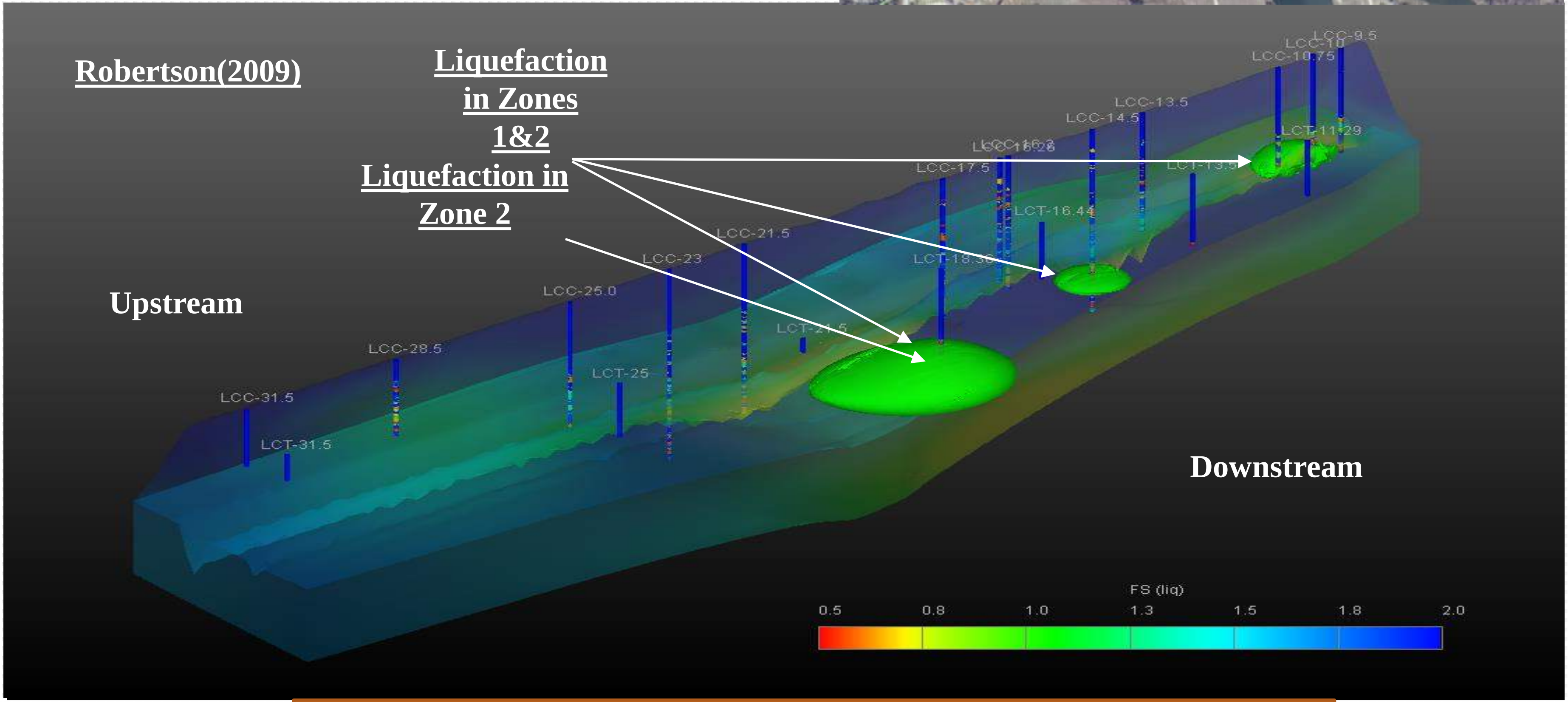
a=0.4g;M4.5 ⇨ M5.5 ⇨ M6.5



Major findings: Liquefaction in elevation between 632 to 604 ft (Zones 1&2).

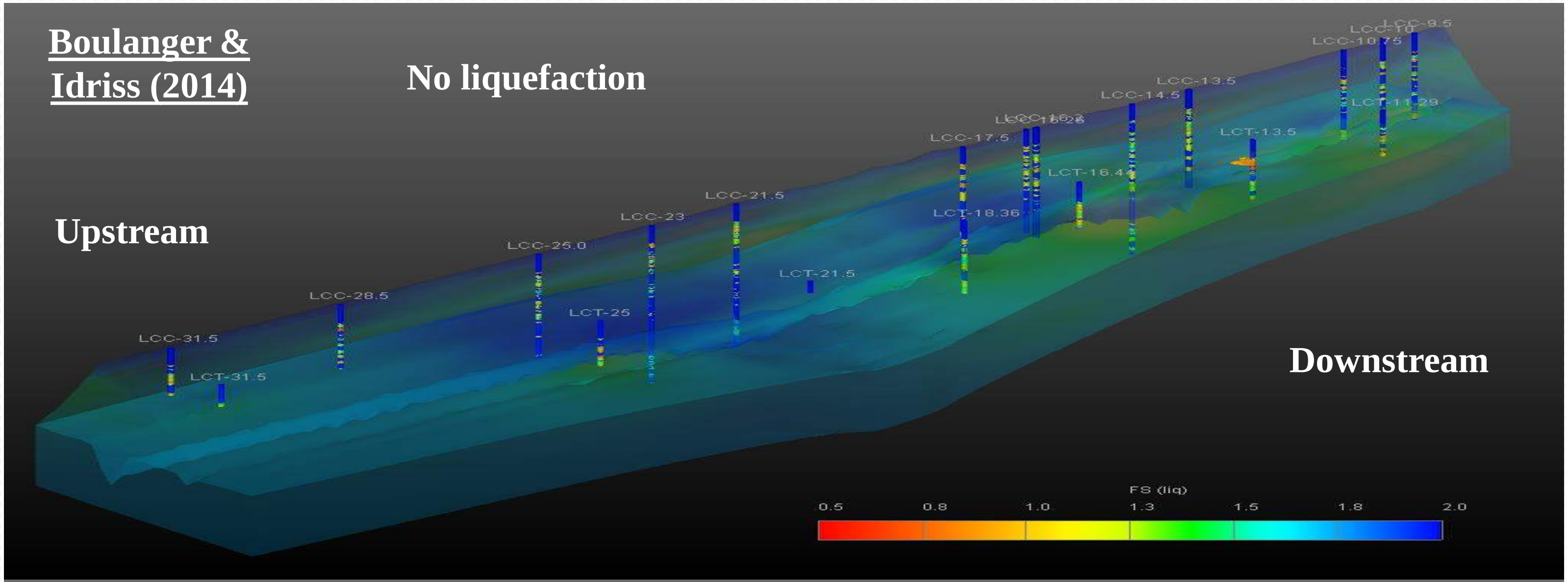
Scenario III: 0.5g, M4.5, M5.5, M6.5; LL: El+649.0

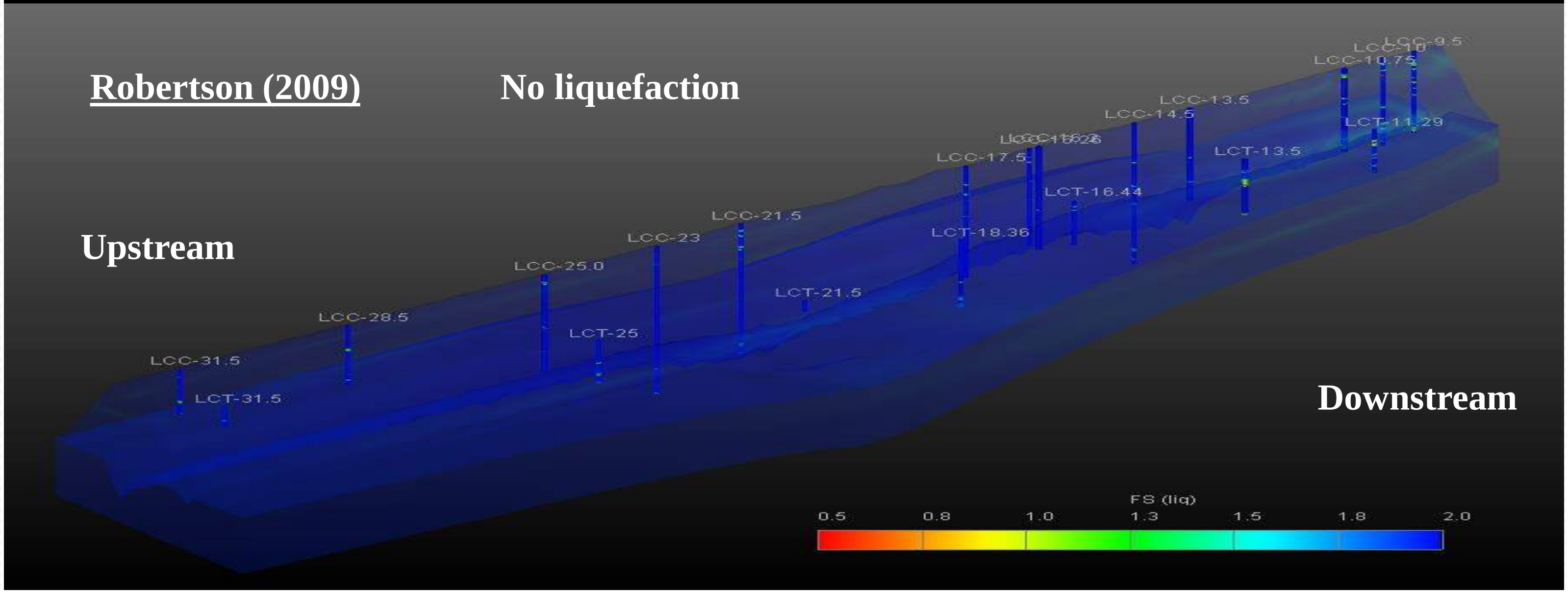
a=0.5g;M4.5 ⟹ M5.5 ⟹ M6.5



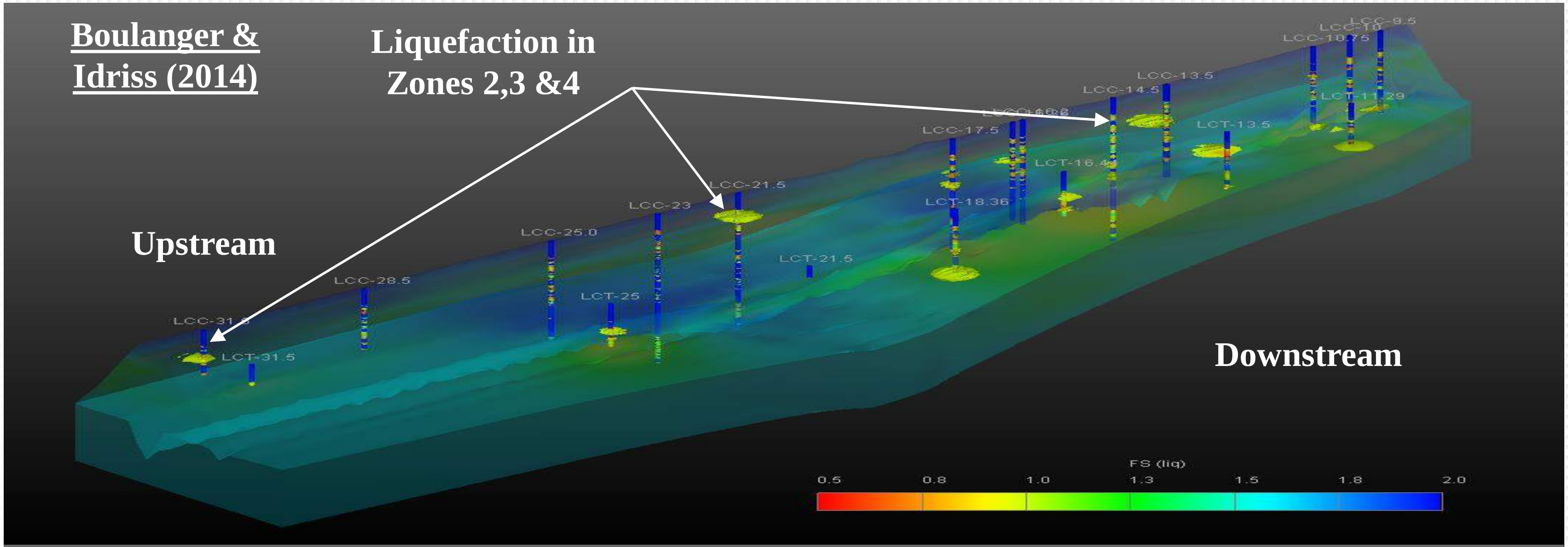
Major findings:
- Liquefaction in elevation between 632 to 590 ft (Zones 1&2).
- Soils are susceptible to liquefaction at earthquakes with higher magnitudes

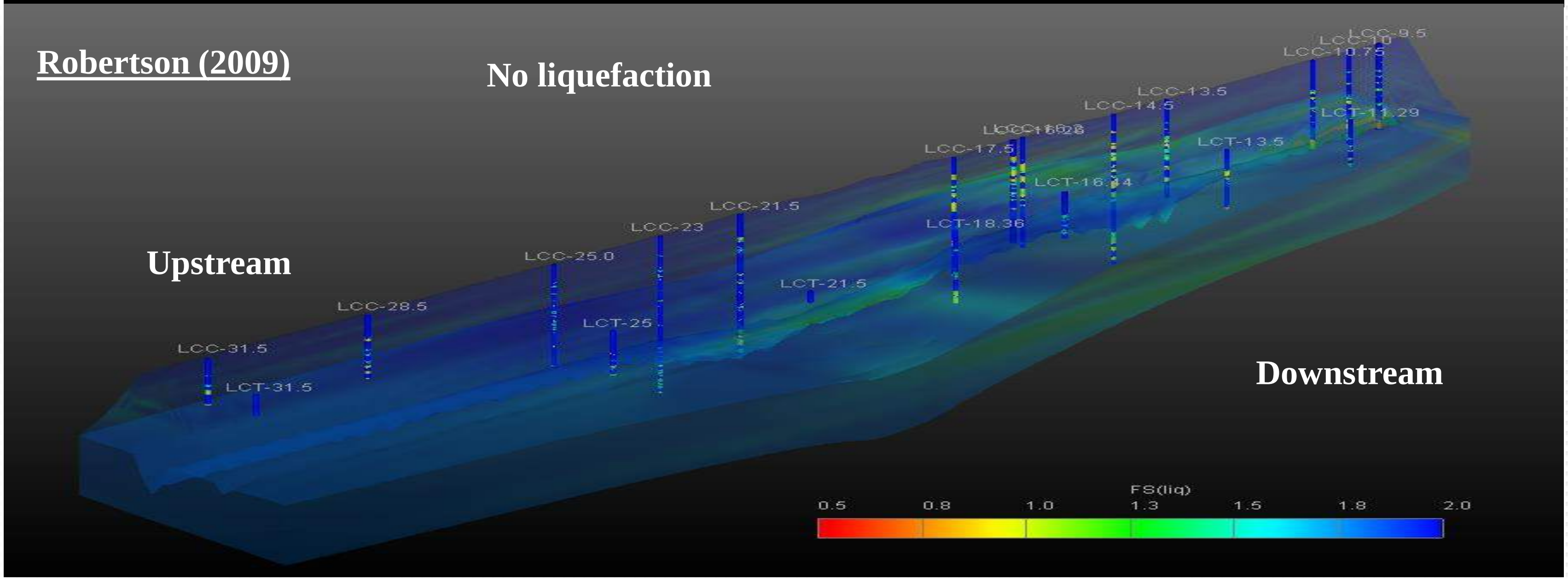
Scenario IV: 0.3g, M4.5; Lake Level: El+672.0



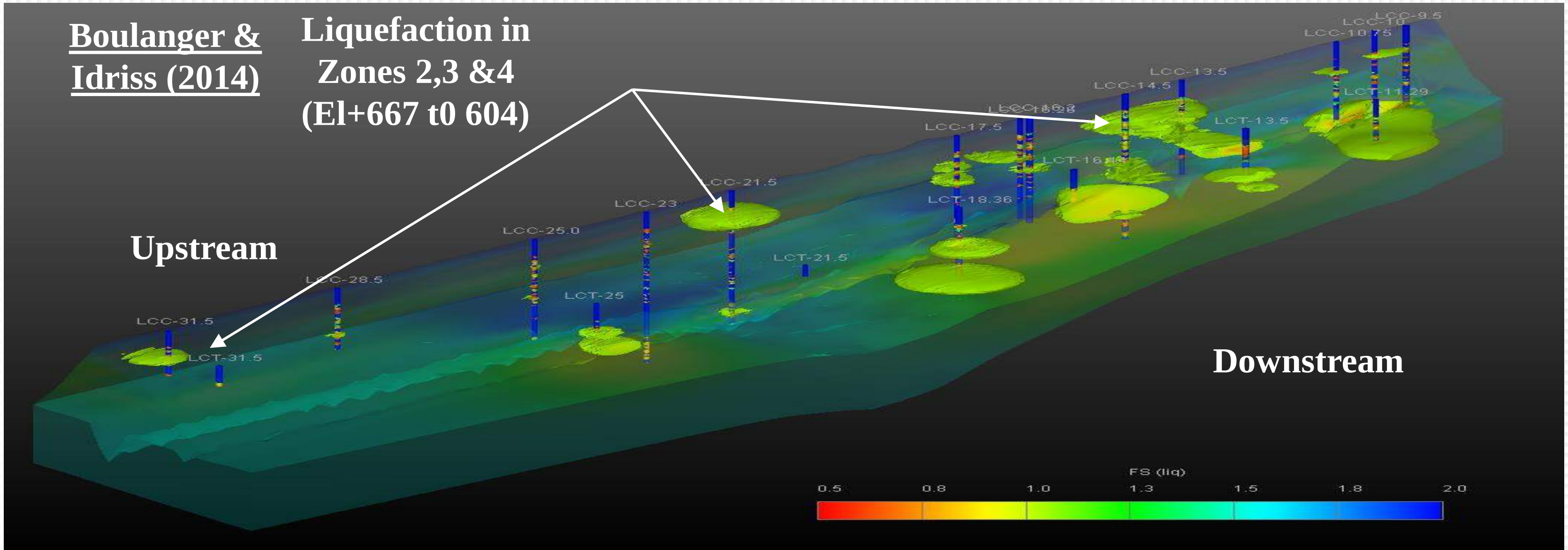


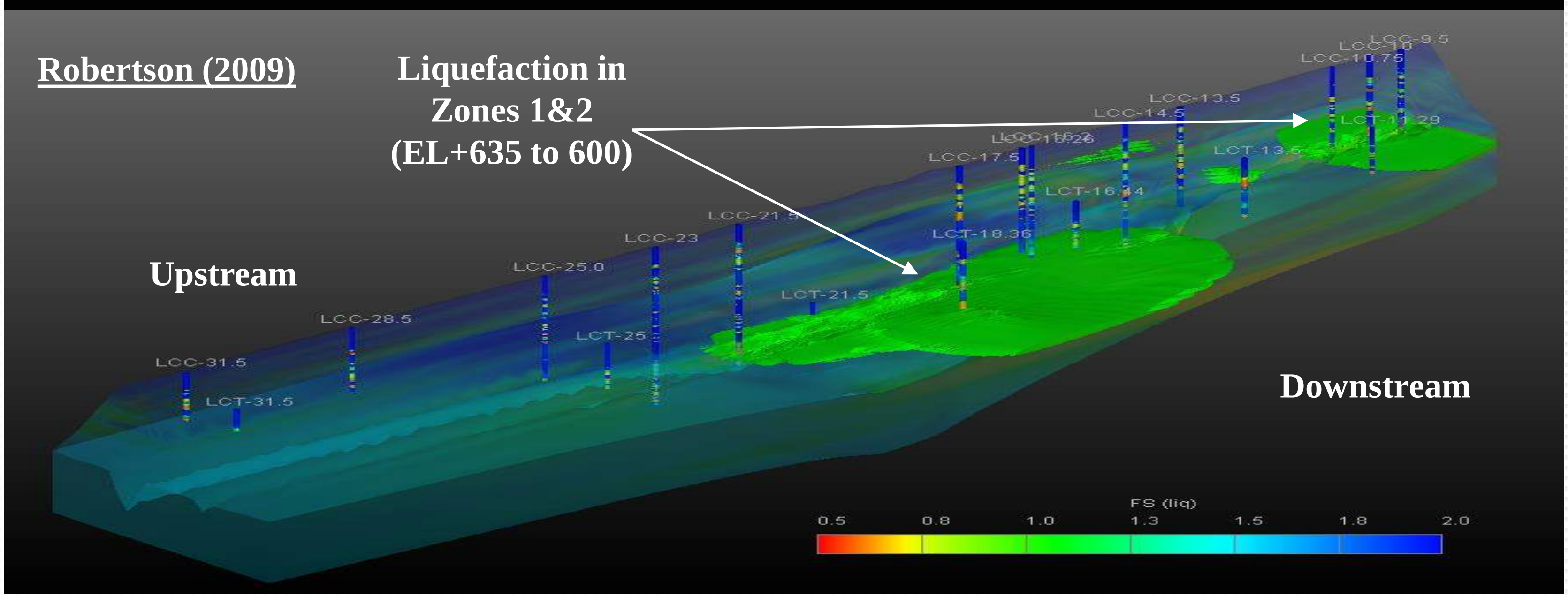
Scenario IV: 0.3g, M5.5; Lake Level: El+672.0





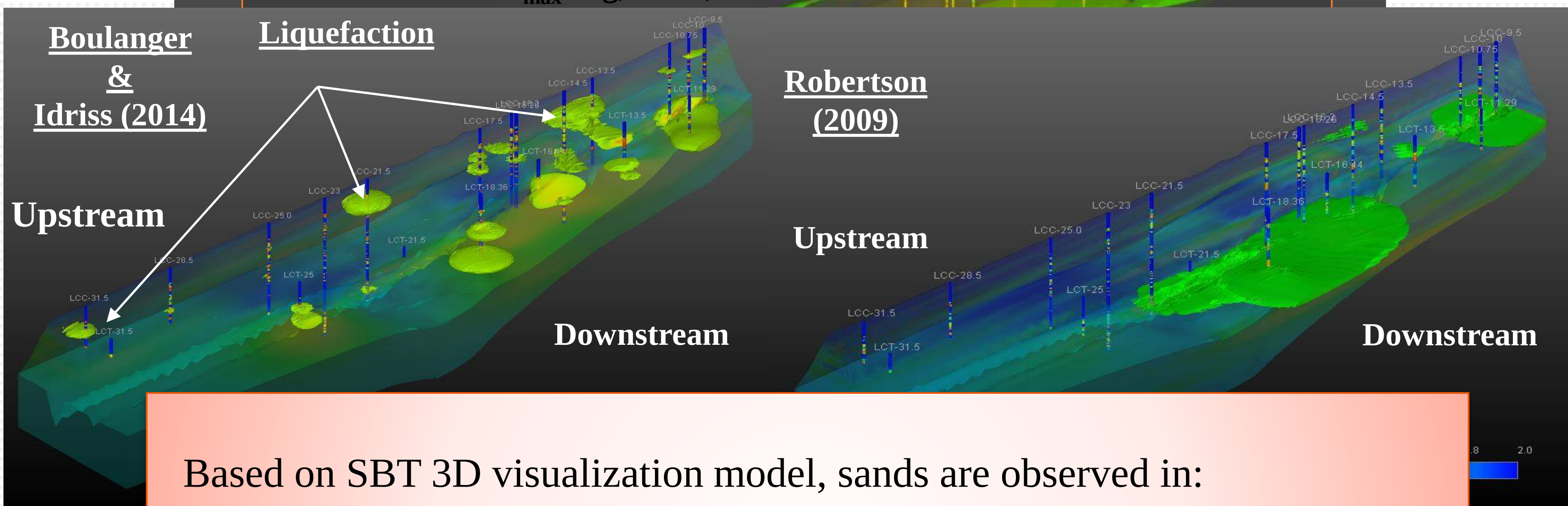
Scenario IV: 0.3g, M6.5; Lake Level: El+672.0





General Insights

a_{max} 0.3g, M6.5; Lake Level: El+672.0



• E

• At hi … 3 & 4

(EL+

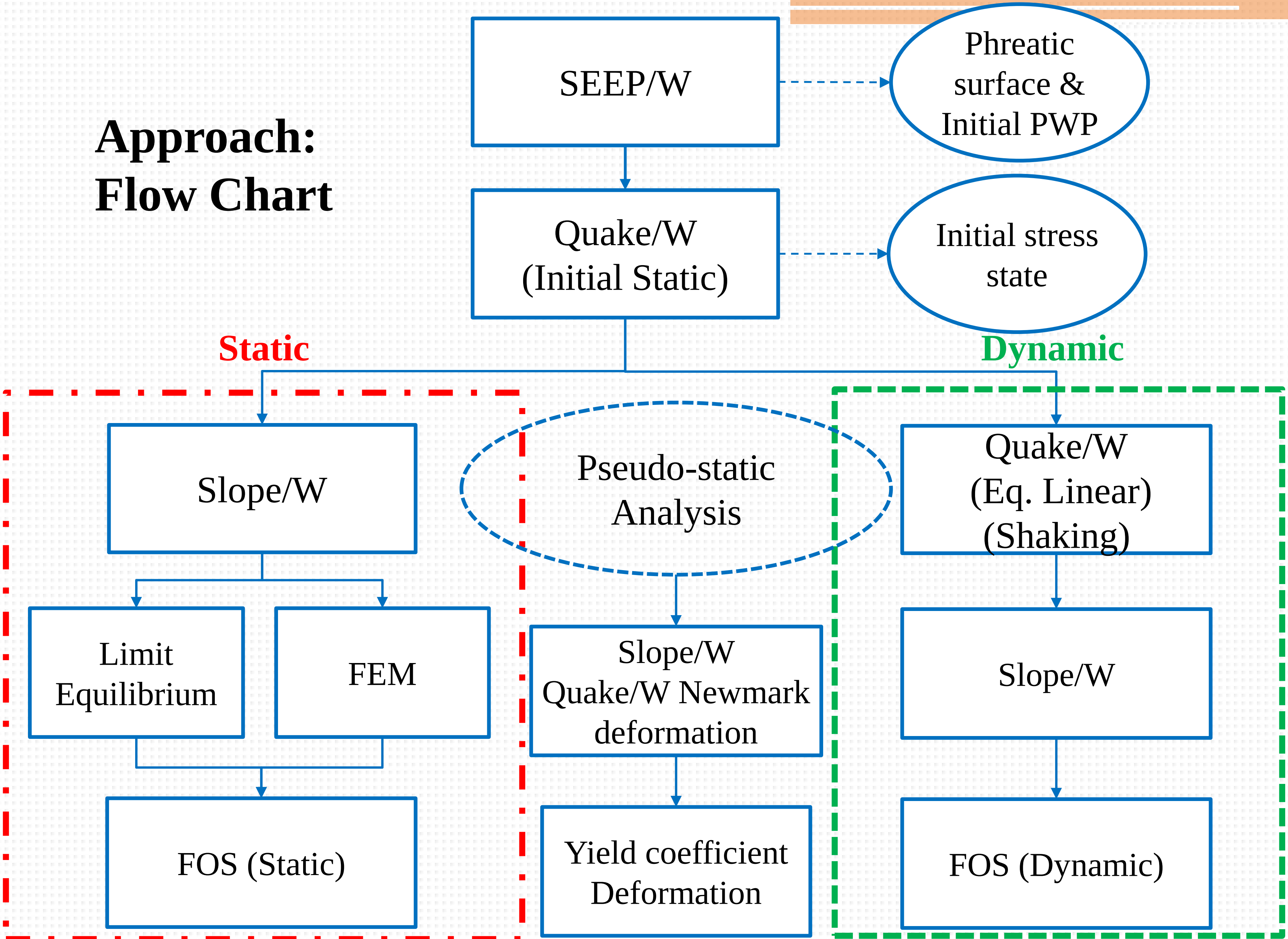
Based on SBT 3D visualization model, sands are observed in:

1) Zone 2 (El+668 to 657) and Zone 4 (El+668 to 645).

2) Top layers of levee (El+682 to 680).

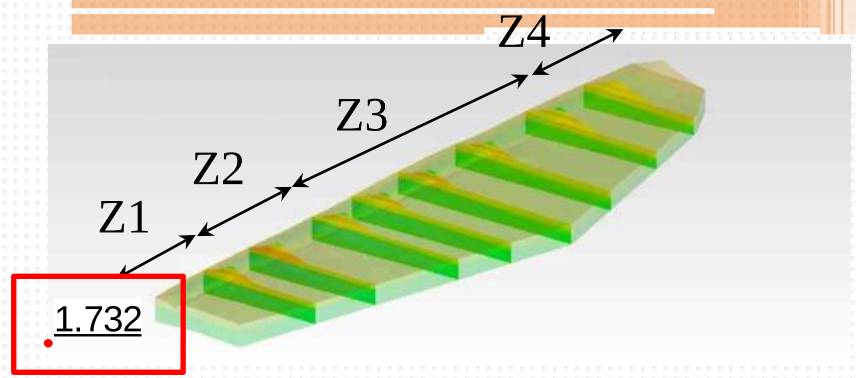
3) Bottom layers of levee (El+630 to 590).

Approach: Flow Chart

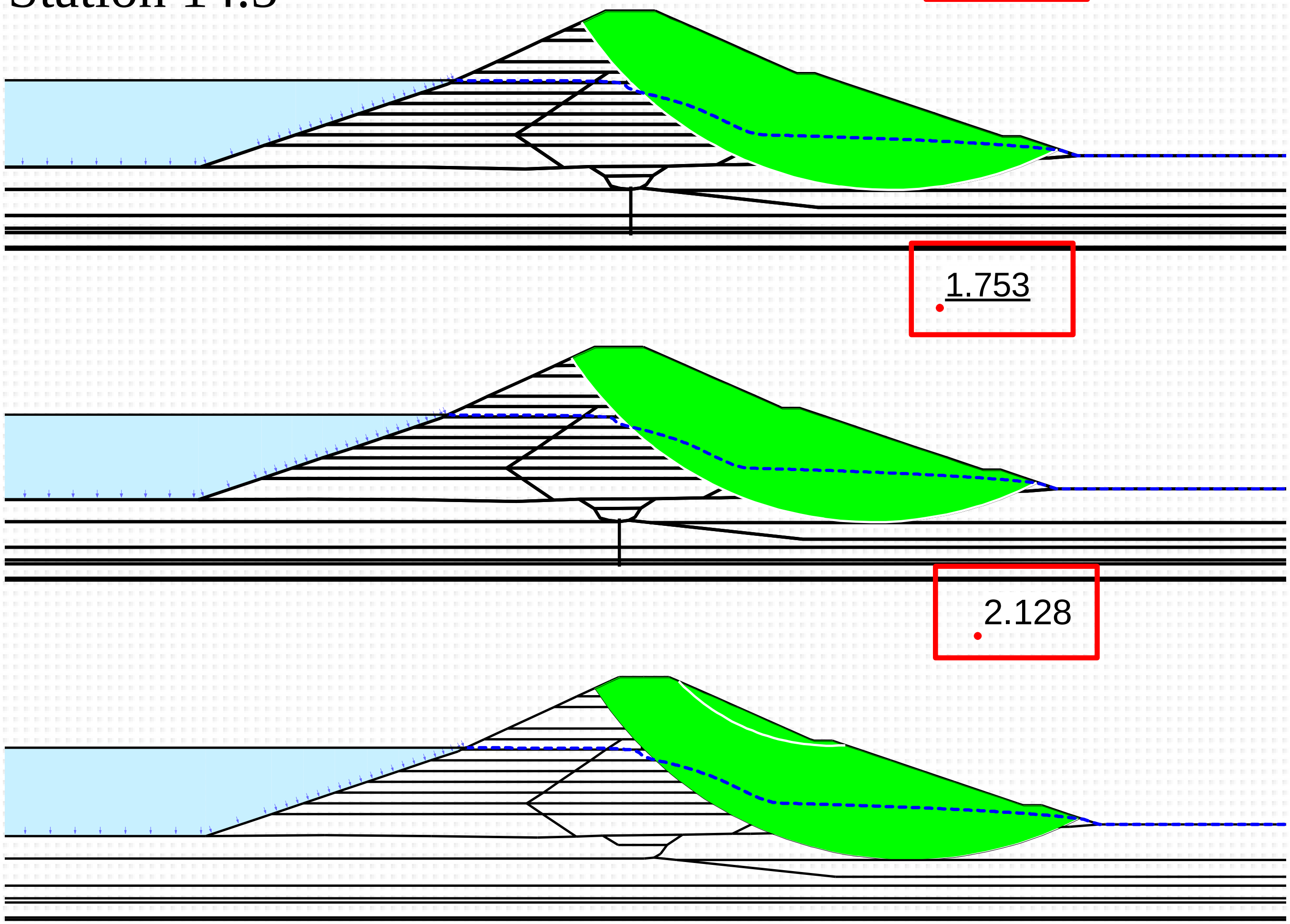


Static Slope Stability Analysis

- Required static FOS = **1.5**



Station 14.5



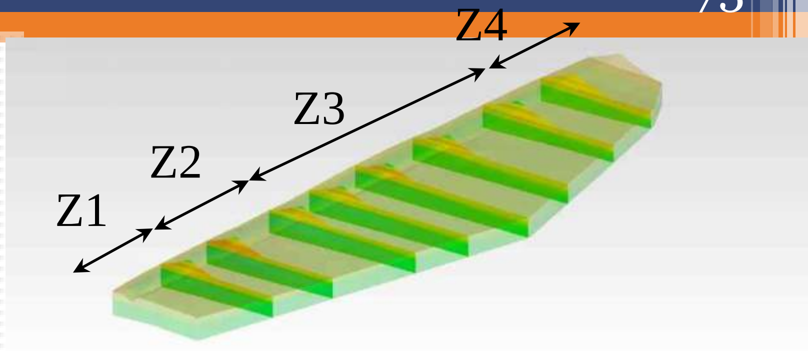
Case-1

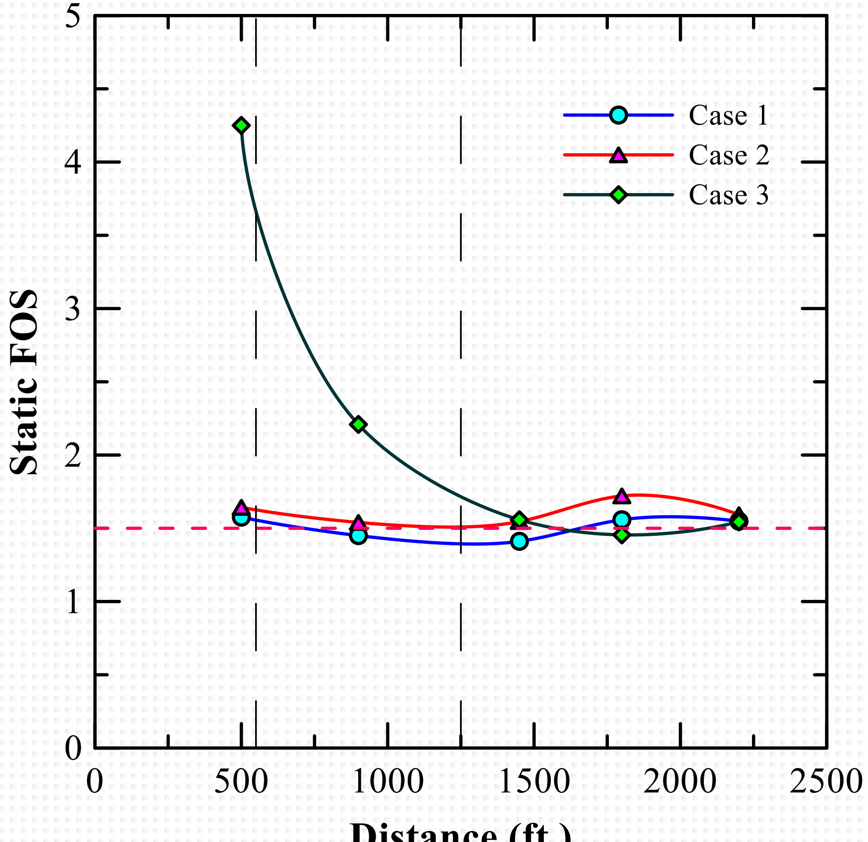
Case-2

Case-3

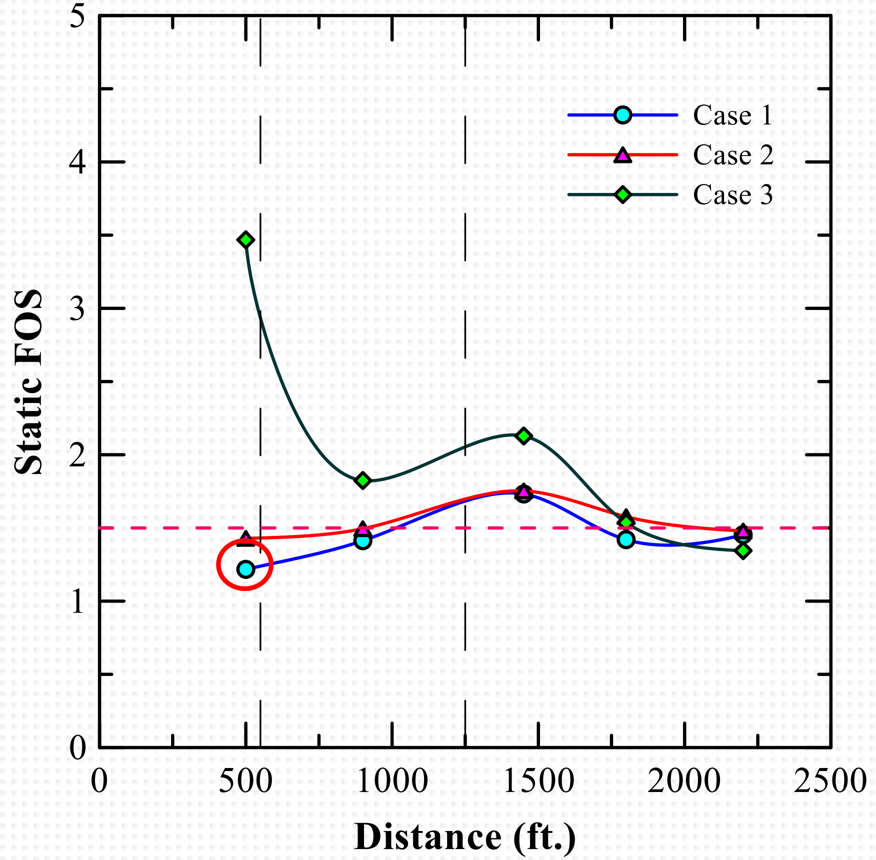
Static Slope Stability Analysis

- Required static FOS = **1.5**





Upstream slope



Downstream slope

<u>Conclusion</u>: All sections, other than Stn.5 (Case-1) satisfy the static FOS requirement.

Identification of critical sections

U/S slope (M < 6.5)

1.8 Hz < Natural frequency < 3.22 Hz

Earthquakes	A	B	C	D	E	F	G	H
Predominant frequency (Hz)	1.14, 1.80	1.51, 2.24, 4.25	2.5, 5.03, 9.57	2.5, 3.37, 7.08	11.82, 11.87	1.95, 4.49, 6.64	5.86, 7.72, 11.38	2.98, 5.81
Peak acceleration (g)	0.001	0.035	0.038	0.04	0.05	0.097	0.146	0.402
Station 5	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 9	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Just below 1
Station 14.5	Safe	Safe	Safe	Safe	Safe	Just below 1	Just below 1	Critical
Station 18	Safe	Just below 1	Safe	Just below 1	Safe	Critical	Just below 1	Critical
Station 22	Safe	Safe	Safe	Safe	Safe	Critical	Just below 1	Critical
Station 27	Safe	Safe	Safe	Safe	Safe	Just below 1	Safe	Safe
Station 33	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 39	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe

U/S slope (M = 7)

Safe — Just below 1 — Critical

Earthquakes	A	B	C	D	E	F	G	H
Predominant frequency (Hz)	1.14, 1.80	1.51, 2.24, 4.25	2.5, 5.03, 9.57	2.5, 3.37, 7.08	11.82, 11.87	1.95, 4.49, 6.64	5.86, 7.72, 11.38	2.98, 5.81
Peak acceleration (g)	0.001	0.035	0.038	0.04	0.05	0.097	0.146	0.402
Station 5	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 9	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Just below 1
Station 14.5	Safe	Safe	Safe	Safe	Safe	Just below 1	Just below 1	Critical
Station 18	Safe	Just below 1	Just below 1	Just below 1	Safe	Critical	Just below 1	Critical
Station 22	Safe	Just below 1	Safe	Safe	Safe	Critical	Just below 1	Critical
Station 27	Safe	Safe	Safe	Safe	Safe	Just below 1	Safe	Safe
Station 33	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 39	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe

Stations 14.5 to 27 may be critical (high PGA); same conclusion as pseudo-static analysis

Identification of critical sections

D/S slope (M < 6.5)

1.8 Hz < Natural frequency < 3.22 Hz

Earthquakes	A	B	C	D	E	F	G	H
Predominant frequency (Hz)	1.14, 1.80	1.51, 2.24, 4.25	2.5, 5.03, 9.57	2.5, 3.37, 7.08	11.82, 11.87	1.95, 4.49, 6.64	5.86, 7.72, 11.38	2.98, 5.81
Peak acceleration (g)	0.001	0.035	0.038	0.04	0.05	0.097	0.146	0.402
Station 5	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 9	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Critical
Station 14.5	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 18	Safe	Just below 1	Just below 1	Just below 1	Safe	Critical	Critical	Critical
Station 22	Safe	Just below 1	Safe	Just below 1	Safe	Just below 1	Critical	Critical
Station 27	Safe	Just below 1	Safe	Just below 1	Safe	Critical	Critical	Critical
Station 33	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 39	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe

D/S slope (M = 7)

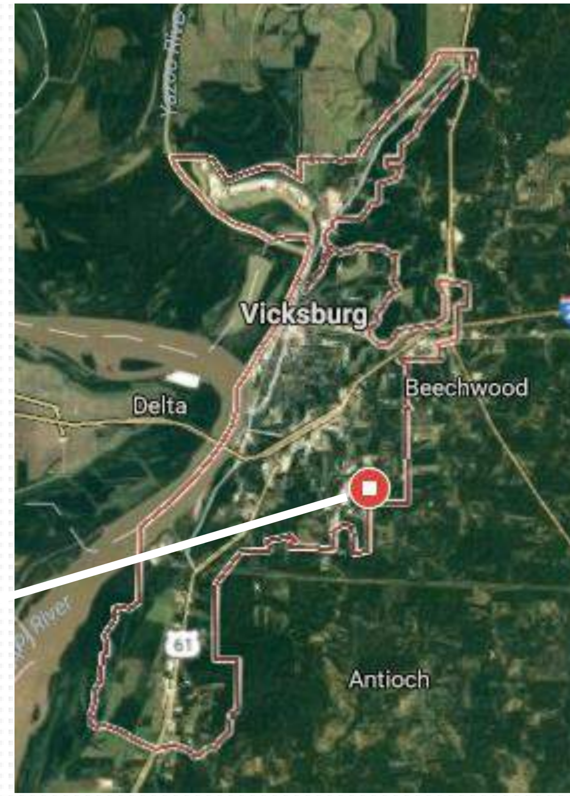
Safe | Just below 1 | Critical

Earthquakes	A	B	C	D	E	F	G	H
Predominant frequency (Hz)	1.14, 1.80	1.51, 2.24, 4.25	2.5, 5.03, 9.57	2.5, 3.37, 7.08	11.82, 11.87	1.95, 4.49, 6.64	5.86, 7.72, 11.38	2.98, 5.81
Peak acceleration (g)	0.001	0.035	0.038	0.04	0.05	0.097	0.146	0.402
Station 5	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 9	Safe	Safe	Safe	Safe	Safe	Just below 1	Safe	Critical
Station 14.5	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 18	Safe	Just below 1	Just below 1	Just below 1	Safe	Critical	Critical	Critical
Station 22	Safe	Just below 1	Safe	Just below 1	Just below 1	Critical	Critical	Critical
Station 27	Safe	Just below 1	Safe	Just below 1	Just below 1	Critical	Critical	Critical
Station 33	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Station 39	Safe	Safe	Safe	Safe	Safe	Safe	Safe	Safe

Stations 18 to 27 may be critical (high PGA); same conclusion as pseudo-static analysis

Development of 3D Model for Poor House Berm

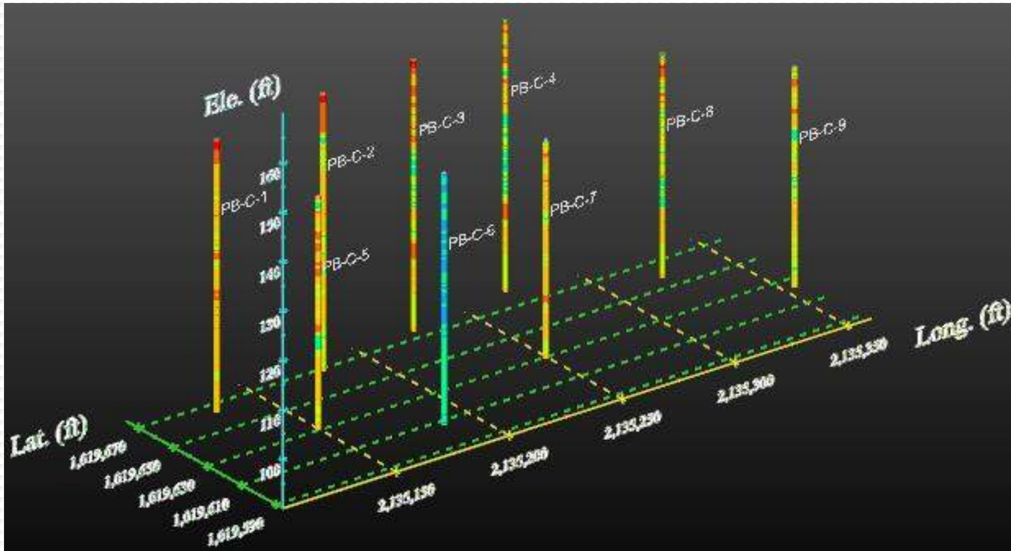
Poor House Berm



Field Investigations

- Field Investigation – 9 CPTU soundings & 3 Soil borings

Generation of Volumetric Grid

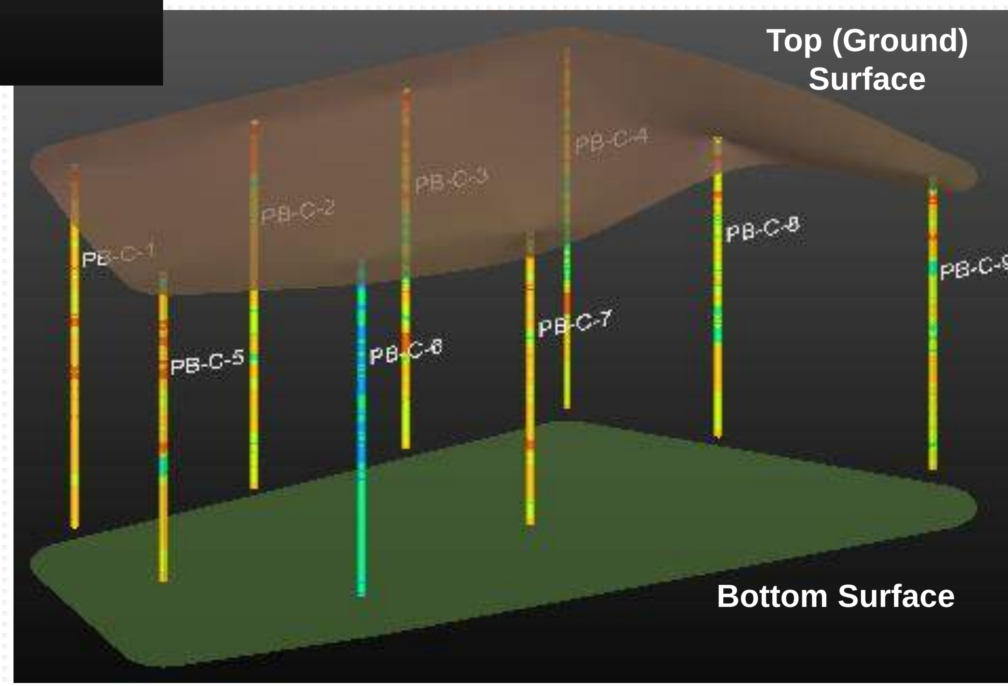


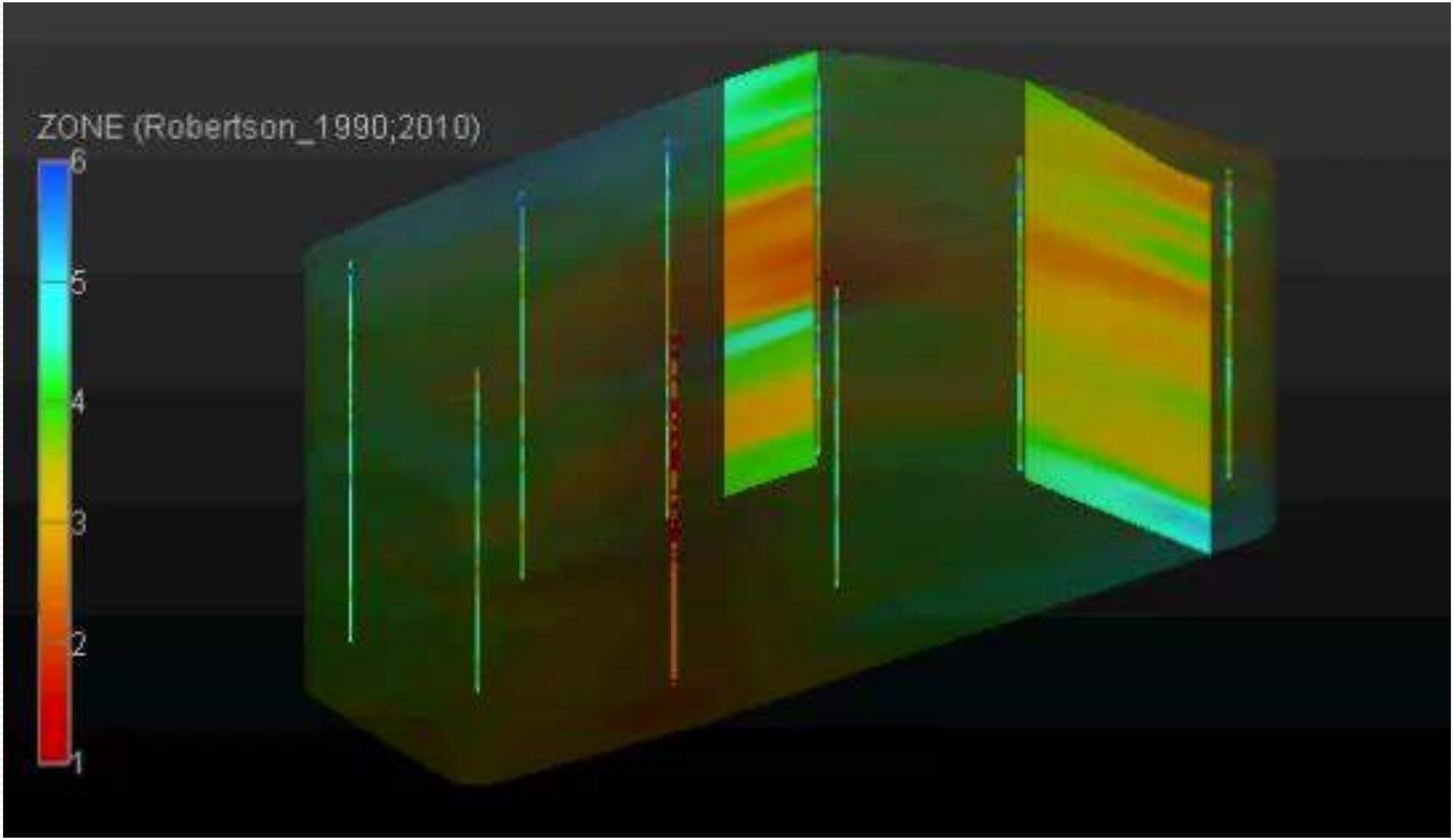
Boring Log Collection Data (Coordinates & Soil Properties)

- Nine (9) CPTs (Information Provided)
- Soil Properties are obtained based on CPT correlations
- CPTs are located in a 3D Dimensional Space

Ground and Bottom Surface

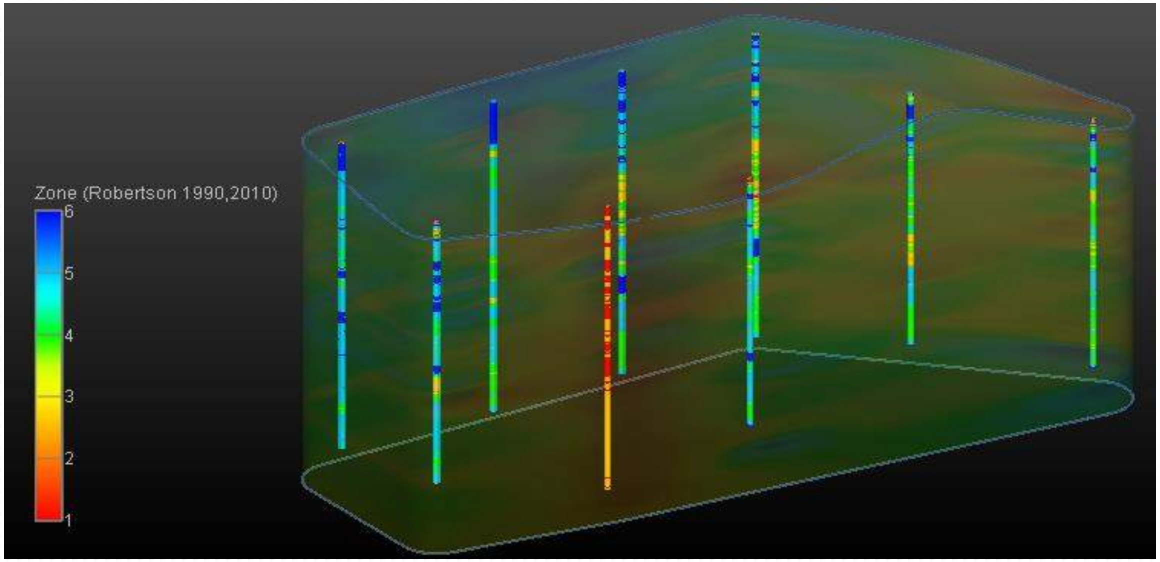
- Generation of Ground Surface (Elevation) and Bottom Surface (Depth of boring logs)
- Two surfaces generated to be interpolated (Kriging, natural neighbors, Spline)





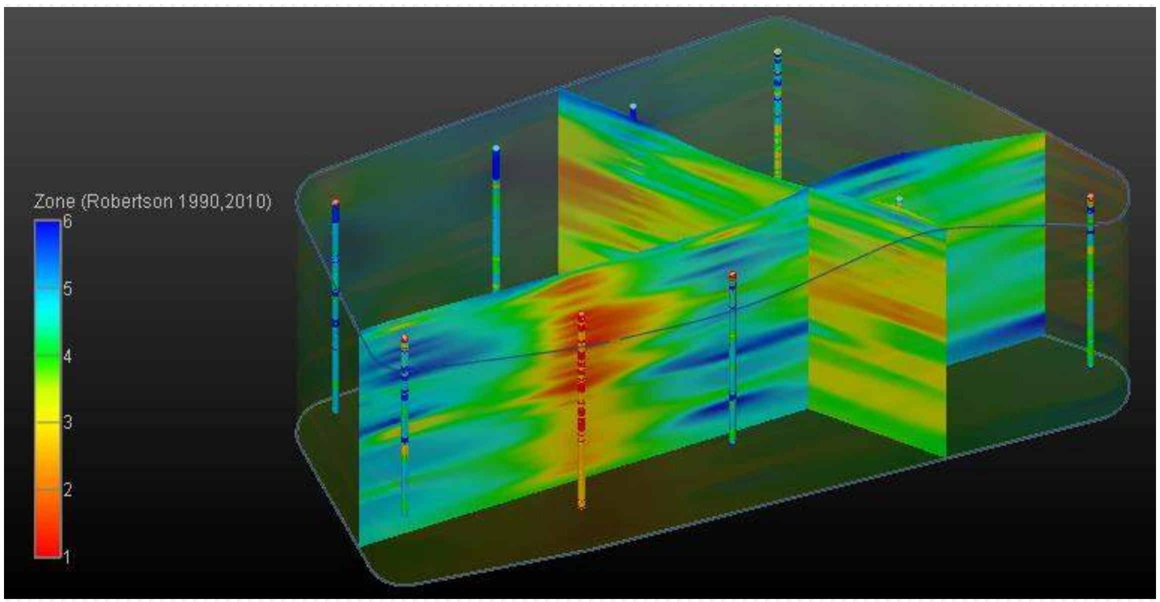
ZONE (Robertson_1990;2010)
6
5
4
3
2
1

Soil Properties 3D Visualization (Geostatistics)



Kriging Interpolation

- Soil Behavior Type (SBT) data, Robertson, 1990; 2010, is interpolated within the volumetric grid.
- Interpolated data can be extracted from the model to validate with CPT data or sample data



Critical Sections

- Different Soil Properties can be interpolated (i.e. friction angle, cohesion, Su) and critical section can be identified.
- Problematic soils (i.e. sensitive clays, lose sands or silts lenses susceptible for liquefaction) can also be identified.

Summary and Conclusions

- Geostatistical with proper care can quantify the uncertainties present in hydraulic fill structures and earthen dams
- Risk-based Resiliency framework - Performance and recreating of high-hazard dams:
  - Instrumentation, Field Monitoring, Computational Visualization and Modeling
  - Develop Quantifiable Metric Systems for Resilient Solutions – High-Quality Research Data and incorporates Variabilities and Uncertainties with Geotechnical Engineering

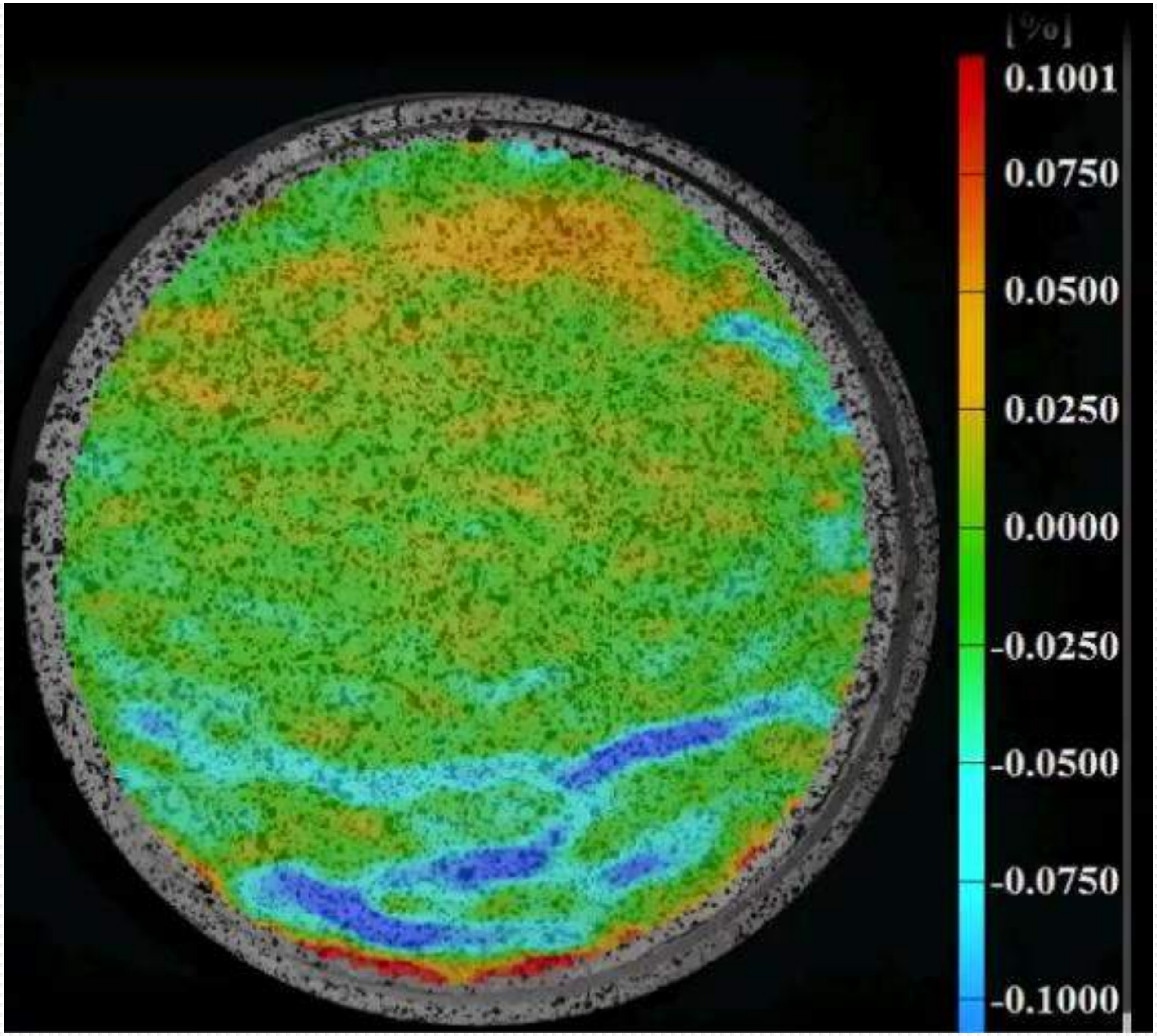
Relevant Publications

1. Bheemasetti, T. V., Puppala, A.J., Verreault, L., Pedarla, A., Weatherton Y.P. (2017). Optimizing Geotechnical Data for Levee Resilience. *Proceedings of the Institution of Civil Engineers- Engineering Sustainability*. Thomas Telford Ltd. pp. 1-12.
2. Chakraborty, S., Bheemasetti, T. V., Puppala, A. J., Das, J. T., Caballero S. (2021). Geomaterial Characterization and Stability Assessment of Hydraulic Fill Dam. *ASCE Journal of Materials in Civil Engineering*. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003553
3. Chakraborty, S., Puppala, A. J., Bheemasetti, T. V., Das, J. T. (2021). Seismic Slope Stability Analysis of a hydraulic fill dam. *ASCE International Journal of Geomechanics*. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001892
4. Puppala, A., Congress, S.S.C., Bheemasetti, T.V., Caballero, S. R. (2018). Visualization of Civil Infrastructure Emphasizing Geomaterial Characterization and Performance, *ASCE Journal of Materials in Civil Engineering*.
5. Caballero, S. R., Bheemasetti, T. V., Puppala, A. J., & Chakraborty, S. (2022). Geotechnical Visualization and Three-Dimensional Geostatistics Modeling of Highly Variable Soils of a Hydraulic Fill Dam. *Journal of Geotechnical and Geoenvironmental Engineering*, *148*(11), 05022006.
6. Chakraborty, S., Bheemasetti, T. V., Puppala, A. J., & Verreault, L. (2018). Use of constant energy source in SASW test and its influence on seismic response analysis. *Geotechnical Testing Journal*, *41*(6), 1102-1116.

There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

Donald Rumsfeld

Thank You!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-0.0250
-0.0500
-0.0750
-0.1000

Soils with Seasonal Climatic Variability

Understand the thermal-mechanical behavior of control soils and develop mix-designs for treating **problematic soils**

Fig. Climate Change Effects in Black Hills region – (a) desiccation cracks & salt precipitation; (b) soil erosion; (c) slope failures; (d) progressive landslide along US16

PSHA TASKS

TASK 1: CHARACTERIZATION OF SOURCES: SPATIAL AND SIZE UNCERTAINITY

40 MILES RADIUS APPROACH-SAMPLE

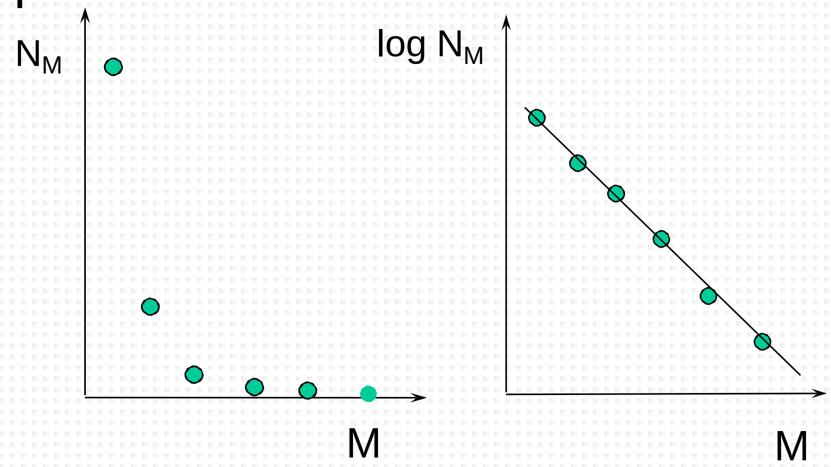
b. SIZE UNCERTAINITY:

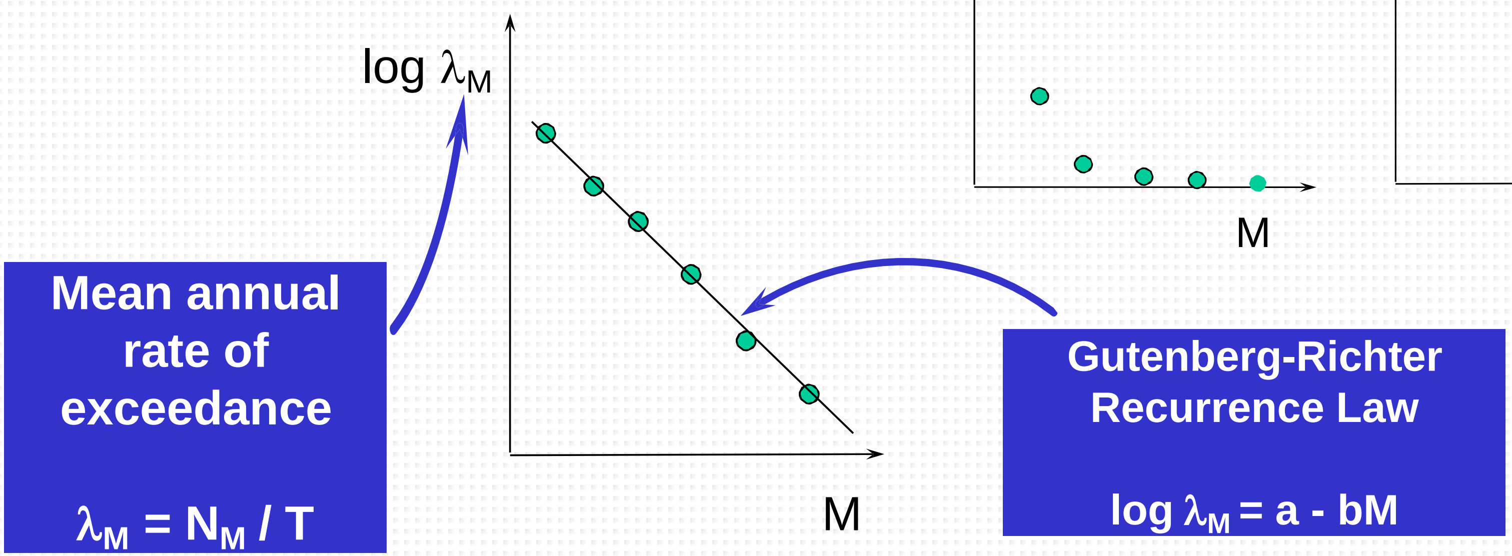
Distribution of earthquake magnitudes

Given source can produce different earthquakes

Low magnitude - often

Large magnitude - rare



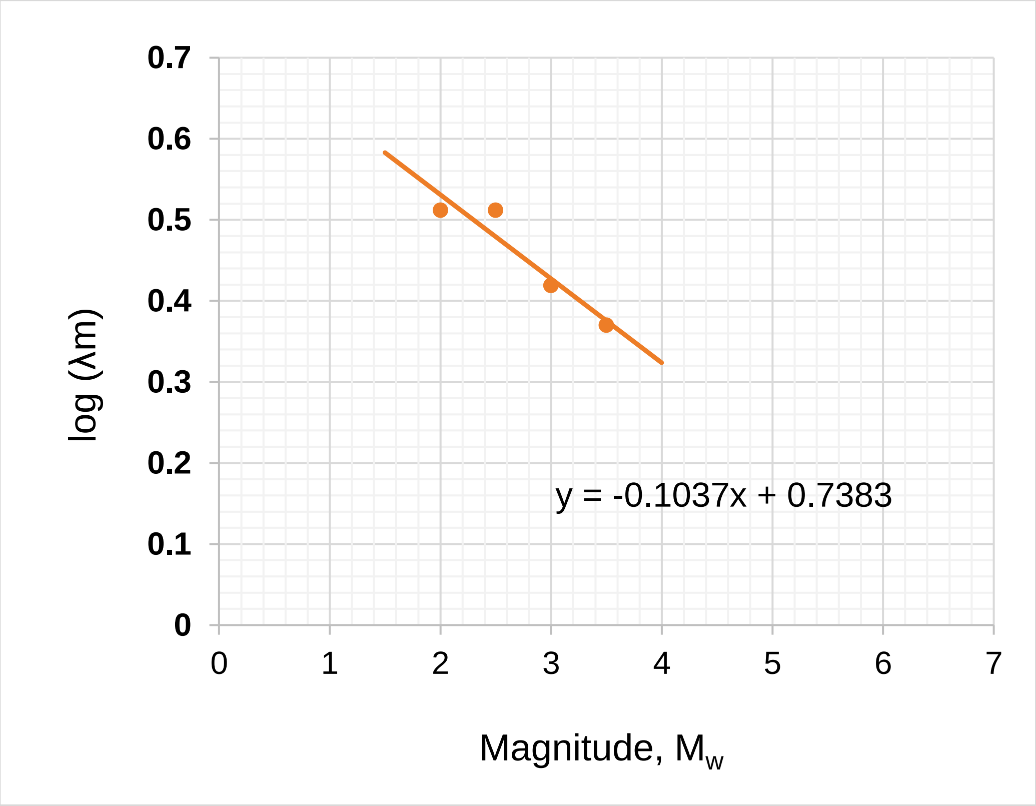


PSHA TASKS

TASK 1: CHARACTERIZATION OF SOURCES: SPATIAL AND SIZE UNCERTAINITY

40 MILES RADIUS APPROACH-SAMPLE

b. SIZE UNCERTAINITY (Source 1-AZLE, TX) Cont.:



$\log \lambda_M = a - bM$

Where:
a= 0.7383
b= 0.1037

Return period (recurrence interval)

$T_R = 1 / \lambda_M$

Source 1
$M_{max=}$ 3.6
$\lambda_M = 0.365$
$T_R = 1/0.365 = 2.7$ years

PSHA TASKS

TASK 1: CHARACTERIZATION OF SOURCES: SPATIAL AND SIZE UNCERTAINITY

40 MILES RADIUS APPROACH-SAMPLE

SIZE UNCERTAINITY (Source 1-AZLE, TX) CONT.:

Recurrence for Source 1

$\log \lambda_M = a - bM$

Where:

a= 0.7383

b= 0.1037

Therefore, temporal distribution of earthquake recurrence:

$v = 10^{a - bM}$

For m_0=2,

$v = 10^{0.7383 - 0.1037(2.0)}$

ν = 3.40

Su

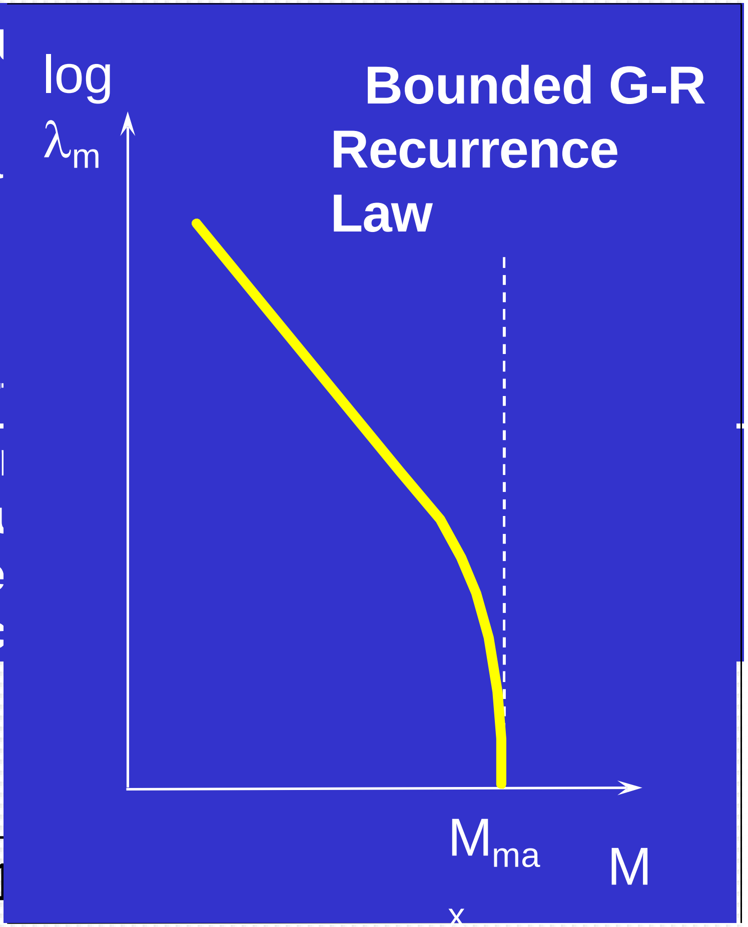
1.1 Assume a minimum
Seismic events less tha
seismic hazard:

1.2 Select a range of Ear

M	# Eqs
2-2.5	5
2.5-3	14
3-3.5	5
3.5-4	2

1.3 Eve
magnitu
modifie
G-R rec

$$\lambda_m = \nu \frac{\exp[-\beta(m-}{1}$$



PSHA TASKS

TASK 1: CHARACTERIZATION OF SOURCES: SPATIAL AND SIZE UNCERTAINITY

40 MILES RADIUS APPROACH-SAMPLE

SIZE UNCERTAINITY (Source 1-AZLE, TX):

Source 1						
M	Range of Distances, R (km)					
	8	10	12.5	15	17	19
2-2.5	0.07113	0.123	0.16598	0.25	0.023	0.0999
2.5-3	0.02912	0.12334	0.15788	0.0945	0.01942	0.01942
3-3.5	0.00921	0.02455	0.02148	0.0754	0.00614	0.00614
3.5-4	0.00231	0.00776	0.00679	0.00388	0.00194	0.00194
4-4.5	0.00092	0.00245	0.00215	0.00123	0.00061	0.00061
4.5-5	0.00029	0.00078	0.00068	0.00039	0.00019	0.00019
5-5.5	9.2E-05	0.00025	0.00021	0.00012	6.1E-05	6.1E-05
5.5-6	2.9E-05	7.8E-05	6.8E-05	3.9E-05	1.9E-05	1.9E-05
6-6.5	9.2E-06	2.5E-05	2.1E-05	1.2E-05	6.1E-06	6.1E-06
6.5-7	2.9E-06	7.8E-06	6.8E-06	3.9E-06	1.9E-06	1.9E-06
7-7.5	9.2E-07	2.5E-06	2.1E-06	1.2E-06	6.1E-07	6.1E-07
7.5-8	2.9E-07	7.8E-07	6.8E-07	3.9E-07	1.9E-07	1.9E-07
Σ						1.35591

$$\lambda_m = \nu \frac{\exp[-\beta(m - m_o)] - \exp[-\beta(m_{\max} - m_o)]}{1 - \exp[-\beta(m_{\max} - m_o)]}$$

Subtasks:

1.1 Probability of M_{avg} (BGRRL) U_{T2}

1.2 Probability of occurrence M_{avg} at each distance range – U_{T1}

1.3 Ground Motion for each combination of M_{avg} and distance using GMPEs

1.4 Calculate the probability of exceedance a specific PGA for each combination

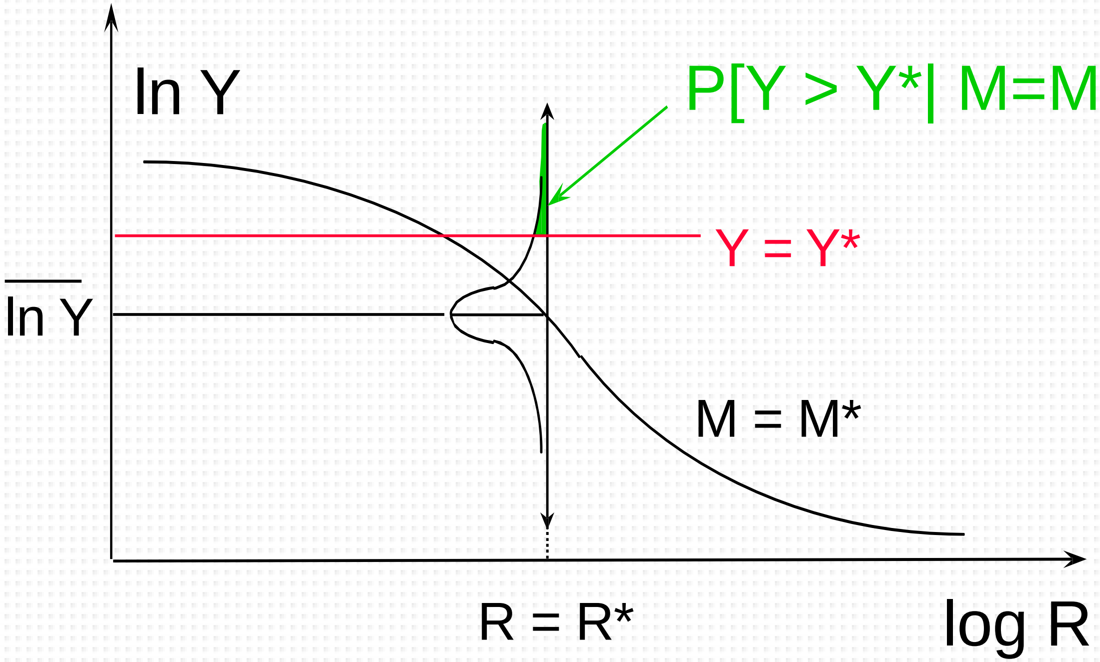
PSHA TASKS

TASK 2: GROUND MOTION PREDICTION USING GMPEs

40 MILES RADIUS APPROACH-SAMPLE

Predictive Relationships: (Source 1-AZLE, TX):

Standard error - use to evaluate conditional probability



A probability is calculated for each PGA (i.e. 0.01g, 0.1g, 0.2g…. 1g)

U_{T3}= Effect of Earthquakes ⇒ **Each combination of M_{avg} and distance range**

PSHA TASKS

TASK 3: SUMMATION OF UNCERTAINTIES FOR EACH SOURCE

PGA=0.1g

Source 1						
M	Range of Distances, R (km)					
	8	10	12.5	15	17	19
2-2.5	0.07113	0.123	0.16598	0.25	0.023	0.0999
2.5-3	0.02912	0.12334	0.15788	0.0945	0.01942	0.01942
3-3.5	0.00921	0.02455	0.02148	0.0754	0.00614	0.00614
3.5-4	0.00231	0.00776	0.00679	0.00388	0.00194	0.00194
4-4.5	0.00092	0.00245	0.00215	0.00123	0.00061	0.00061
4.5-5	0.00029	0.00078	0.00068	0.00039	0.00019	0.00019
5-5.5	9.2E-05	0.00025	0.00021	0.00012	6.1E-05	6.1E-05
5.5-6	2.9E-05	7.8E-05	6.8E-05	3.9E-05	1.9E-05	1.9E-05
6-6.5	9.2E-06	2.5E-05	2.1E-05	1.2E-05	6.1E-06	6.1E-06
6.5-7	2.9E-06	7.8E-06	6.8E-06	3.9E-06	1.9E-06	1.9E-06
7-7.5	9.2E-07	2.5E-06	2.1E-06	1.2E-06	6.1E-07	6.1E-07
7.5-8	2.9E-07	7.8E-07	6.8E-07	3.9E-07	1.9E-07	1.9E-07
Σ						1.35591

Summation of Uncertainties for Source 1

Same approach for Source 2 (40 miles radius), therefore;

For a PGA = 0.1g, 0.2…..1.0

$$\%P_{EXCS1.} = \nu \times U_{t1} \times U_{t2} \times U_{t3}$$

SEISMIC HAZARD CURVES ARE DEVELOPED FOR DIFFERENT VALUES OF PGA

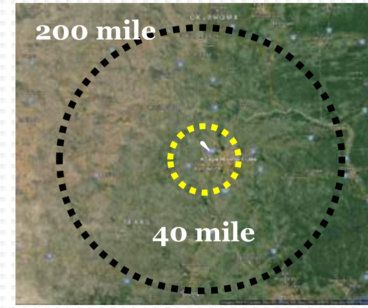
$$\%P_{TOTAL} = \%P_{EXCS1.} + \%P_{EXCS2}$$
$$\%P_{TOTAL} = 1.3559 + 0.3322$$

$$\%P_{TOTAL} = 1.688$$

For PGA=0.1g

Seismic parameters (DSHA)

Identification of sources (40 miles & 200 miles)



Characterization of Sources (Magnitude, Depth, Distance to site)

Geometry of sources (polygons)

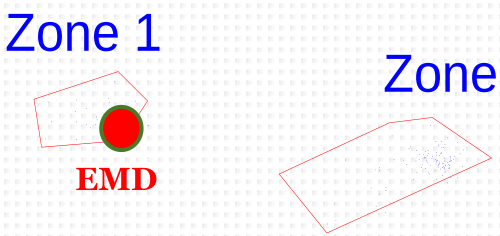
Source: F (M_{max}, R_{min})

Ground Motion Predicting Equations

Selection of Threshold values

List all Sources > Threshold

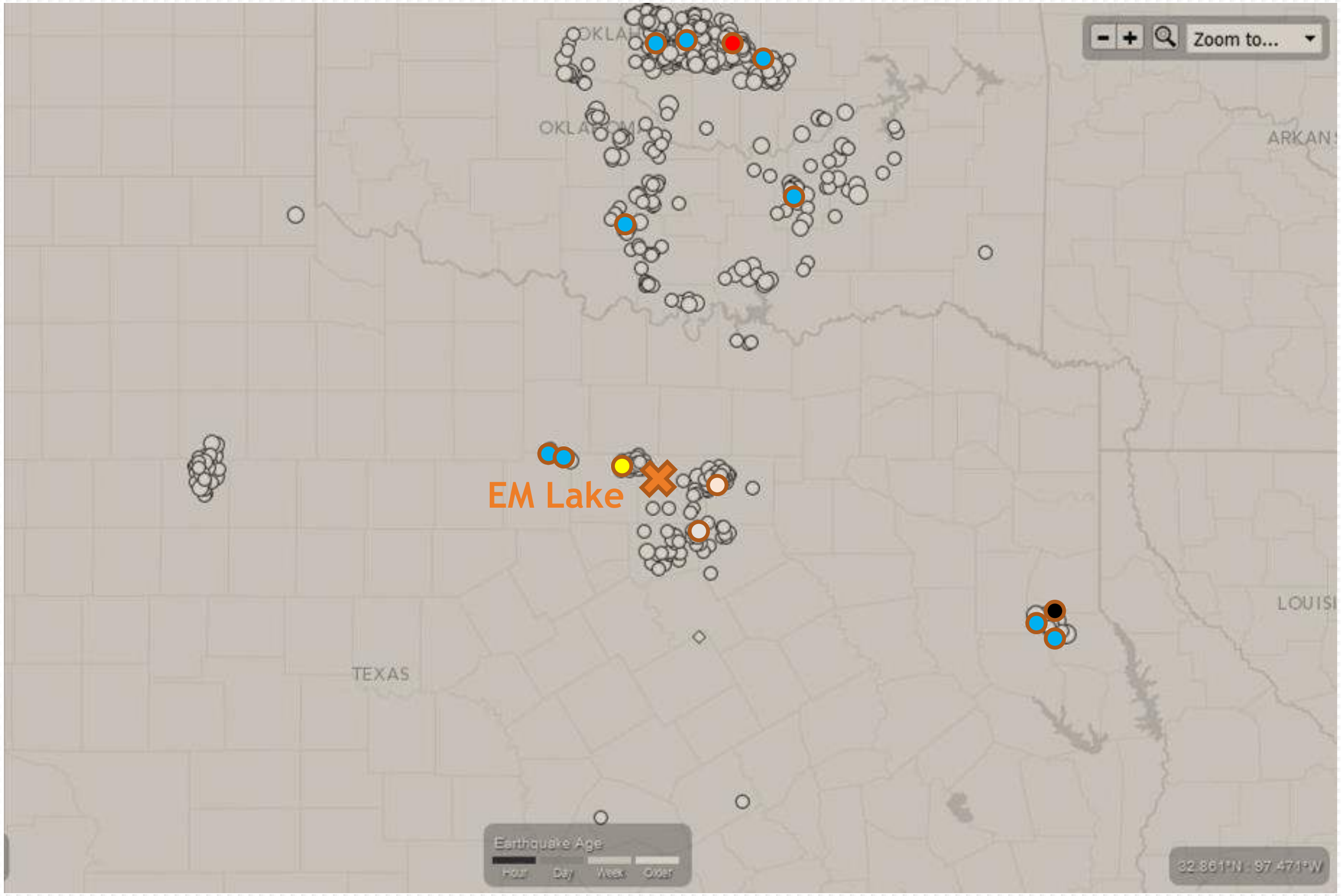
Maximum PGA/PGV/PSA



PGA ~ Peak Ground Acceleration
PGV ~ Peak Ground Velocity
PSA ~ Peak Spectral Acceleration

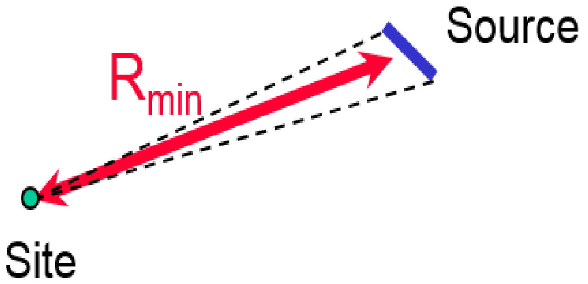
Identification of Sources

- Prague, OK (2011) M5.6
- Eastern Texas (2012) M4.8
- Azle, TX (2013) M~3.6
- Venus, TX (2015) M4.0
- Irving, TX (2015) M3.6
- Others, M~3.0

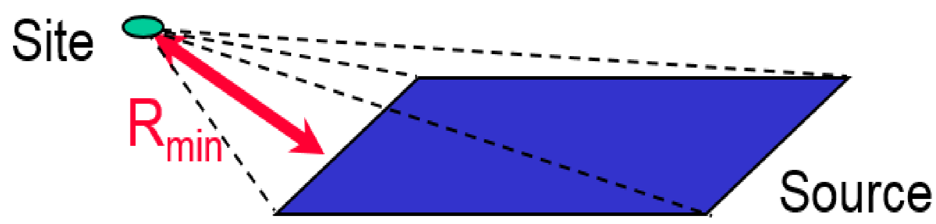


Source: USGS Archives

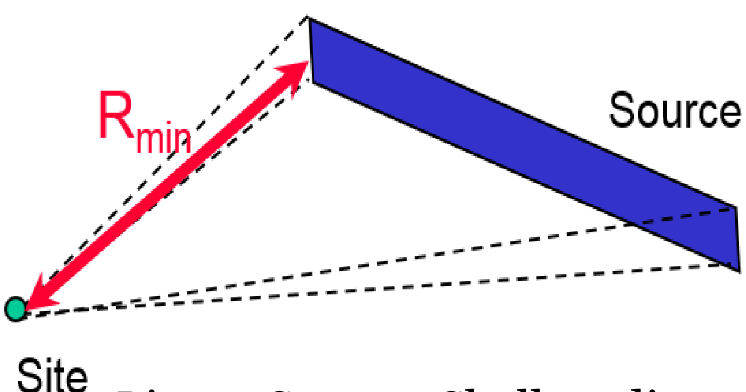
Characterization of Sources



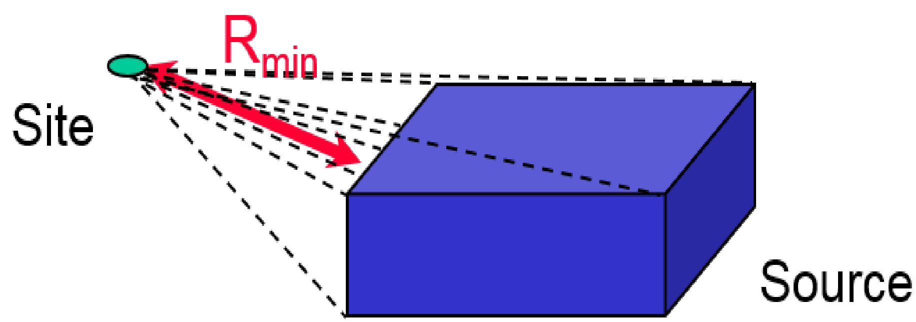
Short distances: Volcanos



Areal Source: Constant depth crustal source



Linear Source: Shallow distant faults

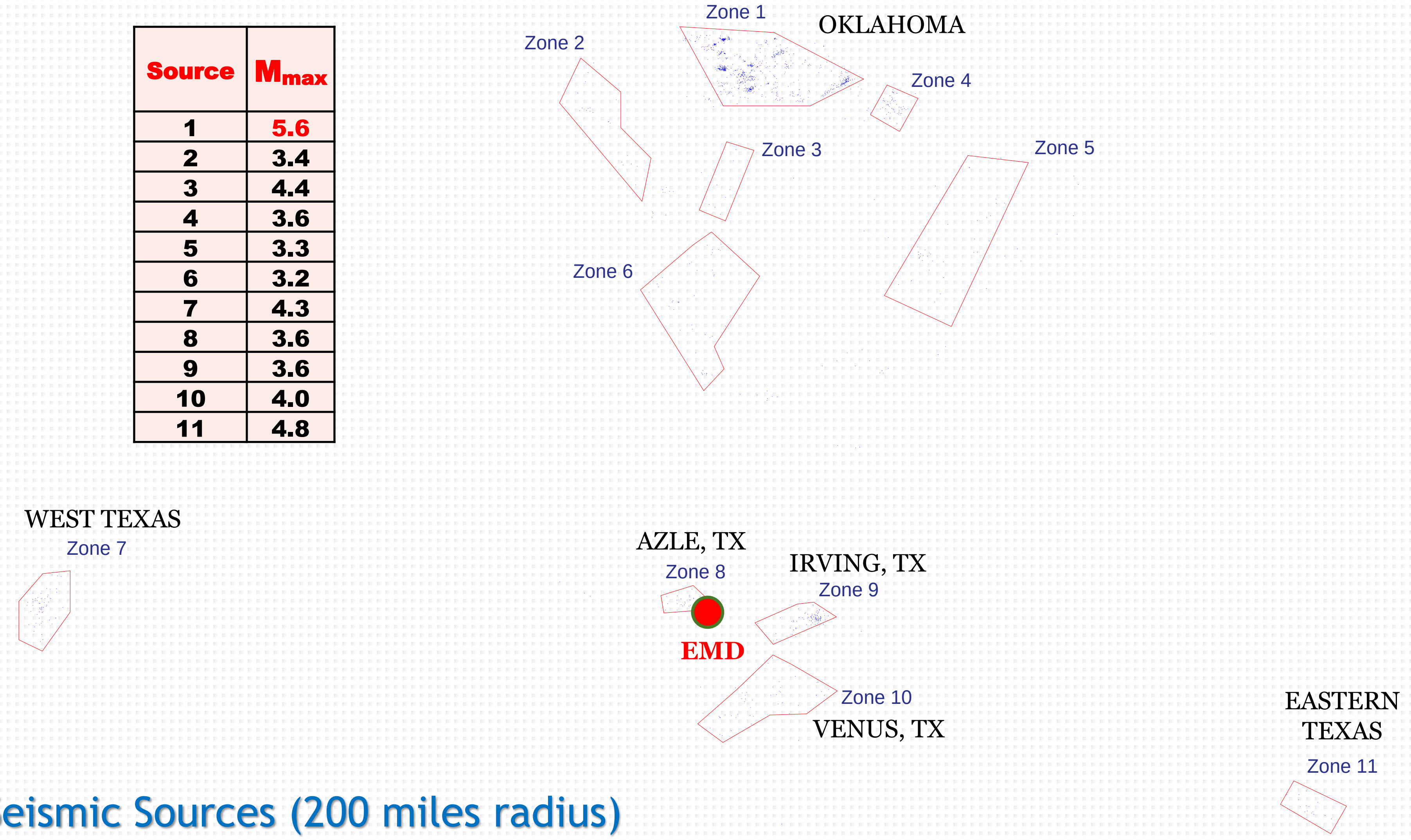


Volumetric Source:
Uncertainty about the origin.
Variation in depths

Deterministic Seismic Hazard Analysis

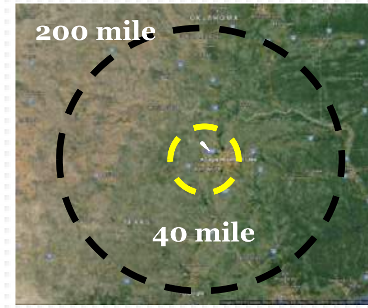
CHARACTERIZATION OF THE GEOMETRY OF THE SOURCES

Source	M_{max}
1	5.6
2	3.4
3	4.4
4	3.6
5	3.3
6	3.2
7	4.3
8	3.6
9	3.6
10	4.0
11	4.8



Seismic Sources (200 miles radius)

Seismic parameters (DSHA)



Identification of sources (40 miles & 200 miles)

↓

Characterization of Sources (Magnitude, Depth, Distance to site) → **Geometry of sources (polygons)**

↓

Source: F (M_{max}, R_{min}) → **Ground Motion Predicting Equations**

↓

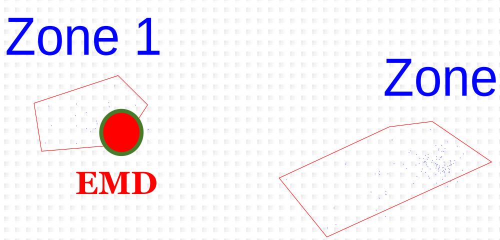
Selection of Threshold values

↓

List all Sources > Threshold

↓

Maximum PGA/PGV/PSA



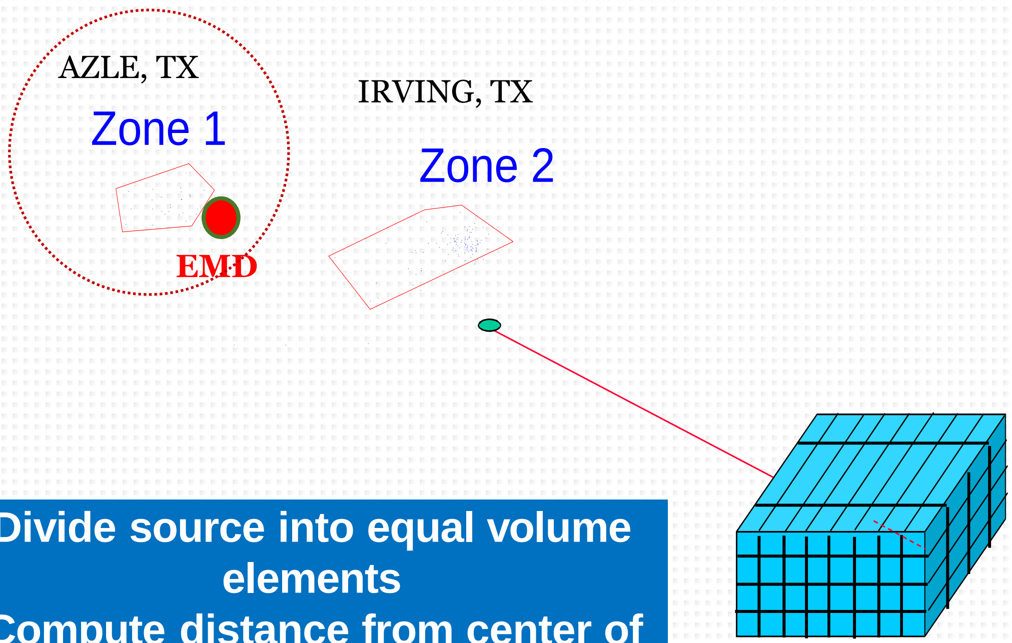
PGA ~ Peak Ground Acceleration
PGV ~ Peak Ground Velocity
PSA ~ Peak Spectral Acceleration

PSHA TASKS

TASK 1: CHARACTERIZATION OF SOURCES: SPATIAL AND SIZE UNCERTAINITY

40 MILES RADIUS APPROACH-SAMPLE

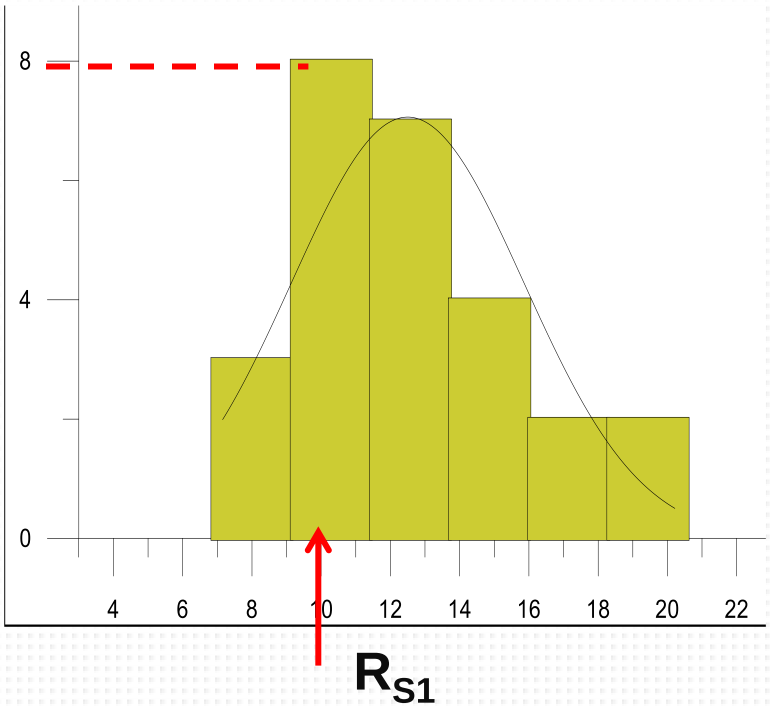
a. SPATIAL UNCERTAINITY:



Divide source into equal volume elements
Compute distance from center of each element
Create histogram of source-site distance

Range of Distances (***)

ZONE 1 (Source 1)



R_{S1}= 10.2 Km

U_{T1}= #R_{S1} / #Obs

U_{T1}= (8/26) = 0.307

PSHA TASKS

TASK 4: SEISMIC HAZARD CURVES (40 MILES RADIUS)

RESULTS (PSHA)

Y	0.01253318	*From Graph*
Time	5	Years
PGA	**Time Period**	**%Prob.**
0.2	**1**	1.25
	5	6.07
	10	11.78
	20	22.17
	30	31.34
	50	46.56
	100	71.44