
# Keynote Lecture:

# Dynamic Analyses of an Earthfill Dam on Over-Consolidated Silt with Cyclic Strain Softening

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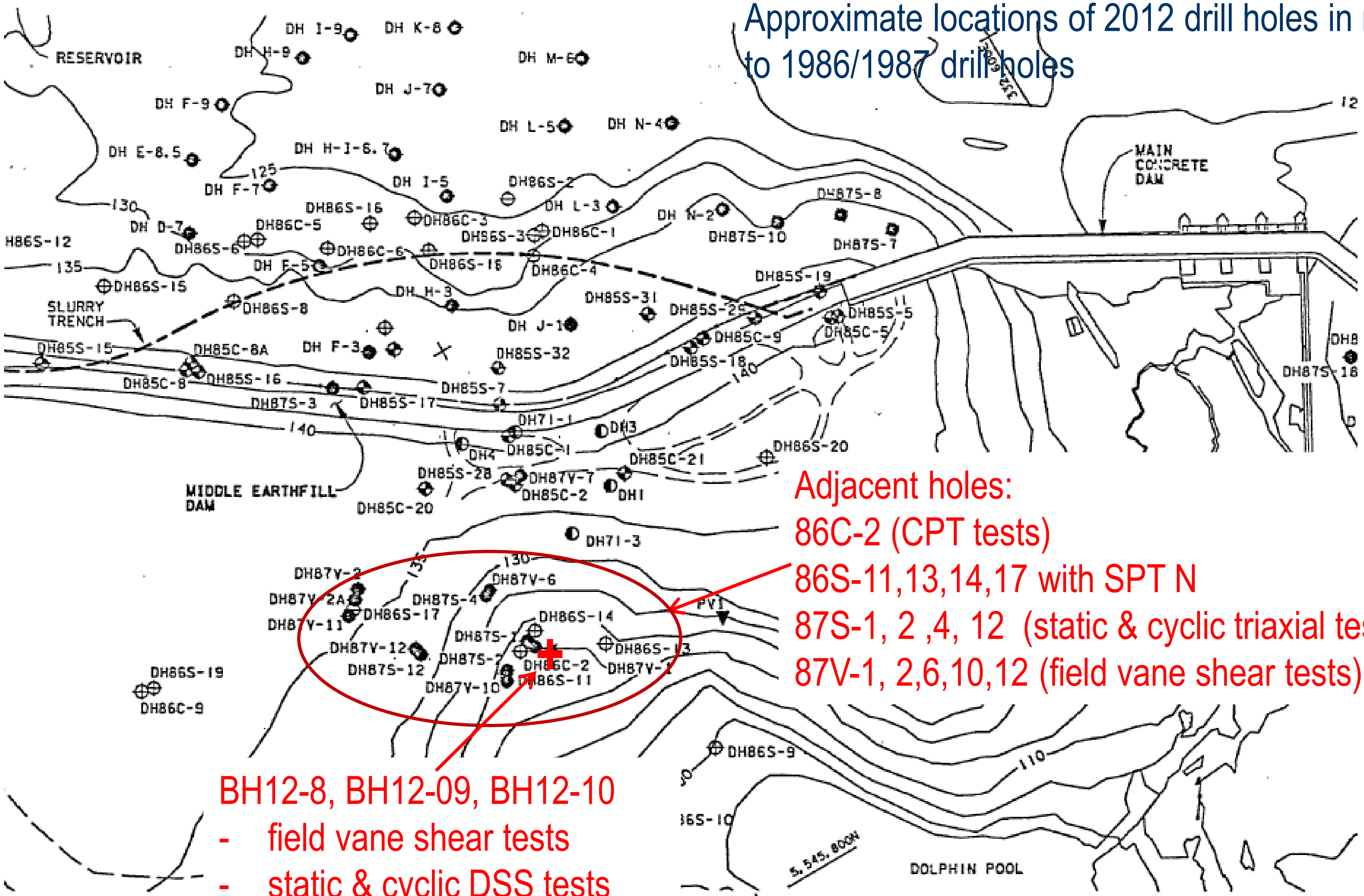
# John Hart Middle Earthfill Dam

An aerial view of the John Hart Middle Earthfill Dam
in British Columbia, Canada

# Summary of Geotechnical Investigations

Approximate locations of 2012 drill holes in relations to 1986/1987 drill holes




Adjacent holes:

86C-2 (CPT tests)

86S-11,13,14,17 with SPT N

87S-1, 2 ,4, 12  (static & cyclic triaxial tests)

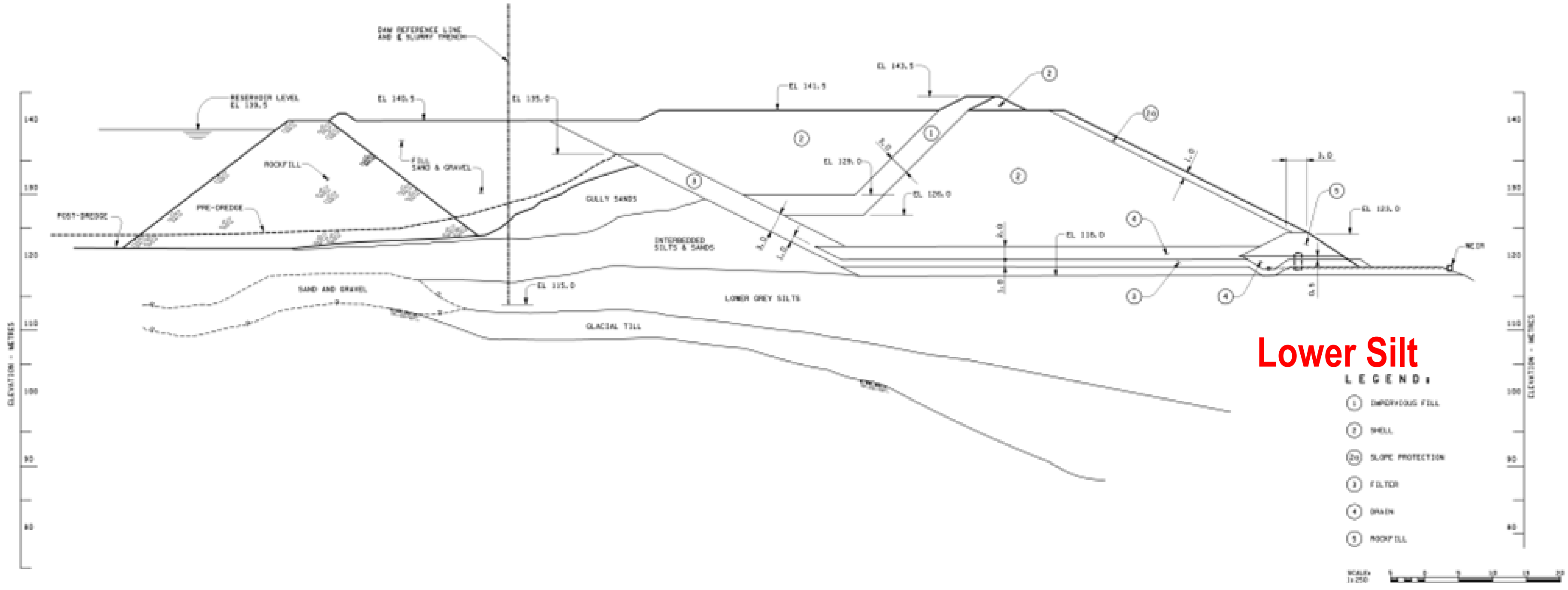
87V-1, 2,6,10,12 (field vane shear tests)

BH12-8, BH12-09, BH12-10

- field vane shear tests
- static & cyclic DSS tests
- piezometers installed

## THE MIDDLE EARTHFILL DAM – A TYPICAL CROSS SECTION:

Existing slurry
trench cutoff wall



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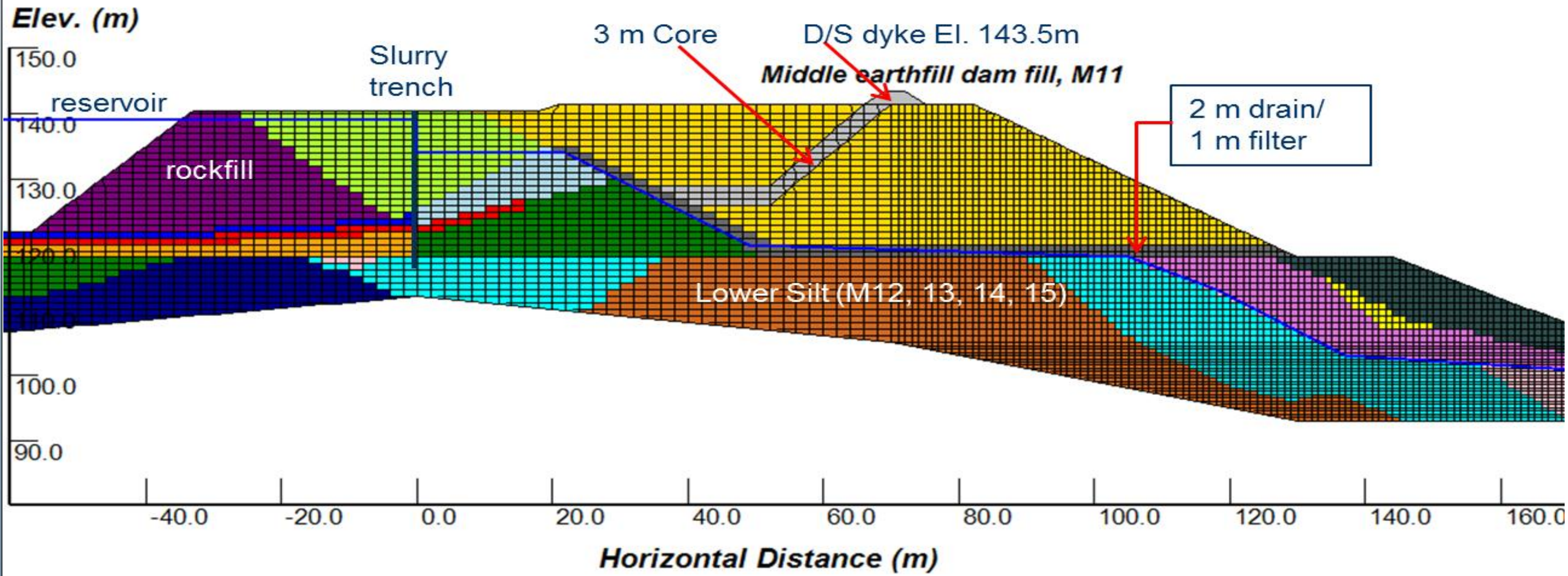
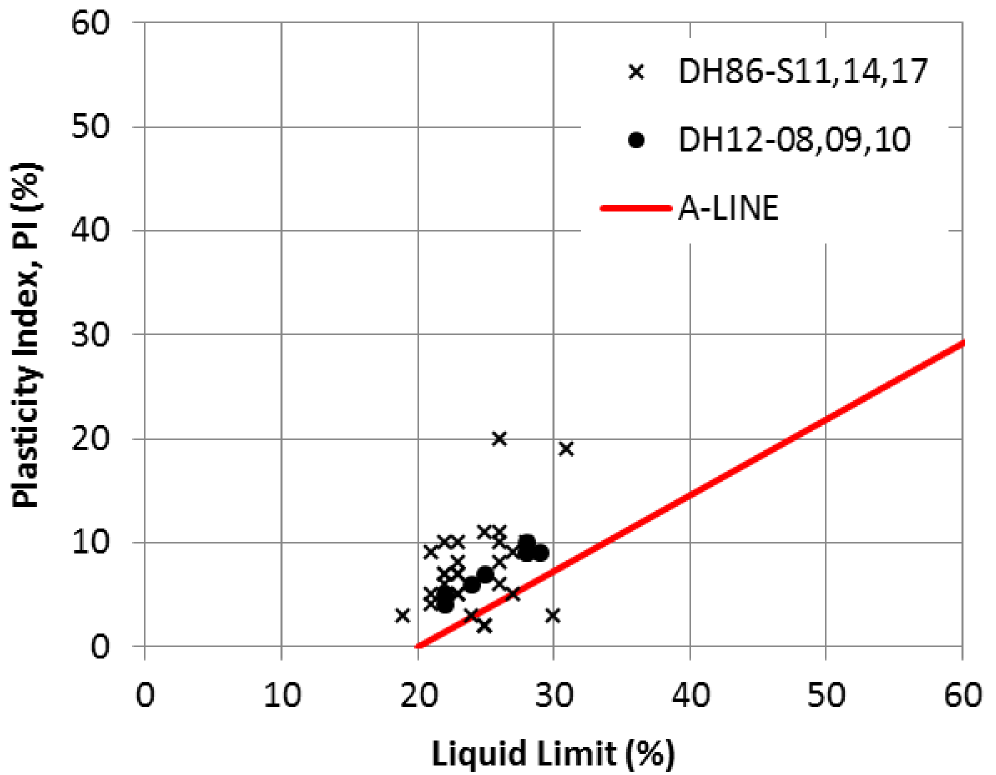



## THE MIDDLE EARTHFILL DAM – FE VIEW OF KEY FEATURES

# Atterberg Limits

Atterberg Limits of the Lower Silt on Casagrande plasticity chart

The Lower Silt consists of
70 – 80% silt size particles and
20 – 30% clay size particles;
but it is classified as low plasticity clay (CL)



# Pre-consolidation pressures

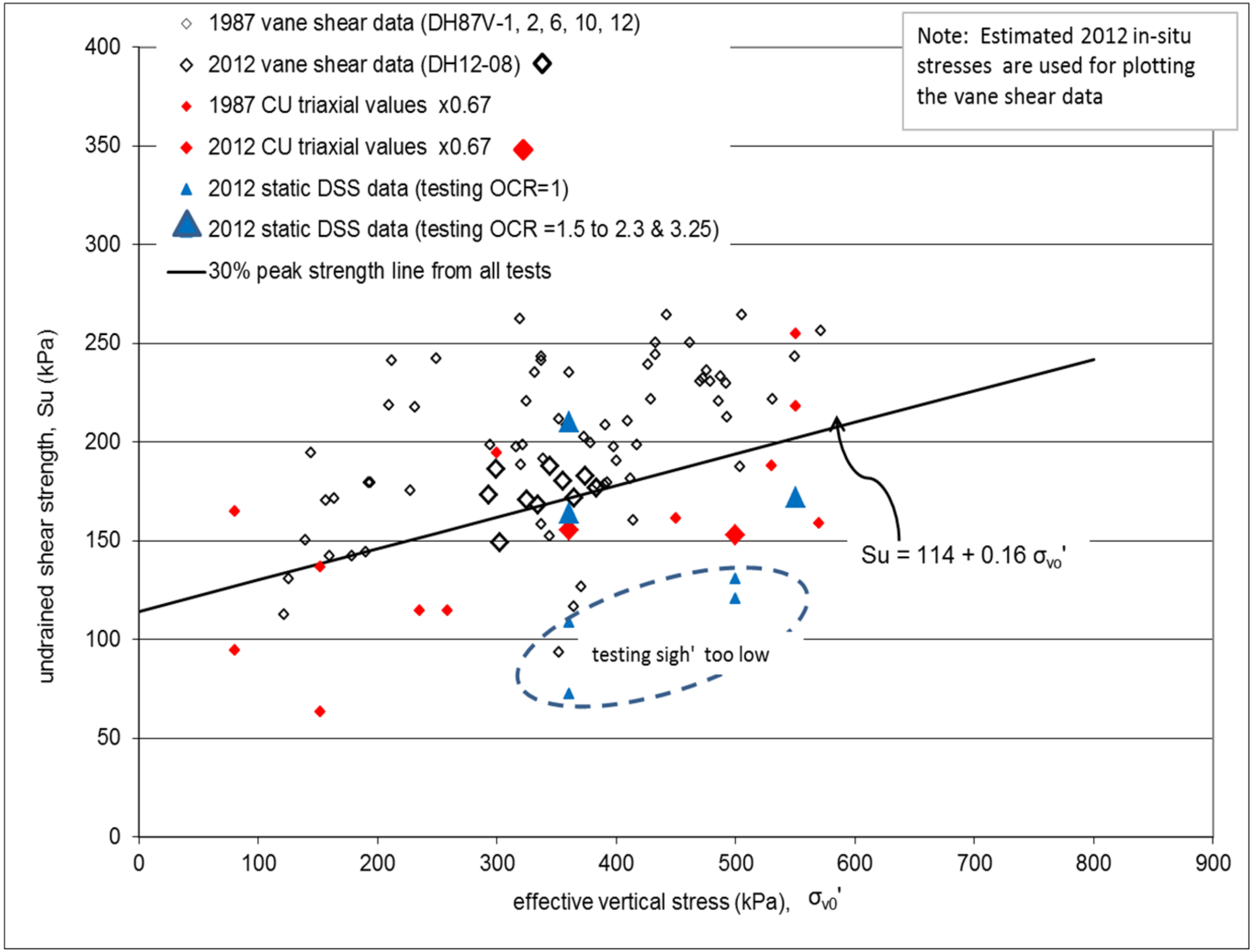
Estimated pre-consolidation pressures from Su estimated from field vane shear tests: 700 to 1170 kPa based on empirical equations Su vs. OCR etc

| DH12-09 Shelby Tube # | Top Elev. (m) | $\sigma_p'$ (kPa) | | |
|---|---|---|---|---|
| | | Casagrande Method | Energy method | |
| 14A | 99.99 | 860 | 825 | |
| 16A | 98.07 | - | - | Sample disturbed |
| 20A | 94.44 | 1170 | 1030 | |
| Note: $\sigma_p'$ = 830 kPa was then used in static and cyclic DSS tests of the Lower Silt with in-situ OCR | | | | |

Pre-consolidation pressures from 2012 laboratory CRS consolidation tests

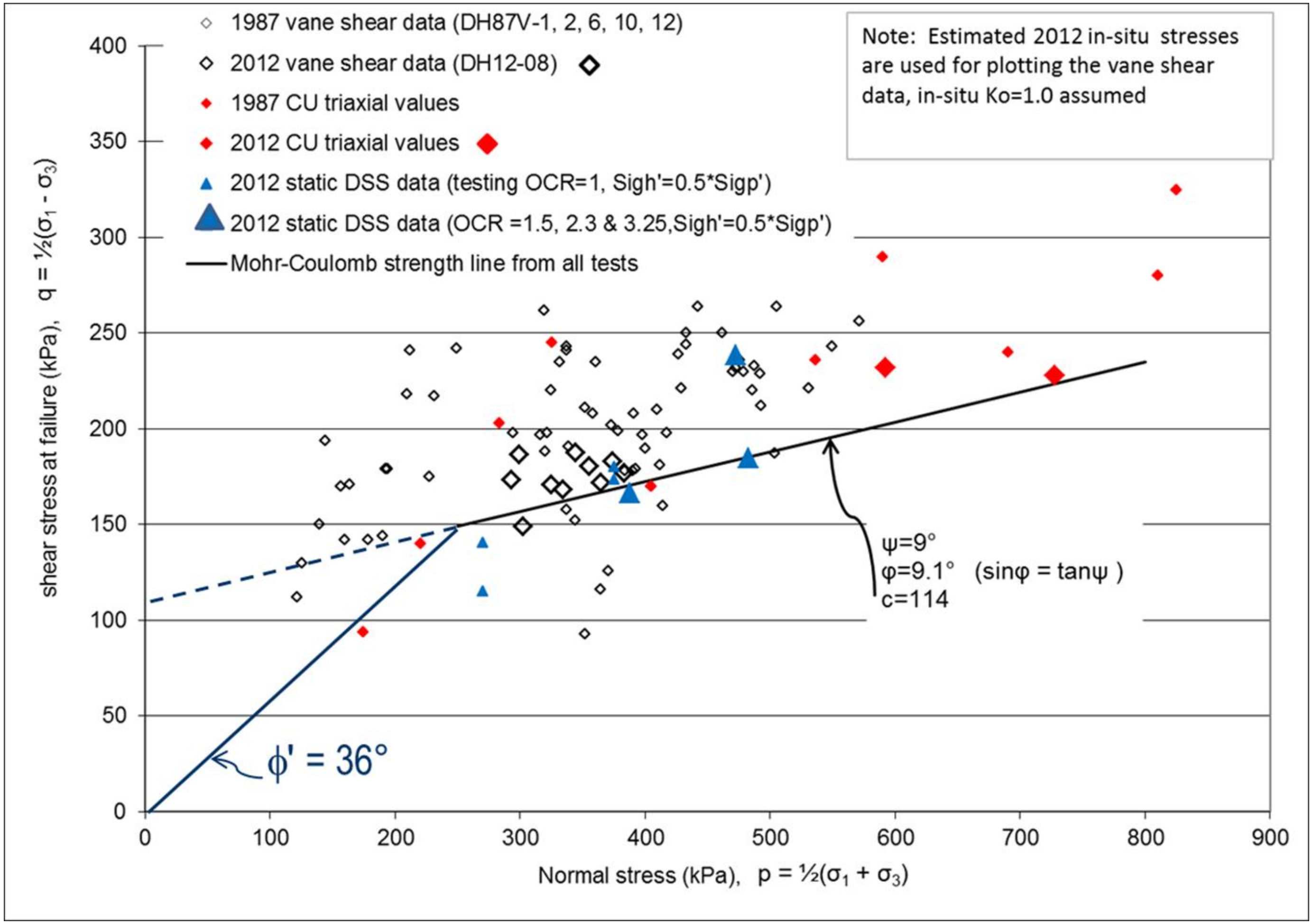
# undrained shear strengths

## Static undrained shear strengths of the Lower Grey Silt

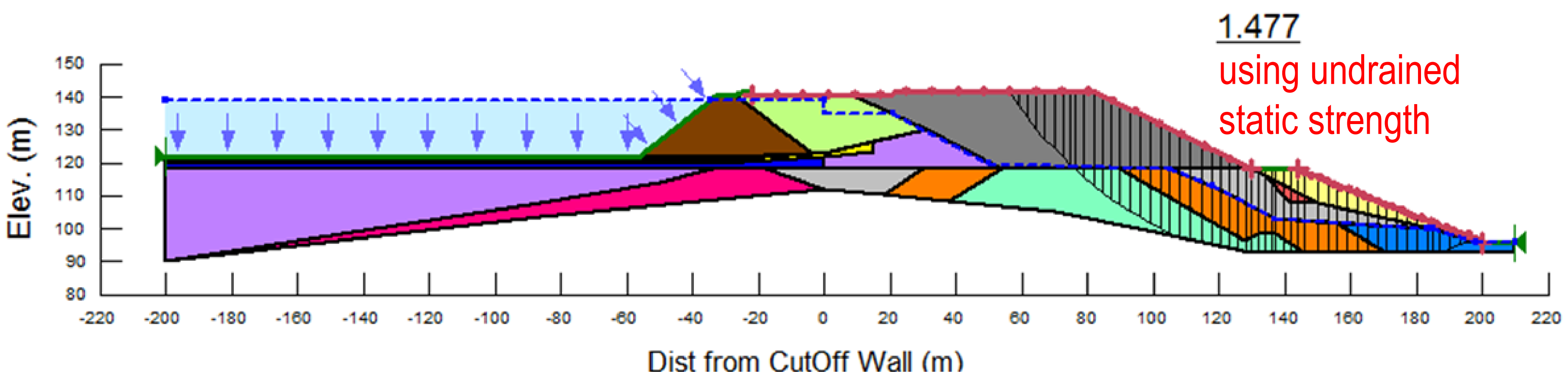


# Mohr Coulomb strength parameters

Static shear strength envelope and Mohr Coulomb strength parameters

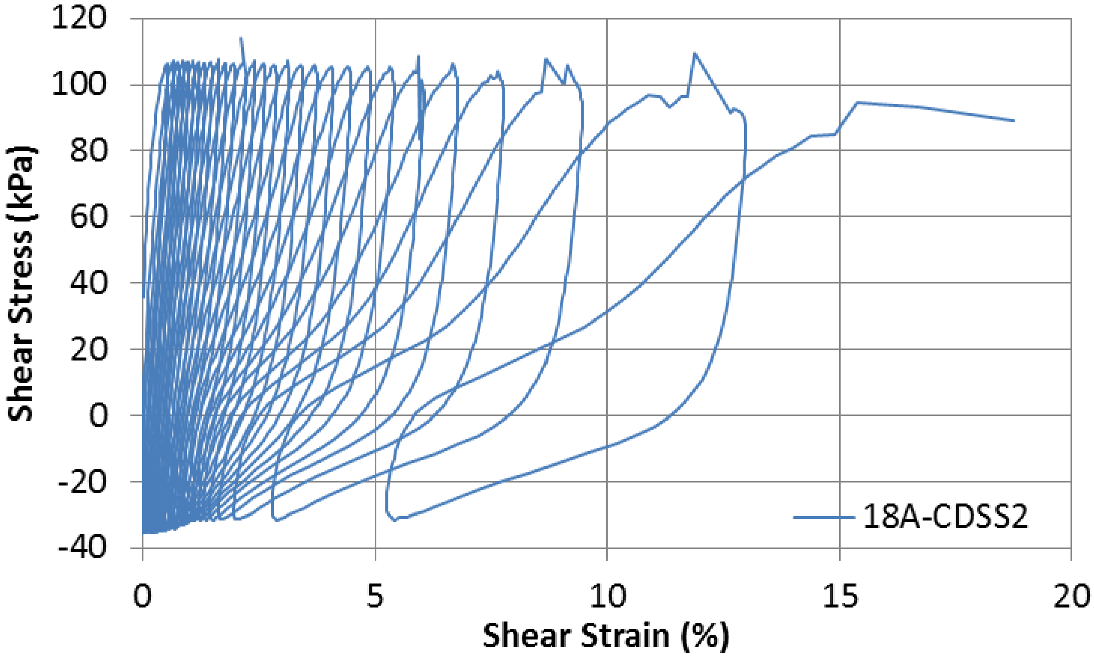


# Static Factor of Safety for D/S slope




Note:
FoS = 1.409
using Mohr Coulomb static
Strength parameters

# Cyclic DSS results

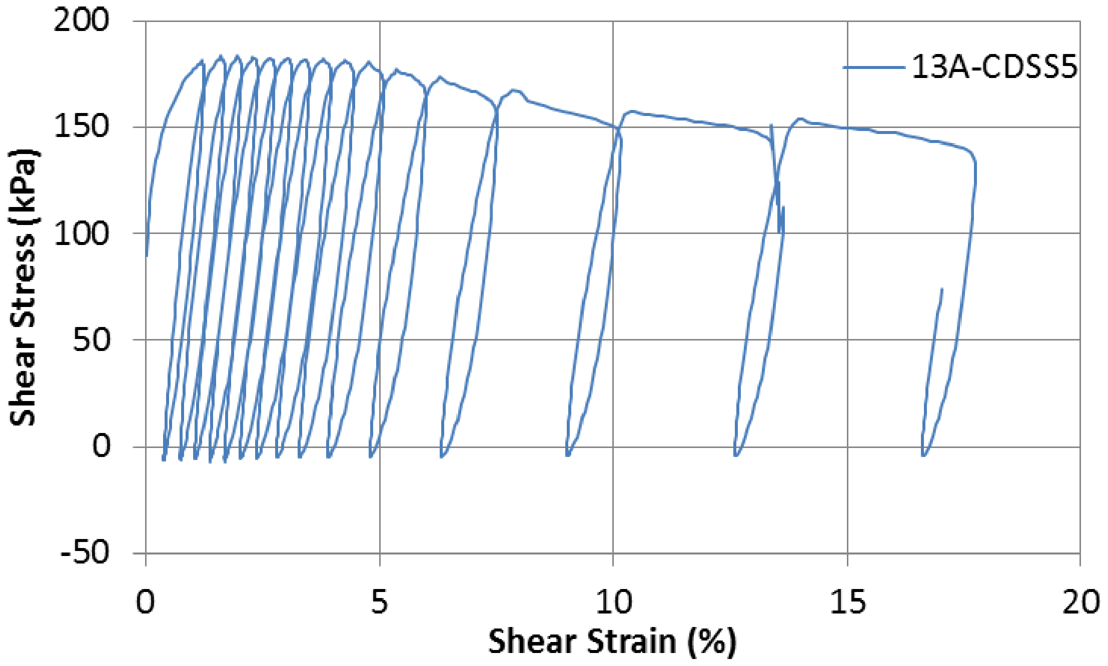



Cyclic stress – strain response of 18A-CDSS2
($\sigma'_{v0}$= 360 kPa, $\sigma'_{p}$= 360 kPa, OCR=1.0, static bias of 36 kPa)

# Cyclic DSS results

Cyclic DSS test results:

1. The Lower Silt showed strain-softening under cyclic loading, similar to sand liquefaction
2. 5% strain criteria seem to be representative
3. testing OCR is critical to response
4. others

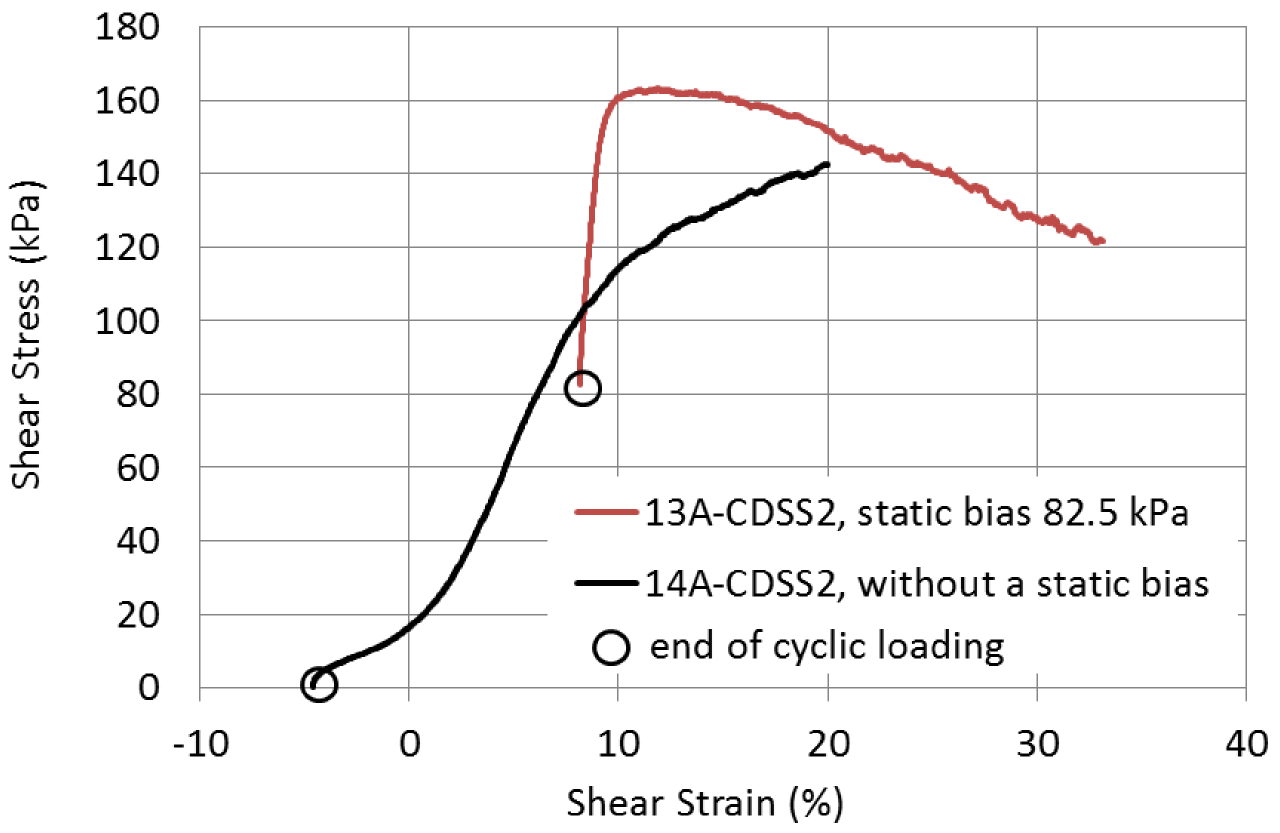



Cyclic stress – strain response of 13A-CDSS5

($\sigma'_{v0}$= 360 kPa, $\sigma'_{p}$= 830 kPa, OCR=2.3, static bias of 90 kPa)

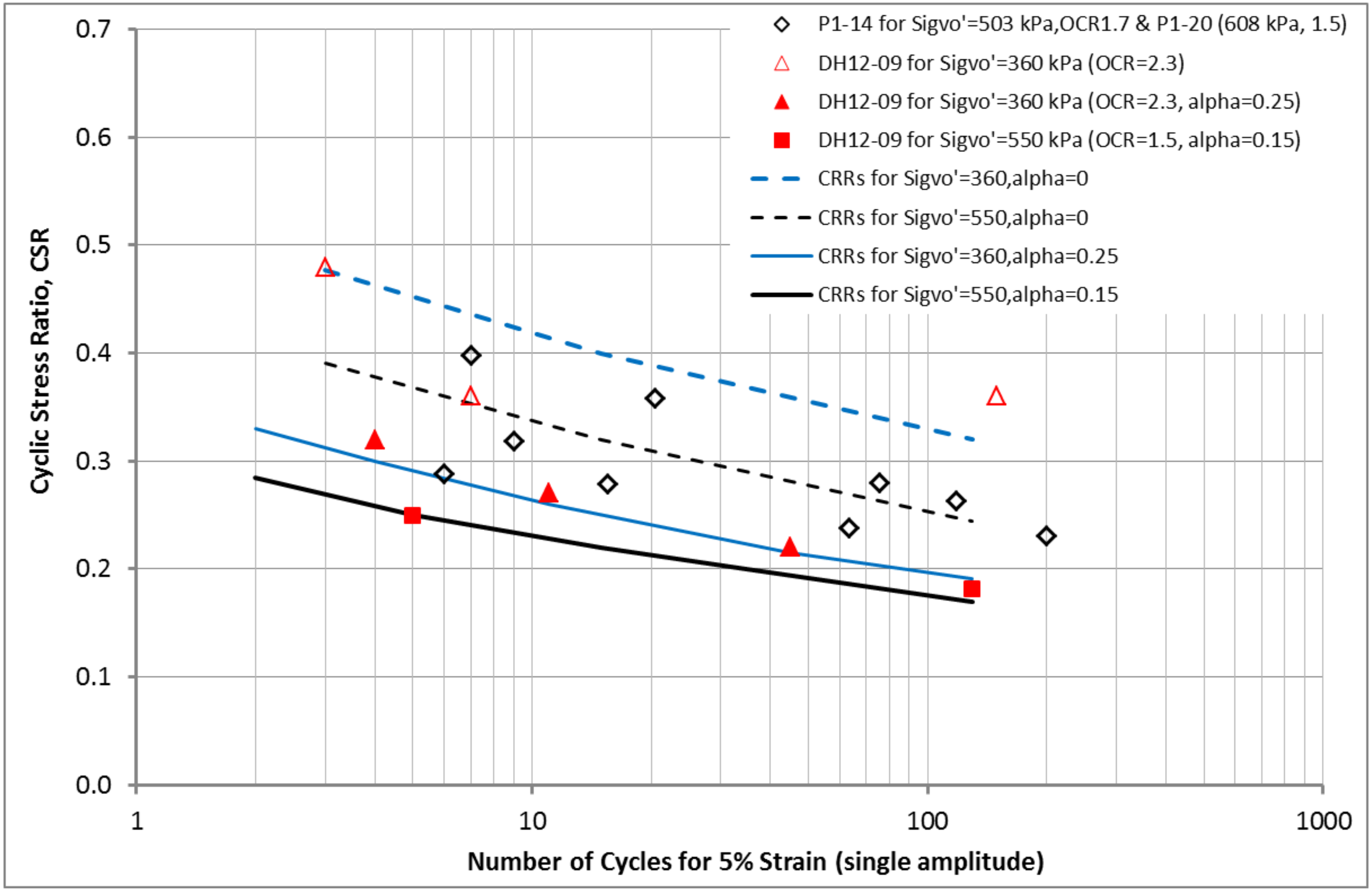
# post cyclic monotonic DSS

## Typical post cyclic-softening static DSS test results



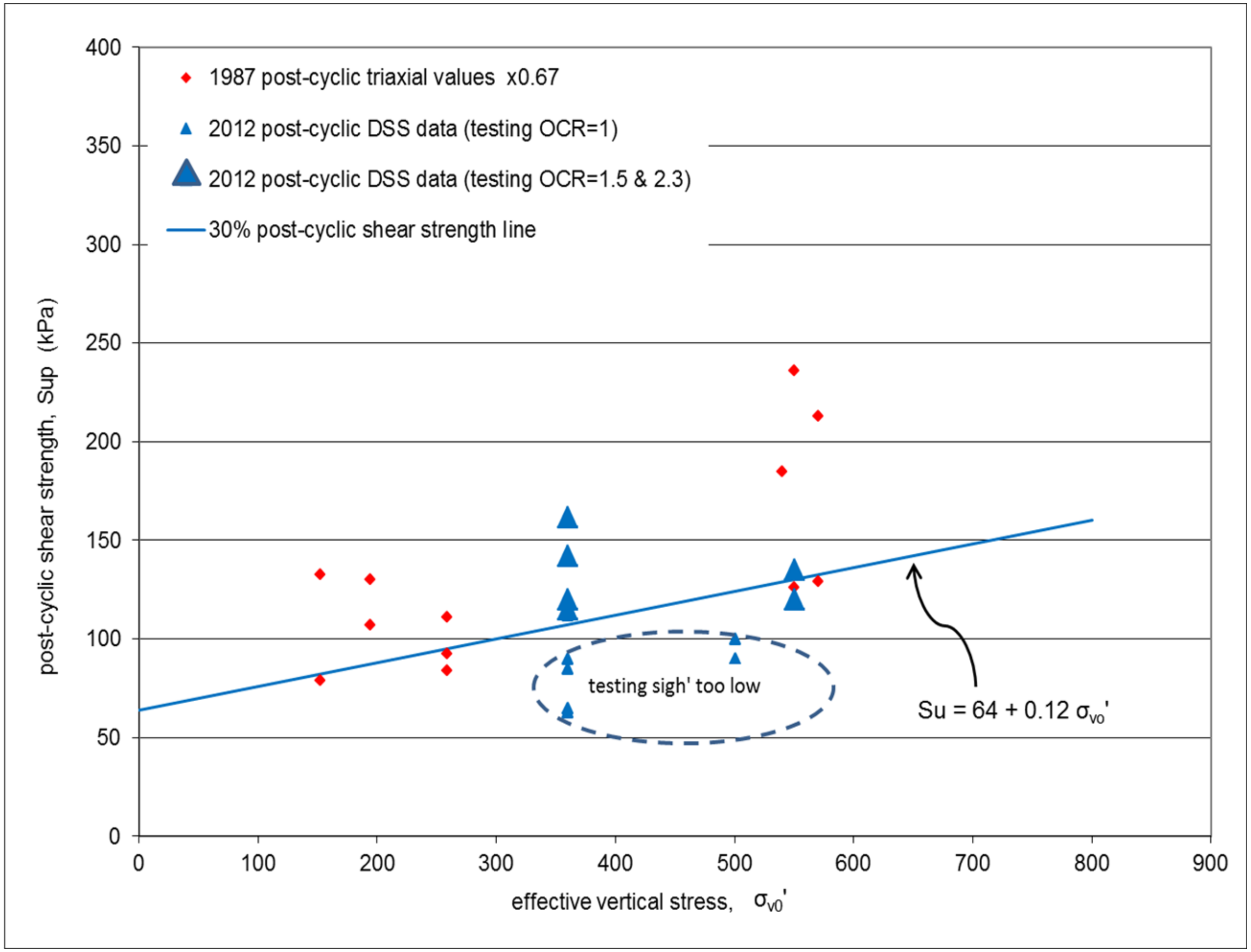
# Cyclic resistance CRR

Cyclic resistance from cyclic DSS tests with estimated in-situ OCR of the Lower Silt



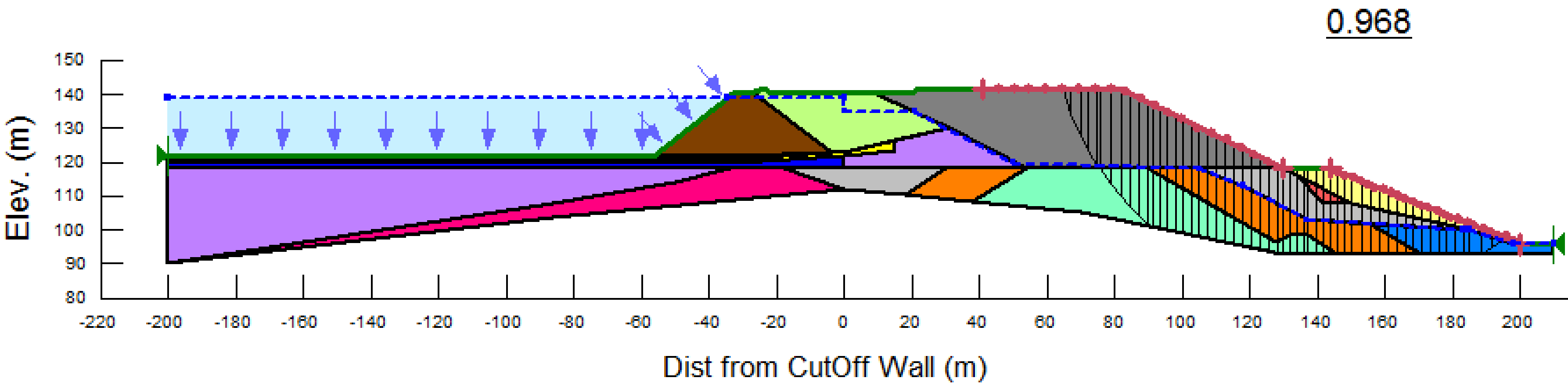
# Post cyclic-softening strengths

## Post cyclic-softening undrained shear strengths



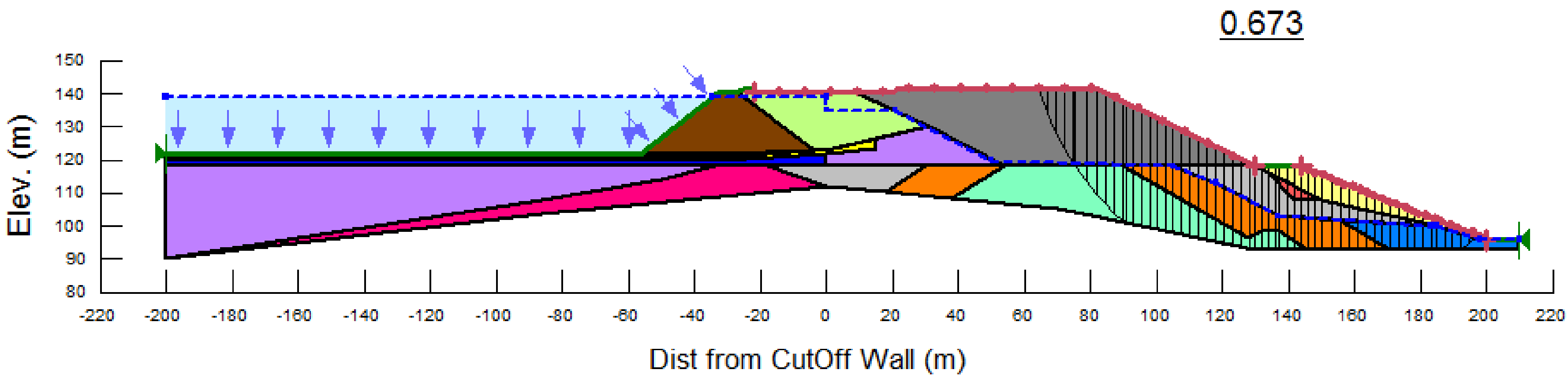
# Factor of Safety of the D/S slope using post cyclic-softening strengths for the Lower Silt

with post cyclic-softening strength from laboratory tests



# Factor of Safety of the D/S slope using remolded strengths for the Lower Silt

with remolded shear strengths from field vane shear tests



# VERSAT Sand model for Sandy soils

Nonlinear relationship between the shear stress and the shear strain:

$$\tau_{xy} = \frac{G_{\max}\gamma}{1 + G_{\max} / \tau_{ult} \bullet |\gamma|}$$

$$G_{\max} = K_g P_a \left(\frac{\sigma_m'}{P_a}\right)^m$$

$\tau_{ult}$ = ultimate shear stress in the hyperbolic model,

Two options:

1. shear strength at start of dynamic loading
2. proportional to the initial shear modulus $G_{max}$

$$\tau_{ult} = \frac{G_{\max}}{R_f}$$

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# VERSAT PWP model for Sandy soils

**Three pore water pressure (PWP) models:**

- Martin-Finn-Seed (MFS) model (1976)
- Modified MFS Pore Water Pressure Model

$$E_r = M \bullet (\sigma_{v0}' - u)$$

- Seed's Pore Water Pressure Model

$$r_u = \frac{2}{\pi} \arcsin\left(\frac{N_{15}}{15}\right)^{1/2\theta}$$

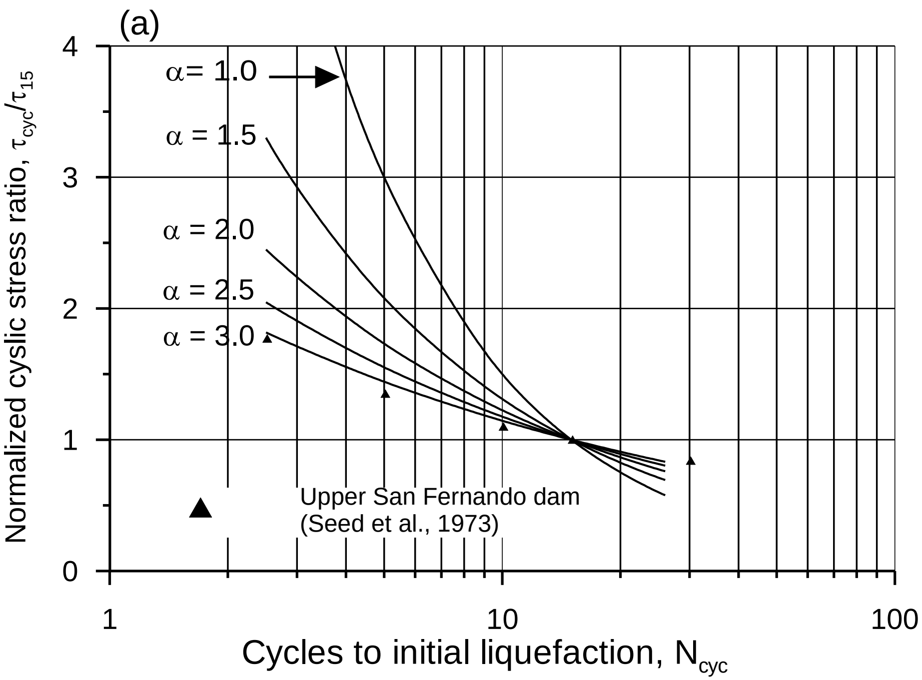
$$N_{15} = \left(\frac{\tau_{cyc}}{\tau_{15}}\right)^{\alpha}$$

Where

α is a shear stress conversion constant that is directly related to the magnitude scaling factor (MSF) (Wu 2001)

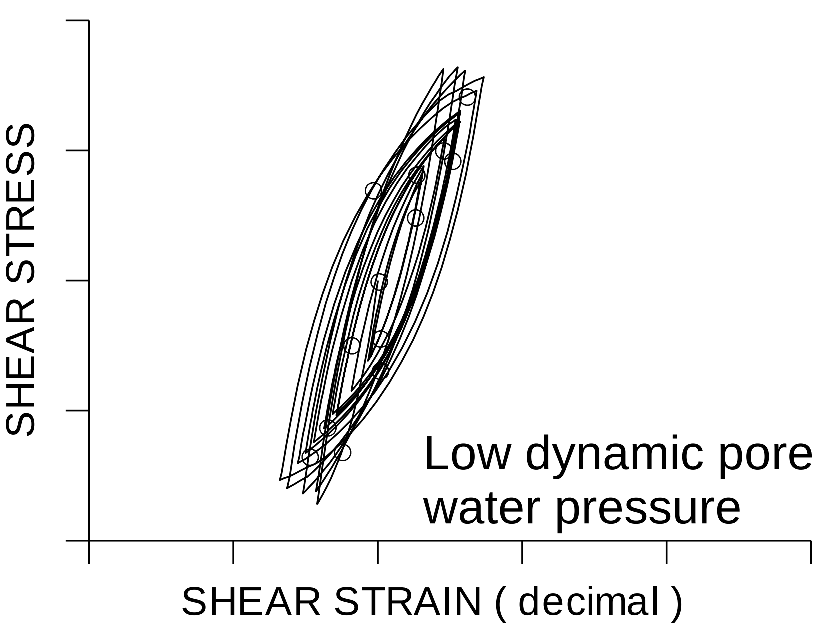
$\tau_{cyc}$ is the shear stress caused by earthquake

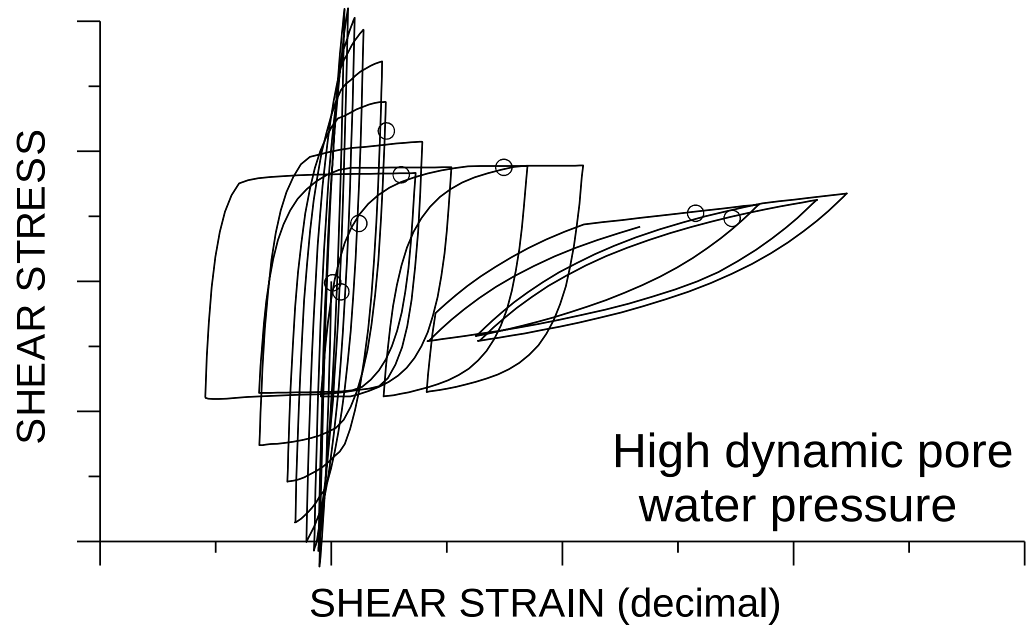
$\tau_{15}$ is the shear stress required to cause liquefaction in 15 cycles, can be determined from $(N_1)_{60}$



# VERSAT Stress-strain response

Nonlinear hyperbolic relationship between the shear stress and the shear strain:



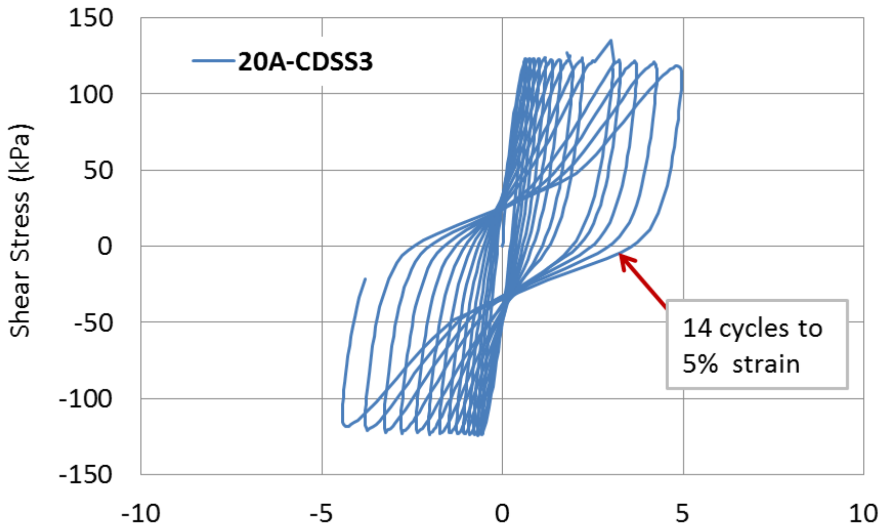



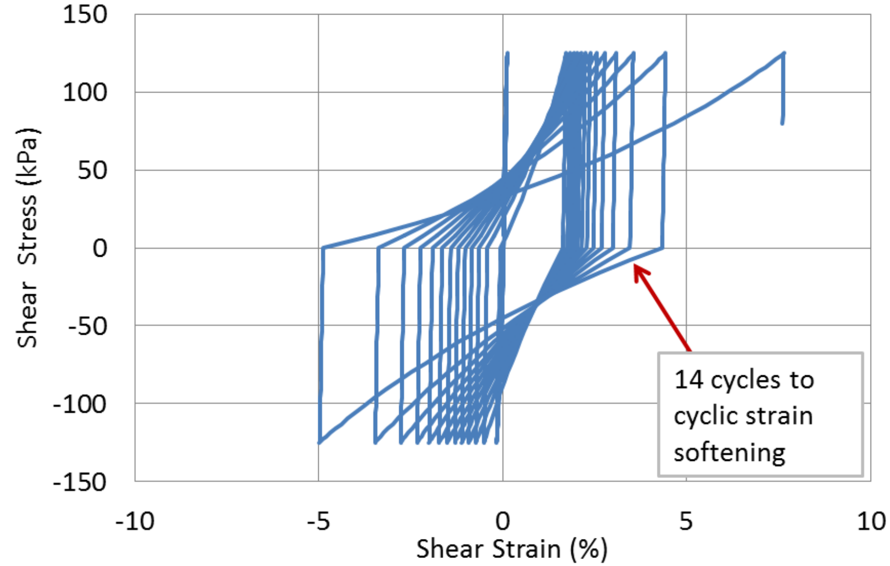
Strain softening but dilative

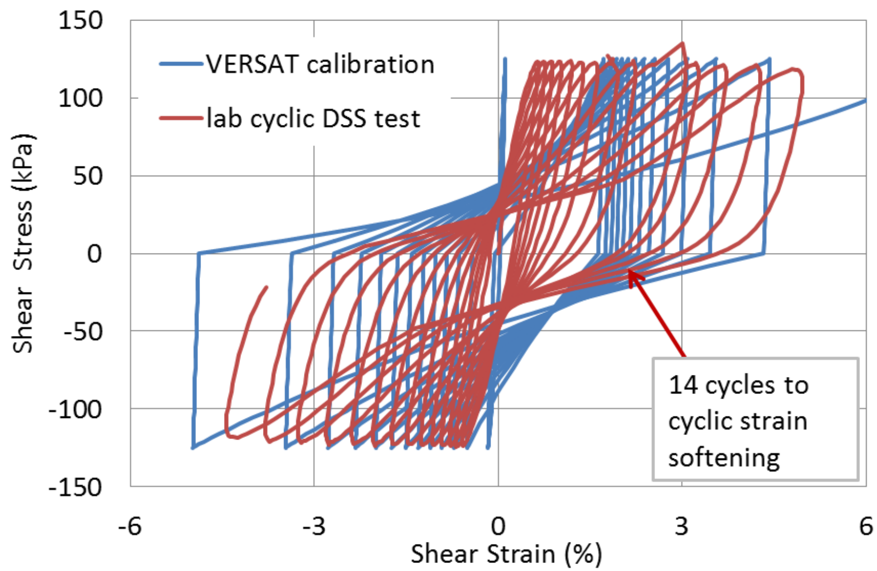
SILT model for the Lower Silt

# VERSAT Dilative SILT Model Calibration

## a). With no static bias: 20A-CDSS3 $\sigma_{vo}$'= 500 kPa

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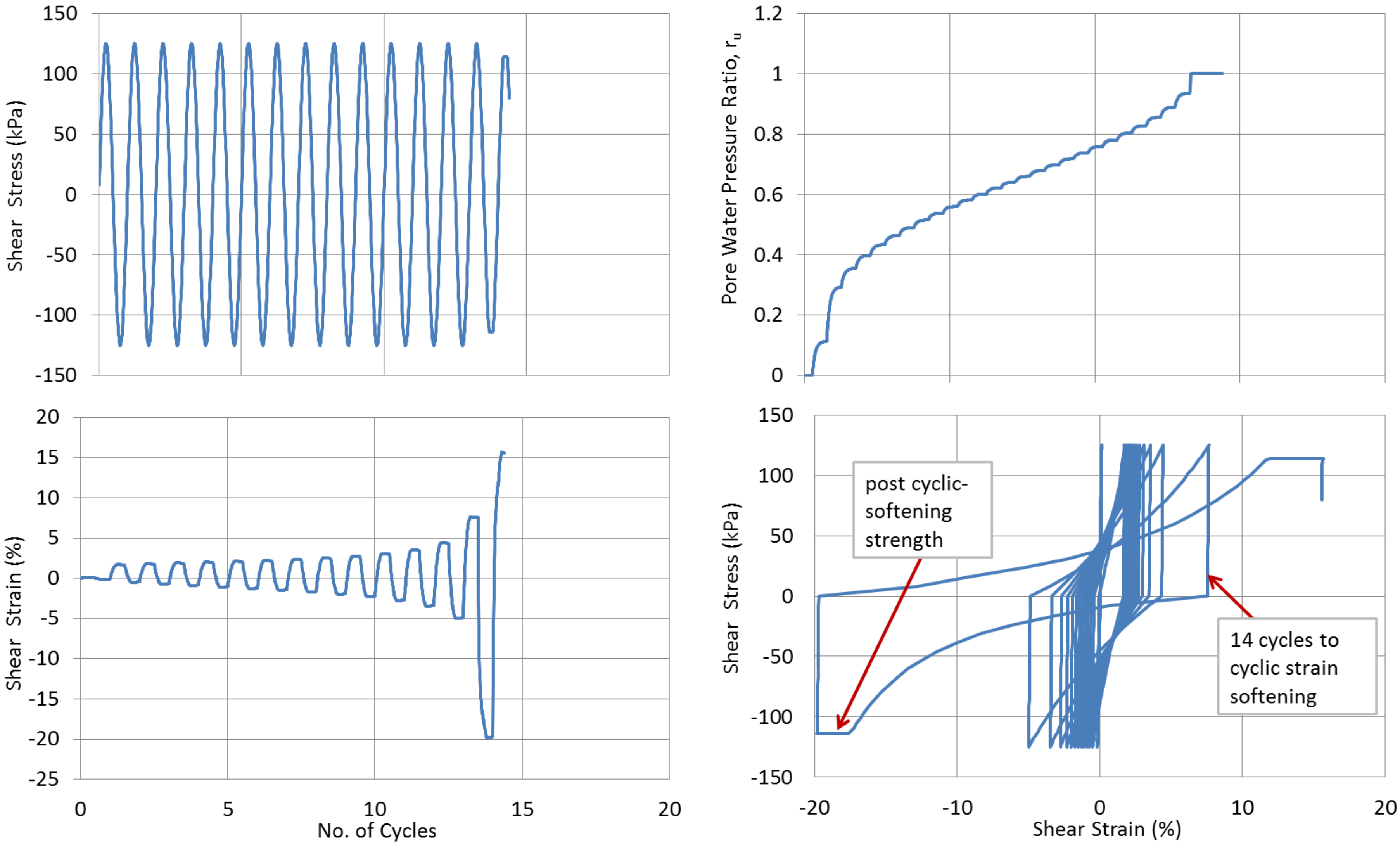
# VERSAT Dilative SILT Model Calibration

## a). With no static bias: 20A-CDSS3 $\sigma_{vo}$'= 500 kPa





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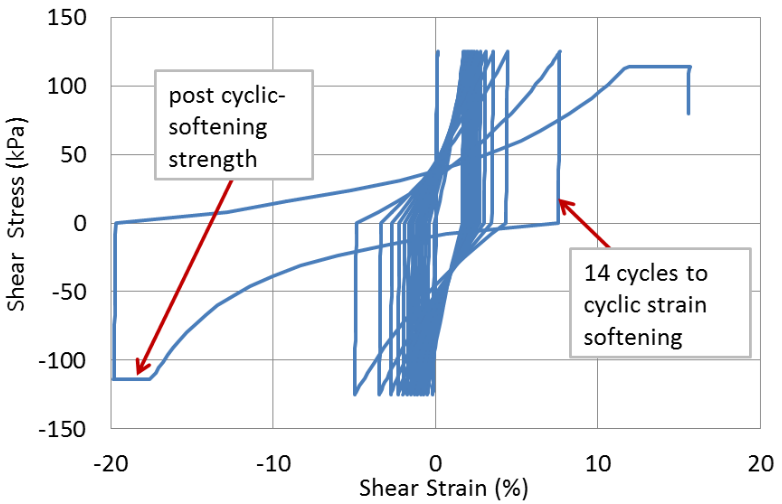
# VERSAT Dilative SILT Model

Dilative SILT Model Equations:

$$\tau_{xy} = \frac{G_0 \gamma}{1 - |\gamma| / \gamma_{ult}}$$

$$G_0 = [1 + \frac{12}{r_{u\_0}}(1 - r_u)] G_{liq}$$

$$\gamma_{ult} = \gamma_{H0} + \frac{r_u - r_{u\_0}}{1 - r_{u\_0}}(\gamma_H - \gamma_{H0})$$




$\gamma_{H0}$ is ultimate shear strain (%) on initial strain softening for $r_u = r_{u\_0}$;
$\gamma_H$ is ultimate shear strain (%) at $n^{th}$ cycle of strain softening for $r_u$ = 1.0;
$G_{liq}$ is initial shear modulus at $n^{th}$ cycle of strain softening, i.e., cylic softening of silts at $r_u$=1.0.

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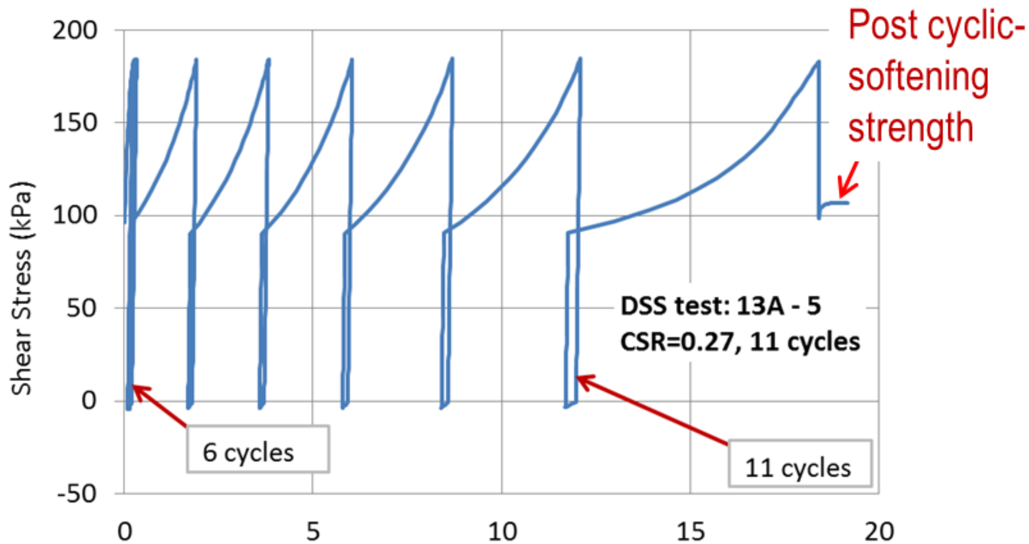
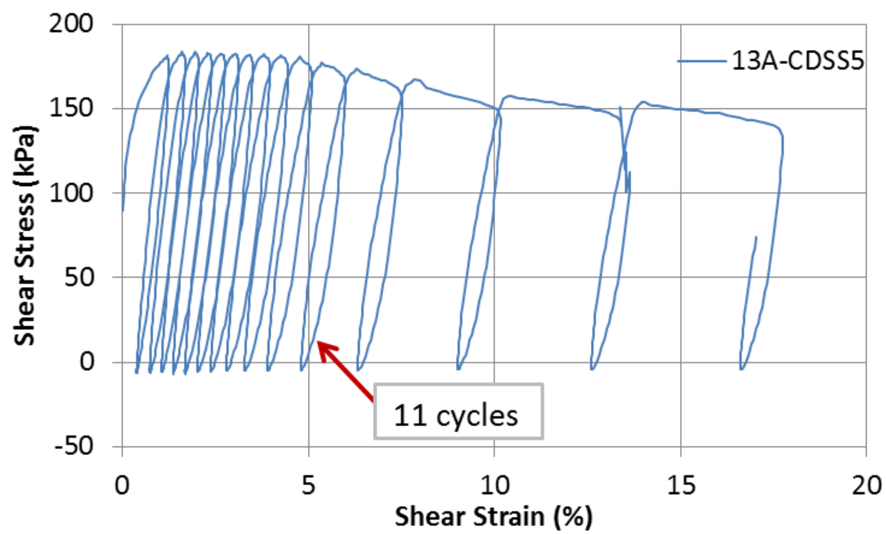
# VERSAT Dilative SILT Model Calibration

## b). With static bias: 13A-CDSS5 $\sigma_{vo}$'= 360 kPa, static bias 90 kPa

**VERSAT SILT model calibration:**

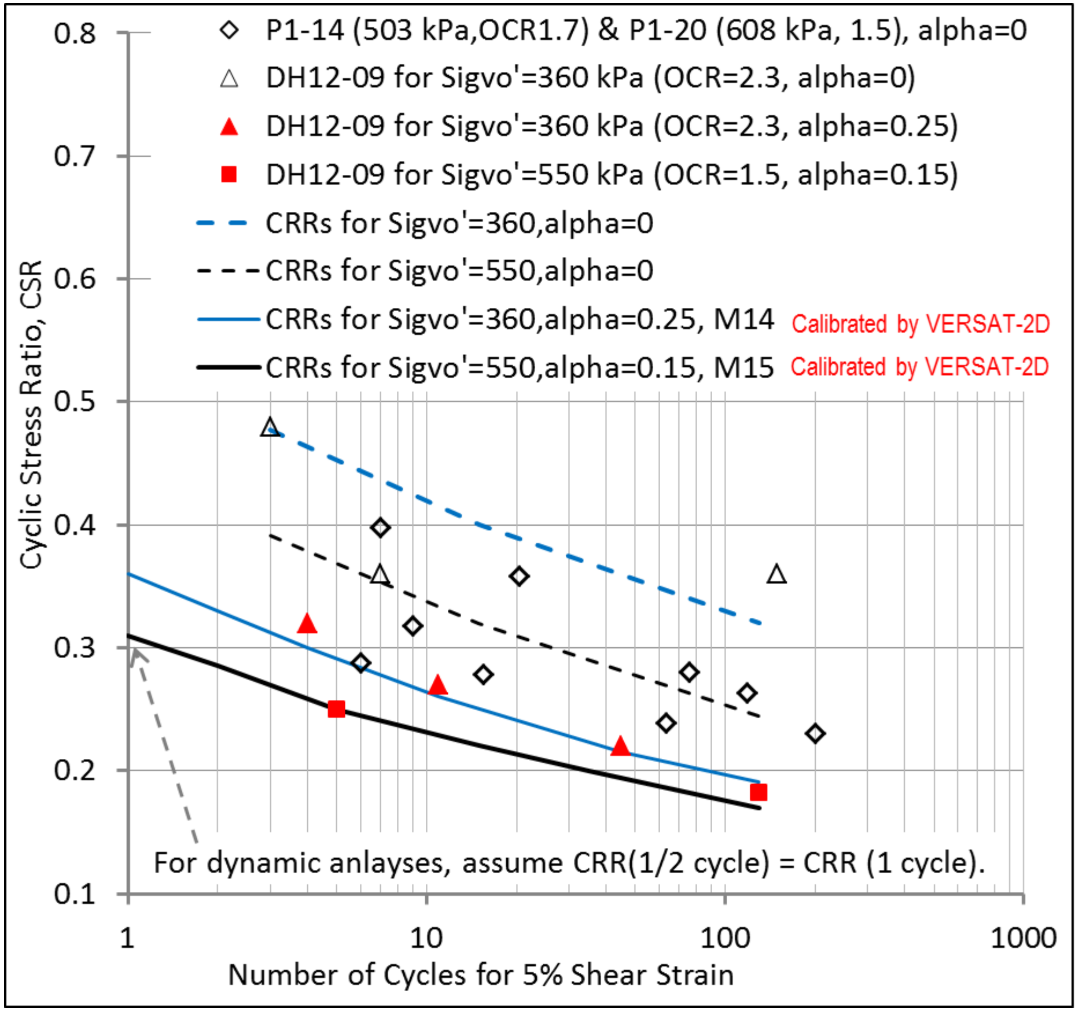



**laboratory cyclic DSS test:**



# VERSAT Dilative SILT Model: CRR

Cyclic resistance of over-consolidated Lower Silt from cyclic DSS tests & Calibrated in VERSAT-2D Silt Model, and also in FLAC UBCSAND model

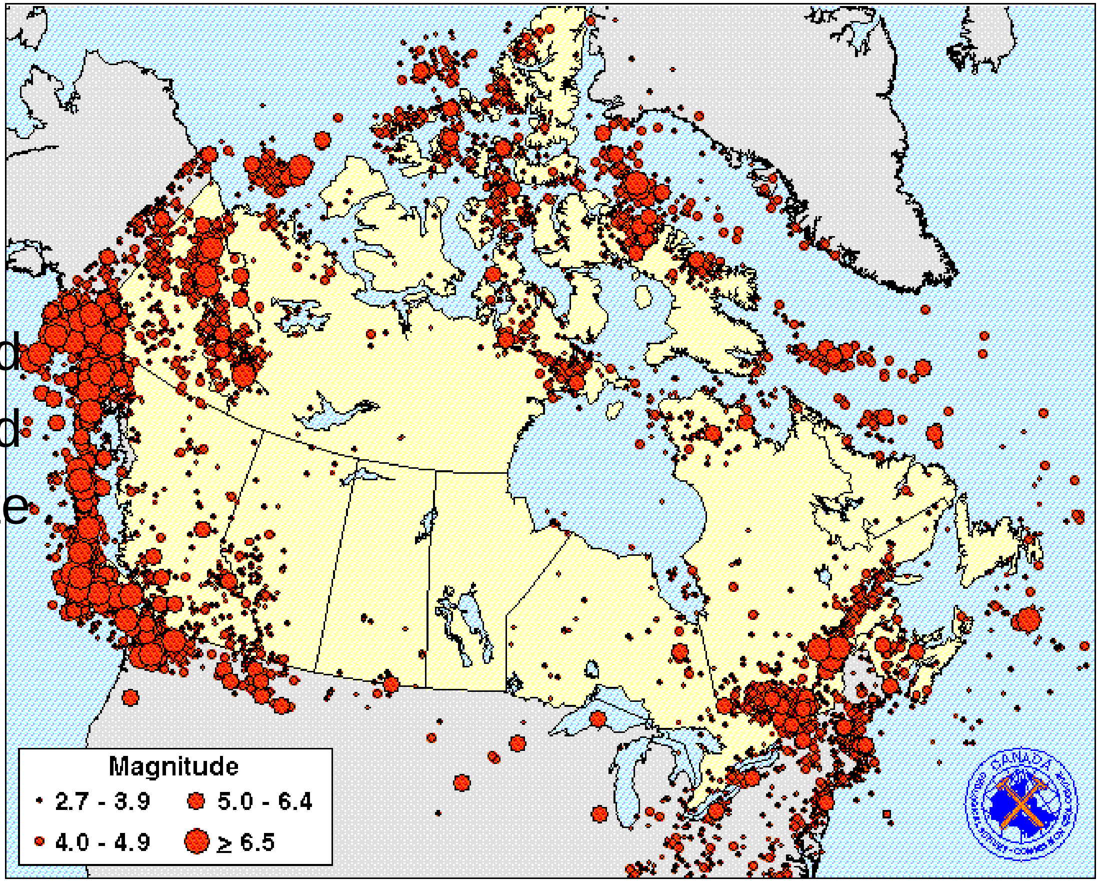


# Seismic Hazards

Damaging Earthquakes in Western Canada

- 1949 M=8.1 Queen Charlotte Islands
- 1946 M=7.3 Vancouver Island
- 1918 M=7.0 Vancouver Island
- 1872 M=7.4 Washington State
- 1700 M=9.0 Cascadia

Seismicity database used to determine Canadian seismic hazard



# BC Hydro PSHA Project

**BC Hydro Seismic Hazard Project :**

- Carried out as a SSHAC Level 3 study
- The goal is to develop inputs that represent the composite distribution of the informed scientific community

**2012 tentative seismic parameters (1/10,000) for John Hart Site:**

- Peak Ground Acceleration (PGA) is 0.66g
- The Cascadia subduction (interface) event makes about 70% of the hazard contribution, and the event is to be included in seismic stability assessment.
- Further correction on the seismic parameters is needed once the actual measured Vs30 of the site rock is considered.

# Input Ground Motions

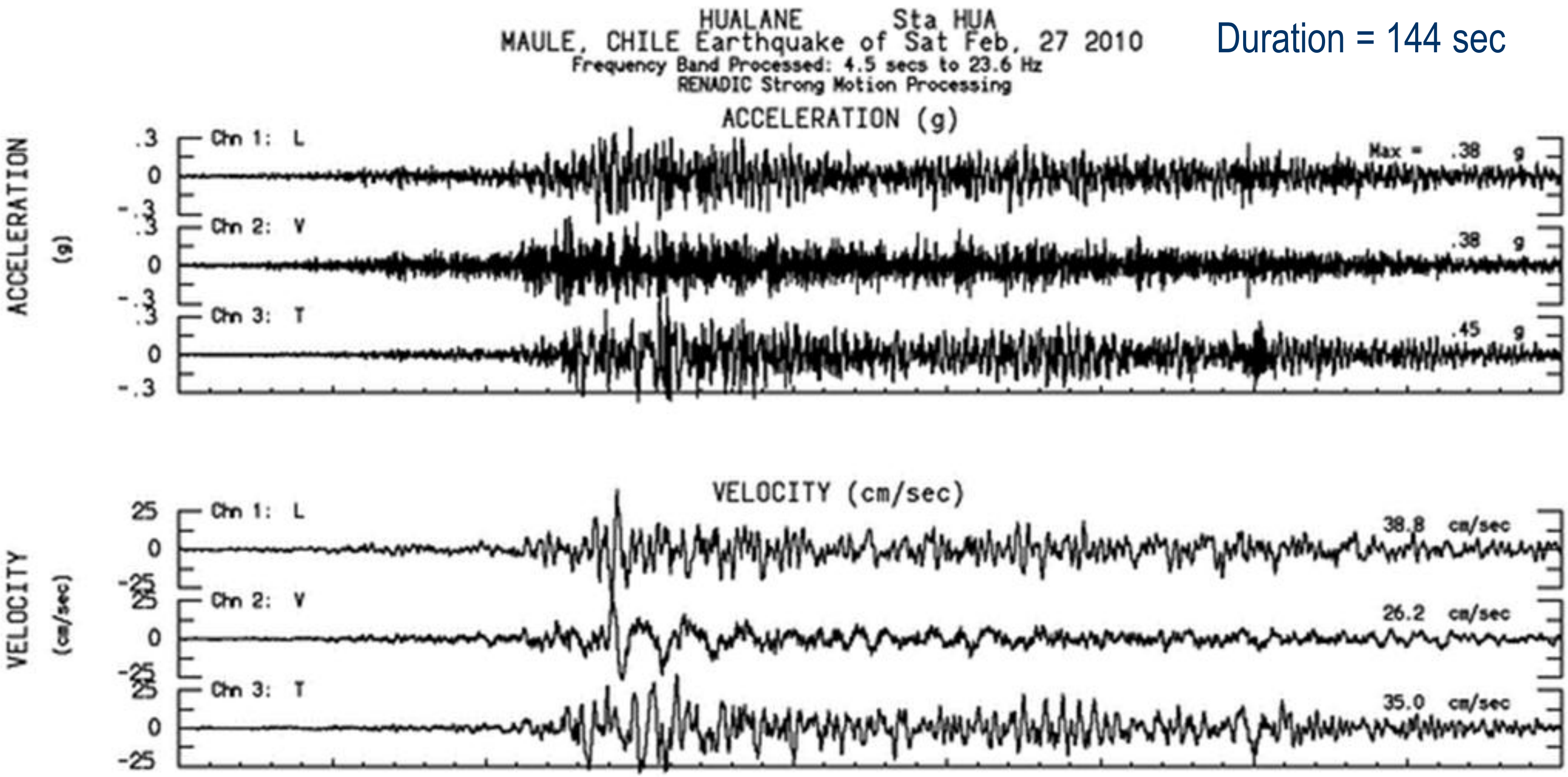
## Input Ground Motions from
## 2012 tentative seismic parameters (1/10,000) for John Hart Site:

| # | Symbol (short name) | Earthquake Record | Record PGA (g) | Record Arias Intensity (AI) | P1 : 1/10,000 | |
|---|---|---|---|---|---|---|
| | | | | | Scaling Factor | Scaled PGA |
| 1 | Hual | Hualane L, Chile Maule 2010 | 0.383 | 7.74 | 1.064 | 0.407 |
| 2 | Myg | MYG009 (Taiwa) EW, Japan Tohoku 2011 | 0.536 | 5.81 | 1.160 | 0.622 |
| 3 | Tcu | Tcu071 W, Taiwan Chi Chi, 1999 | 0.567 | 11.54 | 0.84 | 0.48 |
| 4 | Tabas | Tabas LN, Iran Tabas, 1978 | 0.836 | 9.33 | 0.60 | 0.50 |
| 5 | Chl | Chalor Rd 070, US Northridge, 1994 | 0.225 | 0.61 | 2.18 | 0.49 |

# 2010 Chile Record

Time history for subduction event: 2010 Chile Maule Mw8.8 Event at Hualane_L (SF1.064)

Duration = 144 sec



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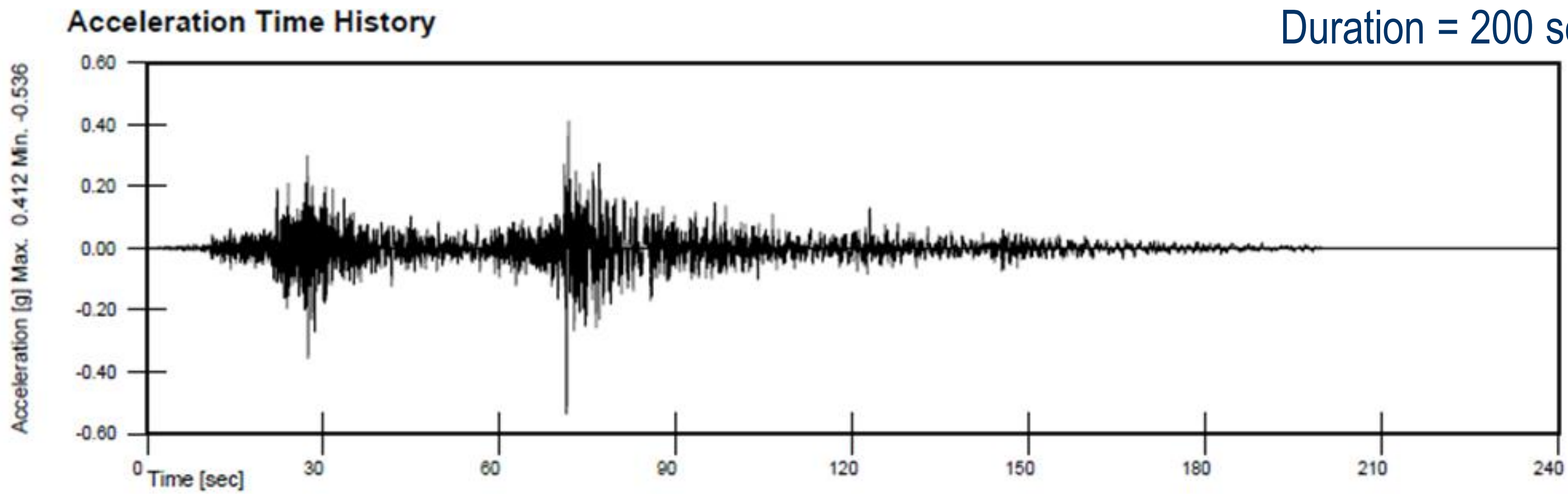
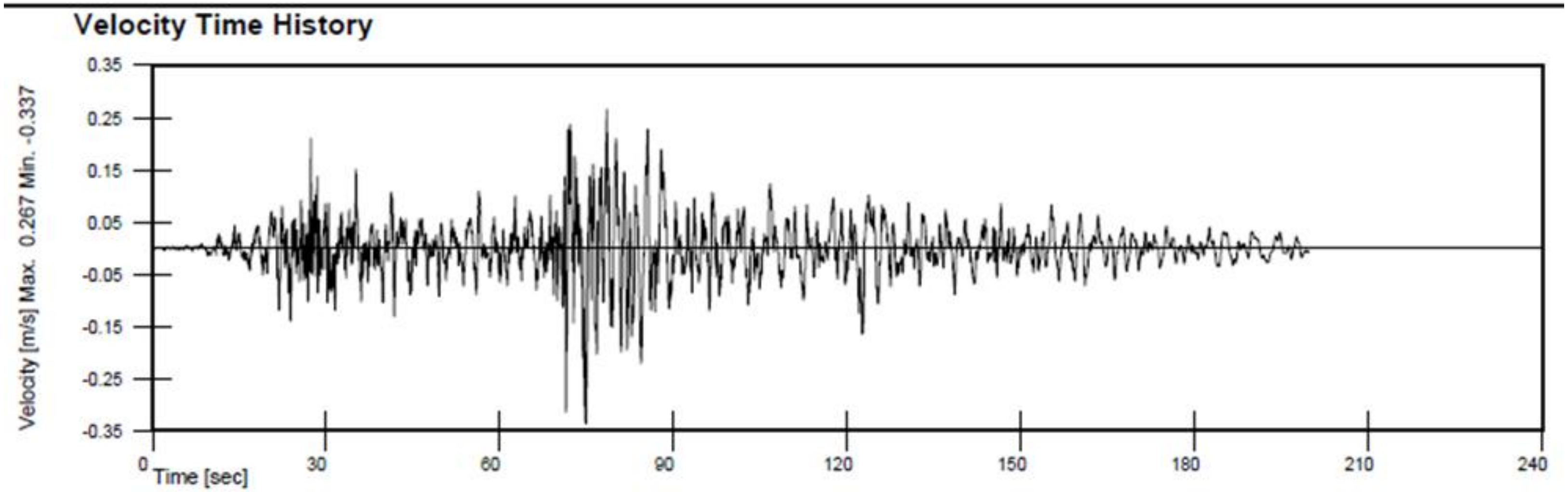
# 2011 Japan Record

Time History of Japan Tohoku  MYG009 record, to be scaled up 1.16

Duration = 200 sec

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# VERSAT-2D FINITE ELEMENT

# &

# FLAC FINITE DIFFERENCE

# DYNAMIC TIME-HISTORY ANALYSES

- Reasons:

  At BC Hydro we are not convinced, due to the complexity of soil behavior, merits and shortfalls in each computer program/constitutive model, and individual's modeling technique and experience, that one computer program using one soil constitutive model will provide the level of confidence in solutions that is suitable for decisions on seismic dam stability.

  Therefore, it is becoming a practice at BC Hydro to use two independent methods of dynamic analyses (VERSAT primary, FLAC for checking) for investigating dam performance under seismic loading.

# VERSAT-2D finite element time-history analyses

The equations of motions describing the incremental dynamic force equilibrium

$$[M]\{\Delta \frac{d^2\delta}{dt^2}\} + [C]\{\Delta \frac{d\delta}{dt}\} + [K]\{\Delta\delta\} = \{\Delta P\}$$

Where

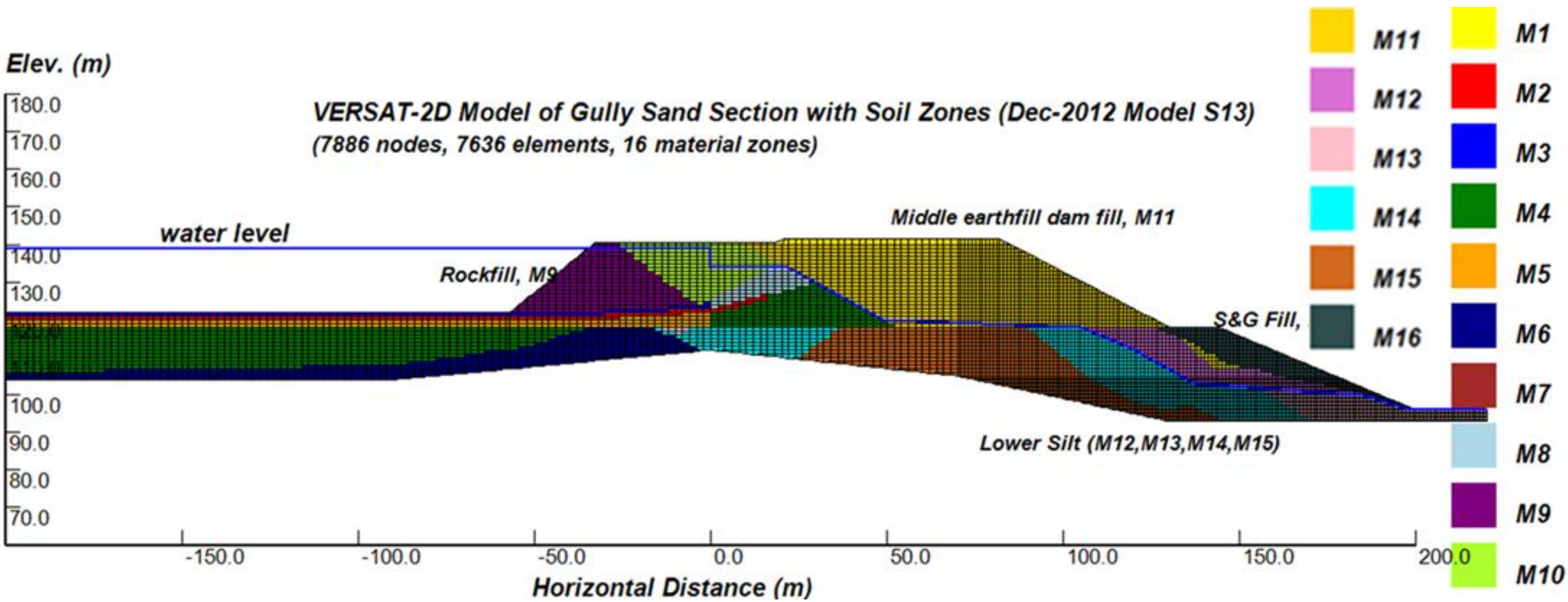
| | |
|---|---|
| [M] | = mass matrices |
| [C] | = viscous damping matrices |
| [K] | = tangent stiffness matrices |
| [Δδ] | = incremental displacement matrices |
| [Δdδ/dt] | = incremental velocity matrices |
| $[\Delta d^2\delta/dt^2]$ | = incremental acceleration matrices |
| [ΔP] | = incremental external load matrices |

Input ground motions Options

1. Acceleration input at the rigid base, incremental inertial forces on the soil mass caused by base accelerations are computed using the Newton's law and applied as [ΔP].
2. the velocity input at the elastic base, incremental shear forces at the base nodes are determined and applied as [ΔP].

# VERSAT Model – A full mesh

VERSAT-2D finite element model showing soil material zones and ground water table of the Middle Earthfill Dam

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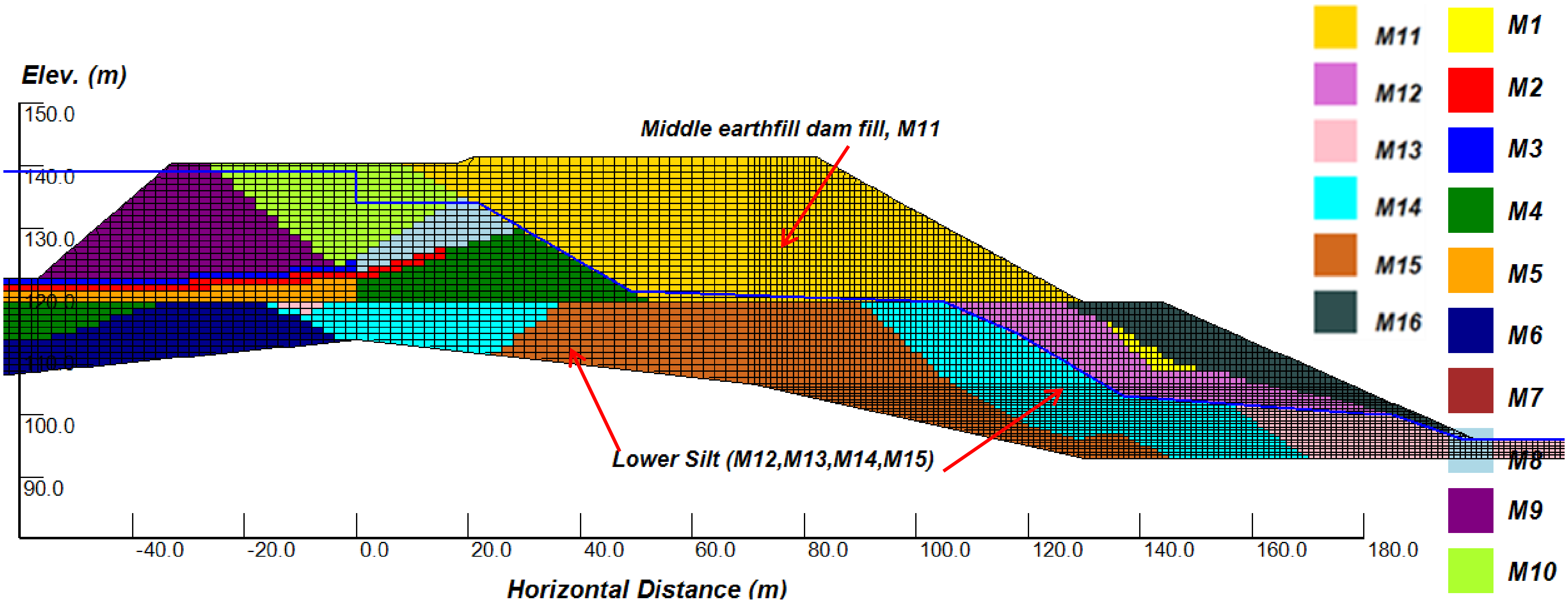
# VERSAT Model: A portion of mesh

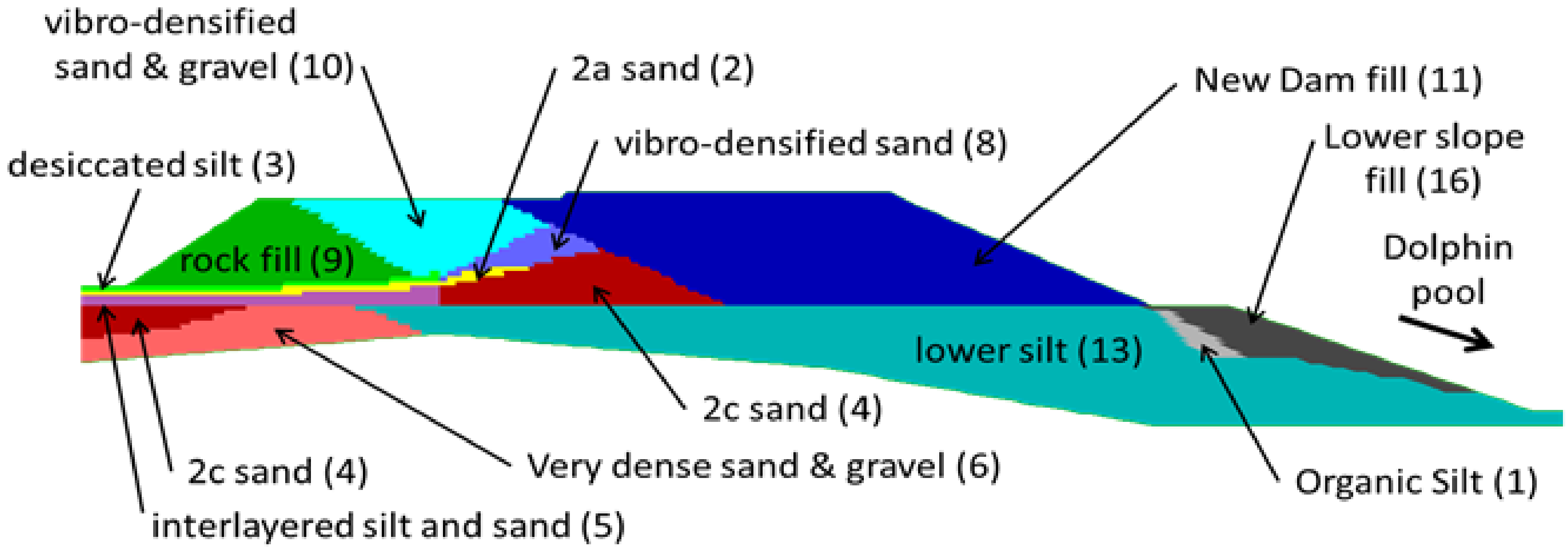



| Mat'l # | Description | Soil Model | Cyclic Resistance $CRR_{15}$ | Other PWP parameters |
|---|---|---|---|---|
| M13 | Lower Grey Silt submerged, $\sigma_{vo}' \leq 250$ kPa | Silt | 0.28 | Kg_liq = 1.0<br>$\theta = 0.5$<br>$\alpha = 8$<br>$r_{uo} = 0.3$<br>$\gamma_{Ho} = 3.5\%$<br>$\gamma_H = 10\%$ |
| M14 | Lower Grey Silt submerged, $\sigma_{vo}'$: 250 – 400 kPa | Silt | 0.25<br>$\sigma_{vo}' = 360$ kPa | |
| M15 | Lower Grey Silt submerged, $\sigma_{vo}'$: 400 – 600 kPa | Silt | 0.22<br>$\sigma_{vo}'=550$ kPa | |
| M12 | Lower Grey Silt, above water table | Silt | No pore water pressure and without strain softening | |

# A main portion of the FLAC model

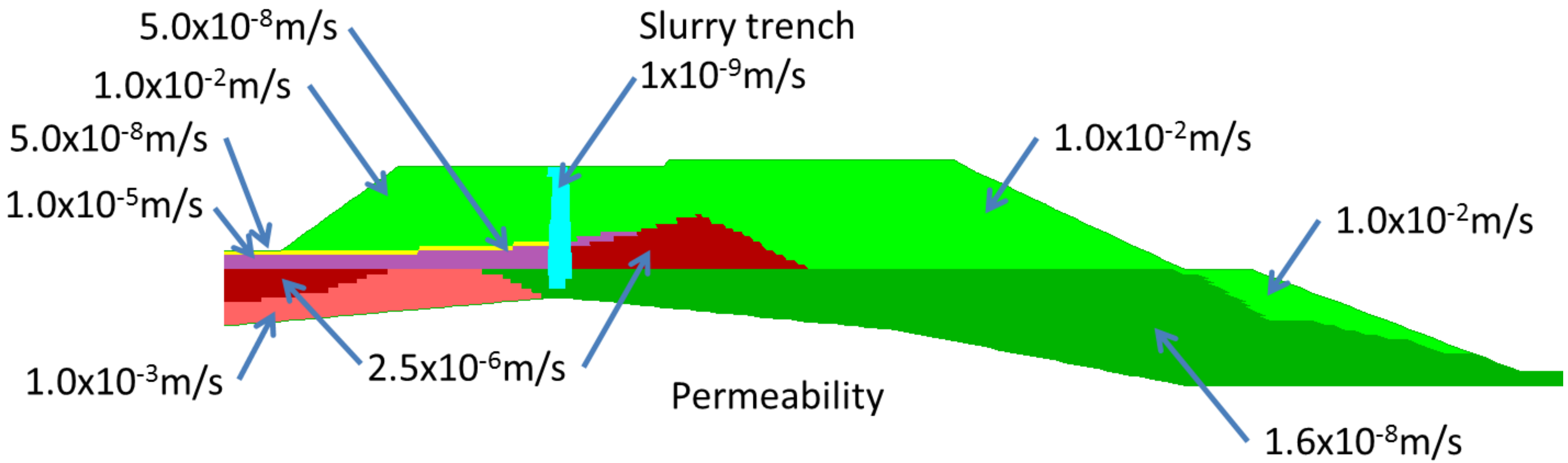
Key Features:

- UBCSAND model used for modeling the Lower Silt, a modification of Mohr-Coulomb stress and strain relationship
- Permeability of soils is used in FLAC groundwater flow mode
- Velocity time history is input at the base of the rigid-base model

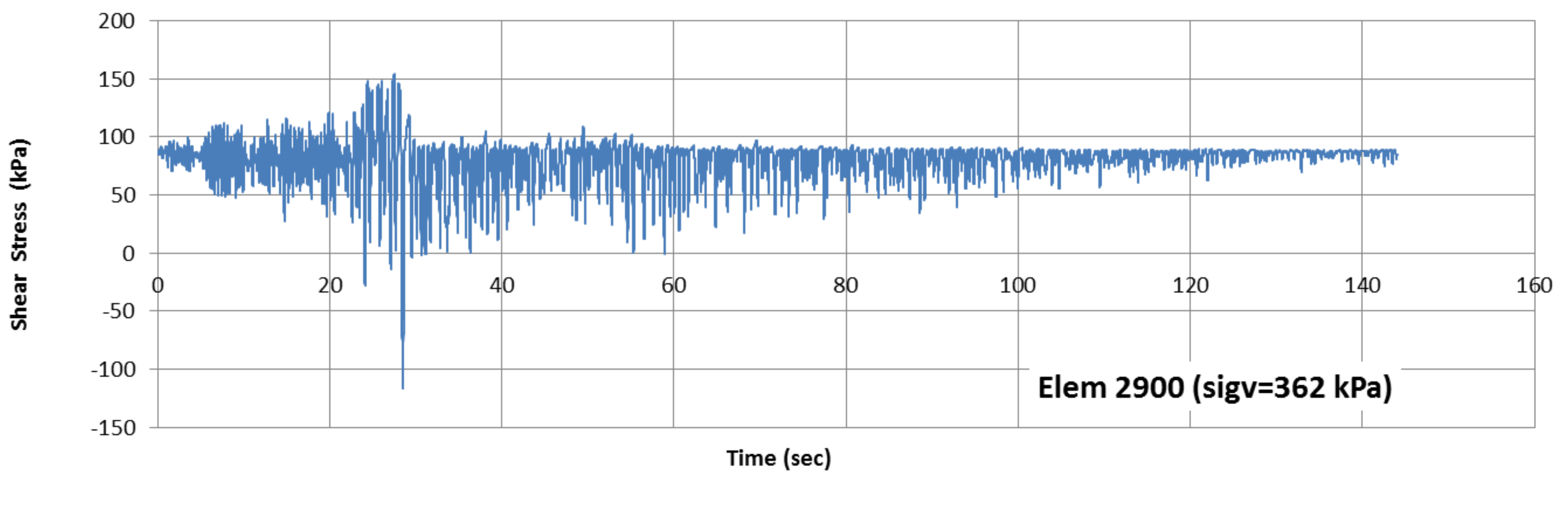


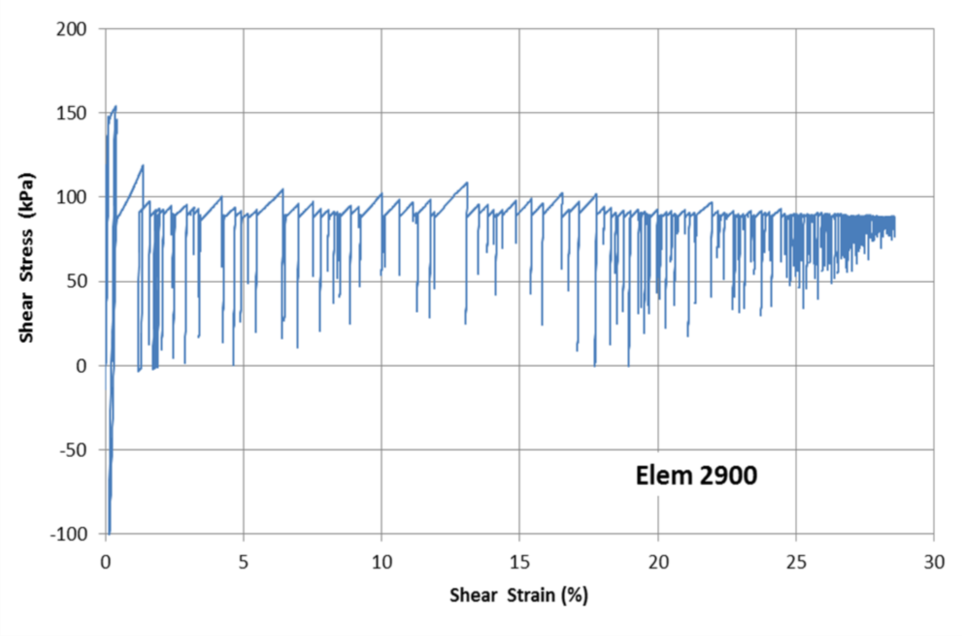
# Permeability in FLAC model

Soil permeability used in FLAC groundwater flow mode



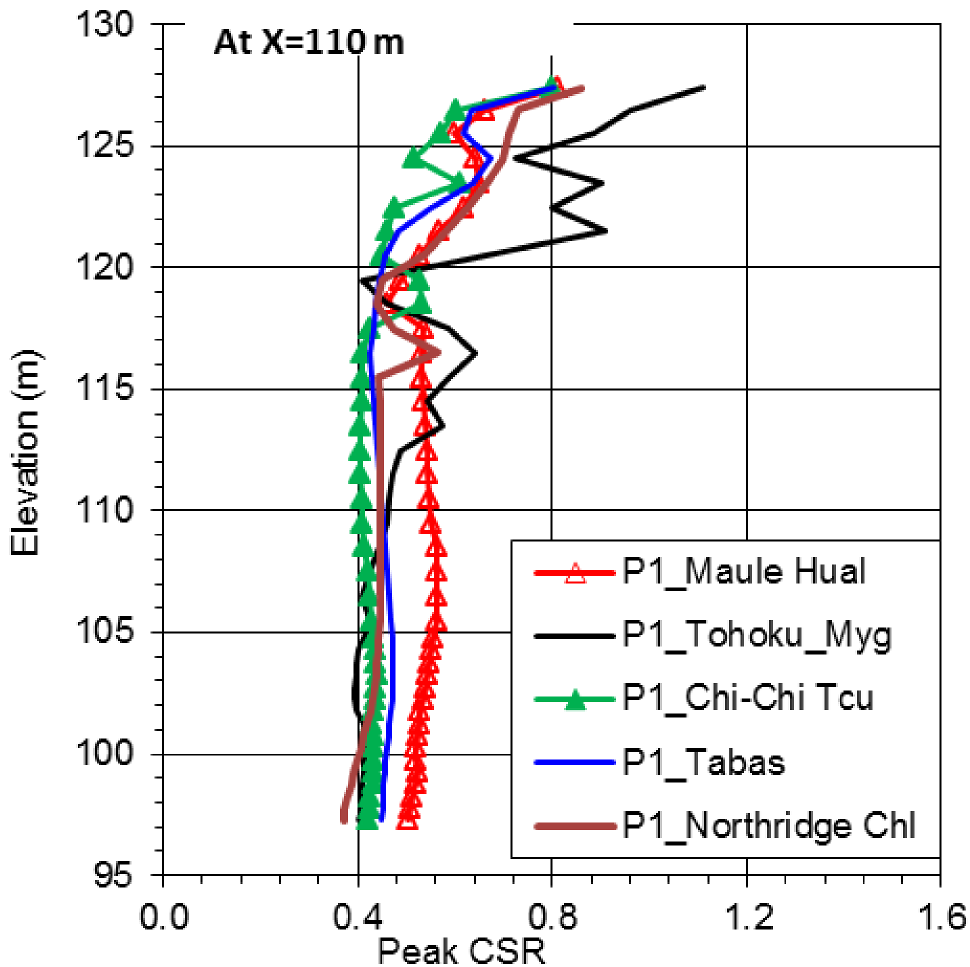
# VERSAT Shear Stress Strain Response



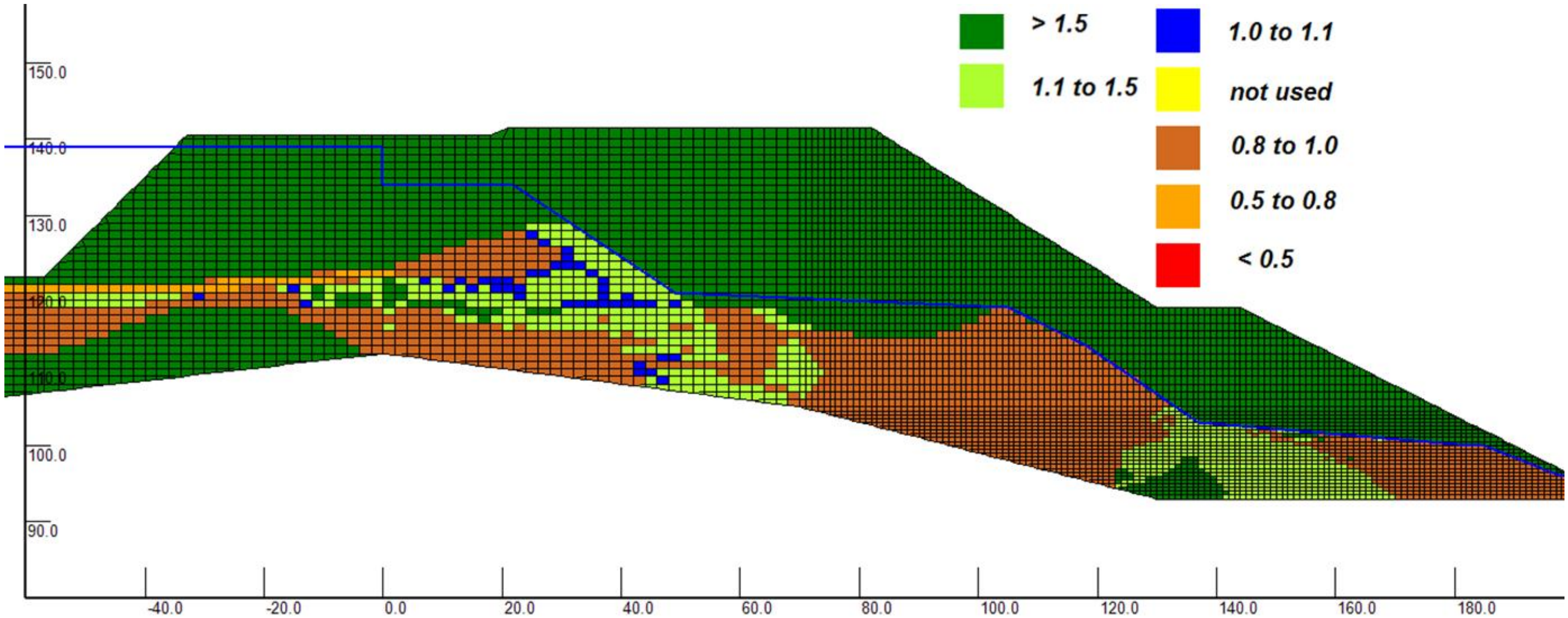
# VERSAT CSRs

Peak CSRs along a soil column at x=110 m (i.e., 110 m downstream of the slurry trench cutoff) from two subduction and three crustal input motions: VERSAT results

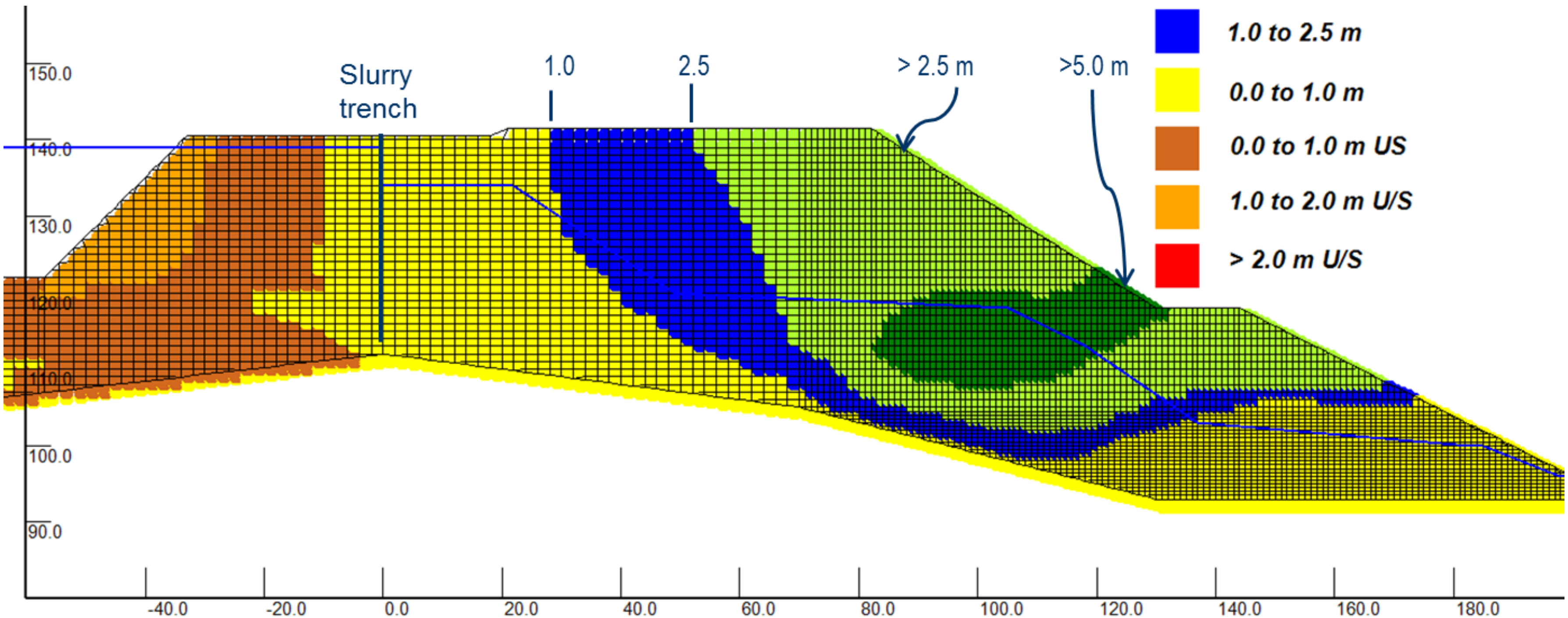


# VERSAT FS_liq

Factors of safety against liquefaction or cyclic strain softening (FS_liq) from the Chi Chi crustal input motion

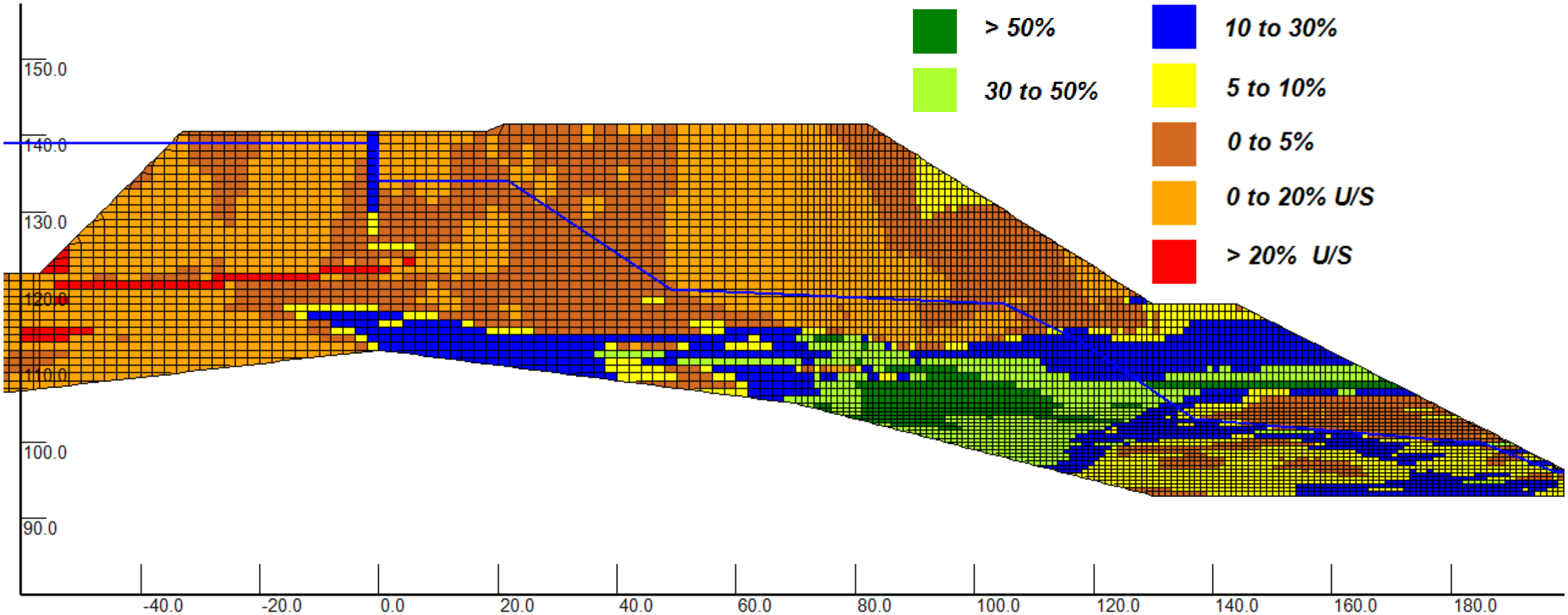


Computed ranges of horizontal displacements from the Chi Chi crustal input motion

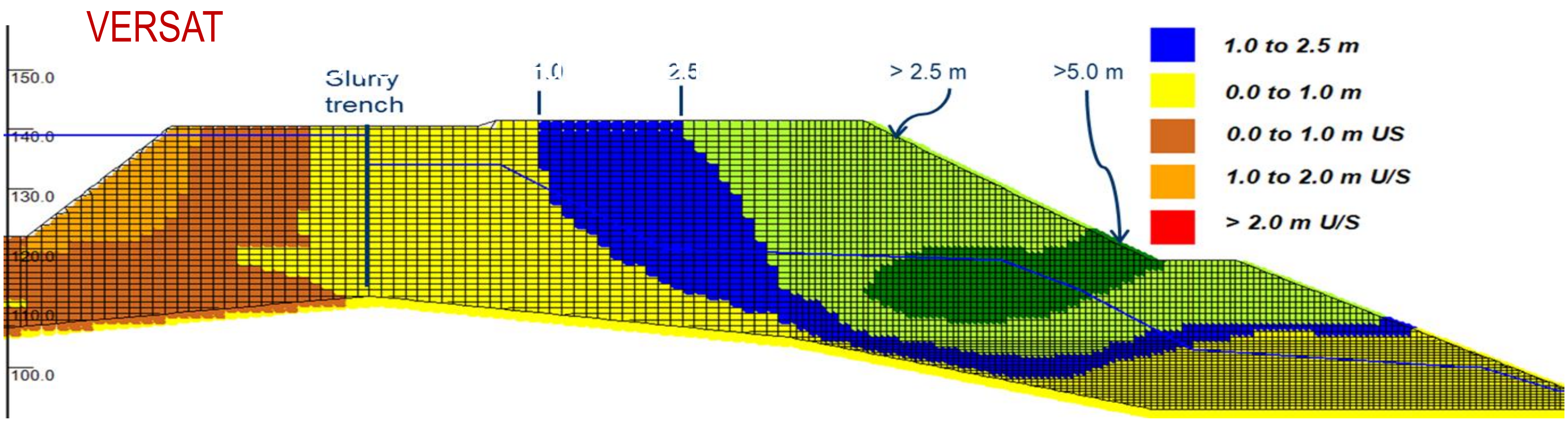


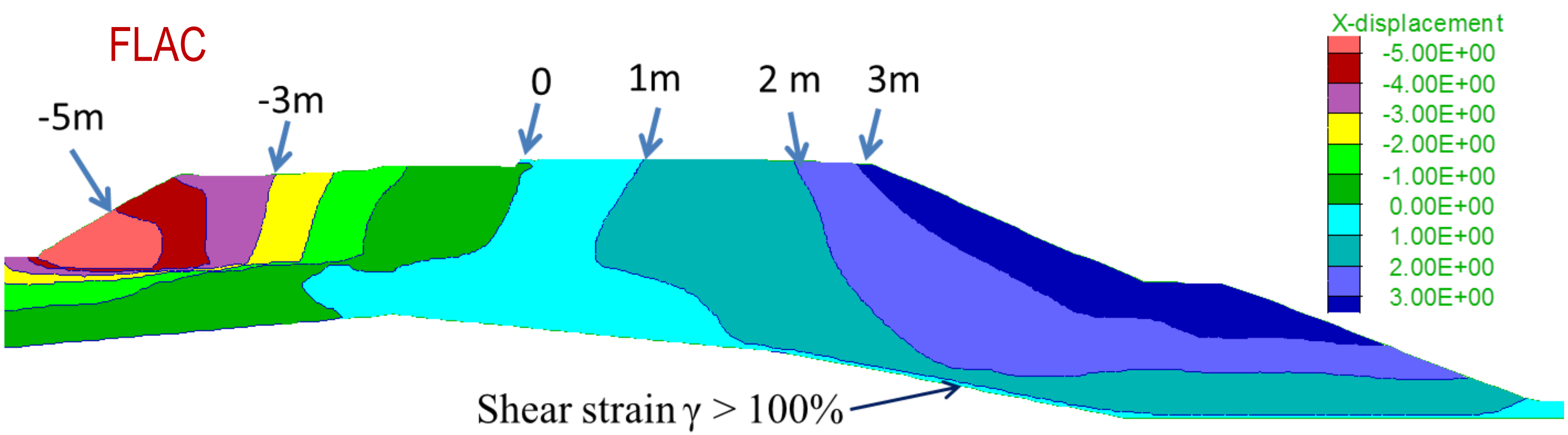
# VERSAT strains

A distribution of shear strains computed from the Chi Chi Crustal Input Motioin



# VERSAT & FLAC: X-DISP

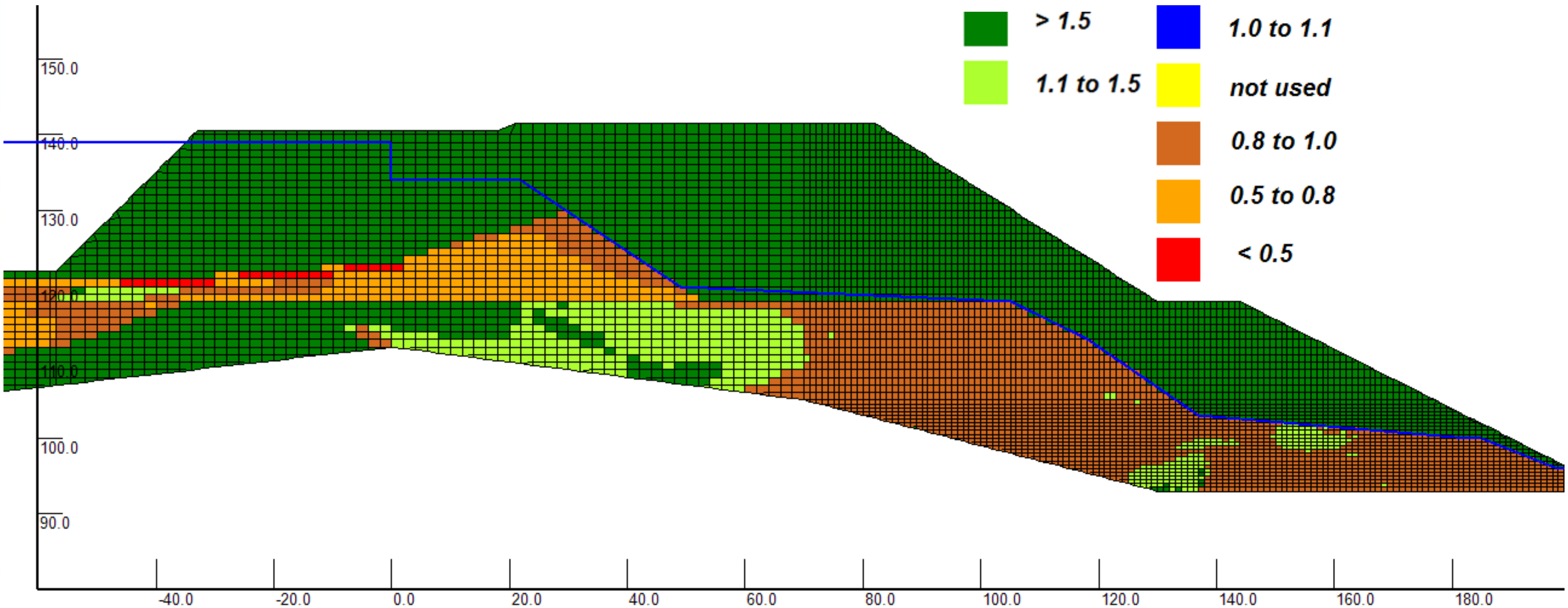



FLAC preliminary results: Ranges of horizontal ground displacements from the Chi-Chi crustal input motion, comparison with VERSAT results

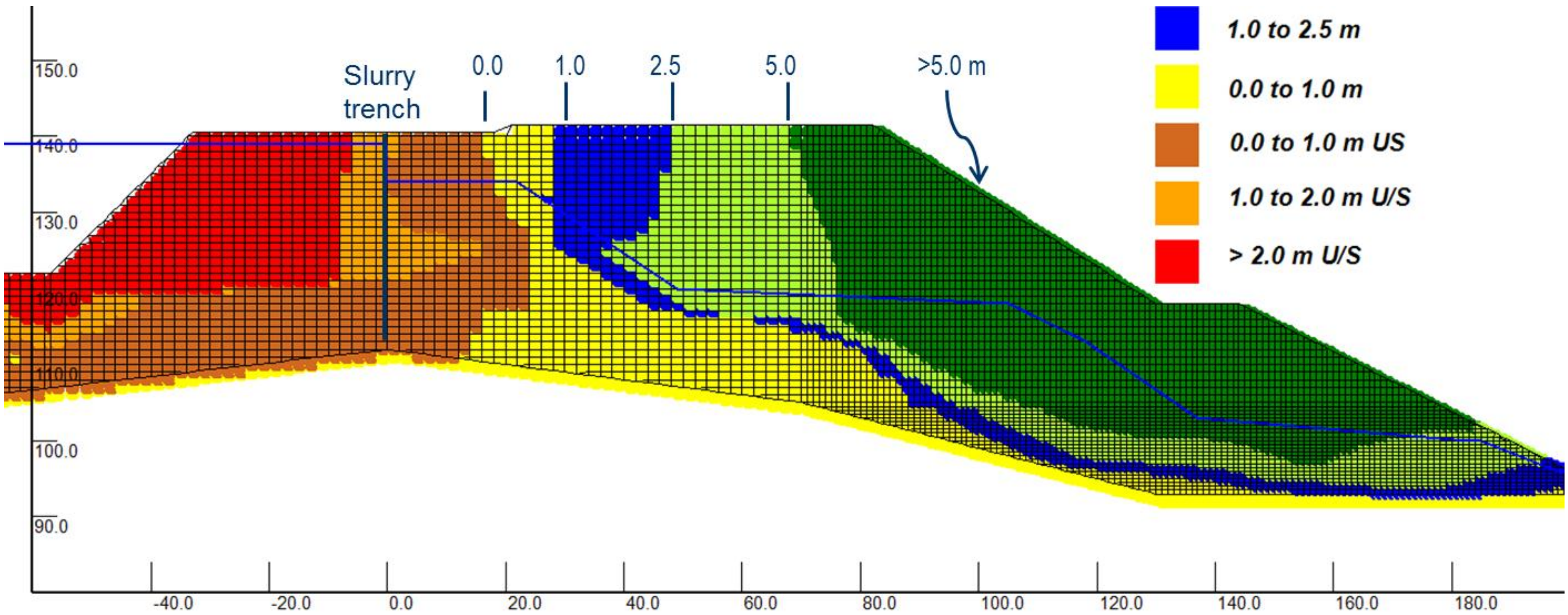
# VERSAT subduction FS_liq

FS_liq from the Tohoku MYG009 subduction input motion, failed at 114 sec



# VERSAT subduction X-DISP

Computed ranges of horizontal displacements from the Tohoku MYG subduction input motion

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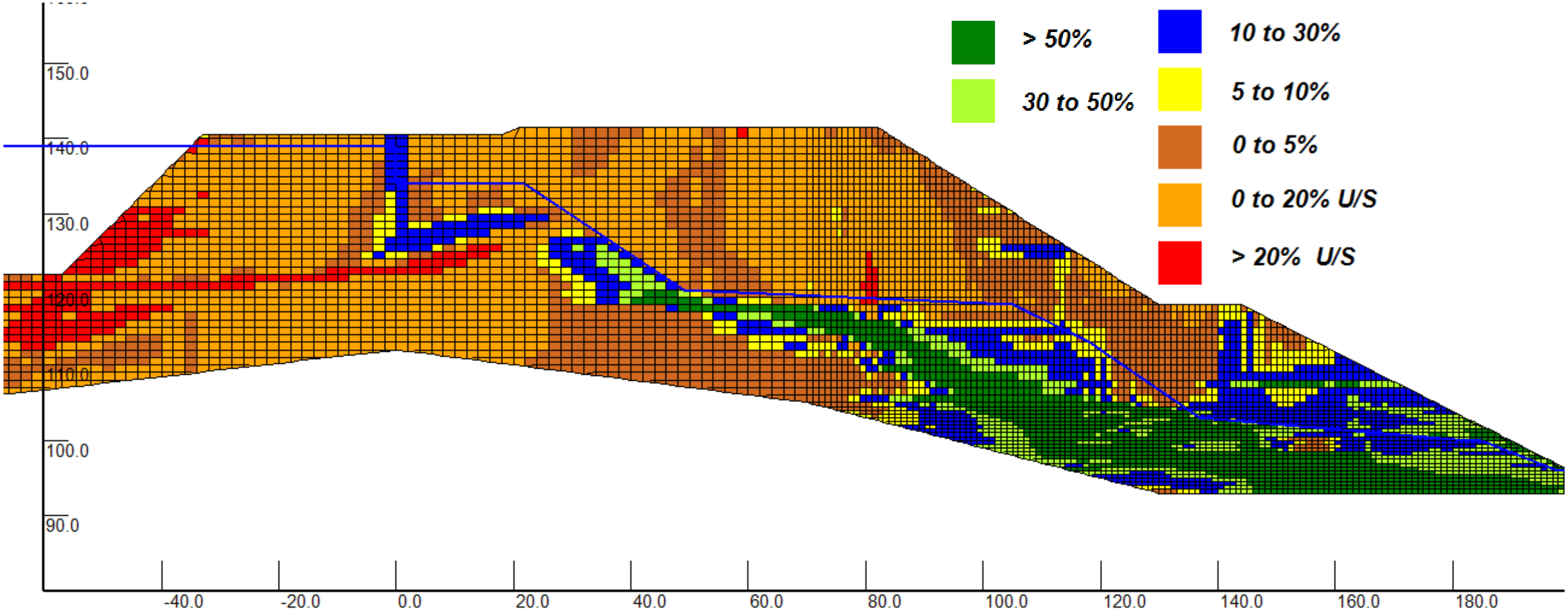
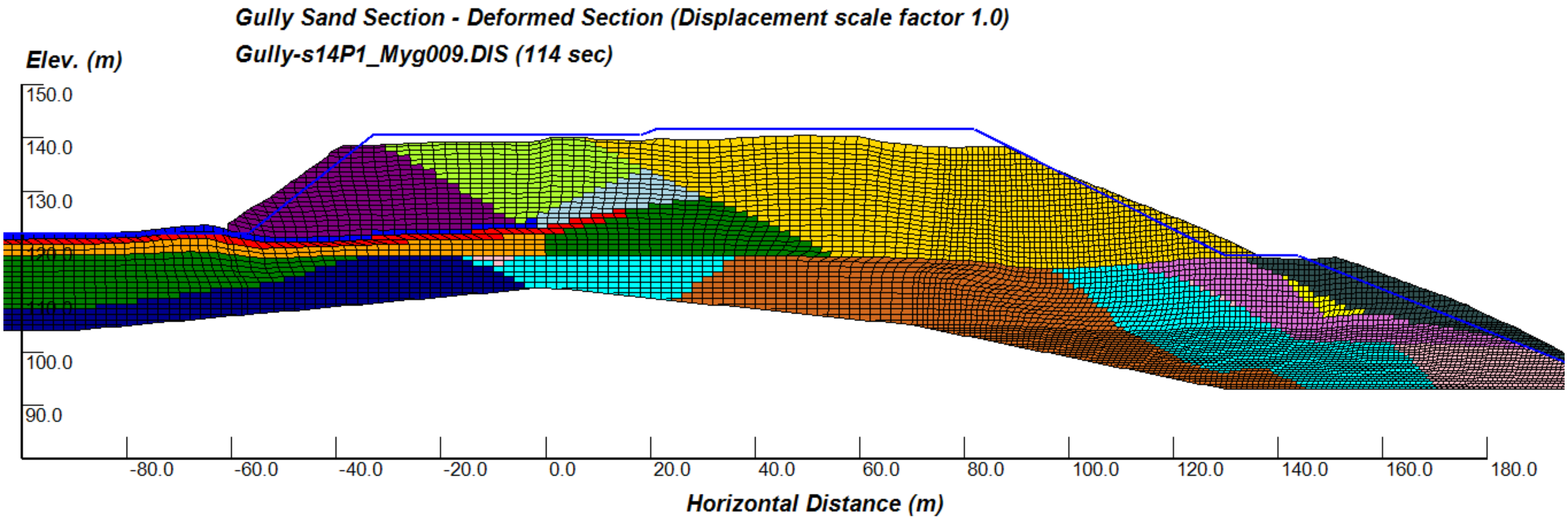
# VERSAT subduction STRAINS

A distribution of shear strains computed from the Tohoku MYG subduction input motion, at 114 sec of motion

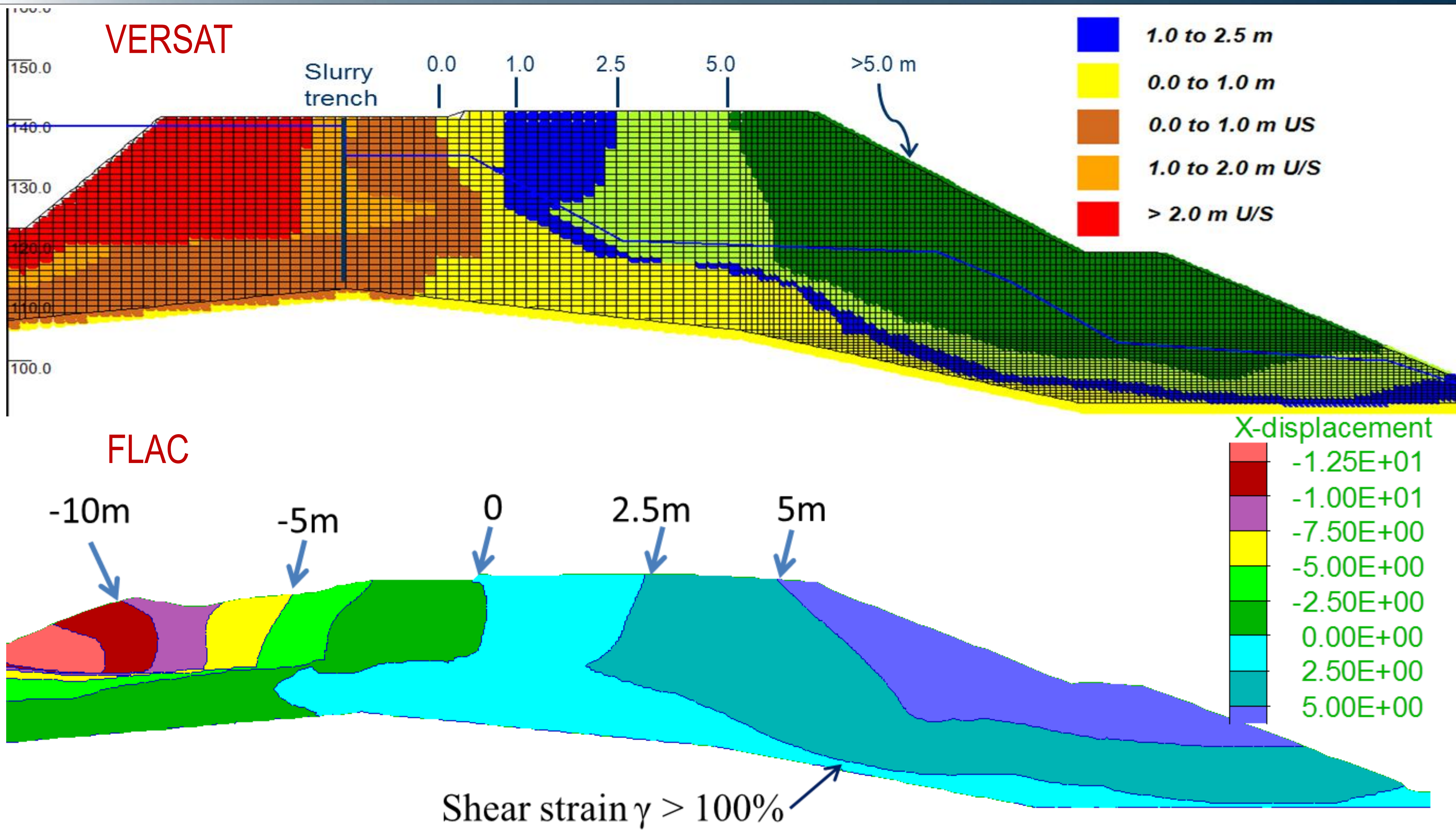


# VERSAT subduction

A deformed cross section (with colored soil zones) computed from the Tohoku MYG subduction motion



# VERSTA & FLAC: subduction X-DISP




FLAC preliminary results: Ranges of horizontal ground displacements from the Tohoku MYG subduction input motion, comparison with VERSAT results

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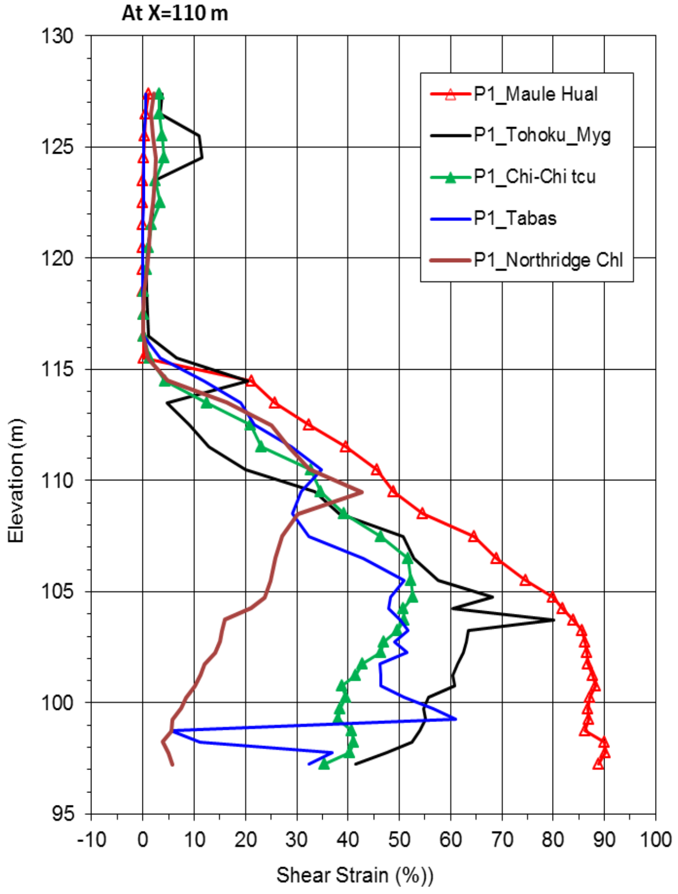
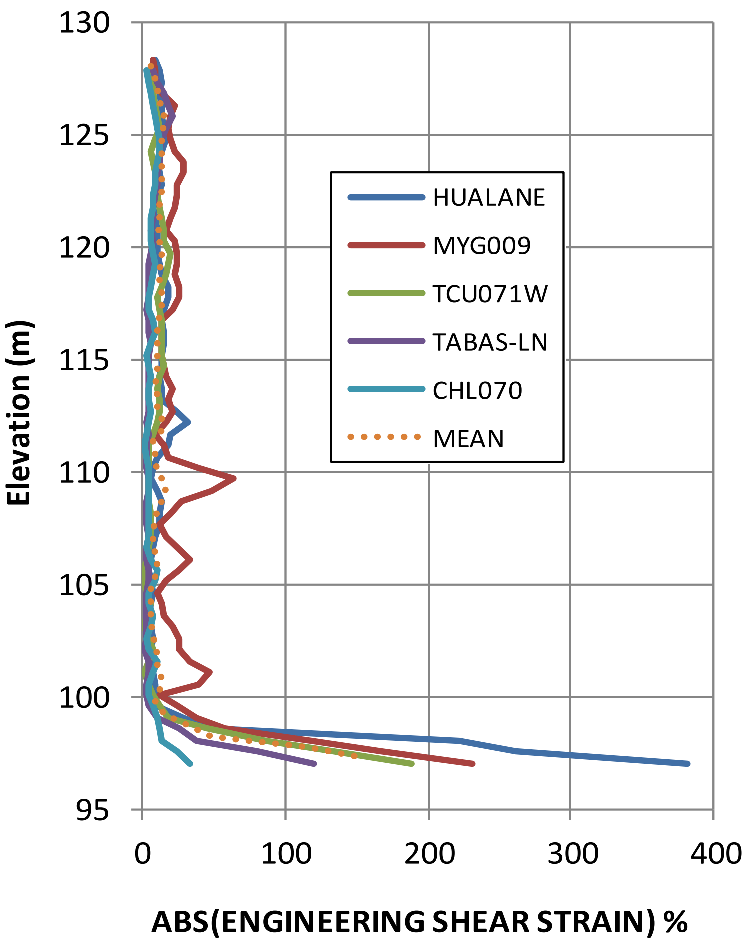
# VERSAT & FLAC: Strains

comparison of shear strains from all five earthquake input ground motions

VERSAT




FLAC



# SUMMARY AND CONCLUSIONS

1. Laboratory cyclic direct simple shear tests confirmed that cyclic resistance of the Lower Silt increase with over-consolidation ratio (OCR);

2. in addition, test results also showed that static shear stress bias can significantly reduce cyclic resistance of the Lower Silt.

3. In dynamic time-history analyses using VERSAT, calibration of the Silt Model for the Lower Silt was carried out using results of the cyclic DSS tests and taking into account the in-situ OCR and initial static shear stress conditions of the Lower Silt.

4. FLAC dynamic analyses the UBCSAND model for the Lower Silt was also calibrated using the results of cyclic DSS tests

# SUMMARY AND CONCLUSIONS

5. the two dynamic analyses give somewhat different ground deformation mechanisms on the downstream slope of the dam

6. it is advisable to check dam performance by independent analyses using different programs and constitutive models; in order to bound solutions of the problem and provide confidence in a decision making.

7. A dilemma will occur when two analyses result in completely different conclusions in terms of dam performance. More experience must be gained and compiled by the engineering community to validate an individual analysis method or a computer program (VERSAT, FLAC, and others).

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# THANK YOU !