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Current North American Practice on Geotechnical Earthquake engineering for Earthfill Dams

(26 November 2010)

Beijing, CHINA

Guoxi Wu, Ph.D., P.Eng.

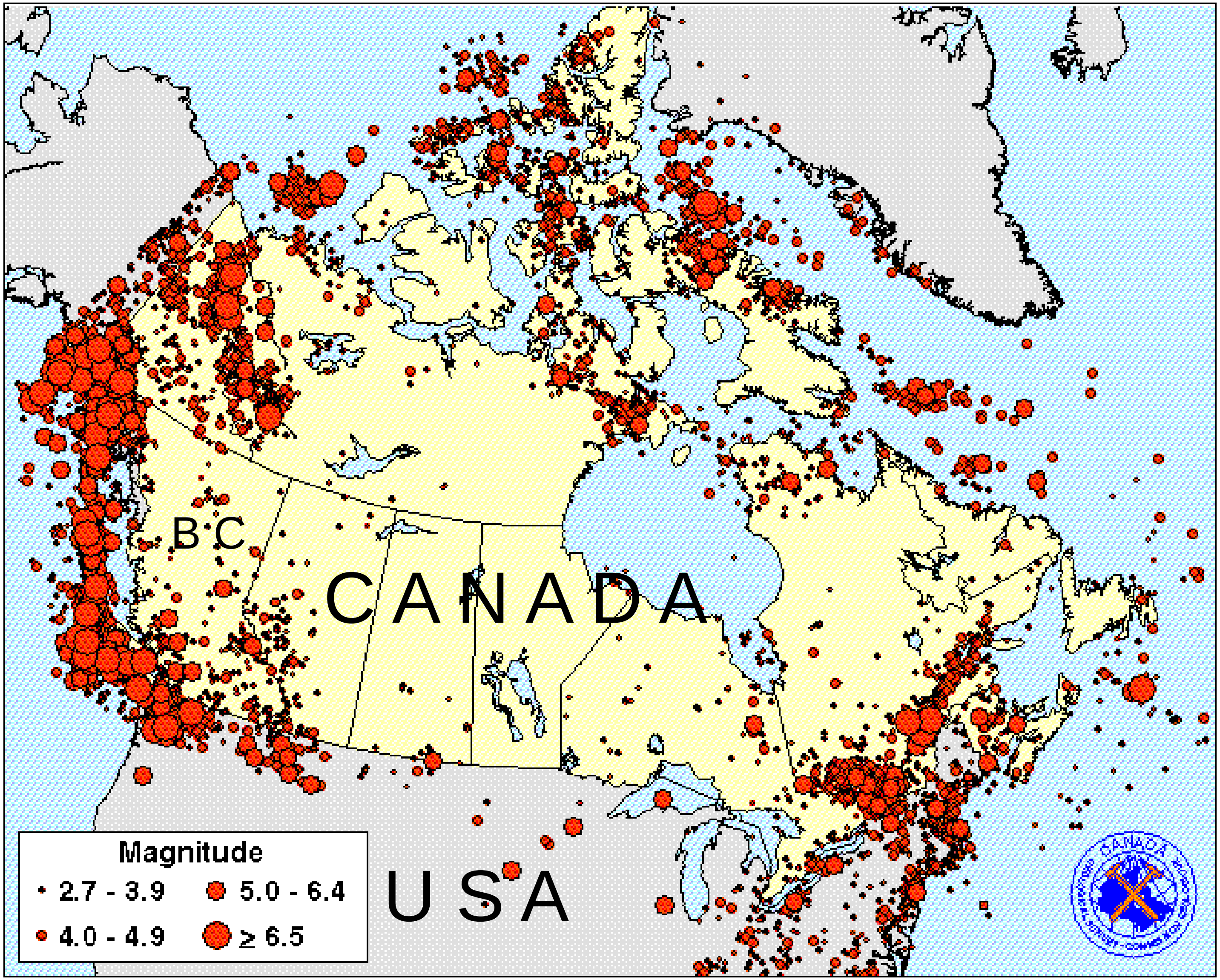
BC hydro

Presentation Outline

- Seismicity of BC
- Seismic Hazard Assessment
- Development of Input Earthquake Time Histories
- Nonlinear Dynamic Time History Analyses of Dam Performance
  - Ruskin dam seismic upgrade
  - John Hart dam seismic upgrade

Seismicity

Seismicity database used to determine Canadian seismic hazard

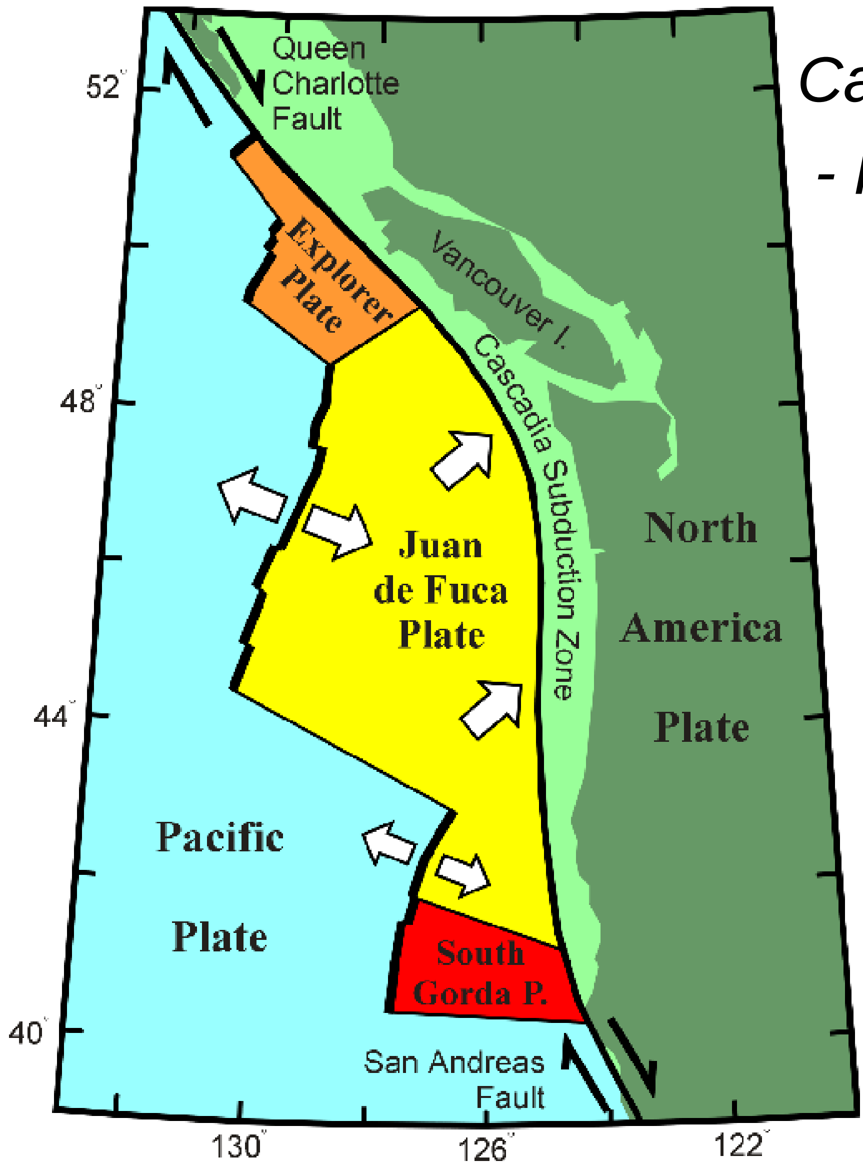


Seismicity

- 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

➢ 1946 Photo:
Port Alberni BC, Chimney rotation

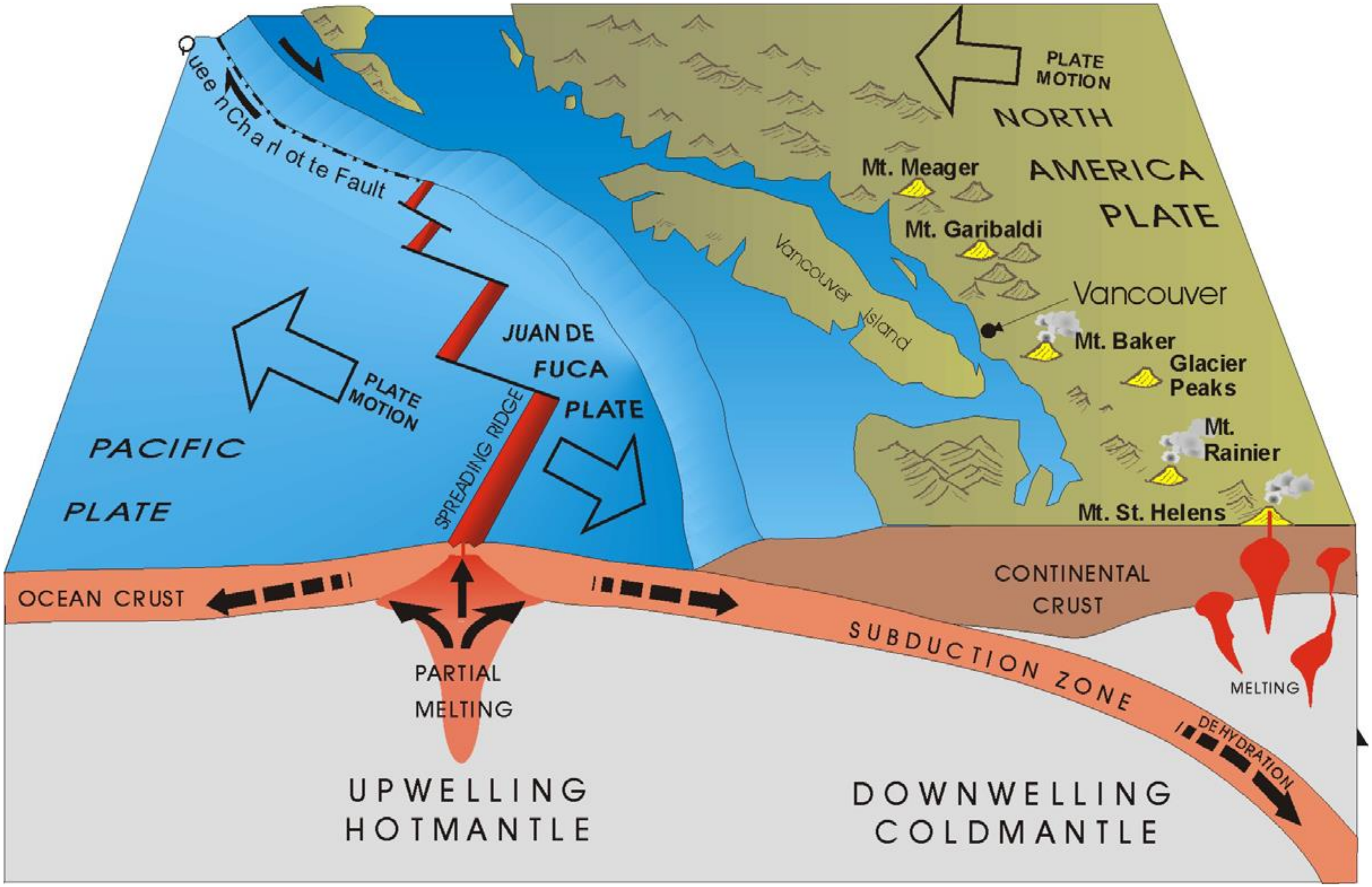
Seismicity



Cascadia Subduction Zone

- Plan

Cascadia Subduction Zone - Section

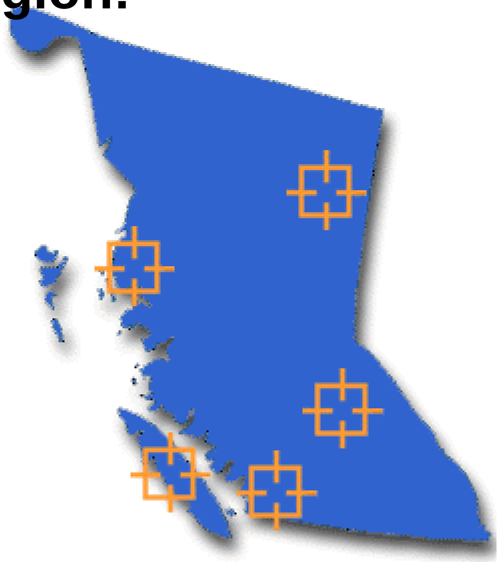


BC Hydro dams

BC Hydro's Electric Generation System

The 30 integrated hydroelectric generating stations (10,000 MW), two gas-fired thermal power plants and one combustion turbine station (total ~1000 MW) = total generating capacity of ~11,000 megawatts (MW).

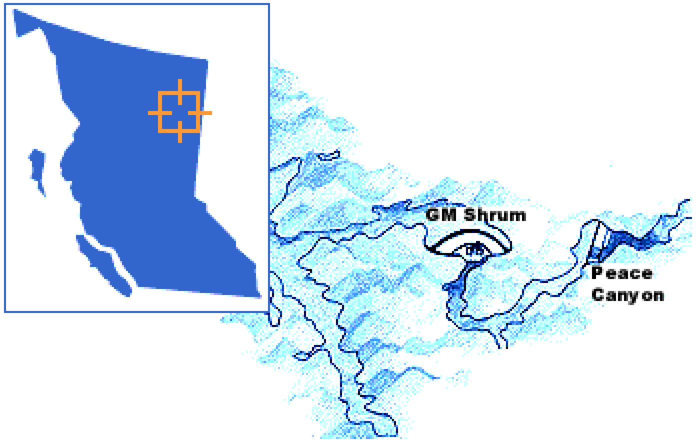
British Columbia (BC) Region:



Peace River: Low seismic region

Bennett dam/GM Shrum (2730 MW)

Peace Canyon (694 MW)



BC Hydro dams

VANCOUVER ISLAND: Very high seismic hazard

Ash River

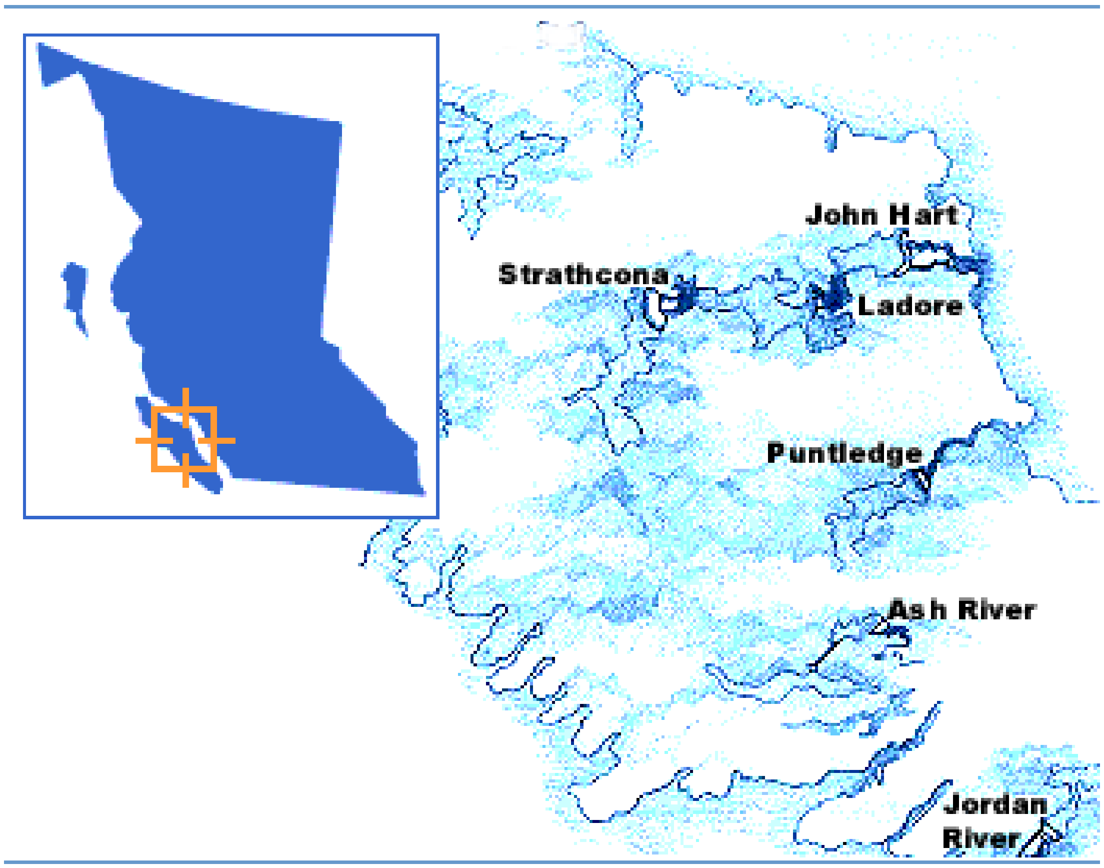
John Hart (126 MW)

Jordan

Ladore (47 MW)

Puntledge

Strathcona (65 MW)



http://www.bchydro.com/about/our_system/generation/our_facilities.html

BC Hydro dams

Lower Mainland: High Seismic Hazard

Alouette (9 MW)

Bridge River (460 MW)

Buntzen (73 MW)

Burrard (950 MW gas)

Cheakamus (158 MW)

Clowhom

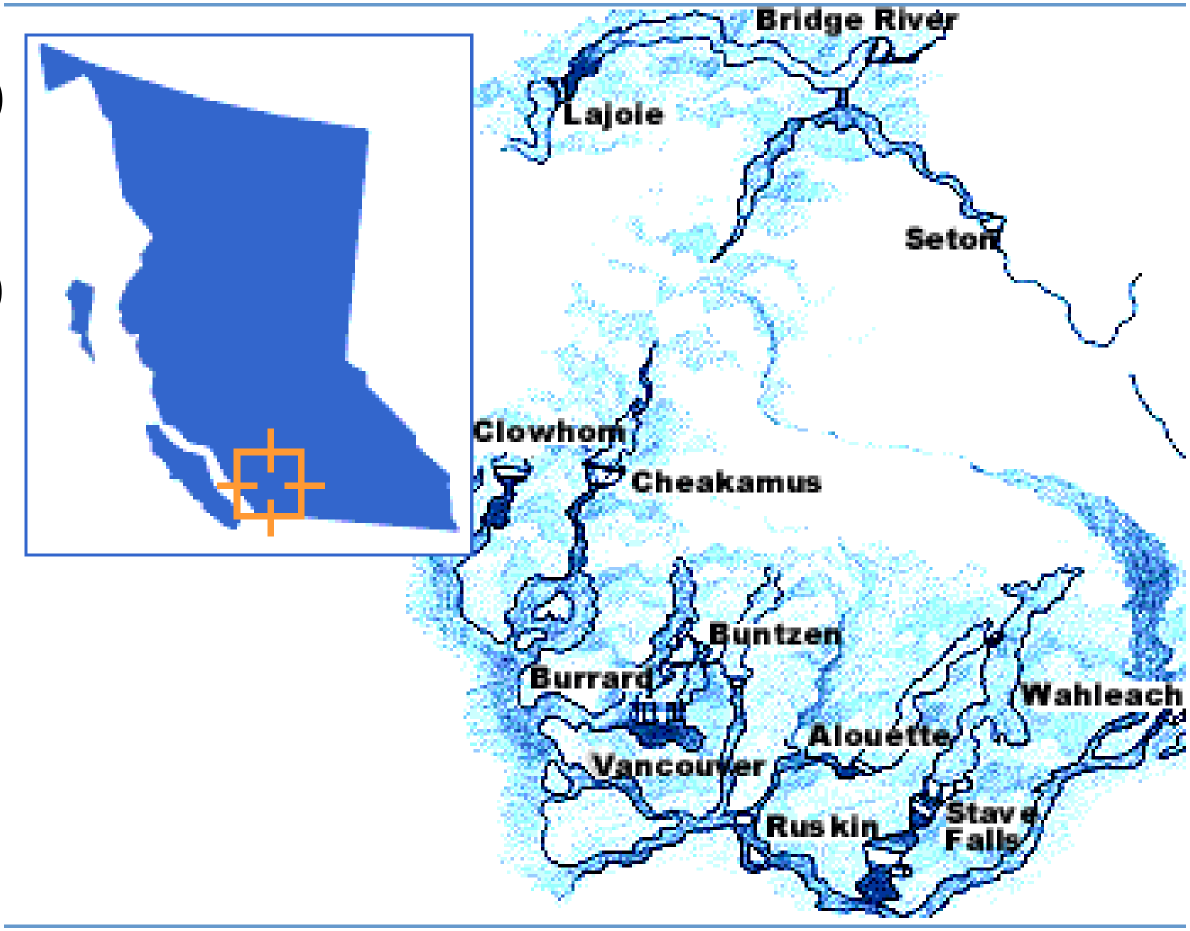
La joie (25 MW)

Seton (48 MW)

Stave Falls (91 MW)

Ruskin (105 MW)

Wahleach (64 MW)



Seismic Hazard Assessment – PSHA

- Late 1970s – Initial BCH dam safety program; growing awareness of seismic hazard

- Early 1980s – PSHA for Lower Mainland & Vancouver Island region
  - EQRISK software
  - Based on 1983 GSC source zone model
  - HBB81 and JB81 attenuations, with & without uncertainty considered
  - Best estimate AEFs of 1/2000 to 1/10,000, depending on attenuation adopted

Seismic Hazard Assessment – PSHA

Early 1990s – Provincial PSHA

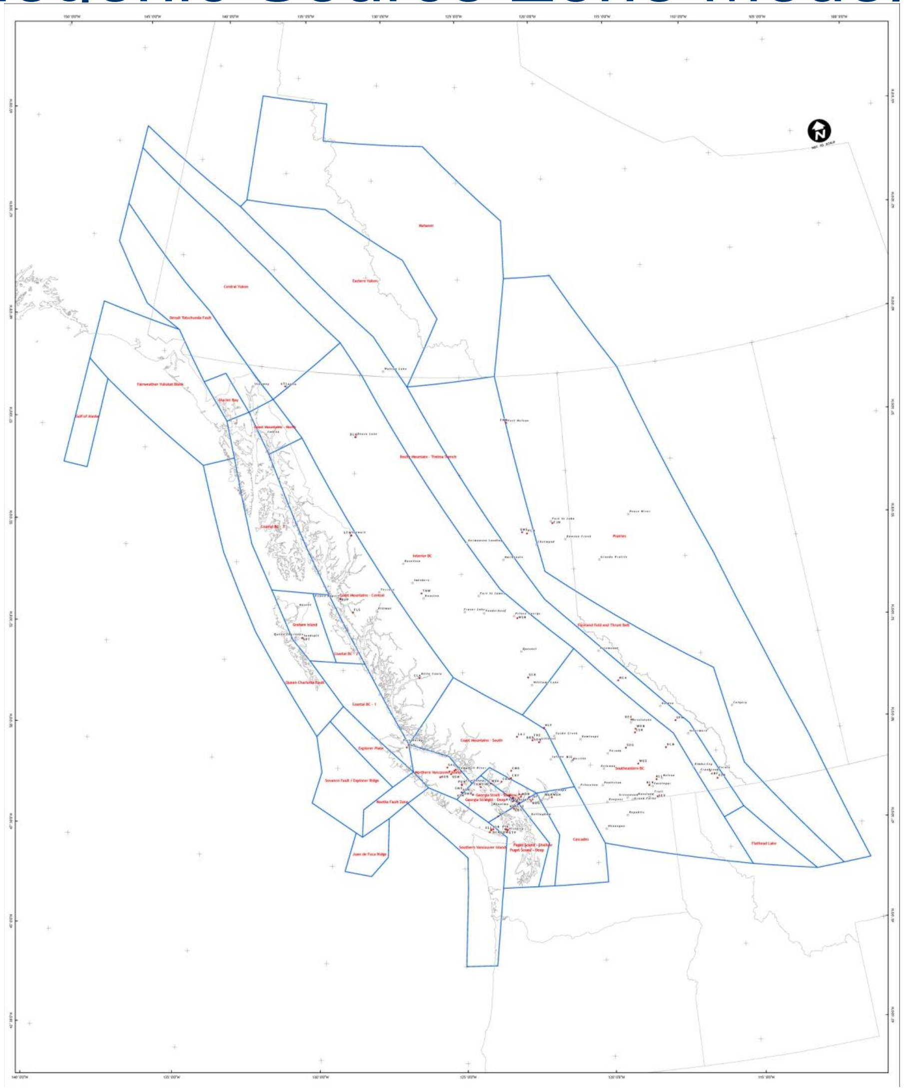
- Continued to use EQRISK software
- BCH-developed source zone model – more zones than 1983 GSC model
- Shallow and deep source zones
- Idriss91 and Crouse91 attenuations, with uncertainties included
- Best estimate AEFs of 1/10,000 for VH consequence dams

Late 1990s

- Introduced HAZ software by N. Abrahamson
- Increased assessment of epistemic uncertainties
- Alternate source models – BCH + GSC-H & GSC-R
- Alternate magnitude-recurrence models
- Alternate attenuation relations, all with uncertainty included
- Variable hypocentral depths
- Mean AEFs of 1/10,000 for VH consequence dams, with uncertainty bands (fractiles)

Seismic Hazard Assessment - PSHA

BCH Seismogenic Source Zone Model



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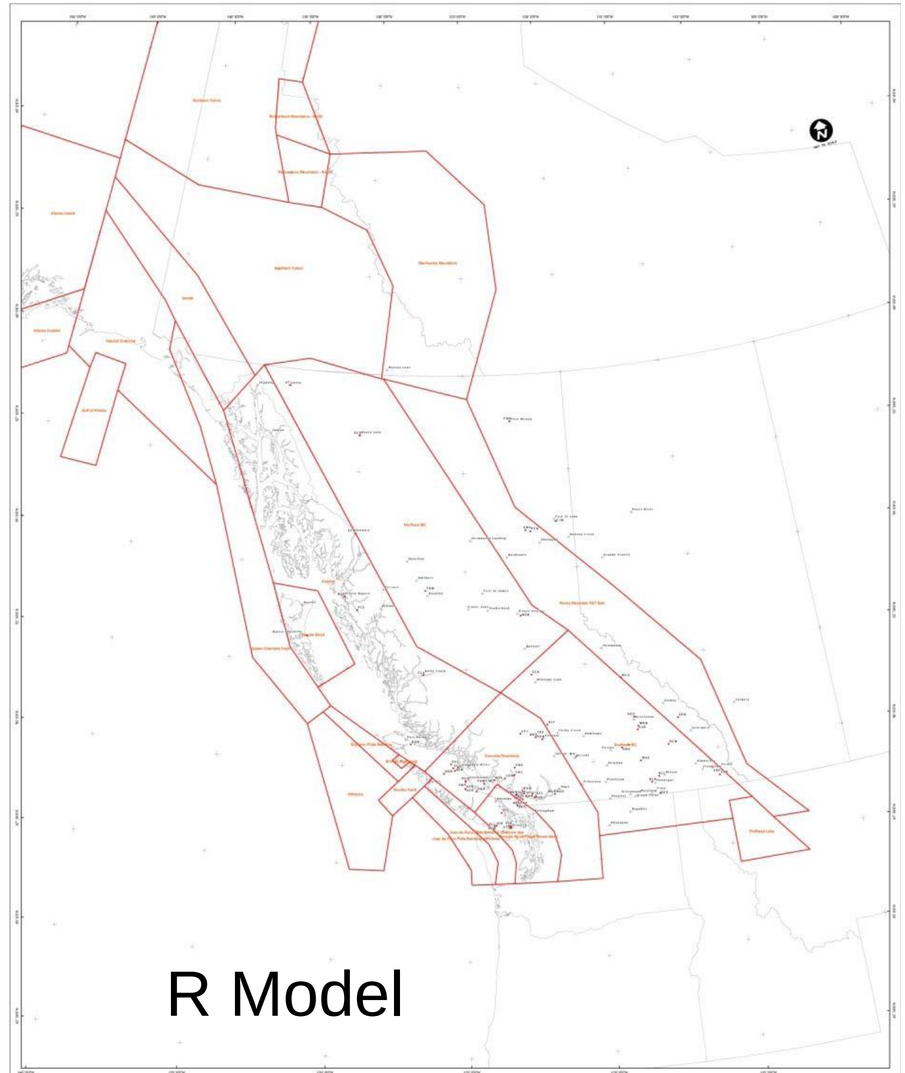
Seismic Hazard Assessment - PSHA

Geological Survey of Canada (GSC) Source Zone Models


H Model


R Model

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Seismic Hazard Assessment - PSHA

Late 1990s to present

- Continued use of multiple model PSHA with assessment of epistemic uncertainties
- Mean AEFs of 1/10,000 for VH consequence dams
- Magnitude-recurrences for BCH source model updated; GSCH and GSC-R models not updated
- Cascadia megathrust earthquakes evaluated as deterministic scenarios
- New attenuation relations introduced periodically
- Increasing attention paid to selection & development of time histories for dynamic analyses of dams and other structures

Dam Safety Guideline Example – CDA 2007

Guidelines comment that full range of seismic loadings should be considered & that quantitative risk analysis is preferred, but note that standards-based approach is most common practice

Dam Class	Mean AEP Of EDGM
Low	1/500
Significant	1/1000
High	1/2500
Very High	1/5000
Extreme	1/10,000

EDGM = Earthquake Design Ground Motion

AEP = Annual Exceedance Probability

Guideline – California Division of Safety of Dams

	Very High Slip Rate 9 or greater mm/yr	High Slip Rate 8.9 to1.1 mm/yr	Moderate Slip Rate 1.0 to 0.1 mm/yr	Low Slip Rate less than 0.1 mm/yr
Extreme Consequence Total Class Weight 31-36	84th	84th	84th	50th to 84th
High Consequence Total Class Weight 19-30	84th	84th	50th to 84th	50th to 84th
Moderate Consequence Total Class Weight 7-18	84th	50th to 84th	50th to 84th	50th
Low Consequence Total Class Weight 0-6	50th	50th	50th	50th

DSOD Consequence-Hazard Matrix
October 4, 2002

- DSHA – focused
- Limited use of PSHA to evaluate conservatism of DSHA
- Minimum Earthquake
  - M6.25, 14s duration
  - 0.15g (50th %ile)
  - 0.25g (84th %ile)

BC Hydro PSHA Project

Current BC Hydro PSHA Project (2007 - 2010?)

- A major undertaken ($ several millions)
- Project is being carried out as a SSHAC Level 3 study.
- The goal is to develop inputs that represent the composite distribution of the informed scientific community.
- As part of a PSHA, we are seeking to identify and model sources of aleatory (random) and epistemic (model and parameter) uncertainty

(SSHAC = Senior Seismic Hazard Assessment Committee)

BC Hydro PSHA Project

Challenges:

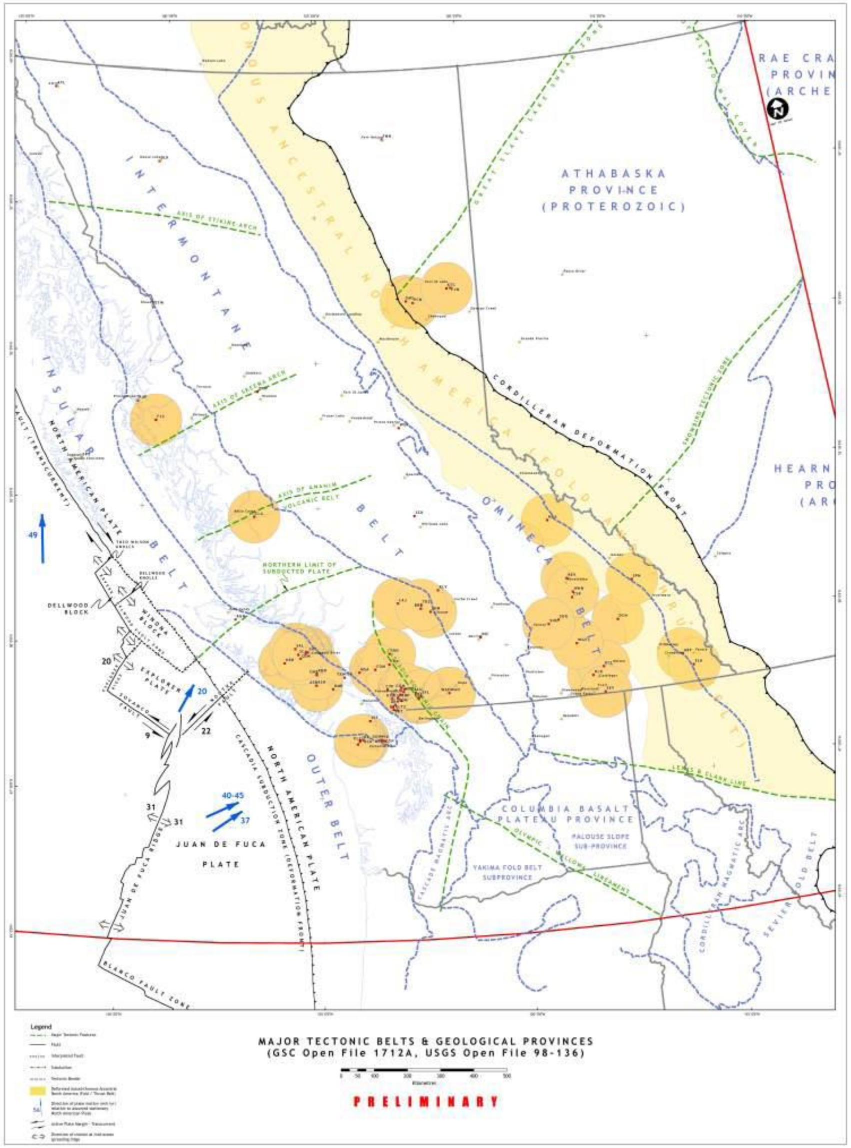
- Huge region to model
- Large amount of seismotectonic information to consider
- Lack of identified active faults
- PSHA project is intended to:
  - Provide ground motion parameters for a wide range of analytical applications
  - Address uncertainties in a comprehensive manner
  - Provide higher confidence in the computed ground motion parameters to enable sound decision-making
  - Improve system wide consistency and stability in setting seismic requirements for the next 10 to 15 years.

BC Hydro PSHA Project

Study Region

for BCH PSHA Project

- *Geographically large*
- *Tectonically diverse; varies from plate boundary (Cascadia) on the west to the stable continental interior in the east*



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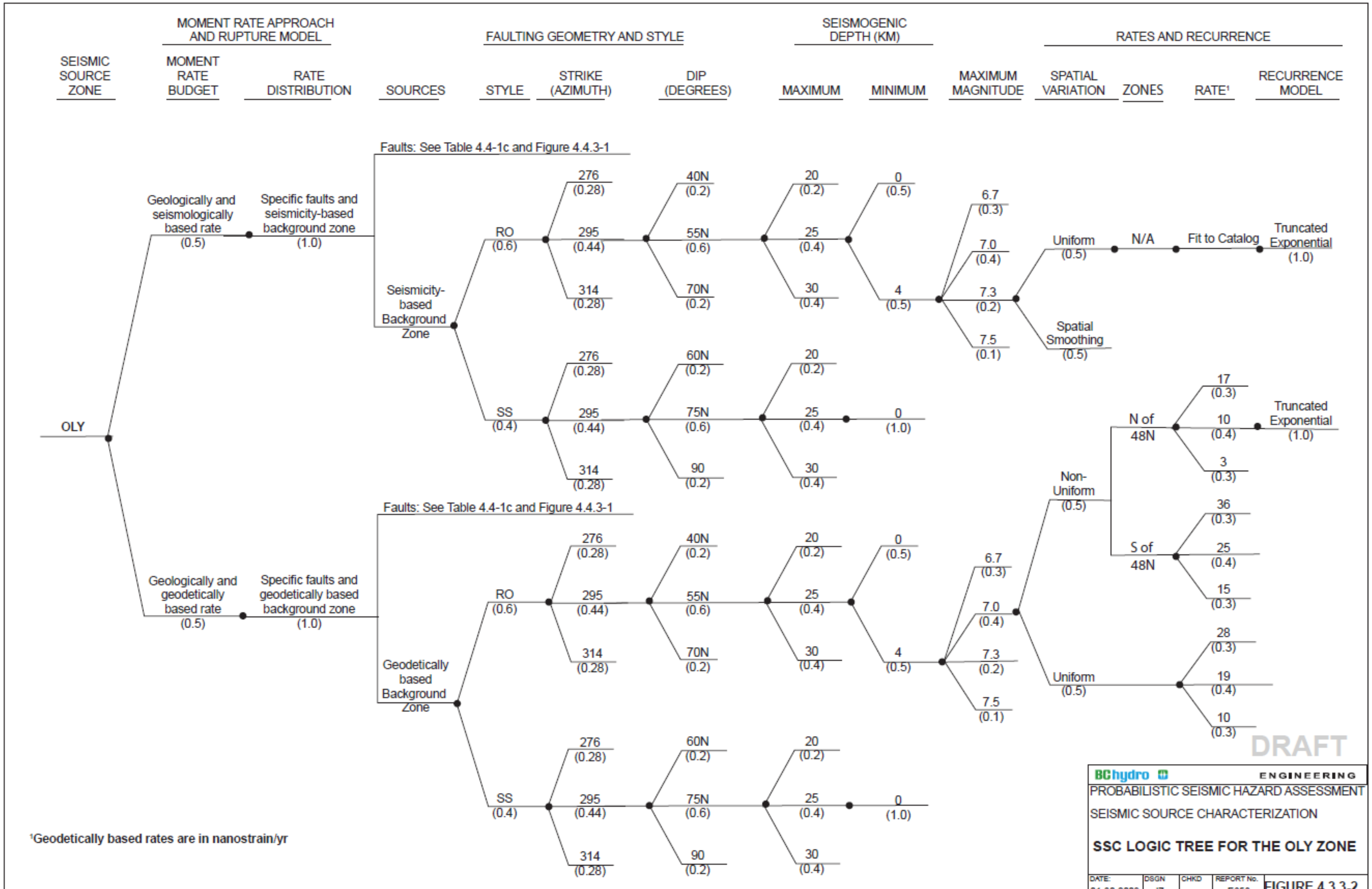
Seismic Source Characterization (SSC) Logic Illustration



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BCH PSHA Project - New Developments (1)

- Earthquake catalogue
  - Merged US catalogue with GSC catalogue & removed duplicates
  - Removed aftershocks & anthropogenic events
  - Converted all magnitudes to Moment Magnitude (MW)
  - Determined magnitude completeness for different regions
- Earthquake recurrence models
  - Traditional recurrence models based on historical seismicity
  - Investigated potential to use geodetic data to estimate crustal strain rates & earthquake recurrence

BCH PSHA Project - New Developments (2)

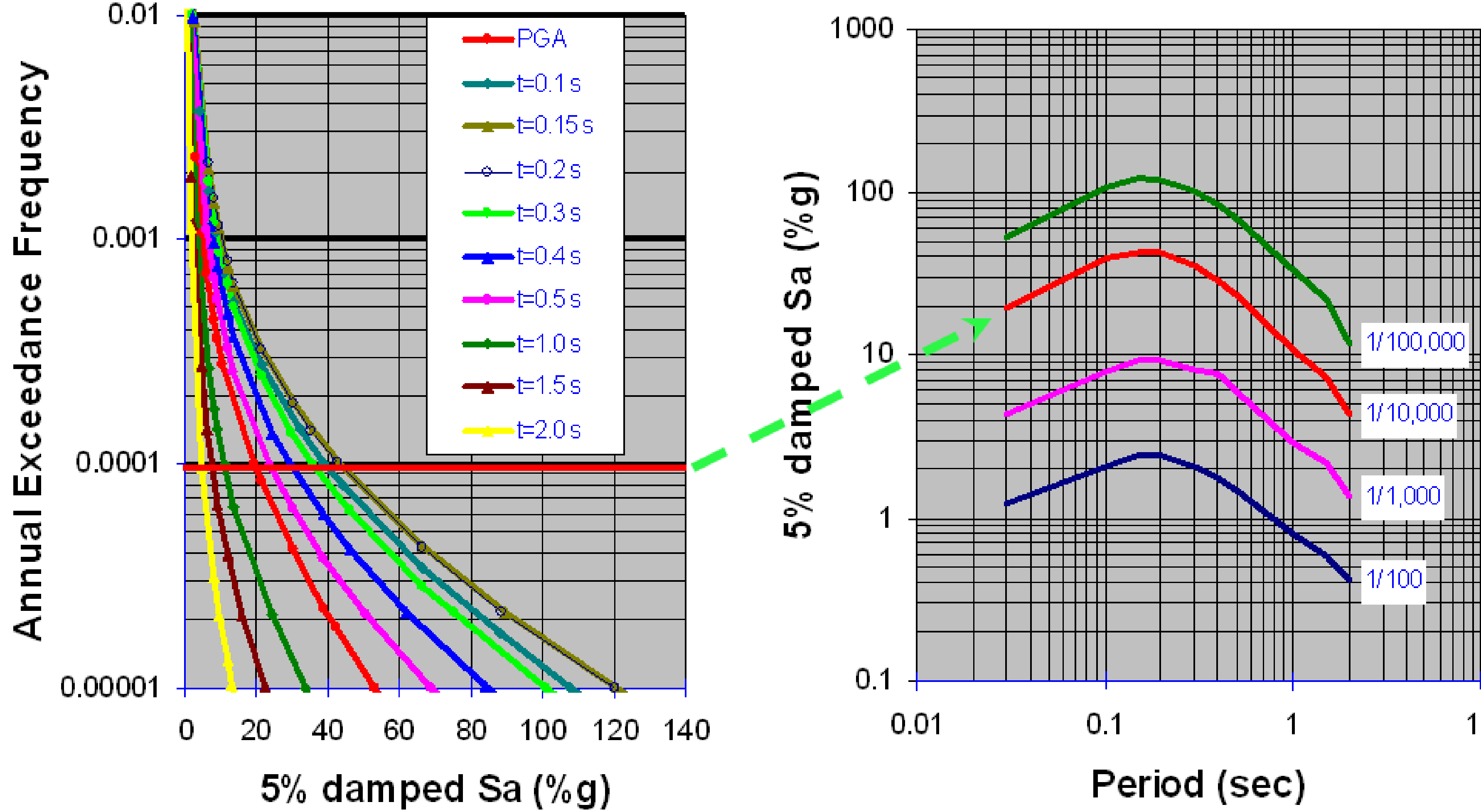
- *Crustal attenuation models*
  - *Validated NGA models against B.C. earthquake data*
- *Subduction zone attenuation model*
  - *Brought together experts from around the world to compile a global database*
  - *Developed a new subduction ground motion attenuation model*
- *Cascadia subduction zone model*
  - *Introduced source model/rupture alternatives*
  - *Recurrence assessment for mega-thrust events based on paleoseismic data, including a clustering model*

BCH PSHA Project - Status

- GM models (N. Abrahamson) are being finalized & documented
- SSC model (M. McCann) is being finalized & documented
  - Rationale for branches & weights in logic trees being reviewed & documented
  - Report preparation
  - Peer Review
- Implementation
  - Software (B. Young)
  - Model inputs
- PSHA production calculations for each dam site (~ 2011)

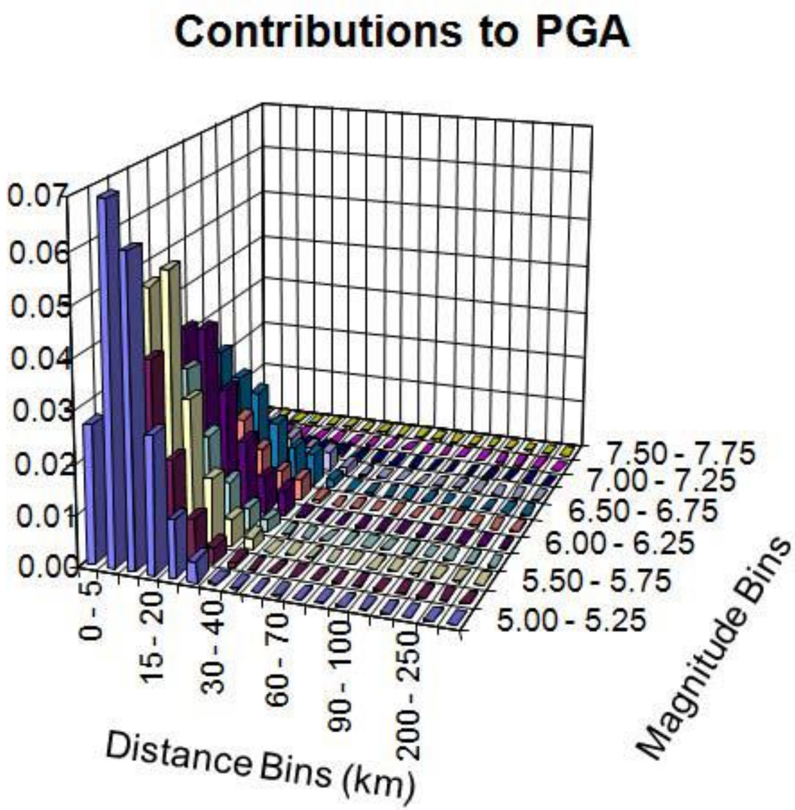
Uniform Hazard Response Spectra (mean hazard, not median)

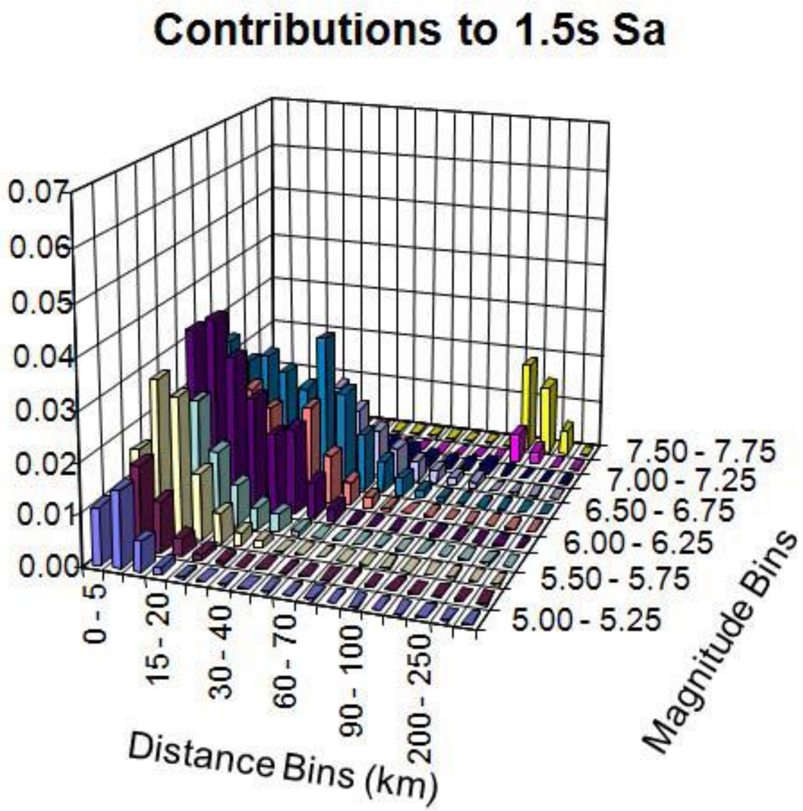
CDA: The mean is the expected value given the epistemic uncertainties. In Canada, the mean Is about 65th to 75th of the hazard distribution.



BC Hydro PSHA Project

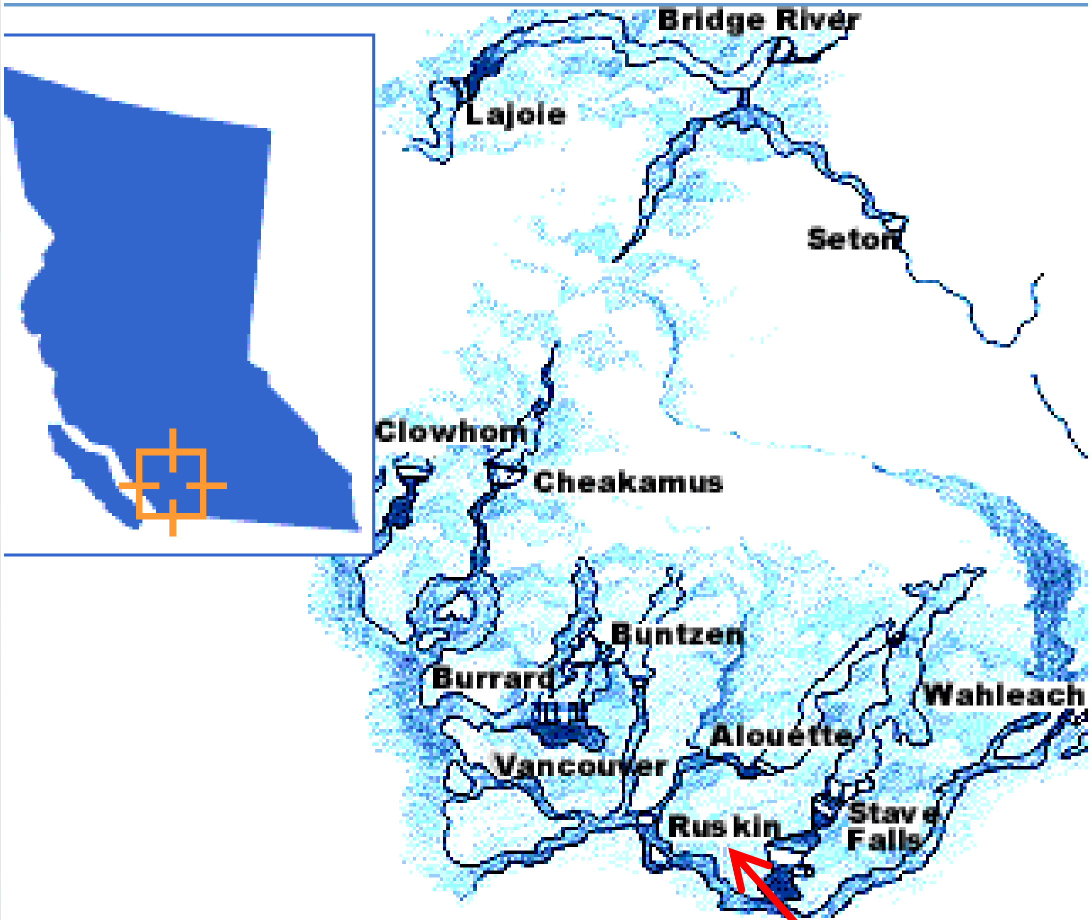
Period-Dependent M/D De-aggregations





AEF = 1/10,000

Ruskin dam seismic upgrade



Ruskin dam seismic upgrade project

Ruskin dam seismic upgrade

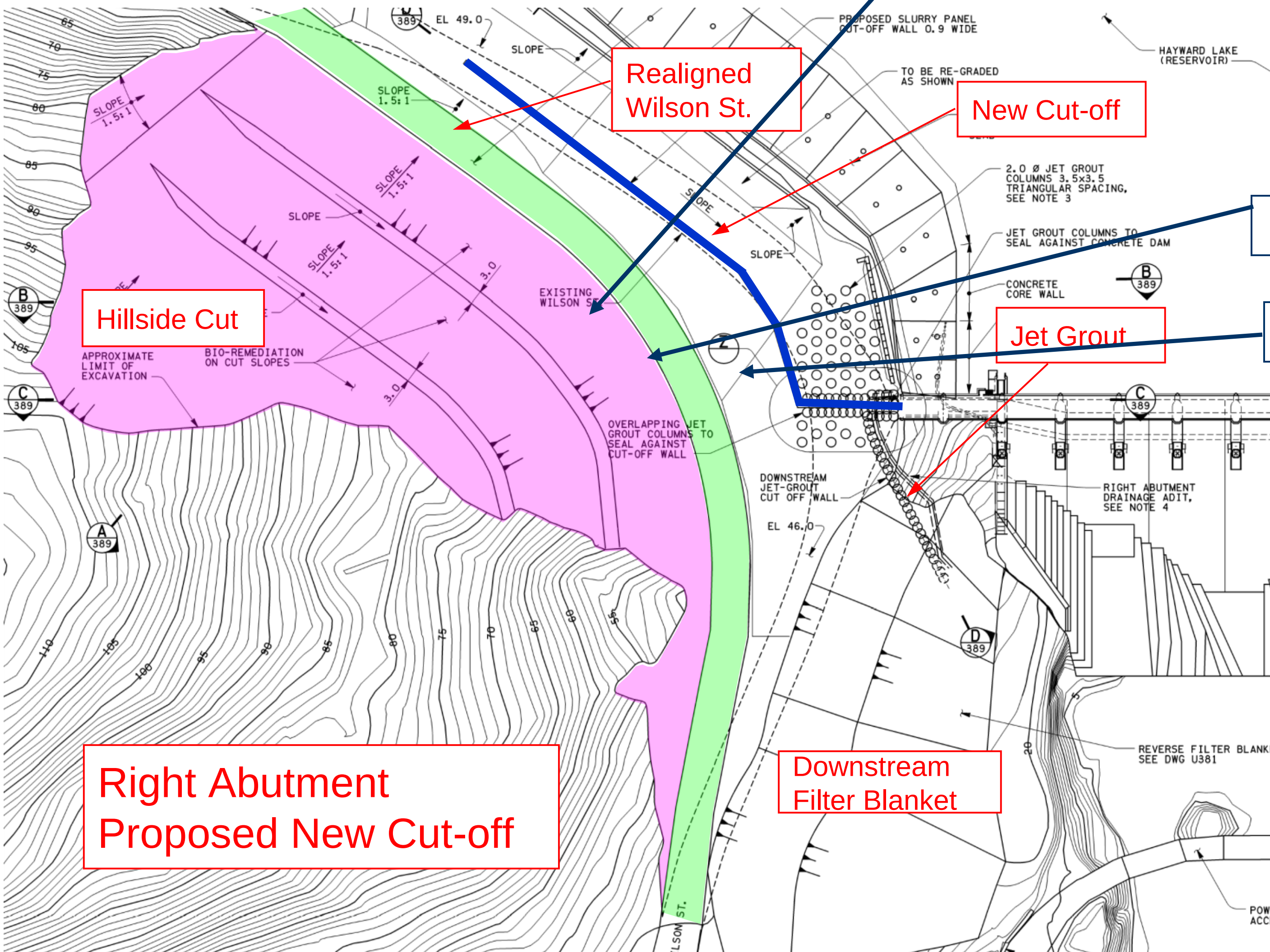
Ruskin dam seismic upgrade

Right Abutment: Has u/s steeply sloping concrete slab “cutoff”; Predominantly natural soils (sands / tills); Exhibited piping upon filling; Remediation undertaken following construction; Seepage/piping issues remain

Ruskin dam seismic upgrade

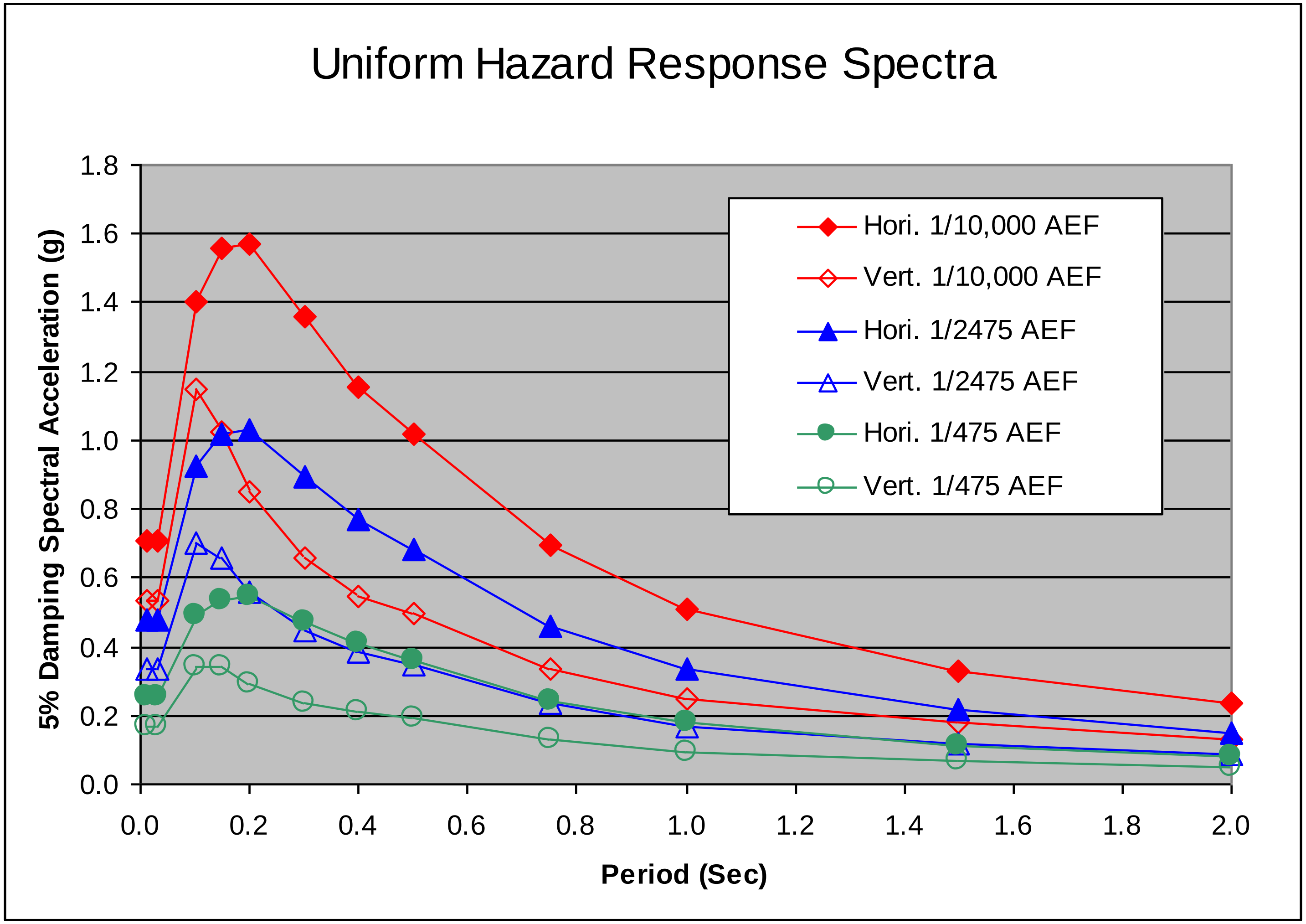
Right Abutment Proposed Upgrade:

MDE1/10,000; PGA0.71g



Ruskin dam site - Seismic Hazard

Seismic Hazard Assessment Update (2009)



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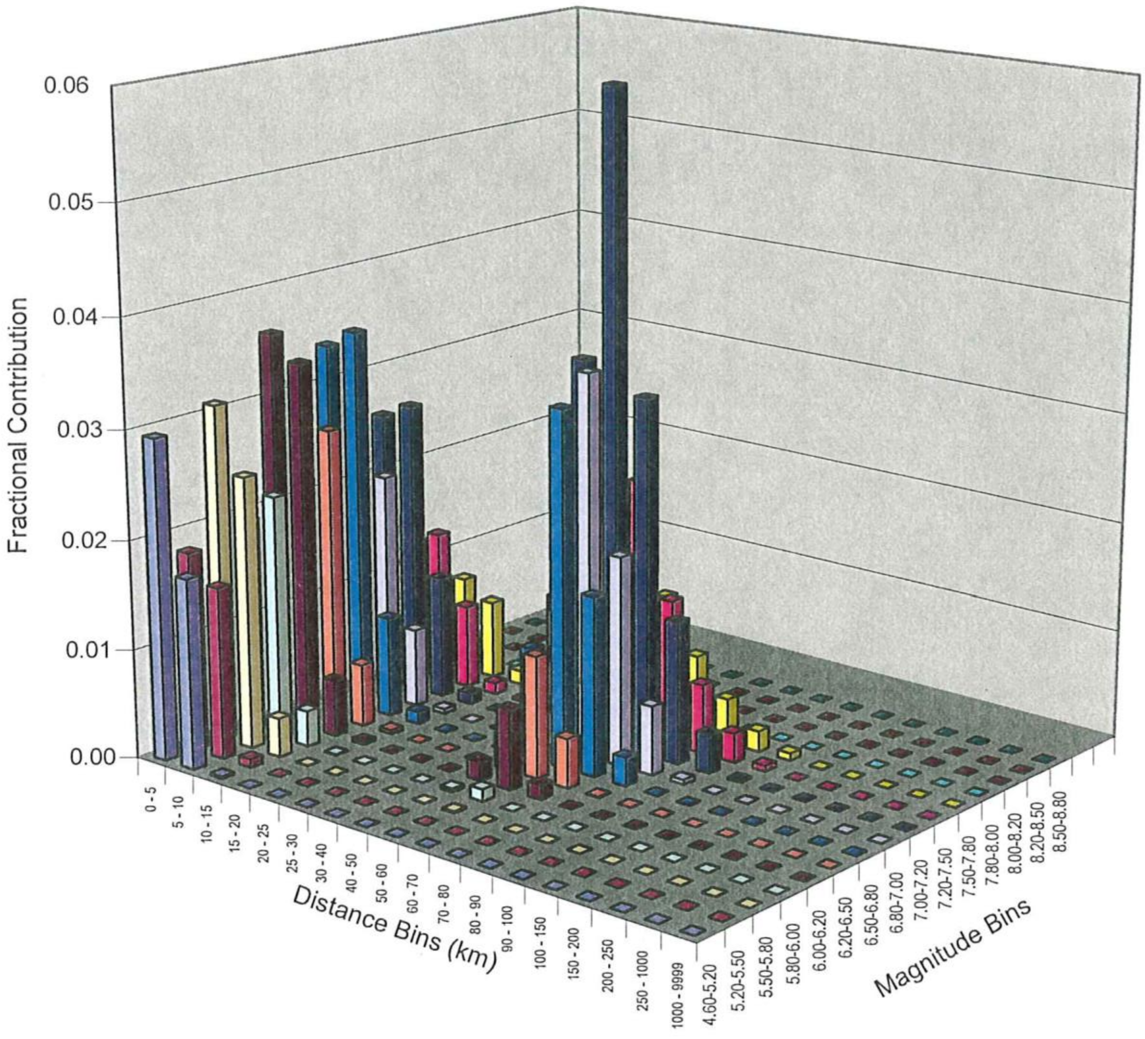
Ruskin dam site – seismic hazard

Hazard De-aggregation at PGA and 1/10,000 AEF



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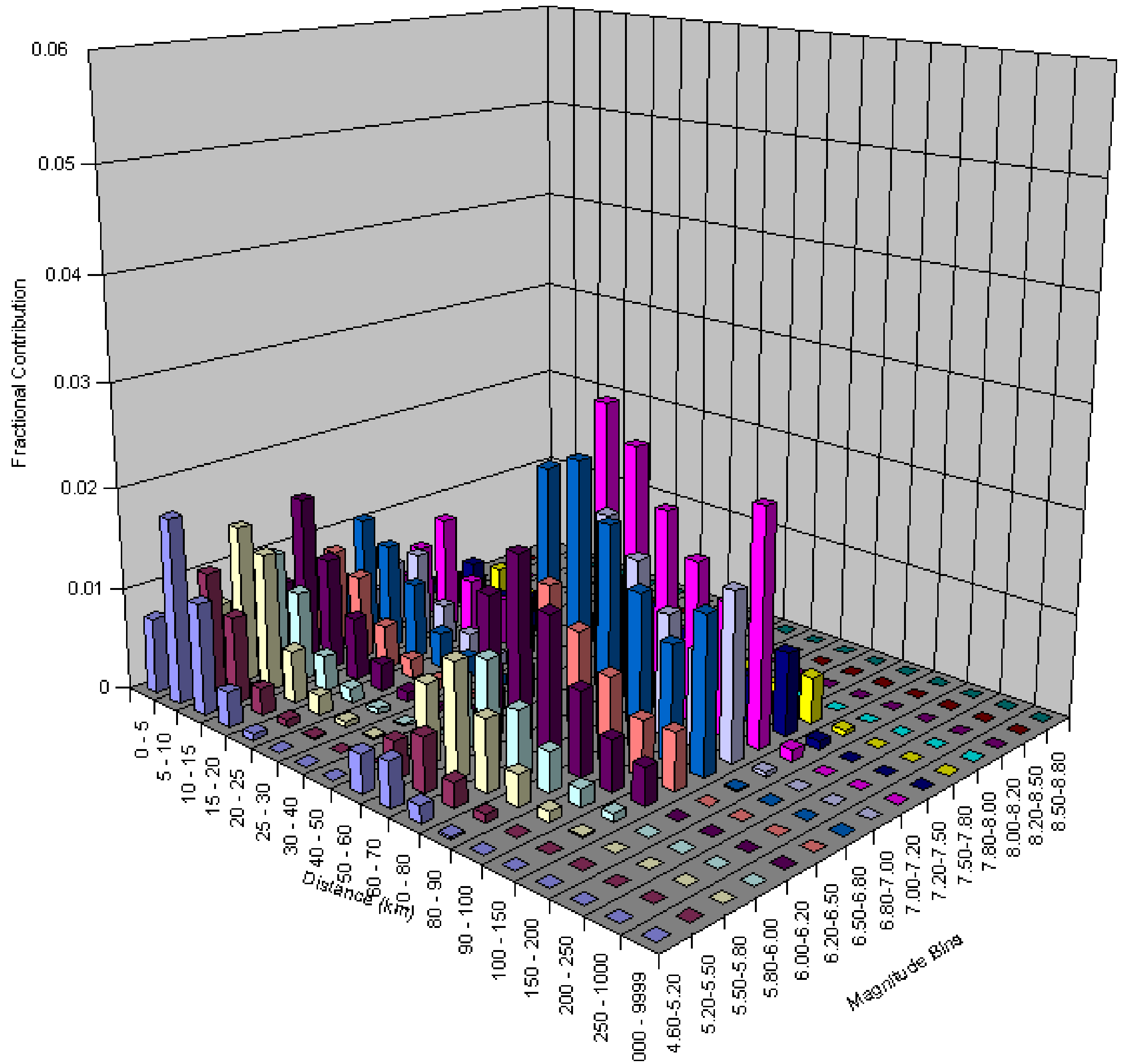
Ruskin dam site – seismic hazard

Hazard De-aggregation at PGA and 1/475 AEF



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Ruskin dam site – seismic hazard

De-aggregation Results for 1/10,000 AEF:

- shallow crustal
- deep intraplate

Period	Crustal earthquake		Deep earthquakes	
	M-bar	D-bar (km)	M-bar	D-bar (km)
PGA	6.3	6	7	57
T=0.15 sec	6.3	6	7.1	56
T=0.5 sec	**6.7**	**8**	**7.1**	**60**
T=1.0 sec	**6.9**	**9**	**7.2**	**59**
T=1.5 sec	7	10	7.2	61

Ruskin dam site - Design Earthquakes

- MDE – 1/10,000 AEF
  - PGA = 0.71 g
  - M7.5
- DBE – 1/2,475 AEF
  - PGA = 0.48 g
- OBE – 1/475 AEF
  - PGA = 0.26 g

Ruskin dam site - Earthquake Time Histories

Selection Criteria / Methodology:

- To preserve the characteristics of natural earthquake ground motions in a dynamic time history analysis

- to use acceleration time-histories recorded during large historic earthquakes from around the world

- shaking intensity of the selected ground motions are adjusted to the earthquake hazard level by linear scaling

- shaking duration are considered by selecting the ground motions from earthquakes of appropriate magnitude

Ruskin dam site - Earthquake Time Histories

- Crustal Earthquakes
  - M = 6.5 to 7.2, D = 0 to 12 km
- Deep Earthquakes
  - M = 6.7 to 7.4, D = 50 to 66 km
- Style of Faulting
  - strike slip,
  - reverse normal
  - reverse-oblique
  - but not including normal or normal-oblique due to local tectonic setting
- A bedrock site, or a Class B site
  - with V_{s30} >760 m/s

Database of Earthquake Records:

1. PEER database –
   - Pacific Earthquake Engineering Research Center strong motion database
2. PEER NGA database –
   - PEER Next Generation Attenuation of Ground Motions
3. COSMOS database-
   - Consortium of Organization for Strong-Motion Observation Systems -

Found 14 records that meet the above criteria.

Method of Scaling

- Method of Scaling
  - Linearly scaled to fit the target spectrum at the period range of interest by minimizing mean square error of the fit over the period range
  - The mean spectrum of all scaled spectra at any period in the range not lower than 85% of the target spectrum.
  - The average of the ratios of the mean scaled spectrum to the target spectrum ≥ 1.
- Concrete Structure (3D arrays including vertical)
  - All records were scaled originally to minimize the mean square error of the spectral fir over a frequency range of 6 to 20 Hz.
  - For each horizontal pair the average of the two scaling factors was used to scale both components. Vertical records were scaled separately.
- Right Abutment (one horizontal component)
  - Scaled linearly to closely fit the target UHS for period of interest from 0.4 to 1.0 second

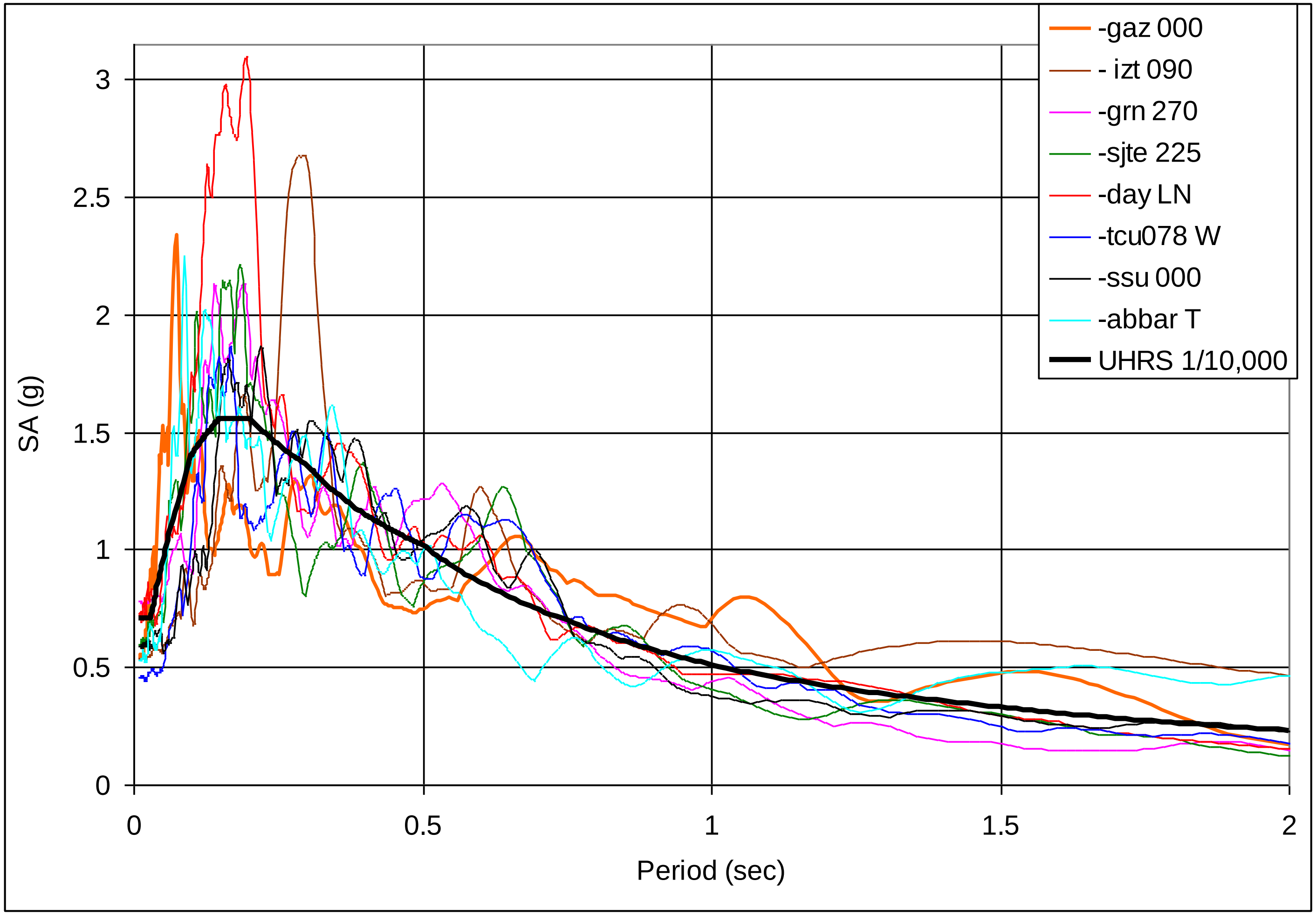
Ruskin Right Abutment: Time History

Ruskin Right Abutment

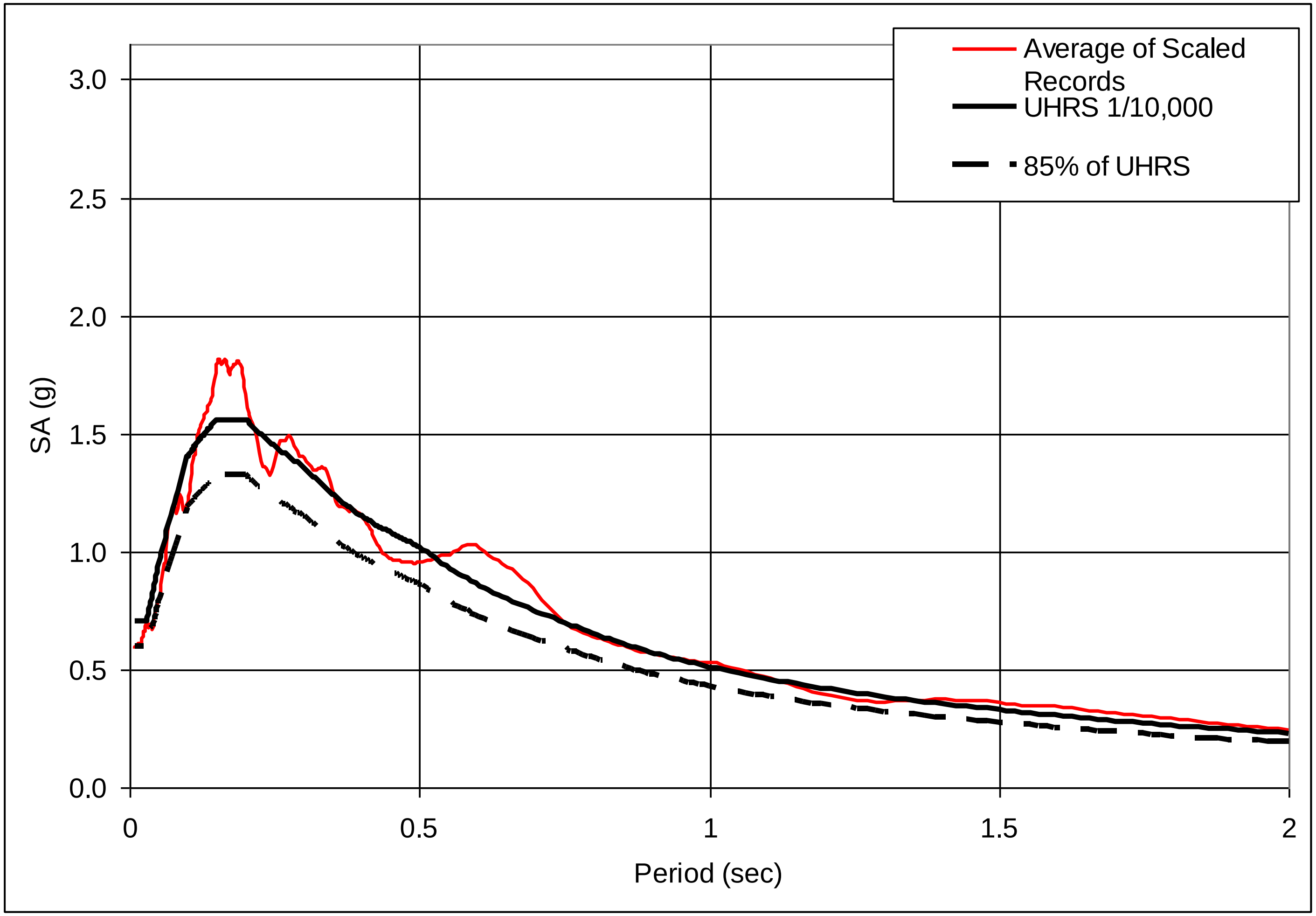
Record #	Earthquake	Station	Magnitude	Strong Shaking Duration (sec)	R_{RUP} (km)	Component (2)	Scaling Factor	PGA after scaling (g)	AI for modified records (m/s)
1	1976 USSR Gazli	9200 Karakyr	6.8	6.4	5	#000	0.88	**0.53**	**3.59**
2	1999 Turkey Kocaeli	Izmit	7.4	13.2	7	#090	2.44	**0.54**	**4.85**
3	1994 US Northridge	#90019 at San Gabriel	6.7	13.05	39	#270	3.01	**0.77**	**4.05**
4	1989/10/18 US Loma Prieta	Santa Teresa Hills San Jose	6.9	10.1	15	#225	2.11	**0.58**	**5.80**
5	1978 Iran Tabas	9101 Dayhook	7.4	12.3	14	LN	2.10	**0.69**	**6.29**
6	1999/09/20 Taiwan Chi-Chi	TCU078	7.6	25.9	8	W	1.00	**0.44**	**5.79**
7	1994 US Northridge	SANTA SUSANA GROUND	6.7	7.28	17	#000	2.07	**0.58**	**3.68**
8	1990 Iran Manjil	BHRC 99999 Abbar	7.4	30.6	13	T	1.05	**0.52**	**8.36**

Note: #1, #2, #4 and 5 have also been used in all up-to-date analyses for the right abutment.

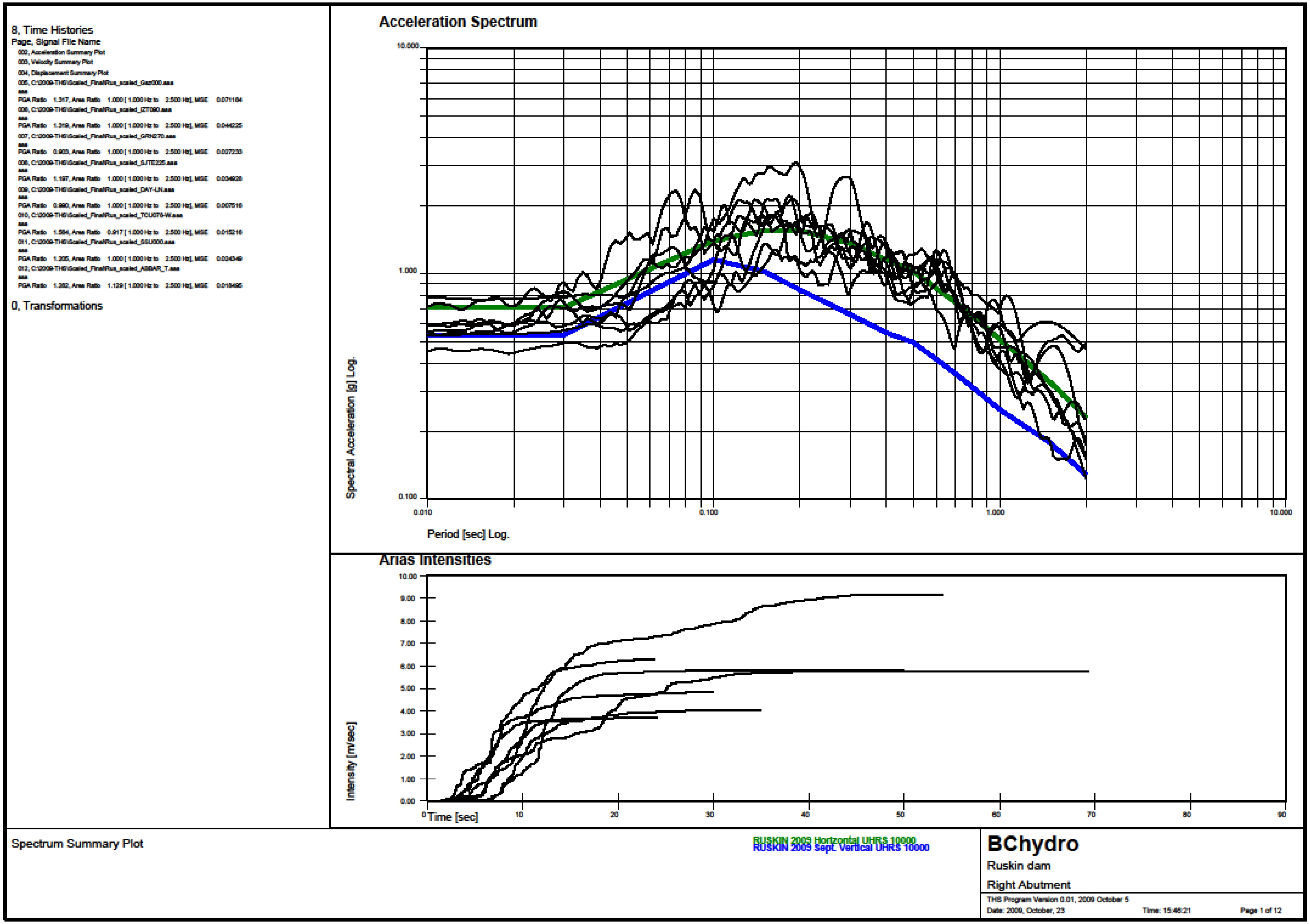
Right Abutment: Time History



Right Abutment: Time History



Right Abutment: Summary of Spectrum



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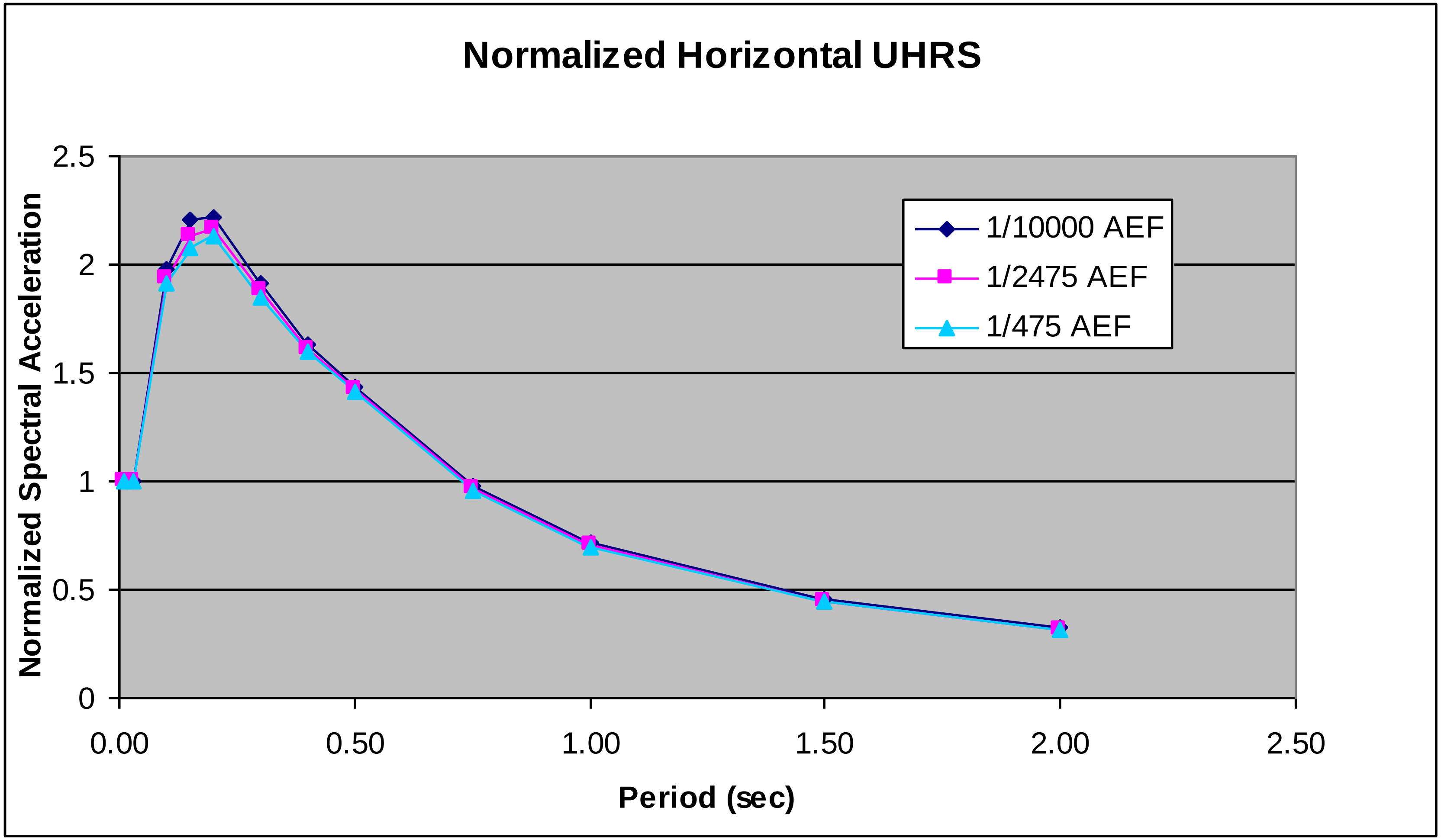
Ruskin dam Normalized UHRS for MDE, BDE, OBE



Ruskin dam site - Earthquake Time Histories

DBE & OBE

- Scaling down from MDE UHRS to DBE/OBE UHRS

Aftershock

- M6.5 with D=10 kM
- Target spectrum = average of the individual median response spectra derived from the 4 attenuation relations
- Select time histories by scaling down from MDE earthquake records

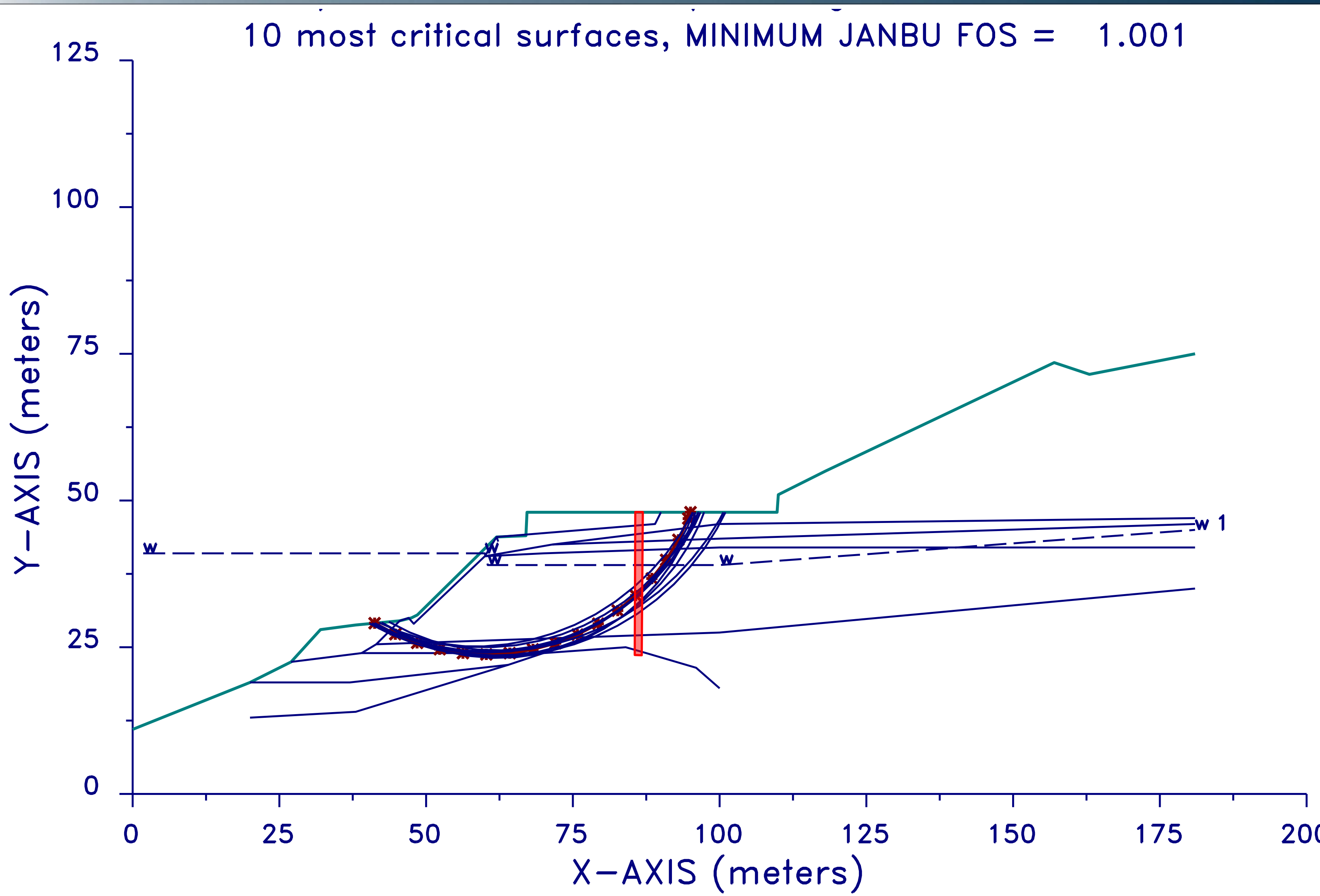
Interplate Subduction

- Use 84^{th} percentile A&B attenuation relationship
- Search subduction records to select one record

Ruskin Right Abutment – Seismic Deformations

- 2-D limit equilibrium analysis carried out for cut-off wall option
- Three cases examined:
  - Existing case
  - Upgrade case with no drainage between cutoff walls
  - Upgrade case with drainage between cutoff walls
- Deformations calculated by using Newmark (1965), Makdisi and Seed (1978), and Bray and Travasarou (2007)

Ruskin Right Abutment – Seismic Deformations



Ruskin Right Abutment – Seismic Deformations

Method	Simplified Newmark	Bray and Travasarou	
Case	-	Mean	84%
Displacement (mm) for existing	260	160	310
Displacement (mm) for upgrade with groundwater at El. 39 m	290	290	570
Displacement (mm) for upgrade with groundwater at El. 34 m	190	200	380

Ruskin Right Abutment – Seismic Deformations

Methods of deformation analyses

- VERSAT-2D (Wutec Geotechnical Int., Canada):
  - dynamic finite element analysis;
  - for production runs of three cross sections;
  - 16 case x 8 time history = 128 analyses

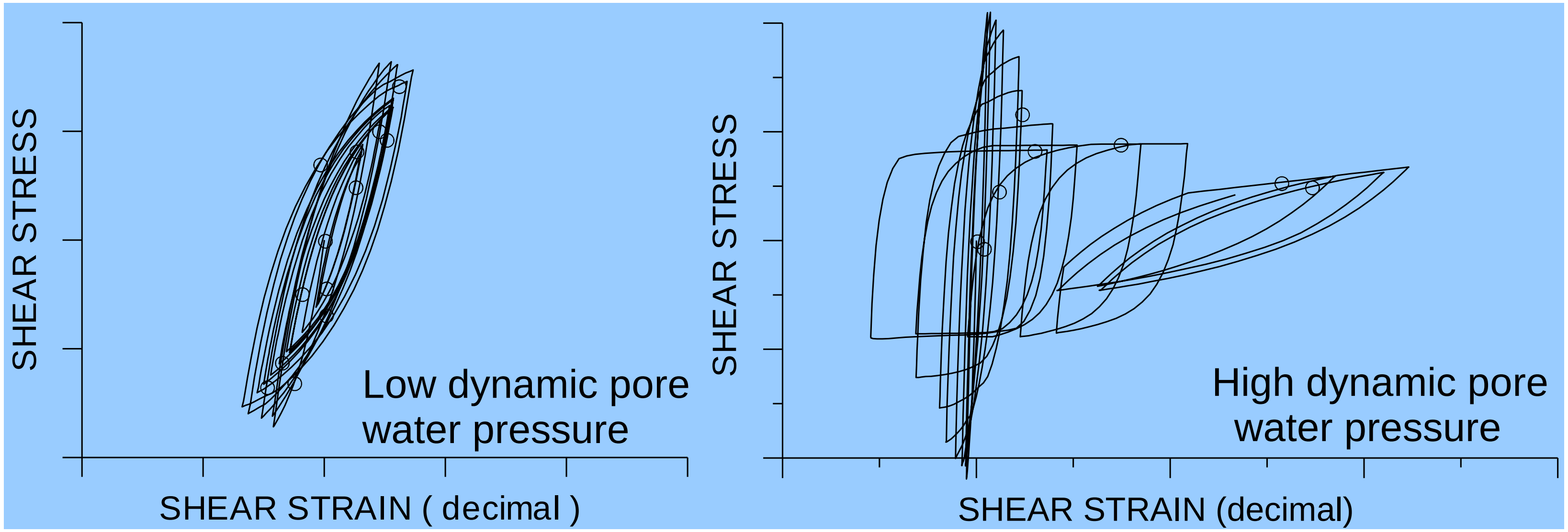
- FLAC-2D (Itasca Consulting Inc., USA):
  - Dynamic finite difference analysis;
  - As independent check
  - Completed 3 runs (2007)

Ruskin Right Abutment – Seismic Deformations

Finite Element Time-History Analysis using VERSAT-2D

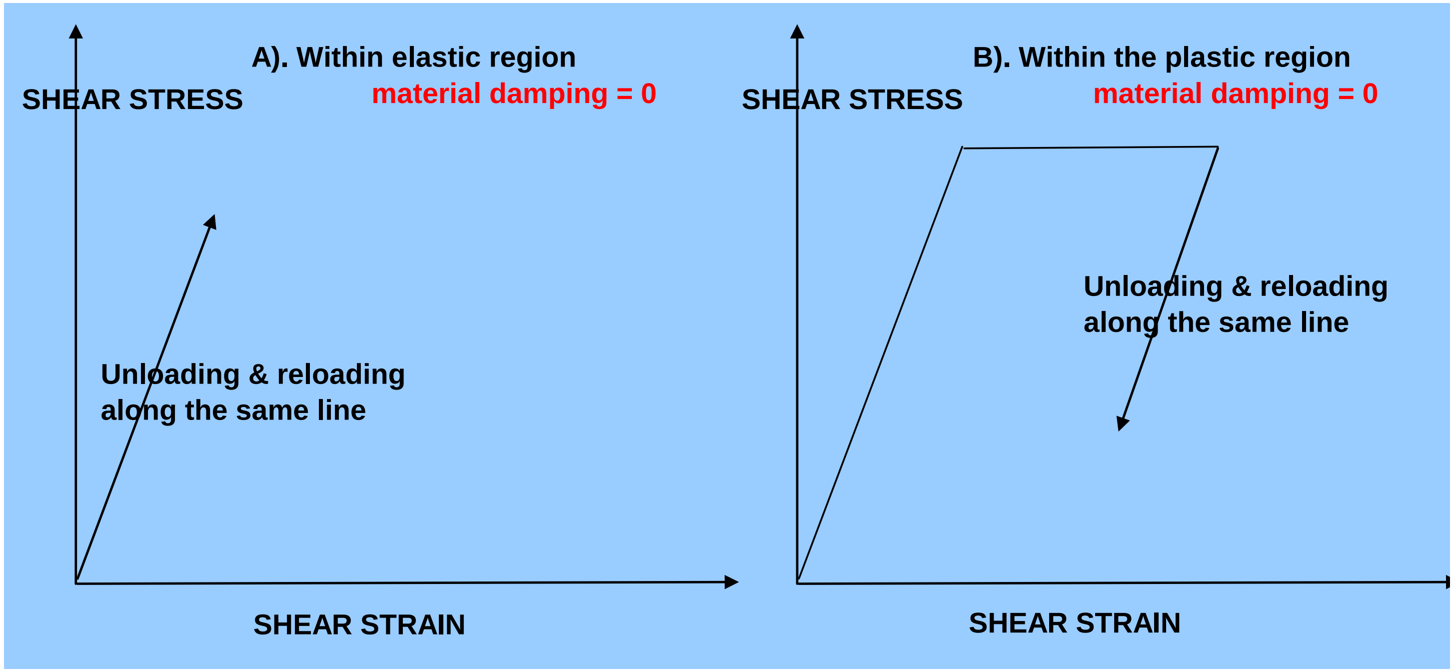
- Finite element method, fast and reliable convergence
- Nonlinear hyperbolic model
- Simulate hysteretic damping of soil under dynamic loads
- Conduct analyses in an effective stress mode if needed

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



Finite Difference Dynamic Analysis using FLAC-2D

- Finite difference method, slower convergence
- Elastic-perfectly-plastic model (bilinear model)
- Rayleigh damping for soil hysteretic damping – very approximate

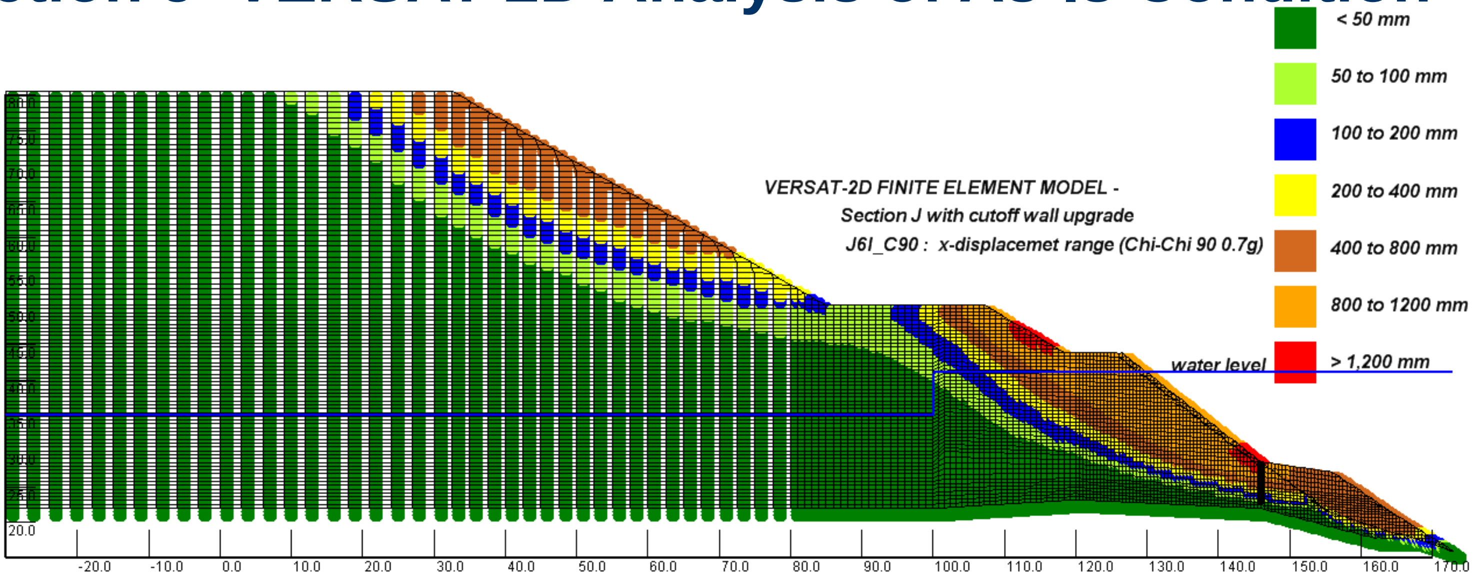


Scope of dynamic analyses

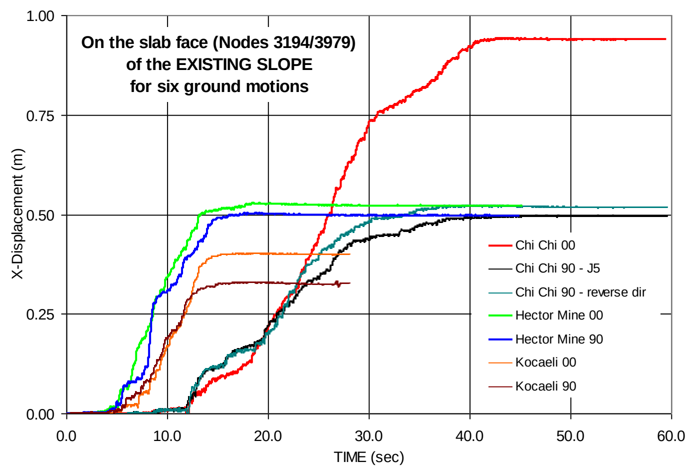
- Section C – through the concrete core wall
  - Existing conditions
  - Upgrade with a cut-off wall
- Section D – through the gravity wall
  - Existing conditions
  - Upgrade with a cut-off wall
- Section J – through the sheet piles
  - Existing conditions
  - Upgrade with a cut-off wall

Ruskin Right Abutment – Seismic Deformations

Section J VERSAT-2D Analysis of As-Is Condition

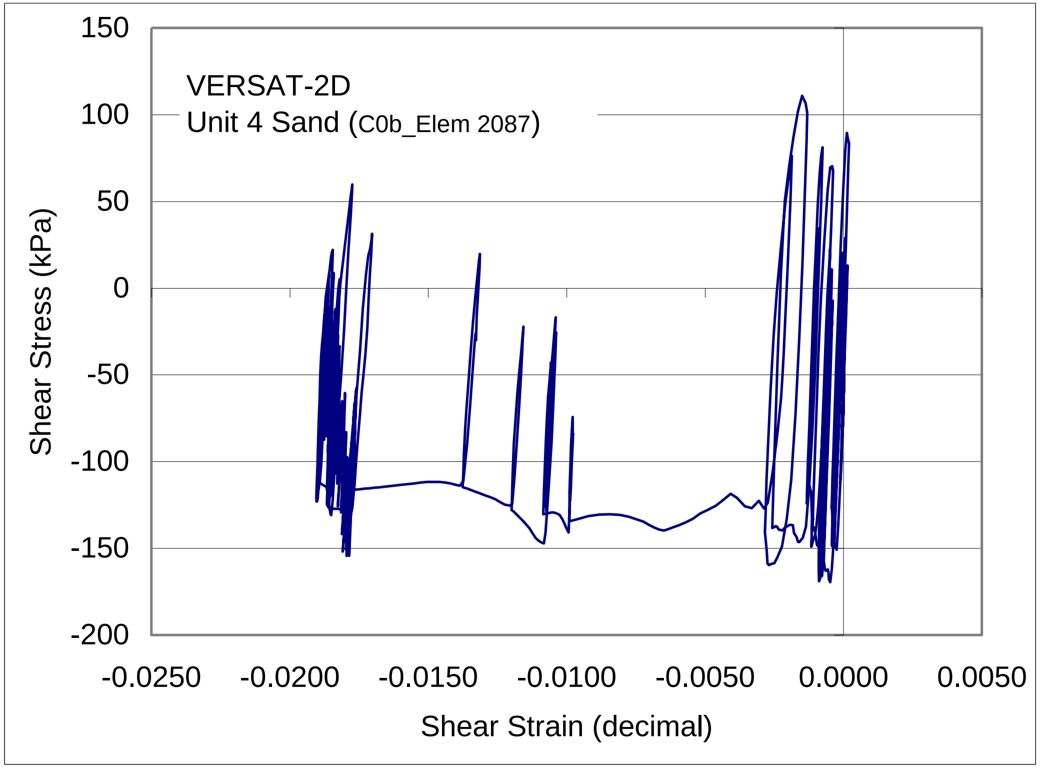


VERSAT-2D Results:
End-of-earthquake horizontal displacements (above), and time histories of x-displacements (right) under various input ground motions.

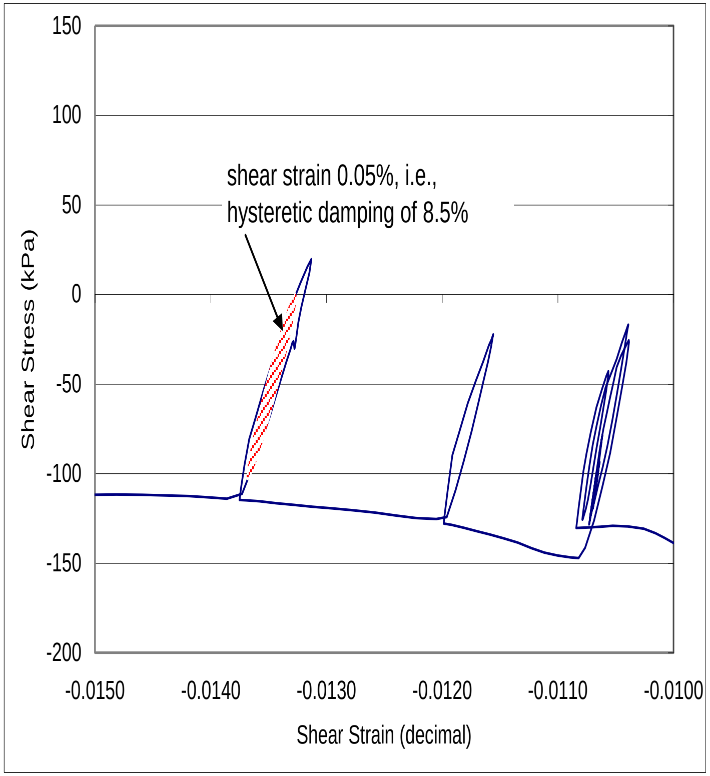


VERSAT-2D nonlinear shear stress – strain response

(a). Shear Stress-Strain History



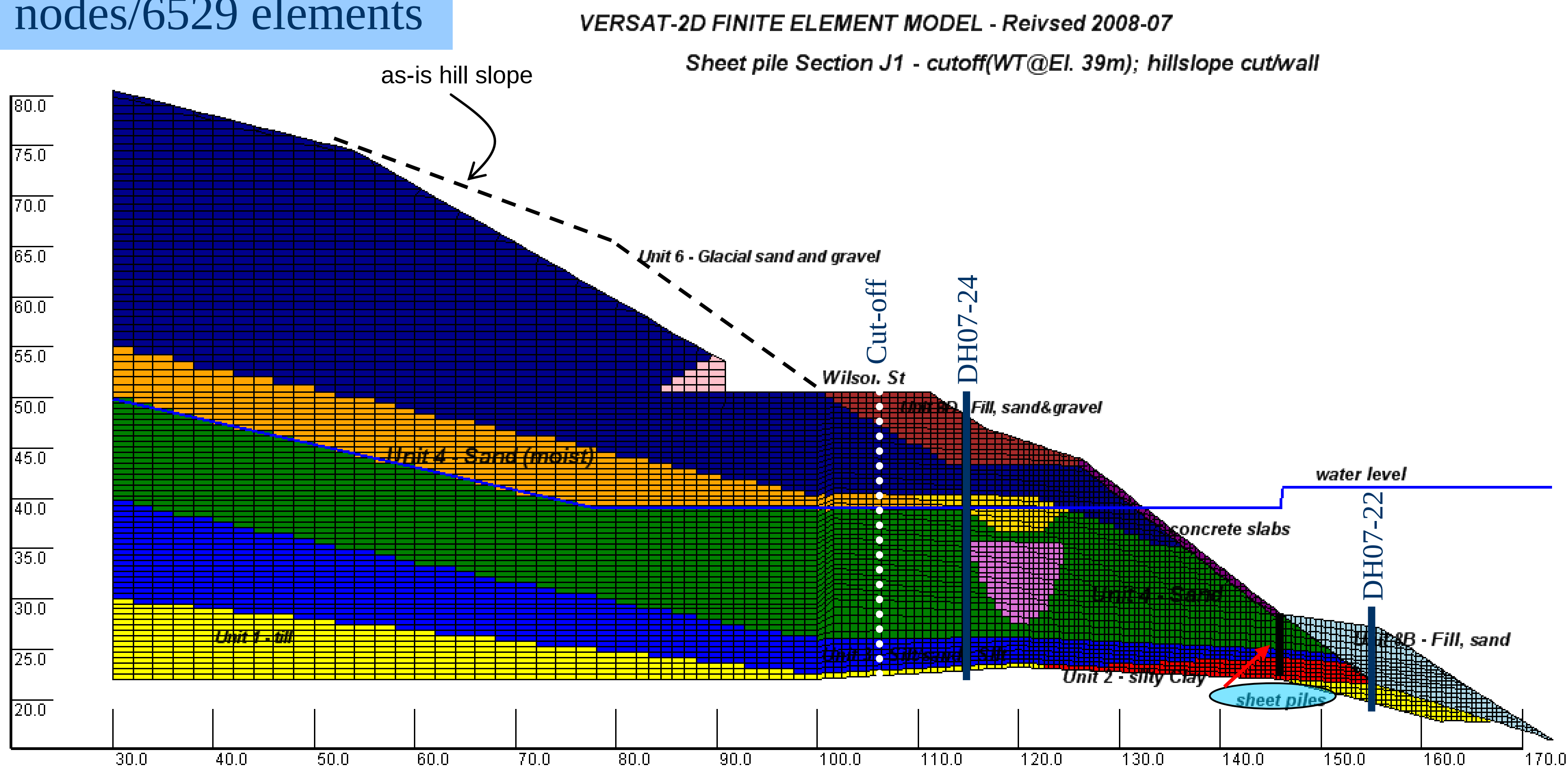
(b). Local Details



Ruskin Right Abutment – Seismic Deformations

Section J VERSAT-2D Analysis of Proposed Upgrade

Model for upgrade case:
6642 nodes/6529 elements



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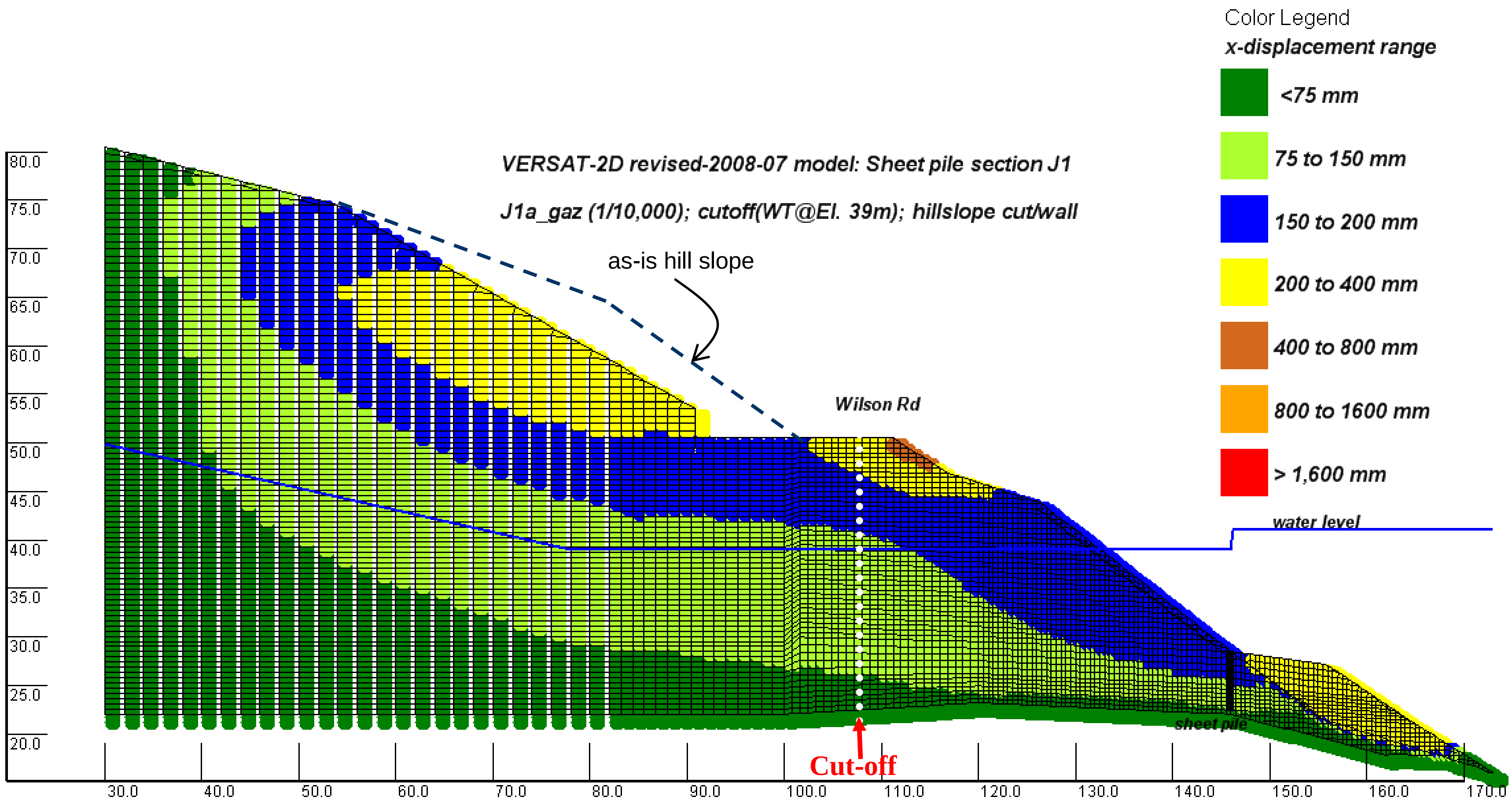
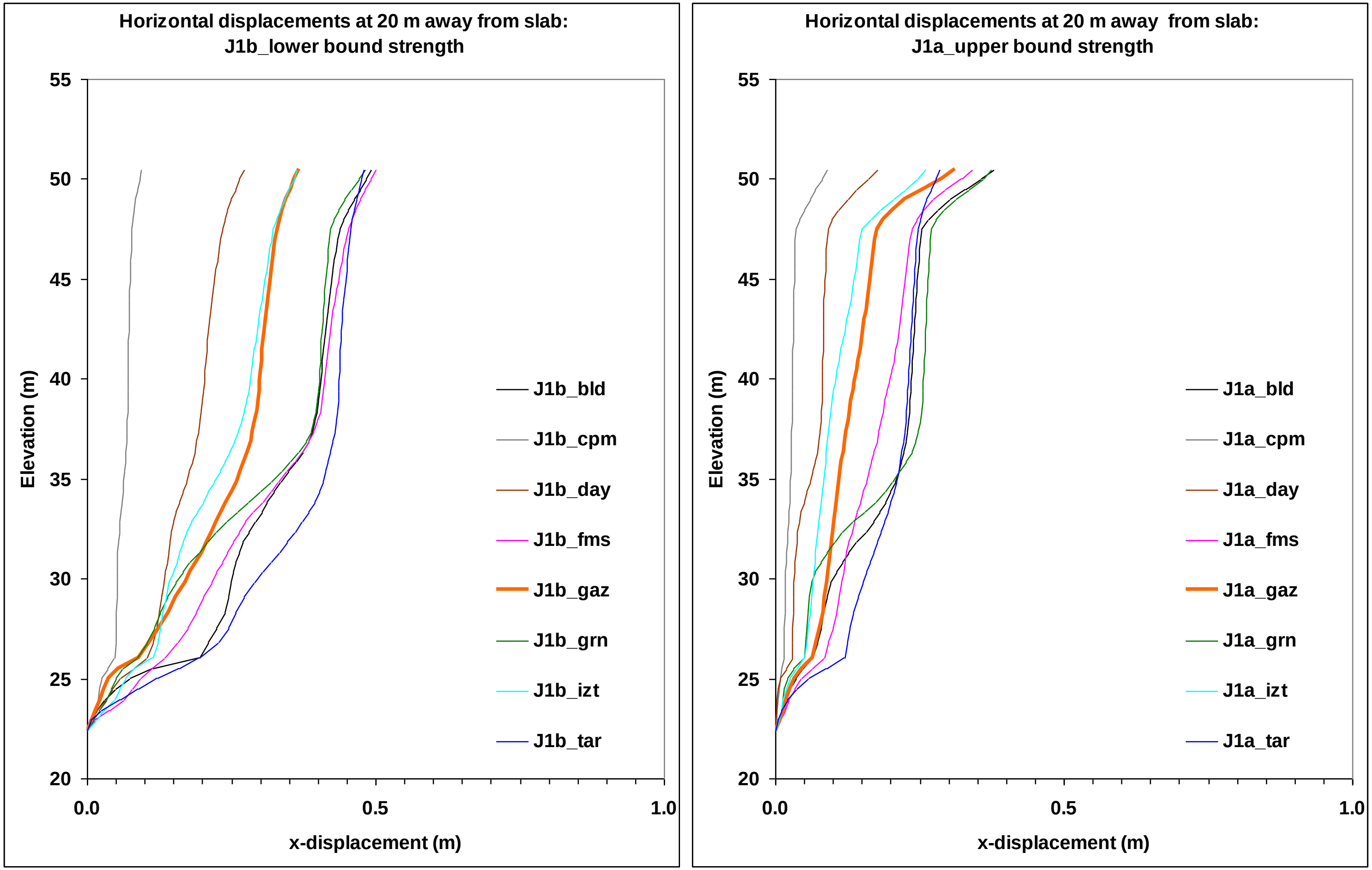
Section J VERSAT-2D Horizontal Displacements

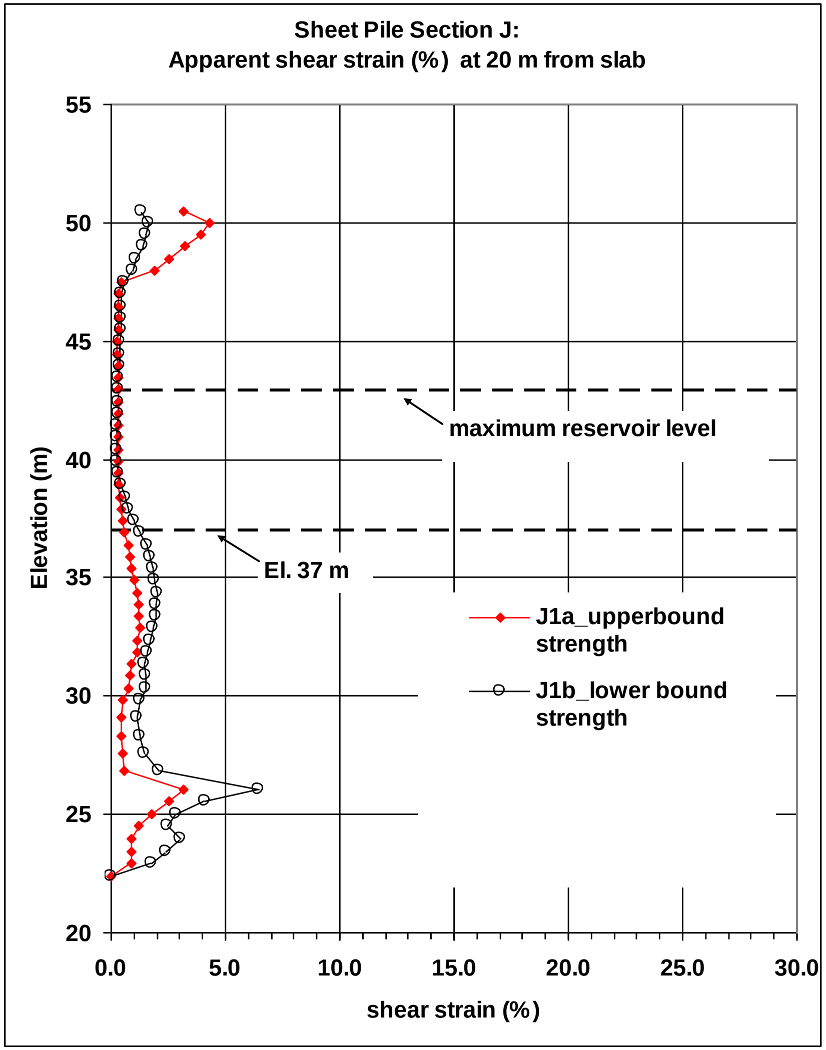


Section J: VERSAT-2D Computed Displacements at Cutoff

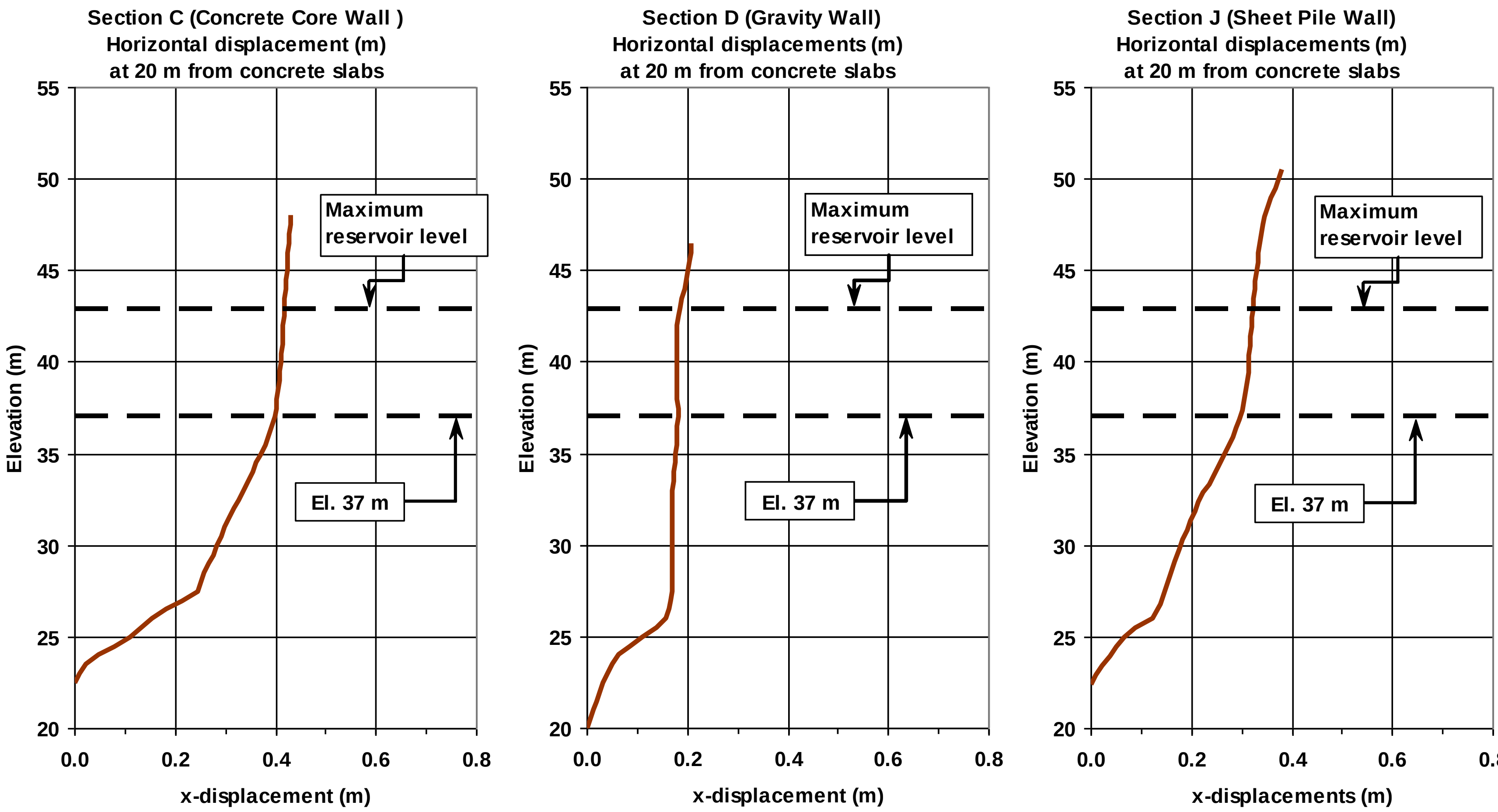


Ruskin Right Abutment – Seismic Deformations

Section J: VERSAT-2D Computed Shear Strains at Cutoff

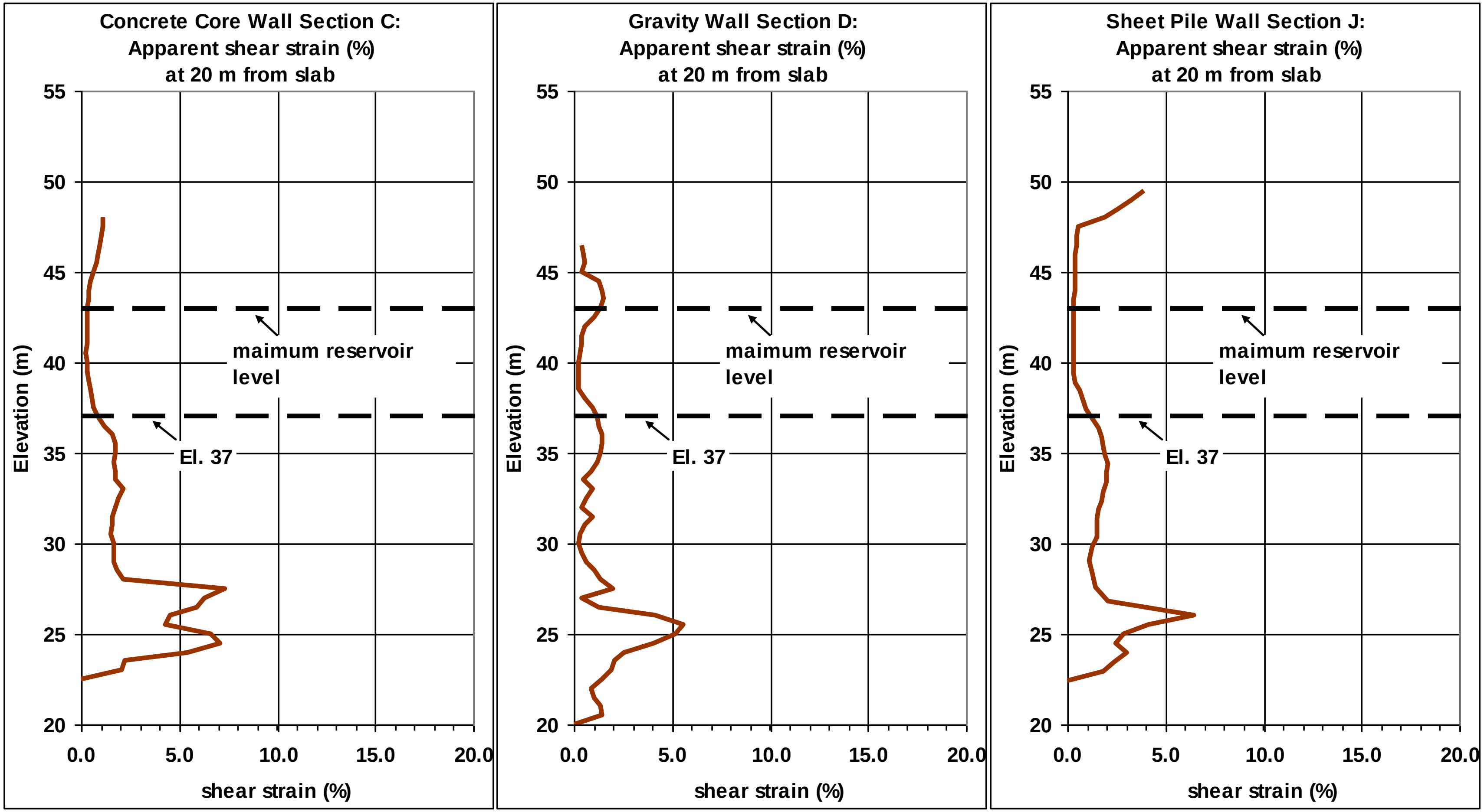


VERSAT-2D Summary of Horiz. Displacements at Cutoff



Ruskin Right Abutment – Seismic Deformations

VERSAT-2D Summary of Shear Strain Profiles at Cutoff



Ruskin Right Abutment – Seismic Deformations

Status of the Project:

Stage 1 completed:

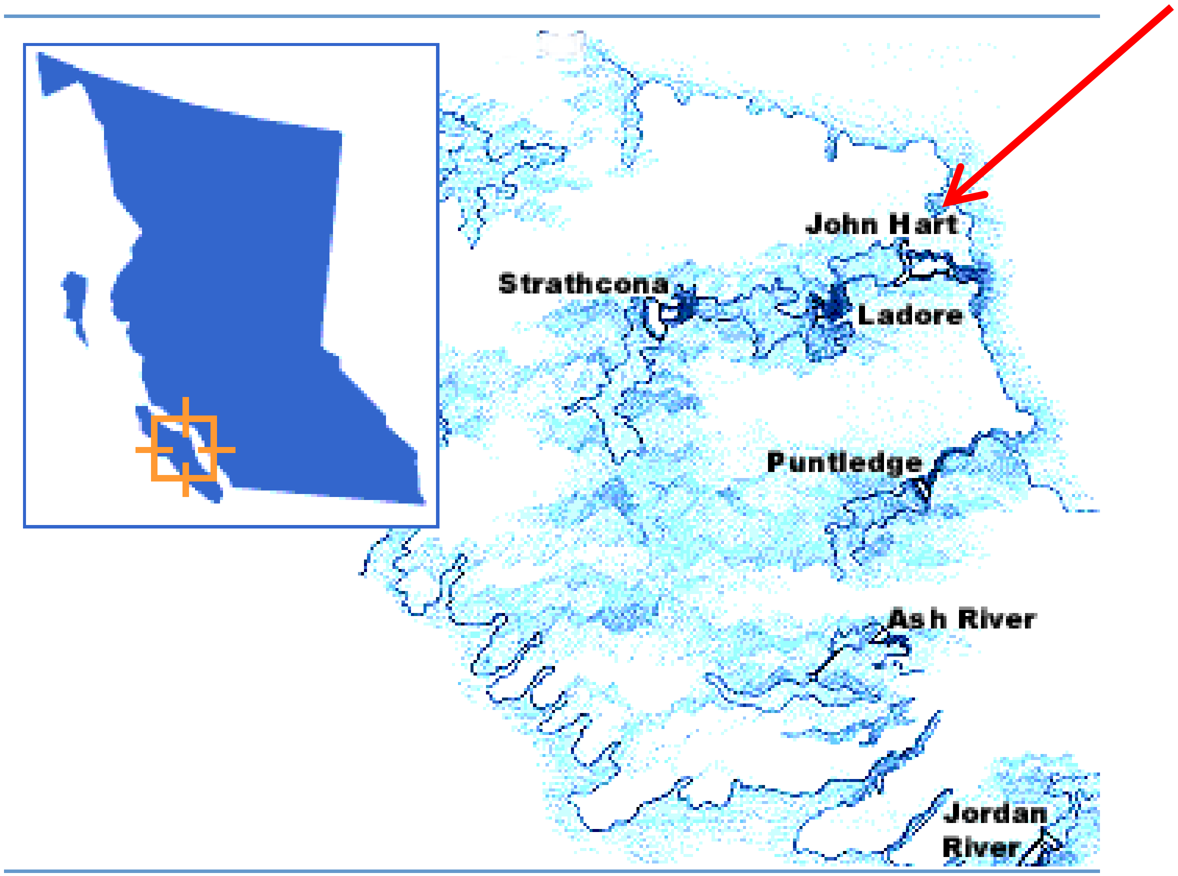
- **hillside cut; downstream filter blanket**

Stage 2 onging:

- **Final design specification for the cutoff wall**
- **Tendering of contract**
- **Implementation in 2011**

Warnings/Disclaims
for Slides No. 29 to 60 (this one) :
Results presented herein are from the early stage of the upgrade design as of 2010; and they are only representative to soil data and seismic hazard data up to 2010.

John Hart Dam – Seismic upgrade project



John Hart Dam – Seismic Upgrade

John Hart Dam

Intake Structure

Middle Earthfill Dam

North Earthfill Dam

Seismic Design Parameters

- **1987/1988 Seismic Criteria**

DBE (1/475 yr)	PGA = 0.32 g
MCE (1/2000 yr)	PGA = 0.60 g

- **Current Seismic Criteria**

Mean AEF	PGA (g)
0.01 (1/ 100)	0.09
0.0021 (1/ 475)	0.23
0.001 (1/ 1,000)	0.33
0.004 (1/ 2,475)	0.48
0.0001 (1/ 10,000)	0.74

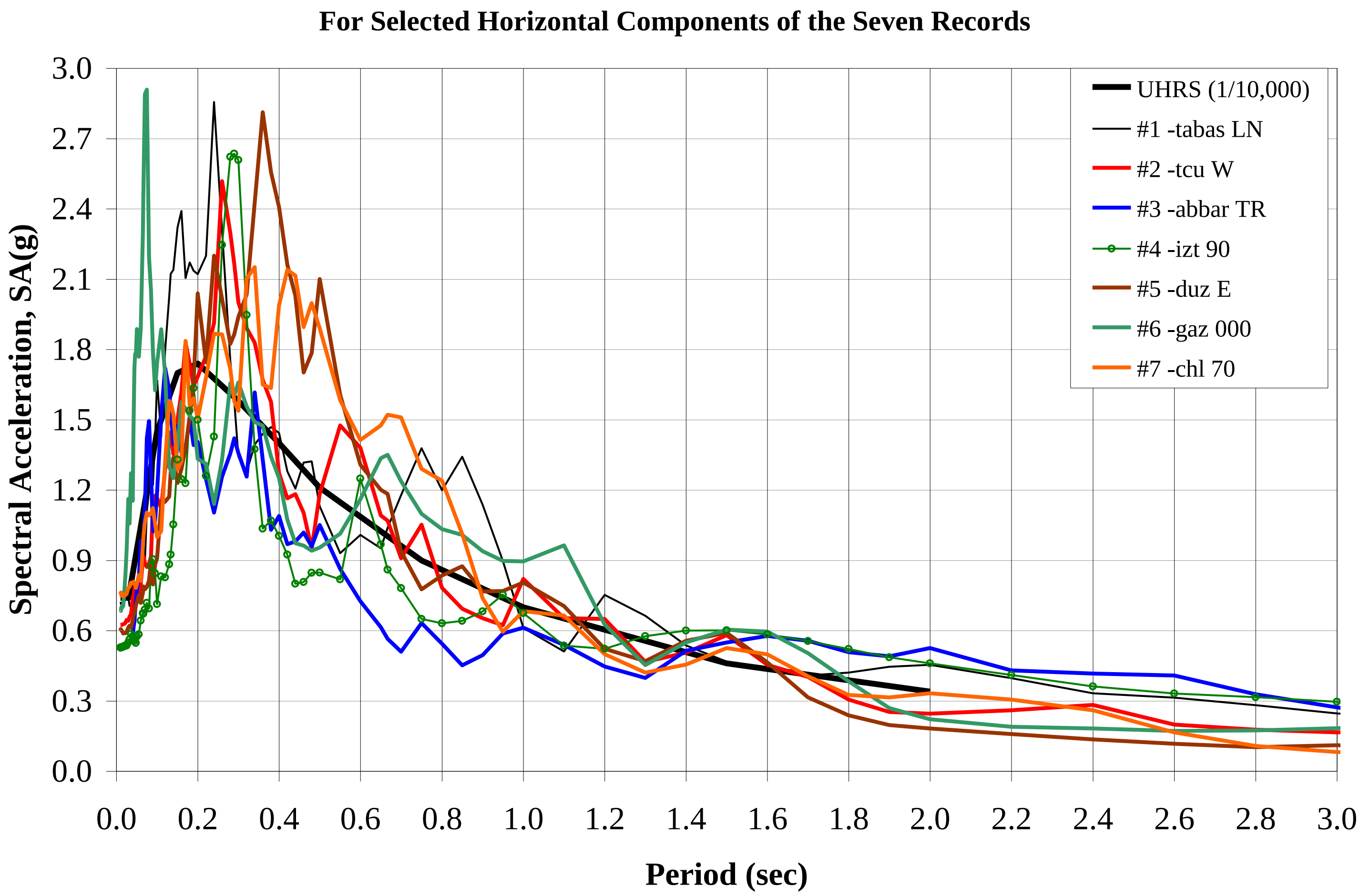
Warnings/Disclaims
for Slides No. 63 (this one) to 89:
Results presented herein are from the Deficiency Investigations (DI) of the dam as of 2010; and they are only representative to soil data and seismic hazard data up to 2010.

- The AEF of 0.0001 event has a dominant earthquake of M7.0 to M7.2 with a source-site distance of less than 10 km.

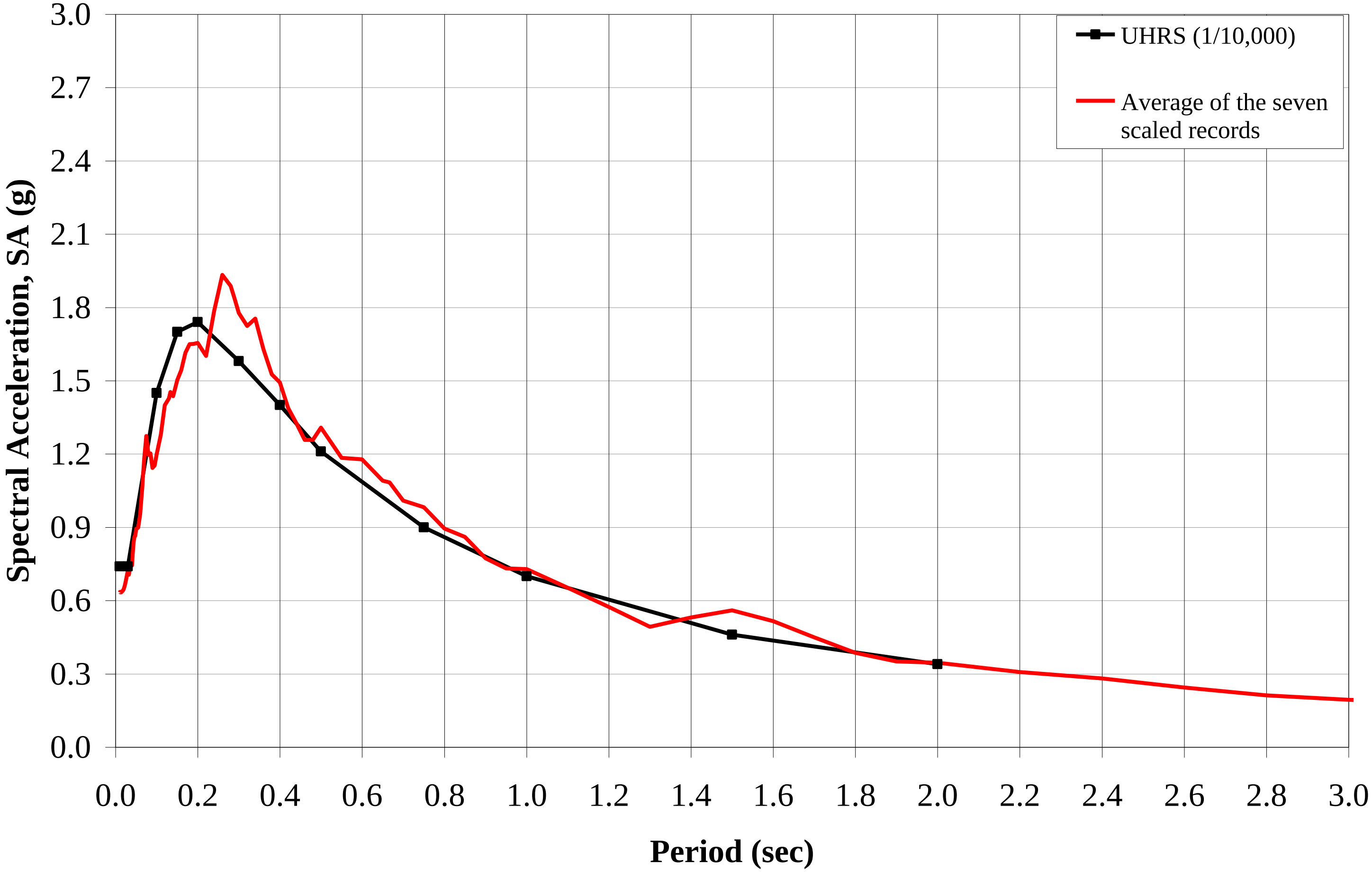
Input Earthquake Time Histroies

Record #	Event	Station	Short Name	Magnitude	Mechanism	Duration (sec)	R_{RUP} (km)	R_{JB} (km) (1)	Vs30 (m/s)	Component	PGA (g)	Scale Factor	PGA after scaling (g)	AI for modified records (m/s)
1	1978/09/16 Iran Tabas	Tabas	tab	7.4	Reverse Normal		3	2	767	LN	0.84	0.85	0.71	8.3
2	1999/09/20 Taiwan Chi-Chi	TCU071	tcu	7.6	Reverse Normal	90	5	0	625	W	0.57	1.10	0.62	11.3
3	1990/06/20 Iran Manjil	BHRC 99999 Abbar	abbar	7.4	Strike Slip	55	13	13	724	T	0.50	1.05	0.52	8.4
4	1999/08/17 Turkey Kocaeli	Izmit	izt	7.4	Strike Slip	30	7	4	811	#090	0.22	2.40	0.53	4.7
5	1999/11/12 Turkey Duzce	531 Lamont 531	duz	7.1	Strike Slip		8	8	660	E	0.12	5.00	0.59	10.3
6	1976/05/17 USSR Gazli	9201 Karakyr	gaz	6.8	Reverse Normal	16	5	4	660	#000	0.61	1.12	0.68	5.8
7	1994/01/17 US Northridge	USC 90015, Chalon Rd, LA	chl	6.7	Reverse Normal		20	10	740	#70	0.23	3.30	0.74	6.7

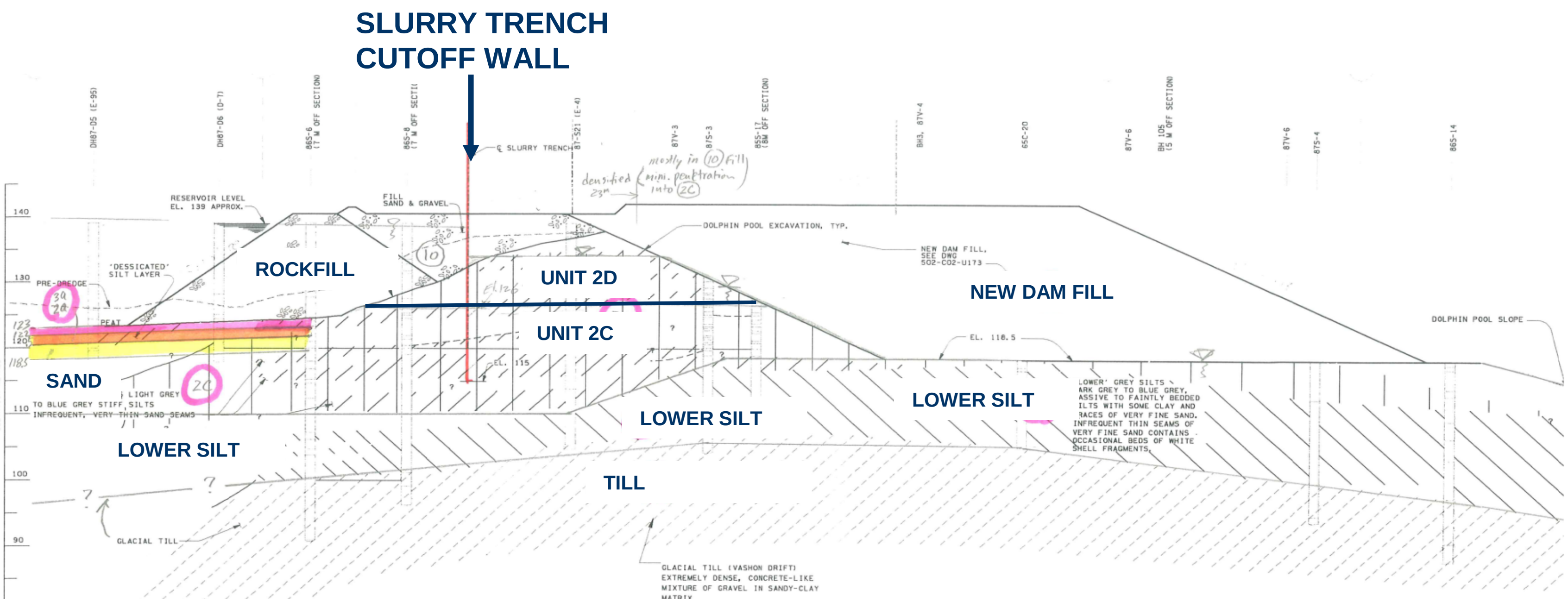
Input Earthquake Time Histroies



Input Earthquake Time Histroies



Middle Earthfill Dam – Section 21



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John Hart Dam – Seismic Deformations

Key Soil Parameters for the Soil Models of the Mid Dam Sections

Unit	Description	Elevation (m)	$(N_1)_{60}$ (30th Percentile)	FC (%) (30th Percentile)	$(N_1)_{60\text{-}cs}$ $=(N_1)_{60}+\Delta(N_1)_{60}$	$(N_1)_{60\text{-}sr}$	S_r/σ_{vo}'	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction angle Φ (°)	V_s (m/s)	K_{2max} (2)
-	Rockfill	122 - 140.5	NA					20	0	40		120
-	Sand&Gravel Fill (vibro-compacted)	122 - 140.5	51		Not liquefiable			20	0	38		74
-	New Dam Fill	118 - 141.5	NA					21	0	38		130
2d	Interbedded Silt and Sand	126 - 135	44	35 (1)		Not liquefiable		19.6	0	36	300	
2a	Sand, some silt	120 - 121	10	< 5	10	10	0.09	19.6	0	35	300	
2b	Sand, some silt	118 - 120	26	< 5	26	26	0.28	19.6	0	35	300	
2c	Interbedded Silt and Sand	110 - 126	17	35 (1)	22	20	0.18	19.6	0	35	300	
3	dessicated Silt	121 - 122	19					19.6	145	0	300	
4b	Sand & Gravel	? - 120	60		Not liquefiable			20	0	40	330	
5	lower grey Silt	below 118	10					19.6	145	0	310	
6	Vashon drift (Till)	variable				Not required in model					760	

(1) FC=35% is assumed for Unit 2c/2d based on data from the Intake area

(2) $G_{max} = 217K_{2max}(\sigma'_m)^{0.5}$ where σ'_m is the effective mean stress in kPa; K_{2max} of 130 for the compacted new dam fill was based on measured V_s data from the Bennett Dam (Figure 2-18 of the 2004 Report No. E239). K_{2max} 0f 74 for the compacted sand and gravel fill was estimated from the $(N_1)_{60}$ which was determined from 56 post-densification Becker Penetration Test Holes.

Limit equilibrium analyses

Section 21 - Upstream Post-liquefaction (FoS=0.87)

Material #: 1
Description: RockFill
Model: MohrCoulomb
Wt: 20
Cohesion: 0
Phi: 40
Piezometric Line: 1

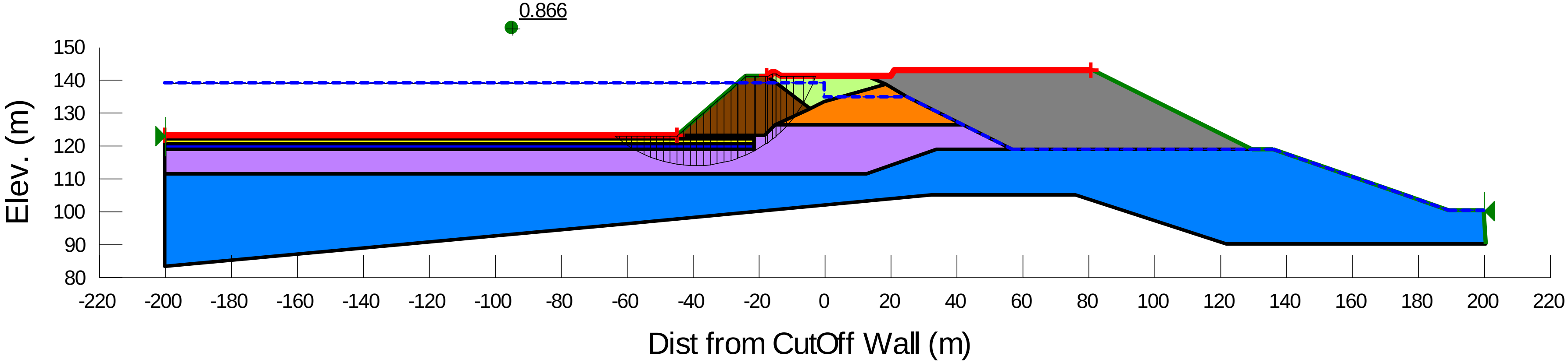
Material #: 5
Description: 2a-Sand
Model: SFnOverburden
Wt: 19.6
Tau/Sigma Ratio: 9.e-002
Piezometric Line: 1

Material #: 7
Description: 2c-Int Silt-Sand
Model: SFnOverburden
Wt: 19.6
Tau/Sigma Ratio: 0.18
Piezometric Line: 1

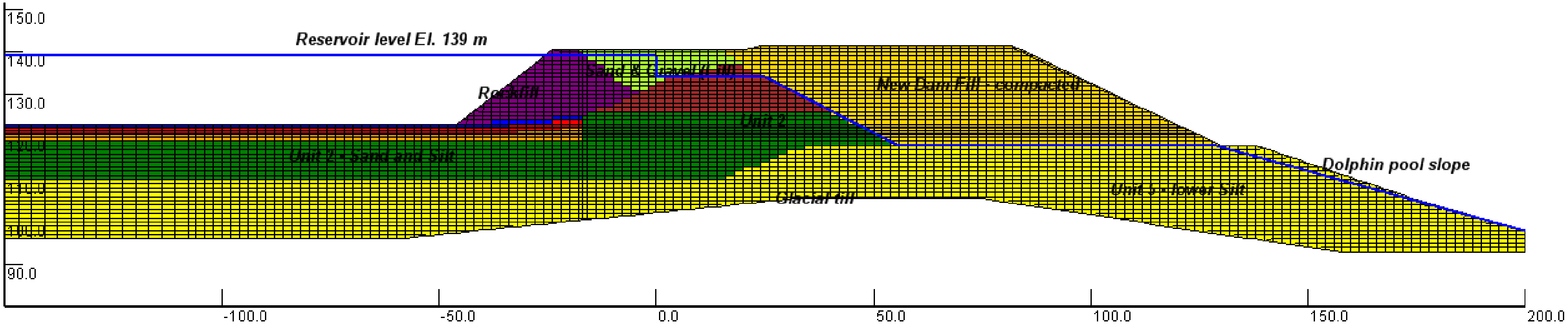
Material #: 2
Description: Sand-Gravel Fill (Vibro)
Model: MohrCoulomb
Wt: 20
Cohesion: 0
Phi: 38
Piezometric Line: 1

Material #: 6
Description: 2b-Sand
Model: SFnOverburden
Wt: 19.6
Tau/Sigma Ratio: 0.28
Piezometric Line: 1

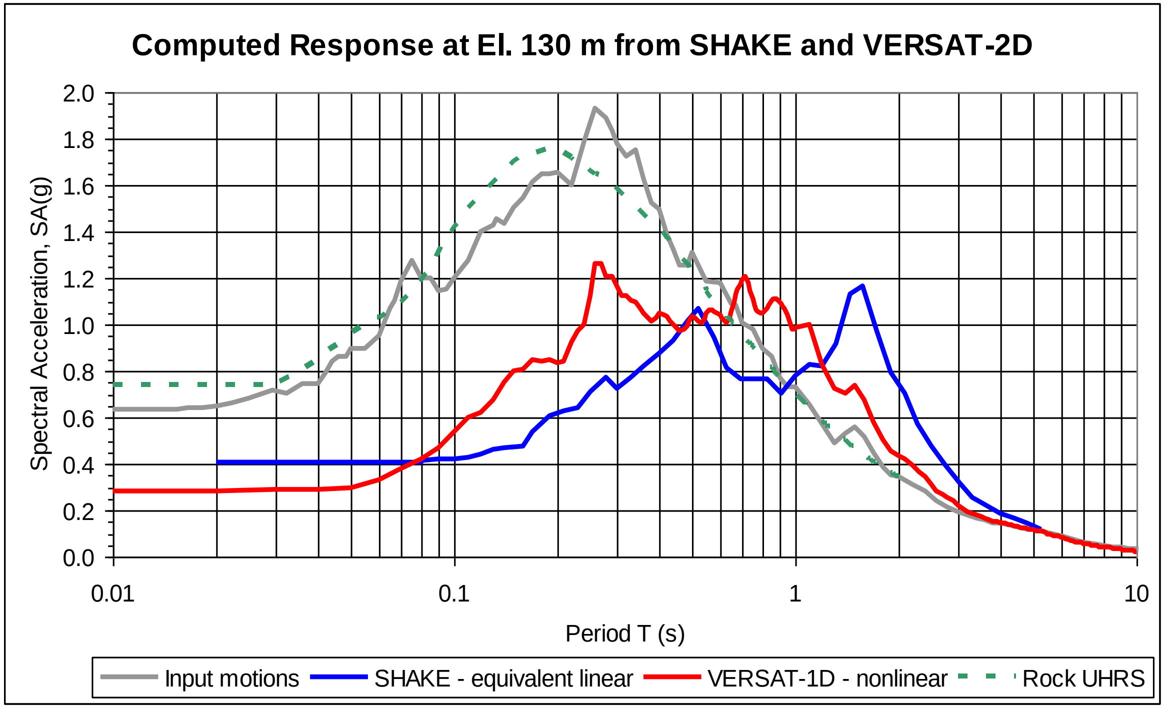
Material #: 8
Description: 3-dessicated Silt
Model: UndrainedPhiZero
Wt: 19.6
Cohesion: 145
Piezometric Line: 1



Middle Earthfill Dam – VERSAT-2D Model



Site Response Comparison



John Hart Dam – Seismic Deformations

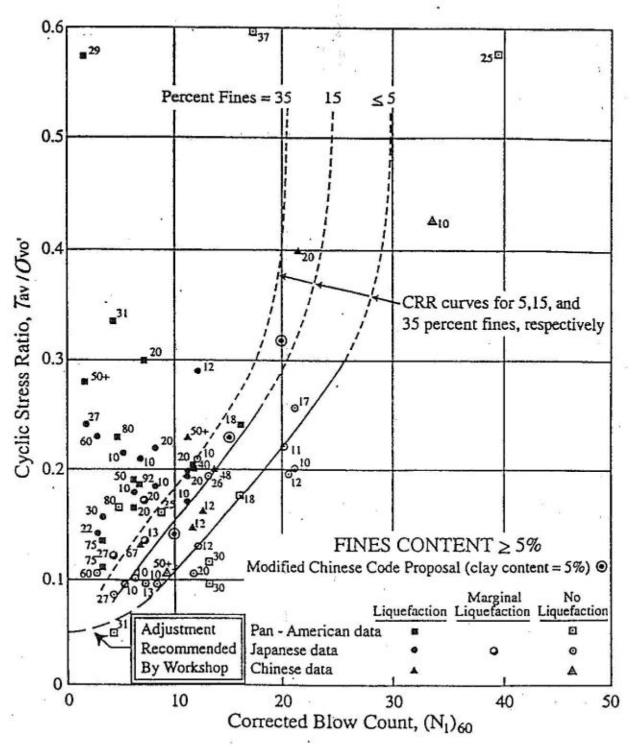
VERSAT-2D Dynamic Effective Stress Model

- Three pore water pressure models
  - Martin-Finn-Seed model (MFS)
  - Modified MFS Pore Water Pressure Model

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

  - Seed's Pore Water Pressure Model

$$u / \sigma_{v0}' = \frac{2}{\pi} \arcsin\left(\frac{N_{15}}{N_l}\right)^{\frac{1}{2\theta}}$$



G. Wu, 2001. Dynamic analyses of the Upper San Fernando dam, Canadian Geotechnical Journal, 2001, Vol. 38: 1-15.

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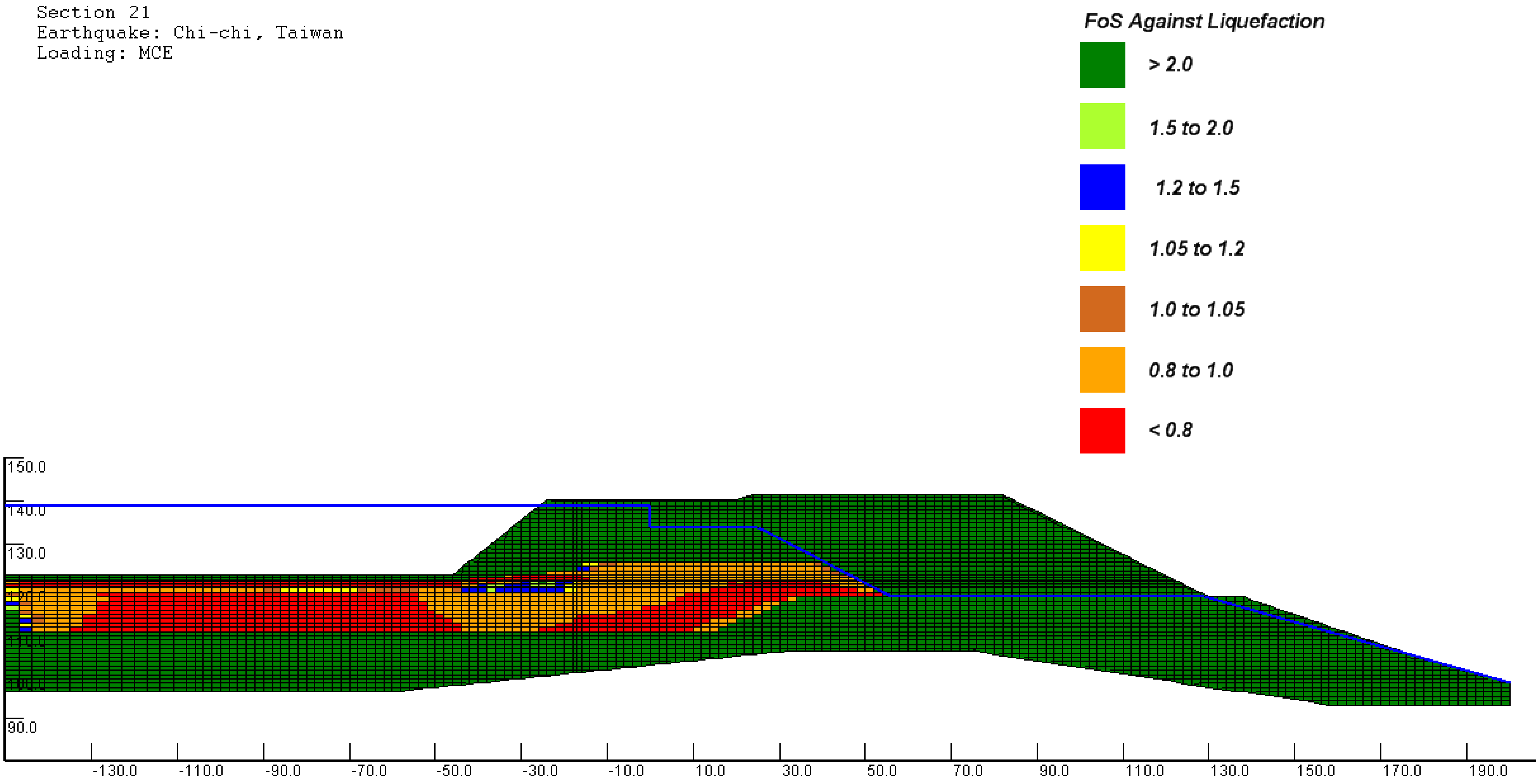
John Hart Dam – Seismic Deformations

Factor of Safety Against Liquefaction: 1/10,000 (Chi Chi record)



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John Hart Dam – Seismic Deformations

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HORIZONTAL DISPLACEMENT CONTOURS: 1/10,000 (Chi Chi record)

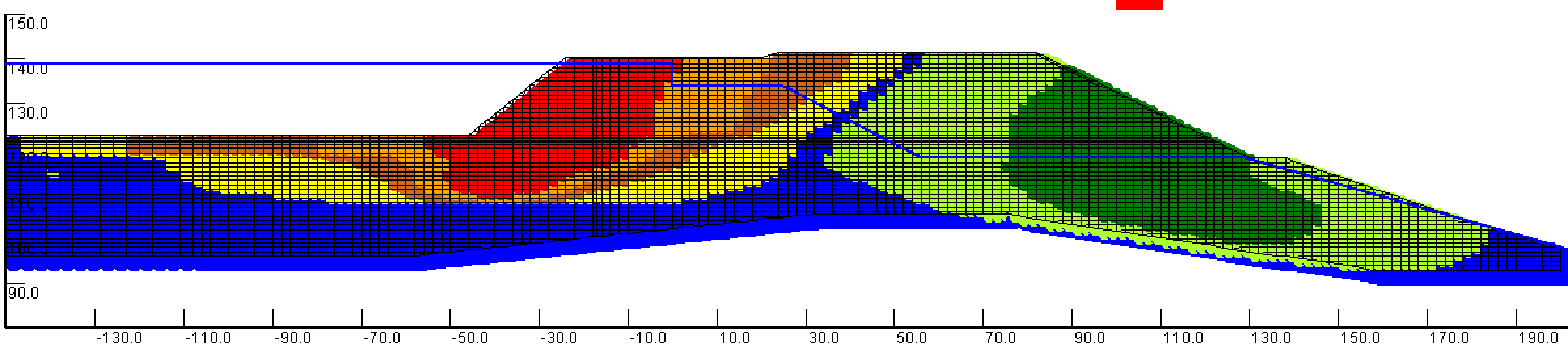
```
Section 21
Earthquake: Chi-Chi, Taiwan
Loading: MCE

Max horizontal displacement at U/S: 5.54 m
Max horizontal displacement at D/S: 0.67 m

Horizontal displacement at Cutoff: -3.10 m
Horizontal displacement at US Crest: -5.16 m
Horizontal displacement at DS Crest: 0.49 m
```

Horizontal displacement (m)

- *> 0.5 Downstream*
- *0.1 to 0.5 Downstream*
- *-0.1 to 0.1 Minor movement*
- *-0.1 to -1.0 Upstraem*
- *-1.0 to -2.0 Upstraem*
- *-2.0 to -3.0 Upstraem*
- *> -3.0 Upstraem*



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John Hart Dam – Seismic Deformations

VERTICAL DISPLACEMENT CONTOURS: 1/10,000 (Chi Chi record)

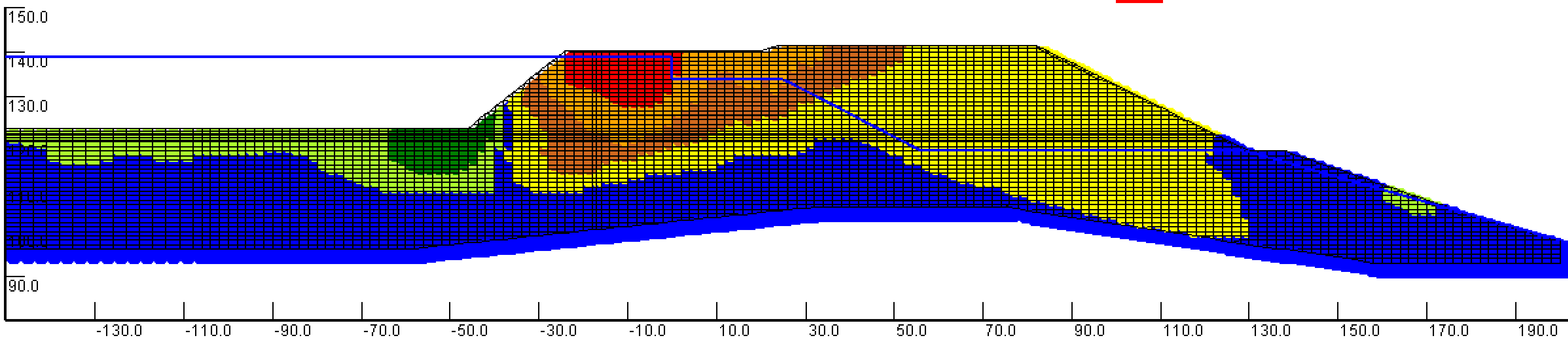
```
Section 21
Earthquake: Chi-Chi, Taiwan
Loading: MCE

Max y-displacement in Up direction: 2.83 m
Max y-displacement in Down direction: 2.14 m

Y-displacement at US Crest: -1.82 m
Y-displacement at DS Crest: -0.26 m
Y-displacement at Cutoff: -1.72 m
```

Vertical Displacement (m)

> 1.0	*up*
0.1 to 1.0	*up*
-0.1 to 0.1	*minor movement*
-0.1 to -0.5	*down*
-0.5 to -1.0	*down*
-1.0 to -1.5	*down*
> -1.5	*down*



John Hart Dam – Seismic Deformations

Summary of Displacements at Top of the Cut-off (Section 21)

Earthquake Record	1/10,000 (*)		1/2475 (*)		1/475 (*)	
	X-disp (m)	Y-disp. (m)	X-disp (m)	Y-disp. (m)	X-disp (m)	Y-disp. (m)
Chi-Chi, Taiwan	-3.10	-1.79	-2.18	-1.44		
Duzce, Turkey	-2.85	-1.48	-2.22	-1.11	-0.98	-0.57
Gazli, USSR	-0.94	-0.59	-0.50	-0.33		
Kocaeli, Turkey	-1.65	-0.92	-1.01	-0.58	-0.24	-0.17
Manjiil, Iran	-2.31	-1.56	-1.22	-0.72		
Northridge, USA	-2.16	-1.25	-1.49	-1.07	-0.51	-0.32
Tabas, Iran	-2.44	-1.38	-1.64	-1.07		
Average	-2.21	-1.28	-1.46	-0.70		

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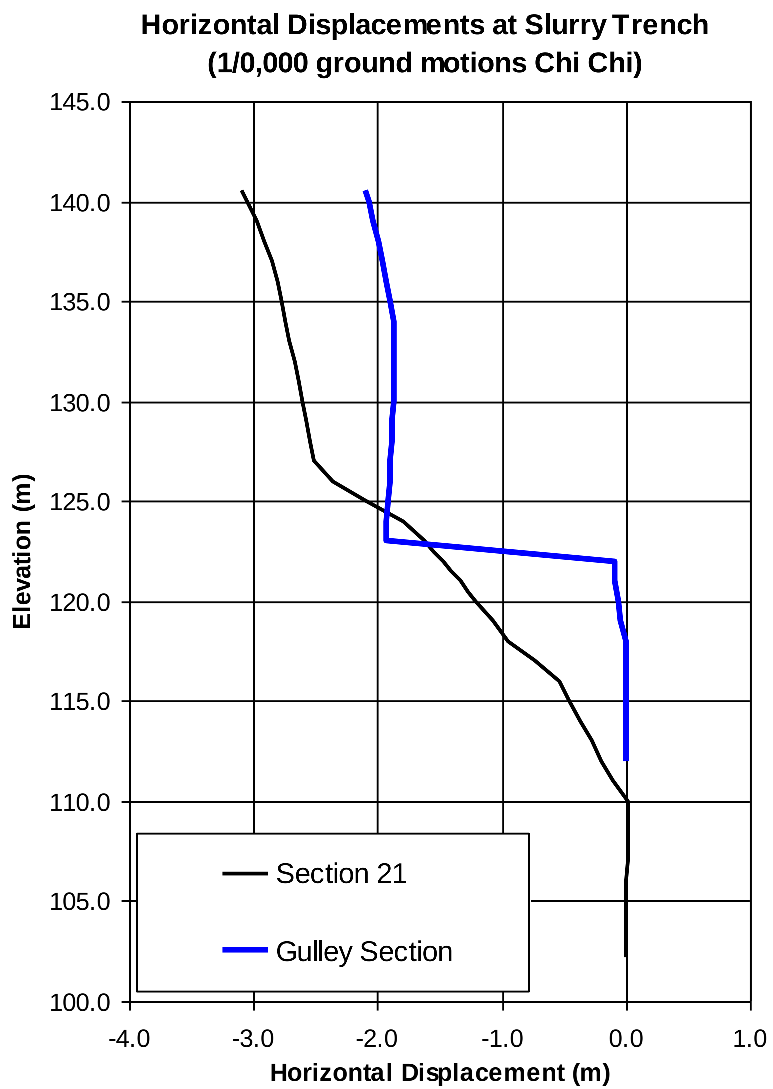
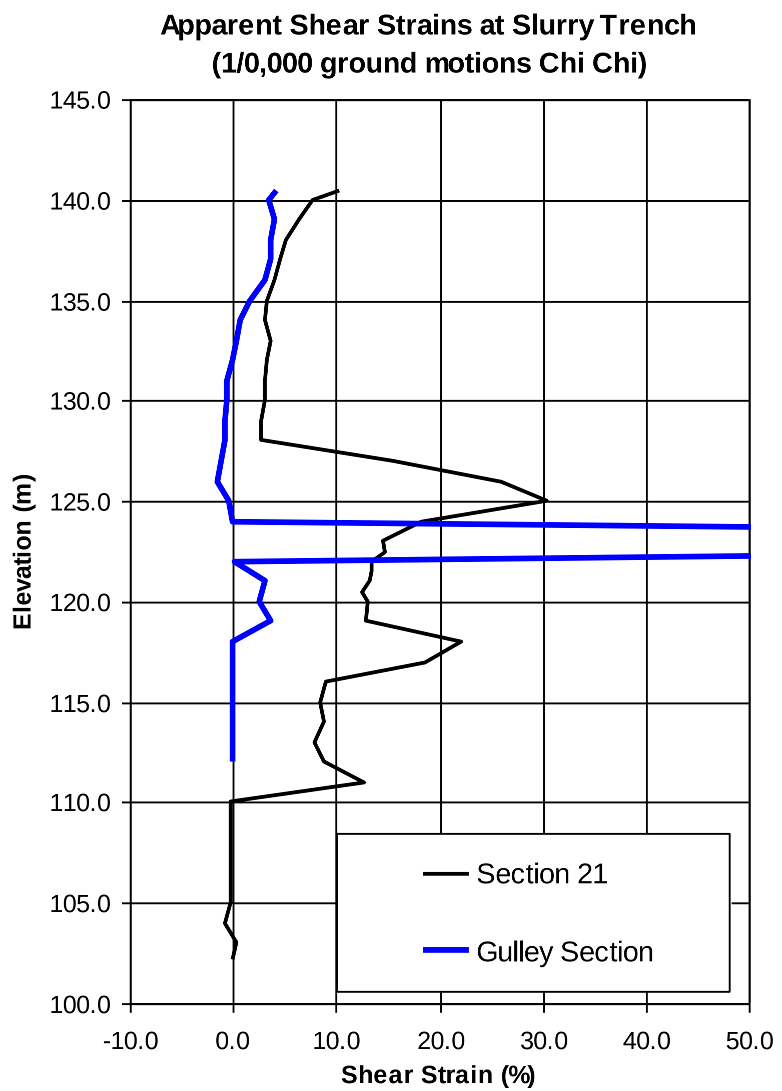
Middle Dam Slurry Trench Performance
Existing condition





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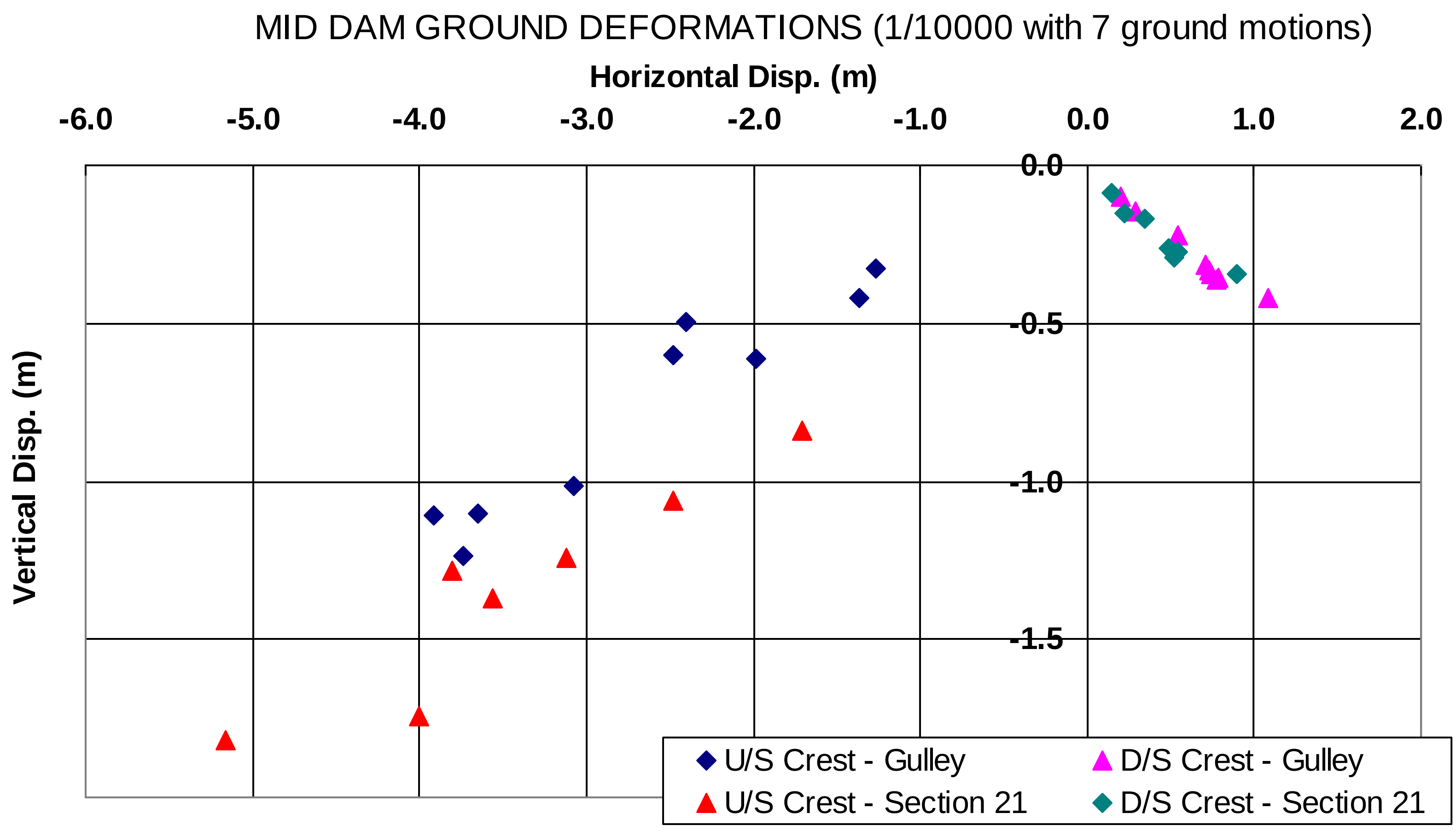
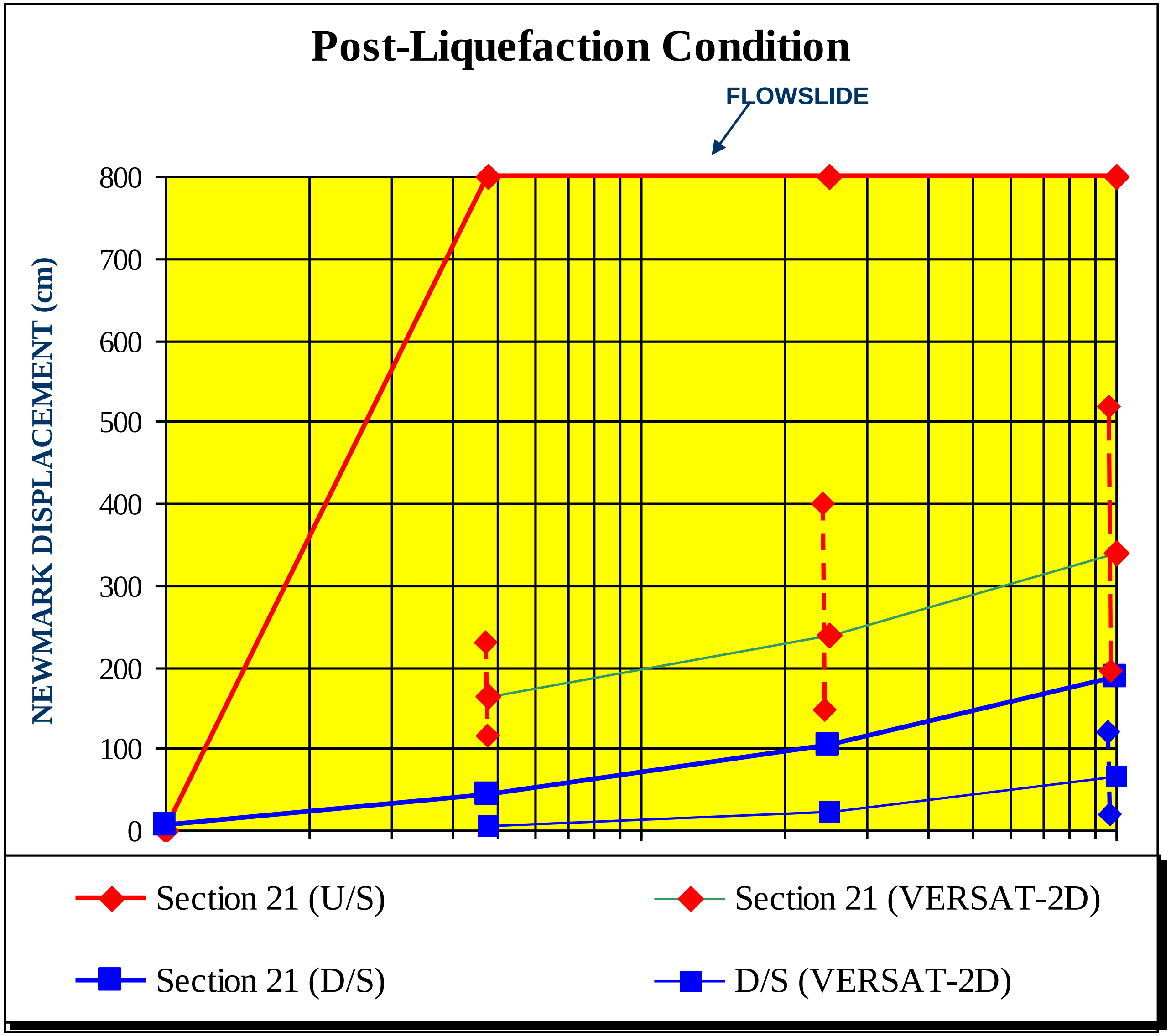
Mid Dam – Summary of Deformations



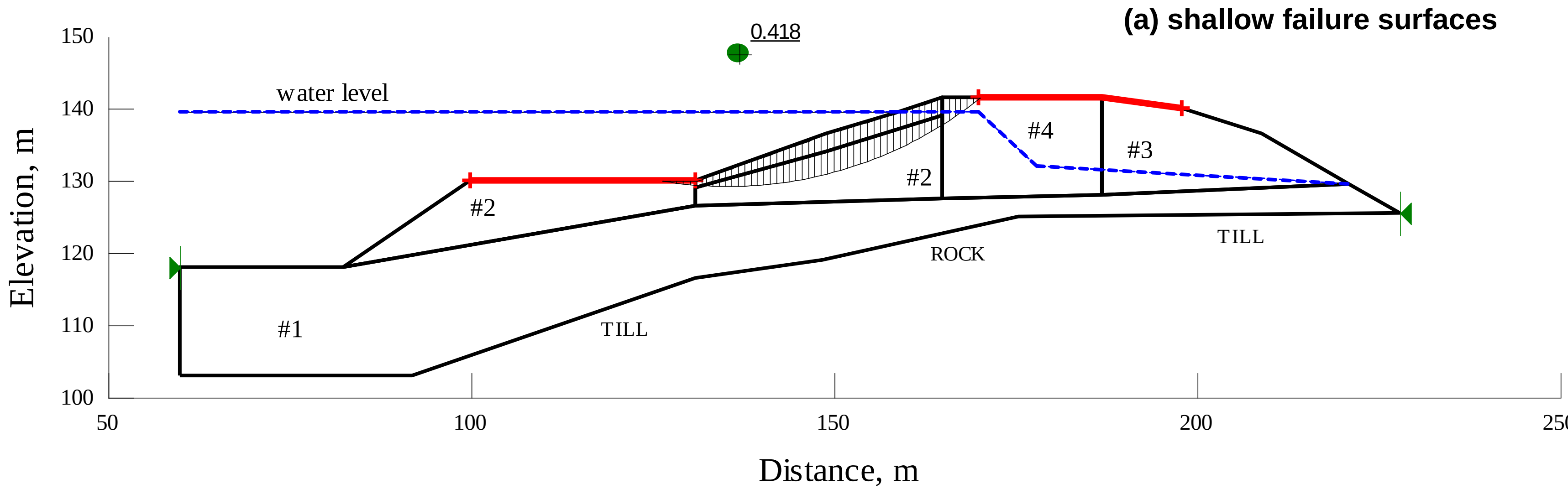
Newmark vs. VERSAT-2D (average) Displacements

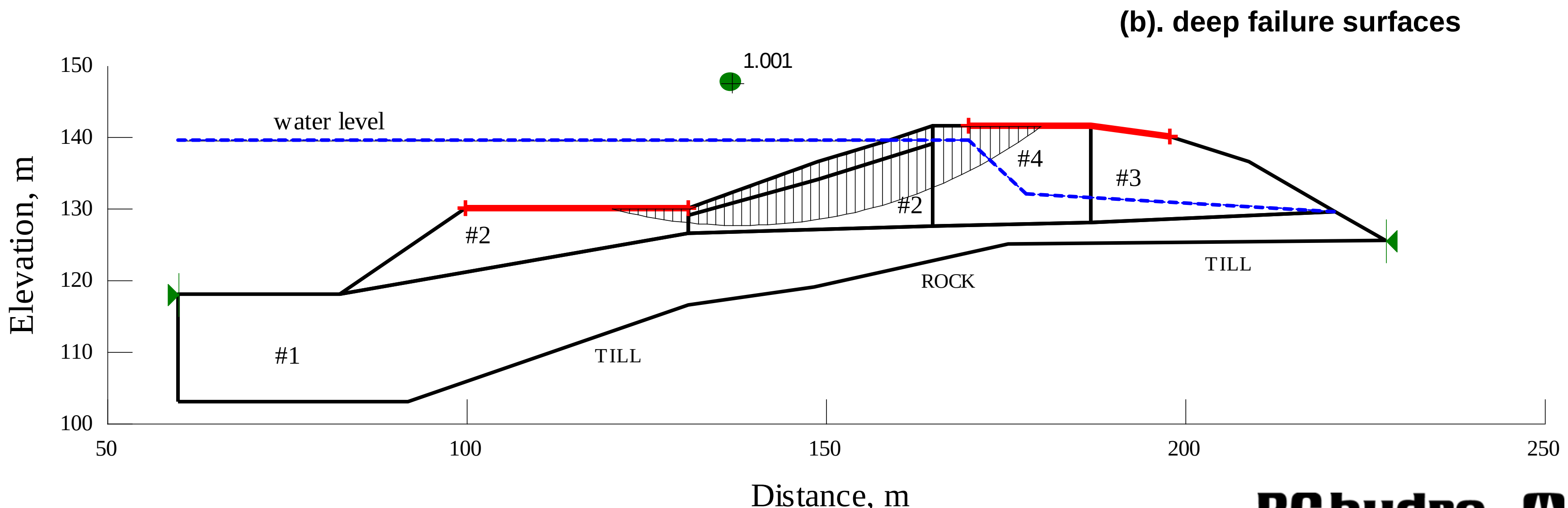


North Earthfill Dam

John Hart Dam – Seismic Deformations

North Earthfill Dam (#2: loose sand, (N1)60=10)





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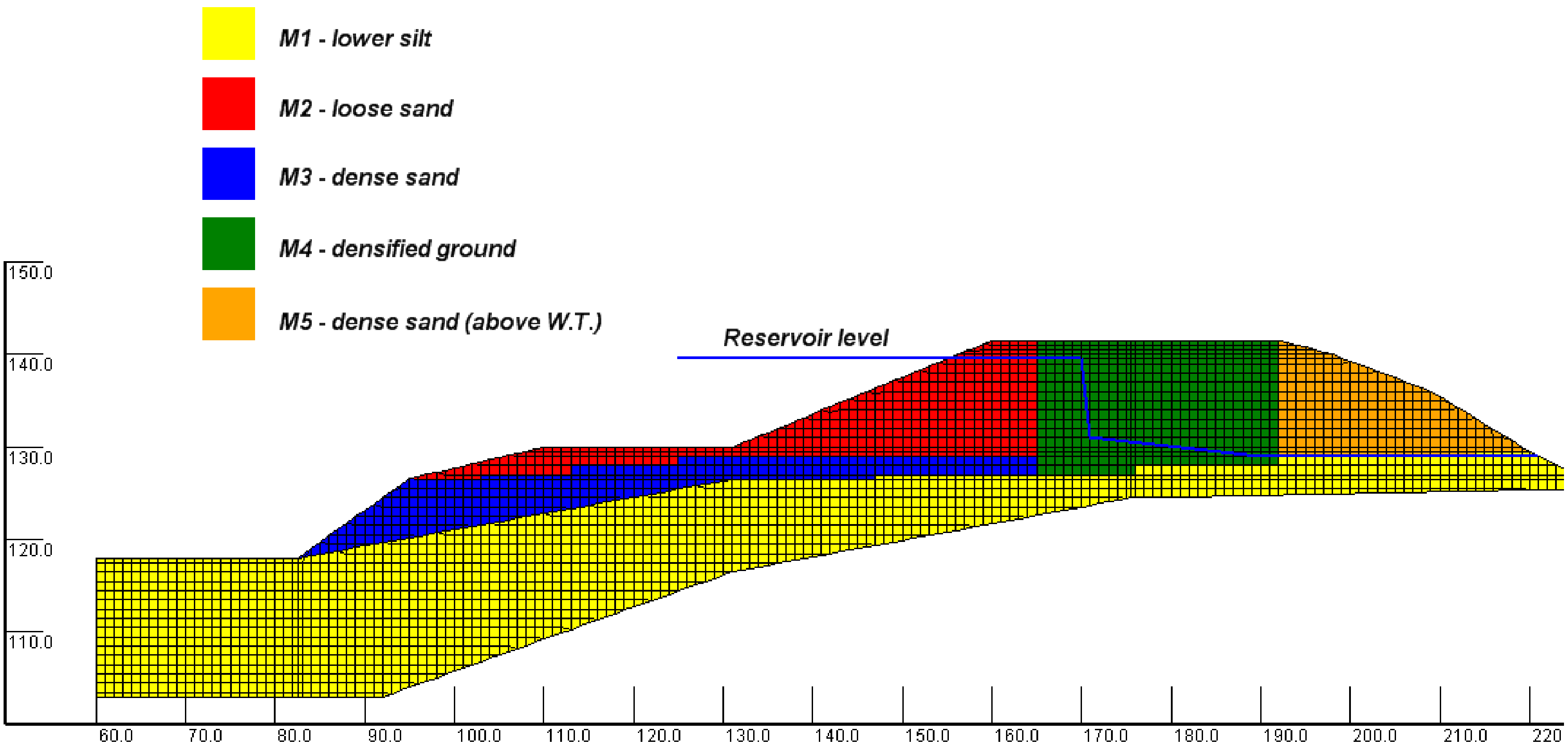
John Hart Dam – Seismic Deformations

North Earthfill Dam – VERSAT-2D Model



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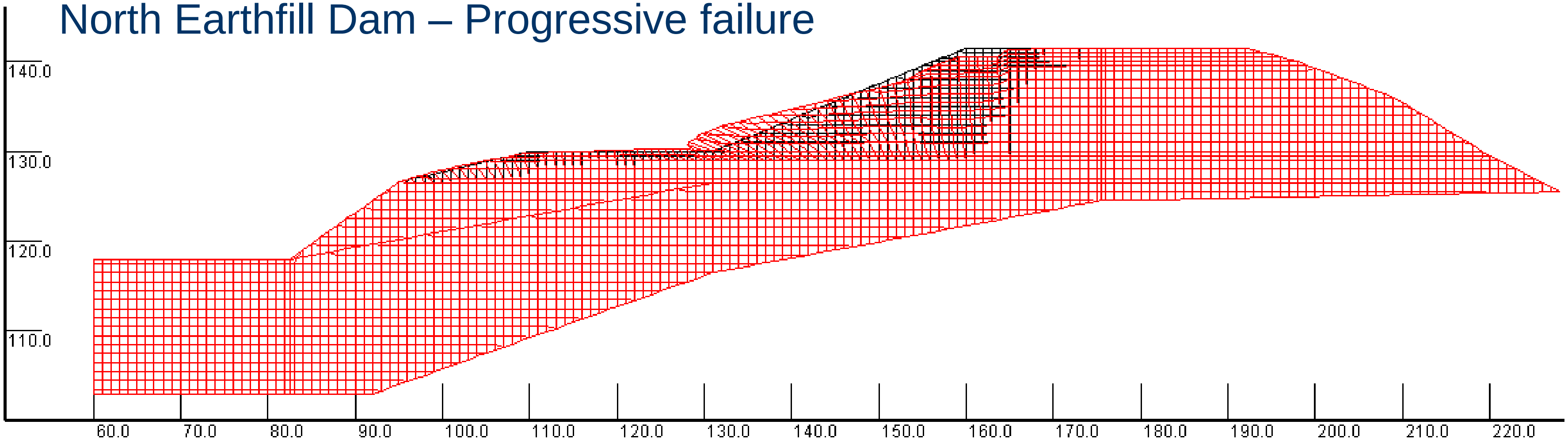
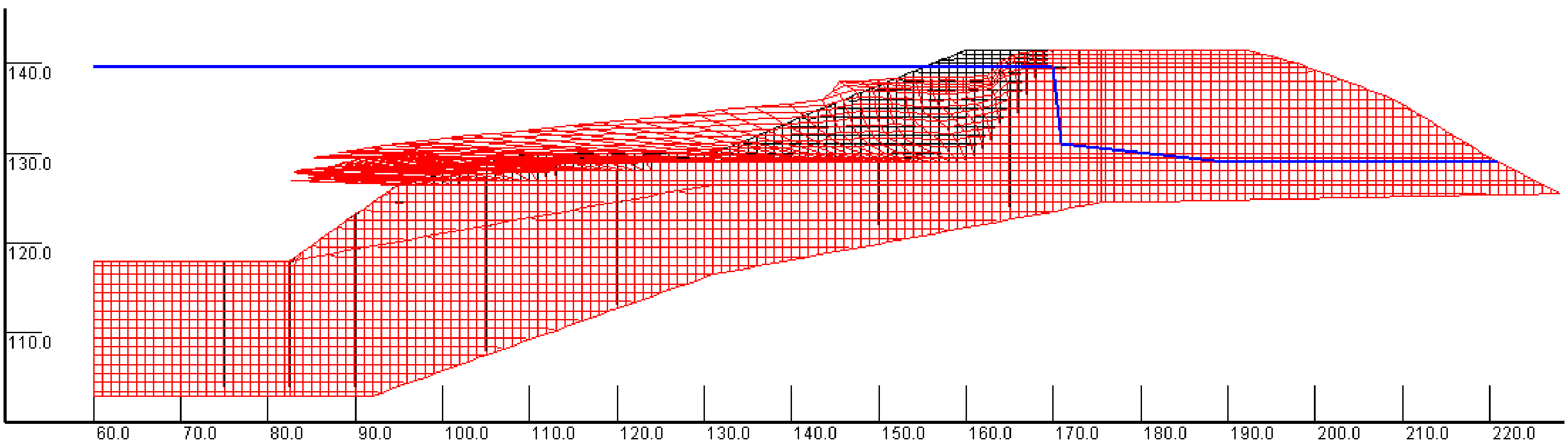
John Hart Dam – Seismic Deformations

North Earthfill Dam – Progressive failure





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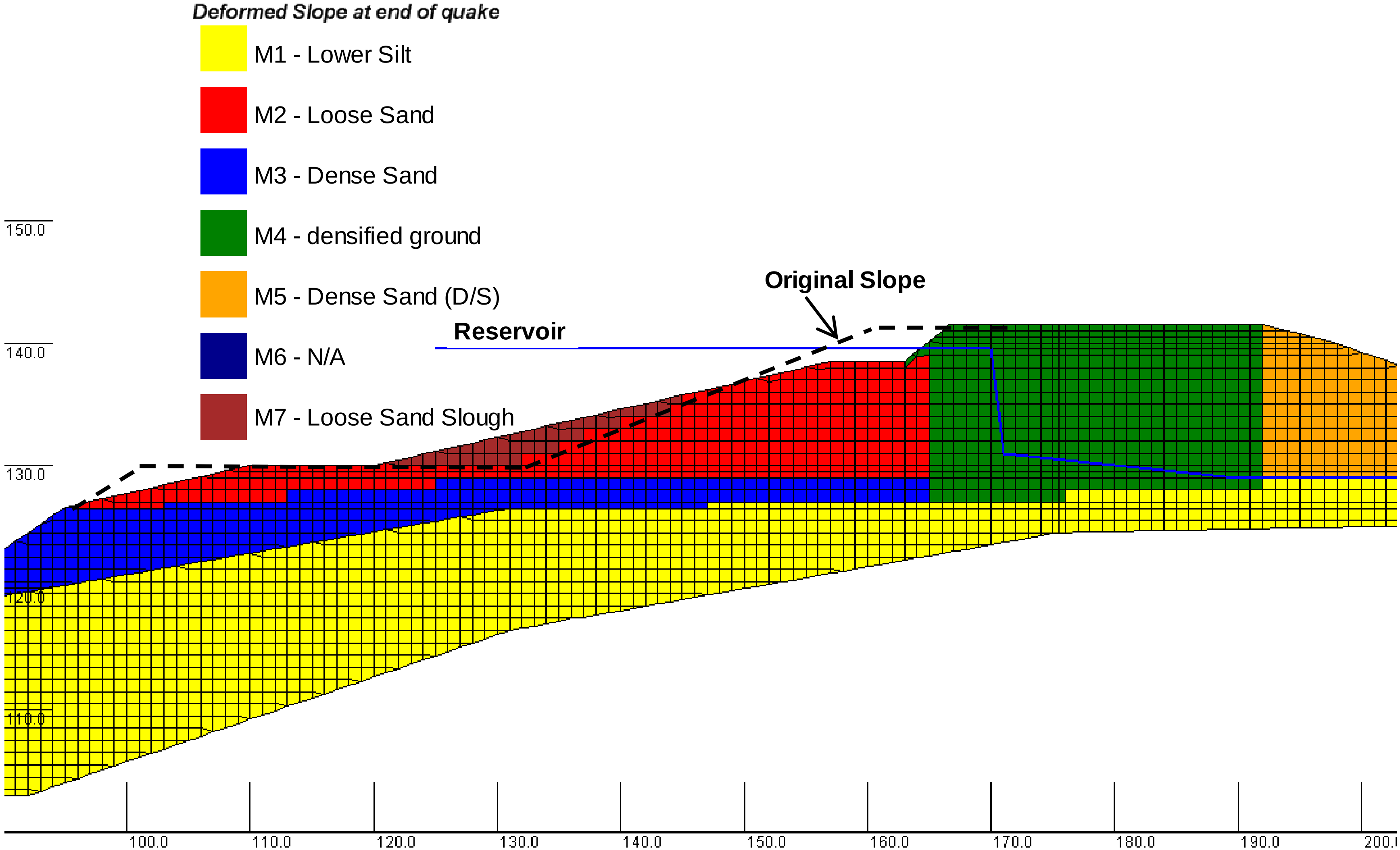
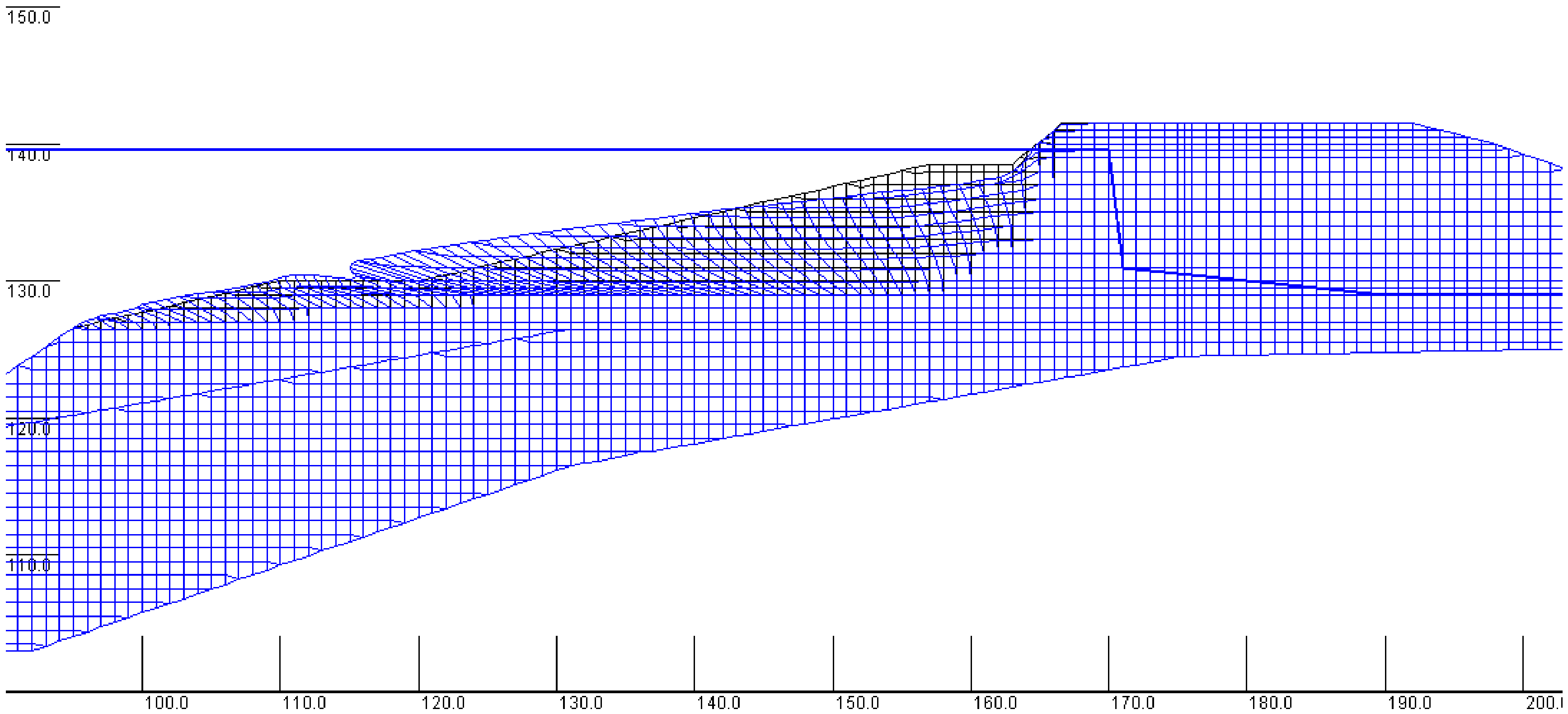
John Hart Dam – Seismic Deformations

North Earthfill Dam – Stage 1 Deformed Slope



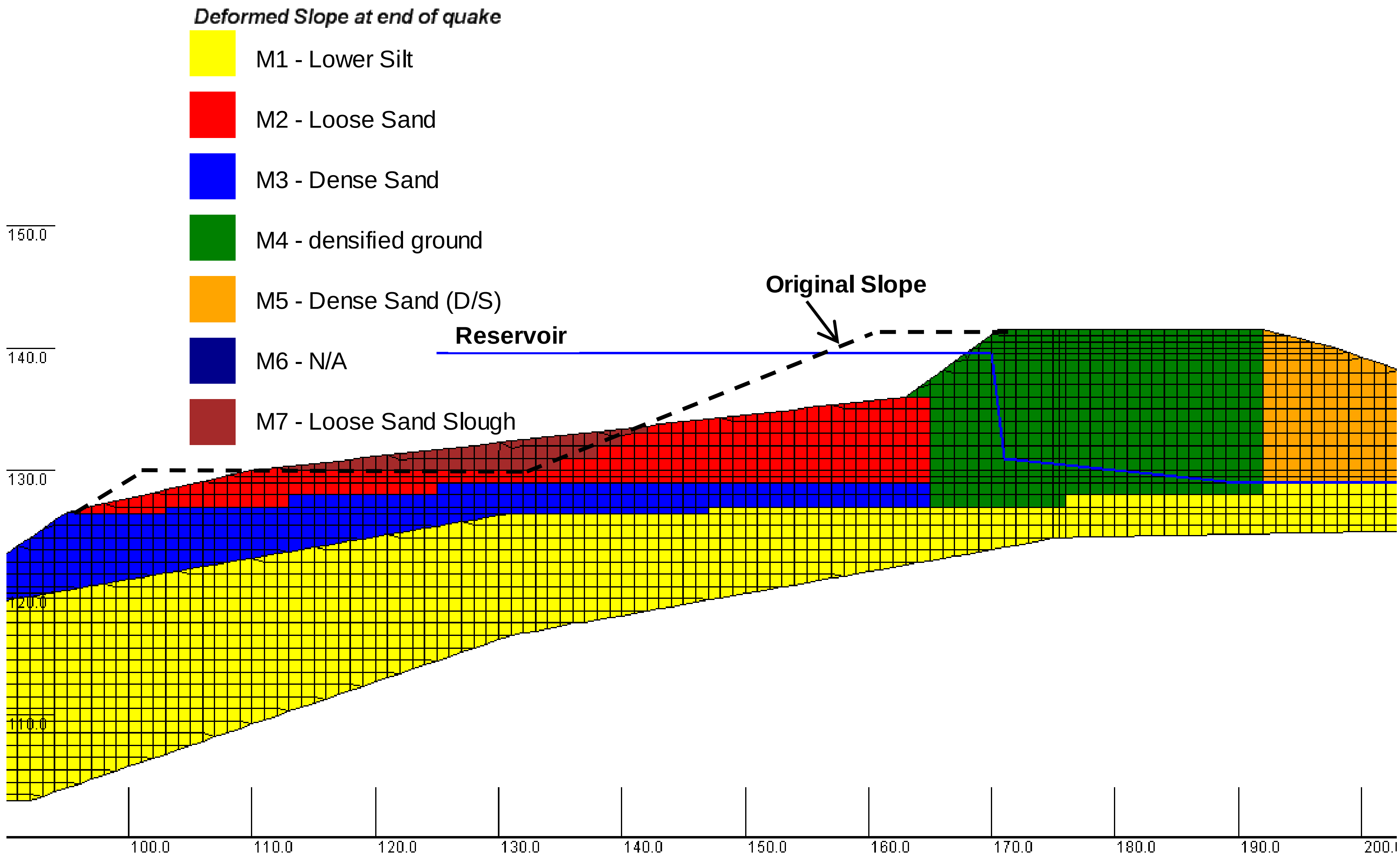
John Hart Dam – Seismic Deformations

North Earthfill Dam – Stage 1 Deformed Slope



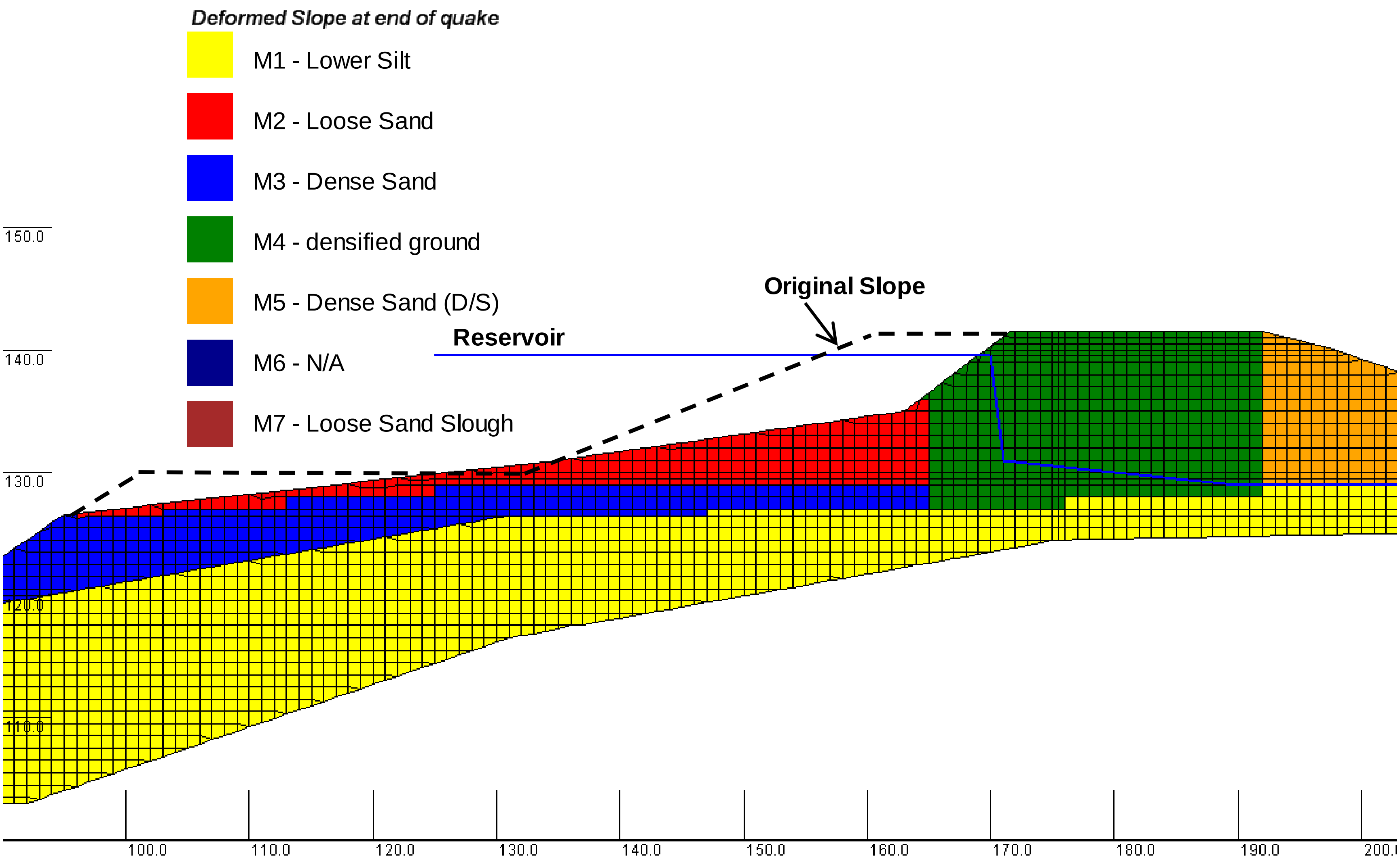
John Hart Dam – Seismic Deformations

North Earthfill Dam – Stage 2 Deformed Slope



John Hart Dam – Seismic Deformations

North Earthfill Dam – Stage 3 Deformed Slope



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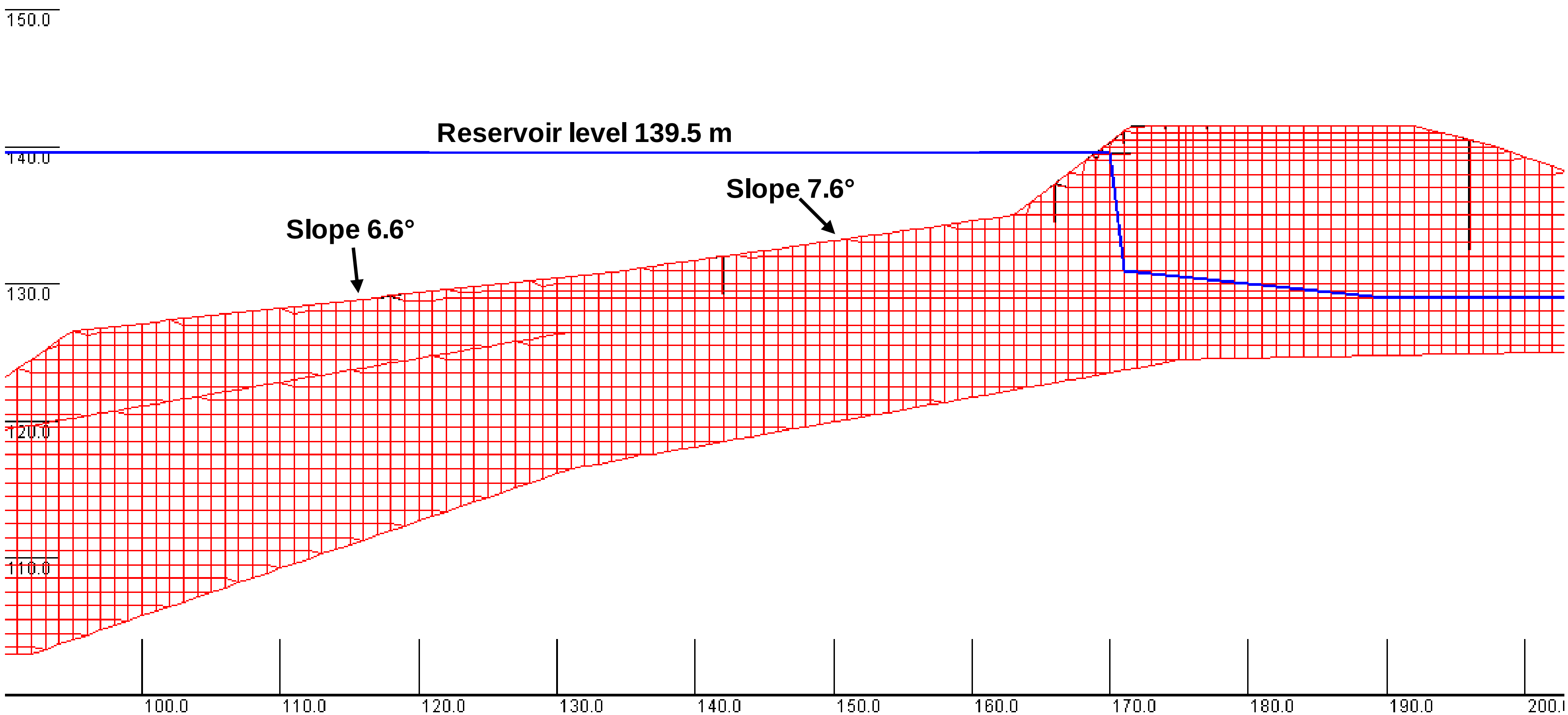
John Hart Dam – Seismic Deformations

North Earthfill Dam – Final Stable Slope



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John Hart Dam Project Status

- Developing upgrade options for the Middle Earthfill Dam
- Implementing an interim jet grout cutoff wall for the North Earthfill Dam
- Developing long-term upgrade options for the North Earthfill Dam

Warnings/Disclaims
for Slides No. 63 to 89 (this one):
Results presented herein are from the Deficiency Investigations (DI) of the dam as of 2010; and they are only representative to soil data and seismic hazard data up to 2010.

Summary

- Seismic Hazard Assessment
- Development of Input Earthquake Time Histories
- Seismic performance assessment based on displacements
  - Simplified Newmark approach
  - Nonlinear Dynamic Time History Analyses using VERSAT-2D, FLAC