Let's talk nonlinearity:

3D Simulation of Seismic Response of the Long Valley Embankment Dam, California

Te-Yang Yeh & Kim Bak Olsen
Department of Geological Sciences, San Diego State University

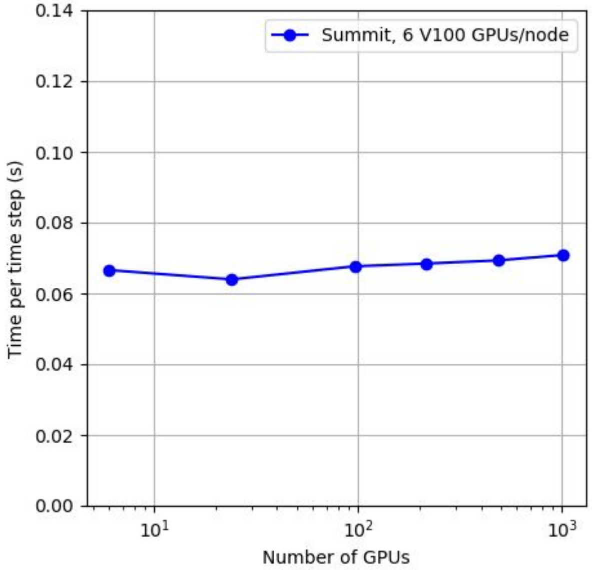
SAN DIEGO STATE UNIVERSITY
Department of Geological Sciences
College of Sciences

California Geological Survey

AWP-ODC : 4th-order Scalable Finite Difference code

Summit supercomputers at OLCF

- Frequency-dependent Q (Withers et al., 2015)
- Discontinuous mesh (Nie et al., 2017)
- Surface topography: O'Reilly, O., T.-Y. Yeh, K.B. Olsen, Z. Hu, A. Breuer, D. Roten, and C. Goulet (**2022**). A high-order finite difference method on staggered curvilinear grids for seismic wave propagation applications with topography, *Bull. Seis. Soc. Am.*, **112 (1)**, 3-22.



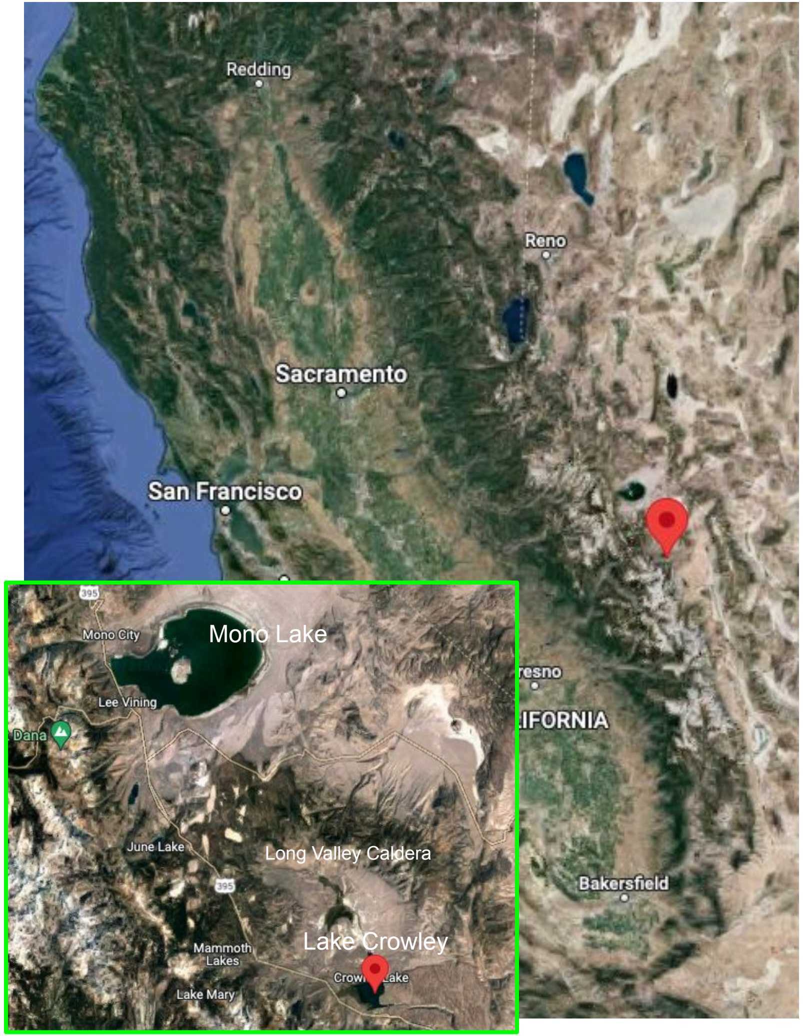
Earthquake Shaking Effects on Embankment Dams

Van Norman dams, 1971 M 6.6 San Fernando (CA) earthquake

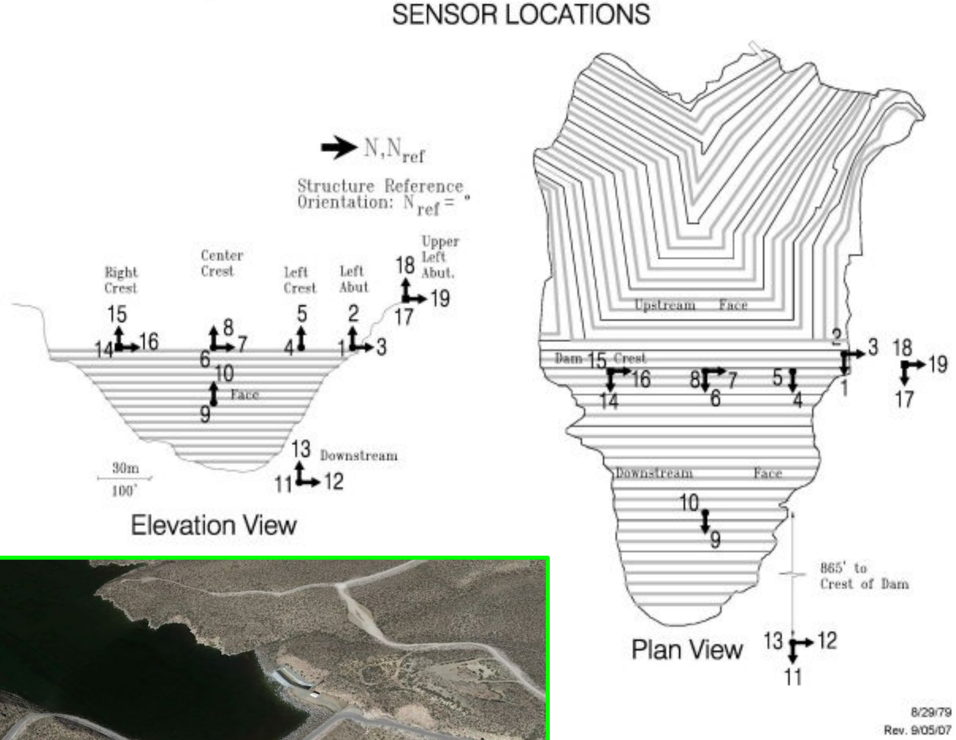
> 1,800 dams and reservoirs, 2008 M 8 Wenchuan (China)

Fujinuma dam, 2011 M 9 Tohoku (Japan) earthquake

CSMIP Strong motion data at Long Valley Dam



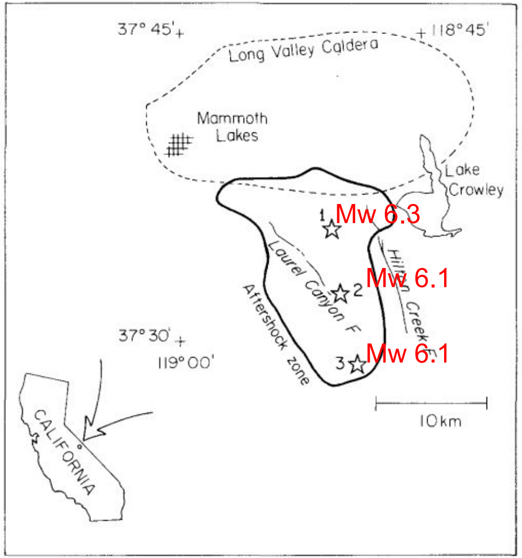
Lake Crowley - Long Valley Dam
(CSMIP Station No. 54214)



Seismic hazards

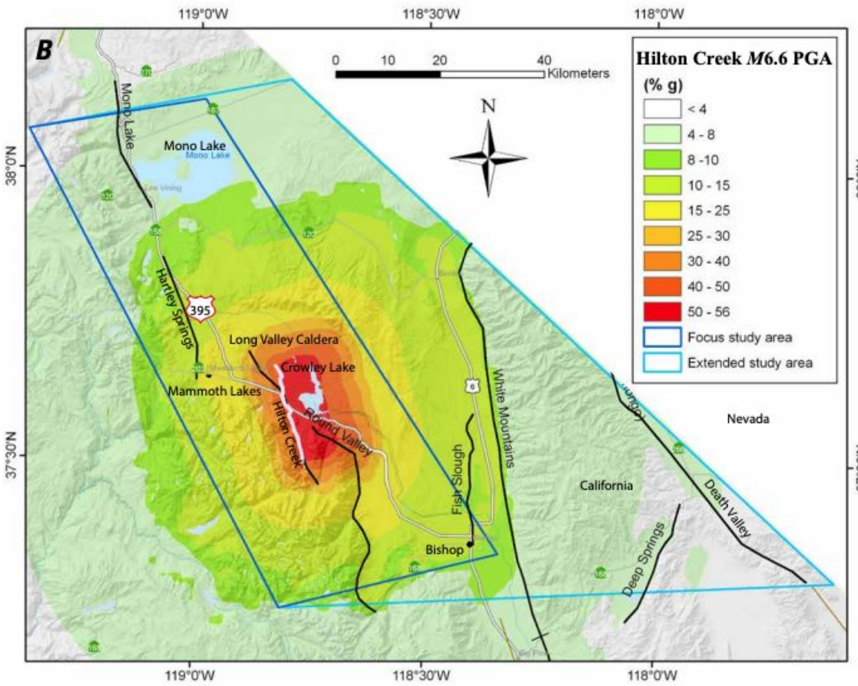
Historical events in the area

1980 Mammoth Lake earthquake series



Given et al. (1982)
BSSA

Hilton Creek Fault Mw 6.6 MCE Scenario



Chen et al. (2014)
USGS report

Approach

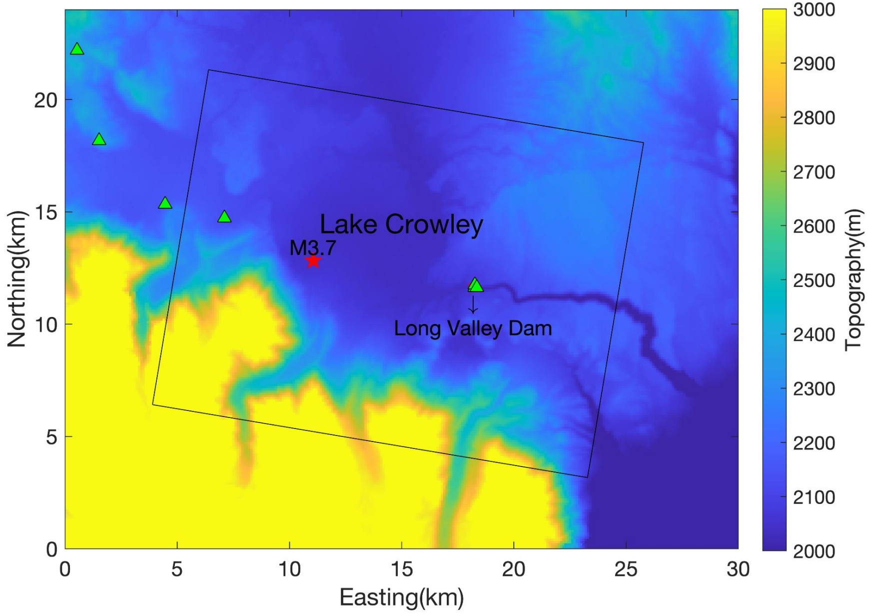
- Reference model: SCEC CVM-S.4.26.M01 (CVM)

- Validation #1: 2015 M3.7 earthquake
  - Geotechnical layer
  - Elastic properties of the LV dam
  - Attenuation model

- Validation #2: 1986 M6.2 Chalfant Valley earthquake
  - Method for generating finite-fault source representation

- Hilton Creek Fault M6.6 scenarios for Maximum Credible Earthquake (MCE)
  - Prediction of 0-7.5 Hz ground motions
  - Linear vs. nonlinear response

Validation event #1
2015 Mw 3.7 earthquake

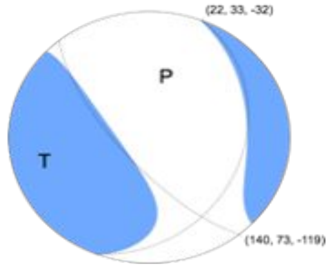


- 20.2 km x 15.1 km x 15 km domain
- Discontinuous mesh:
  5616 x 4320 x 1440 grid points (dh=3.5m)
  1872 x 1440 x 96 (dh=10.5m)
  624 x 488 x 288 (dh=31.5m)
- USGS 1m resolution DEM
- Frequency-dependent anelastic attenuation

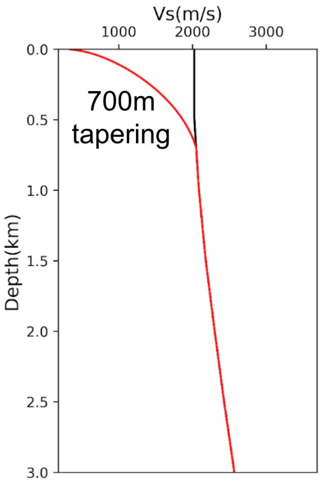
$$Q(f) = 0.075V_S f^{0.2} \quad f > 1Hz$$
$$Q(f) = 0.075V_S \quad f \leq 1Hz$$

- Event information
  - Time: 2015/8/22 13:34:48 UTC
  - Epicenter: Lat: 37.598°N Lon: 118.788°W
  - Depth: 4.8 km
  - Mw 3.71

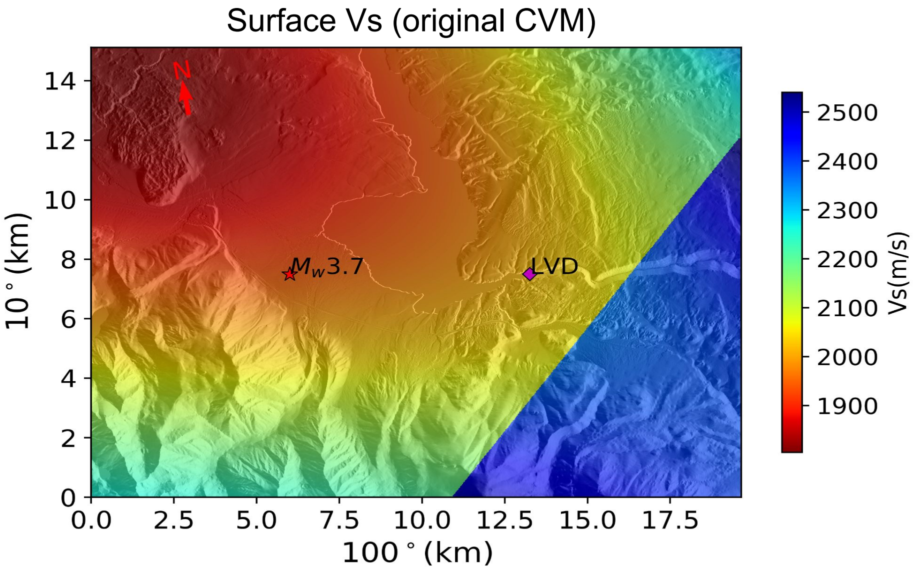
USGS Moment tensor

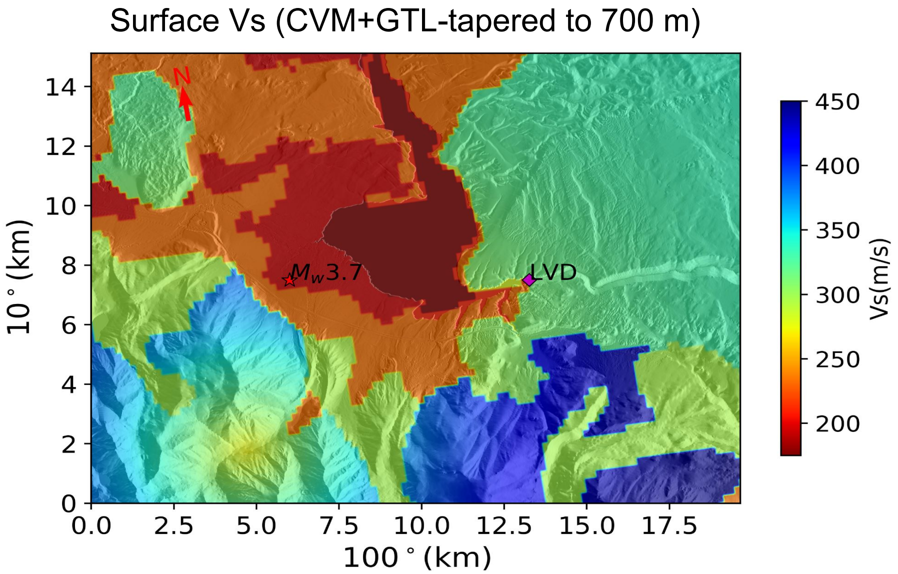


Near-surface Geotechnical Layer (GTL)



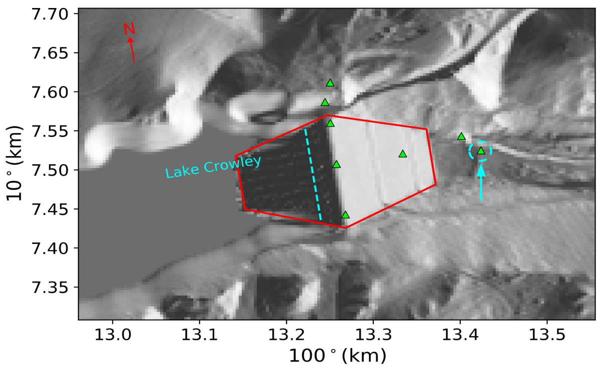
- Vs30 model from Wills et al. (2015)
- Vp, Vs, density formulations from Ely et al. (2010)
- 700m tapering depth

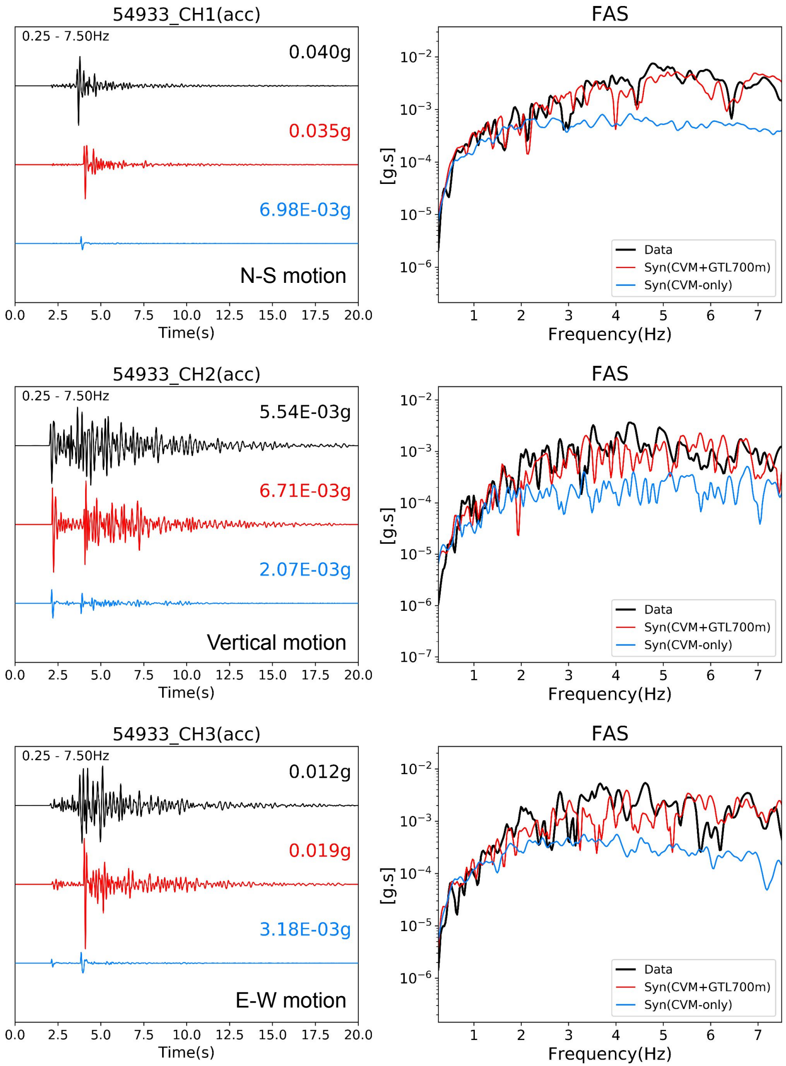




CVM+GTL vs. Original CVM

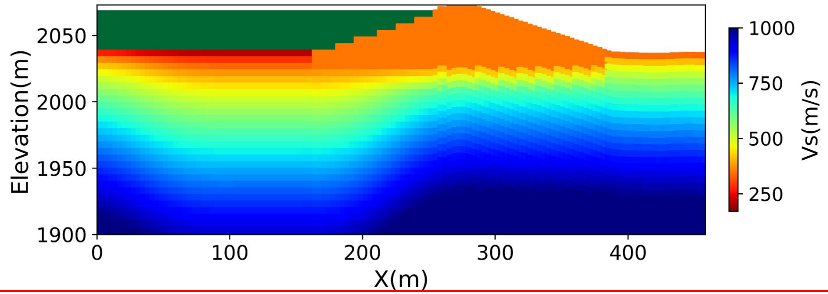
Red: CVM+GTL
Blue: CVM only



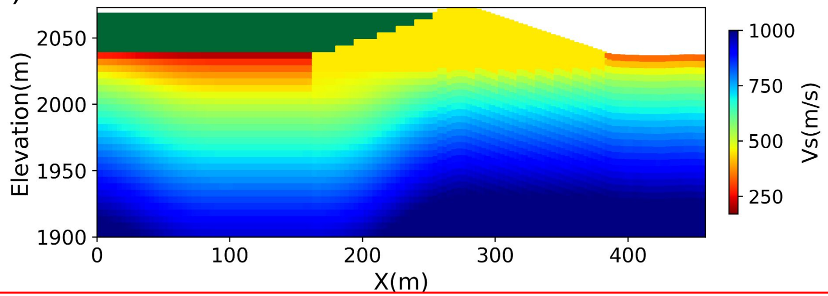


3D Structure of Long Valley Dam

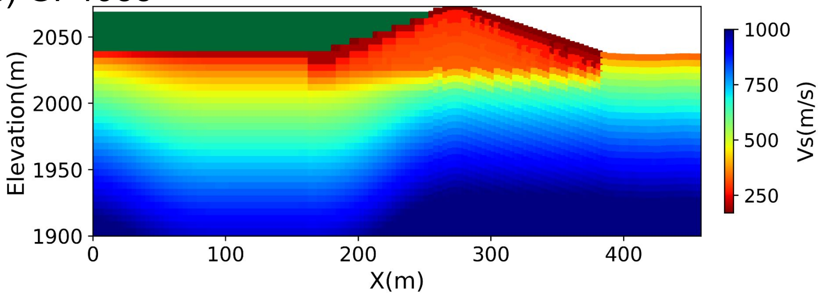
(a) Core Vs=350 m/s

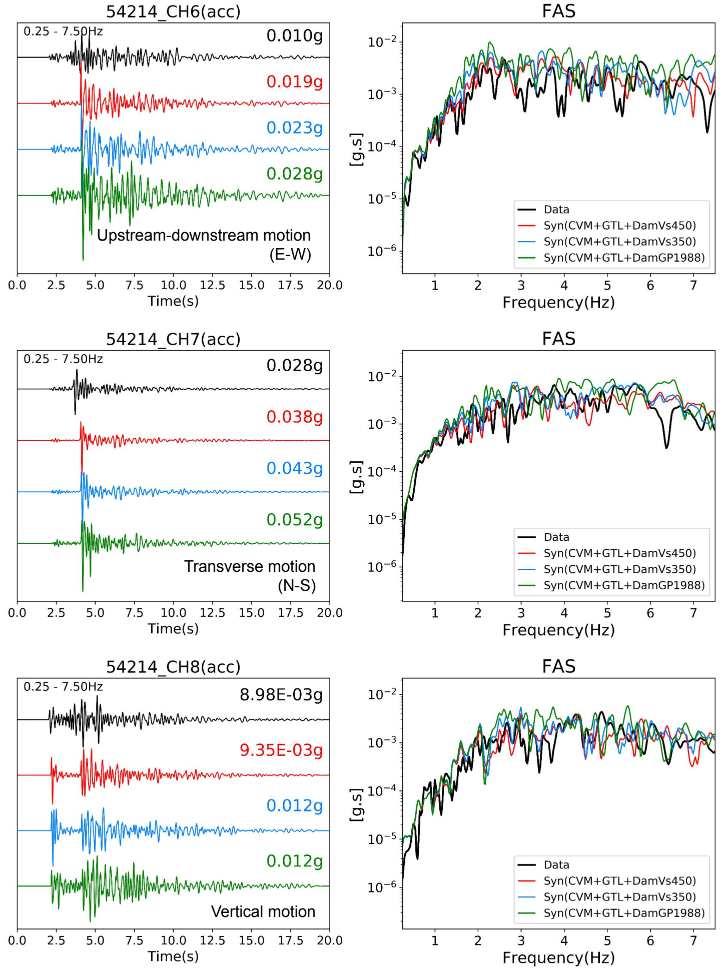


(b) Core Vs=450 m/s



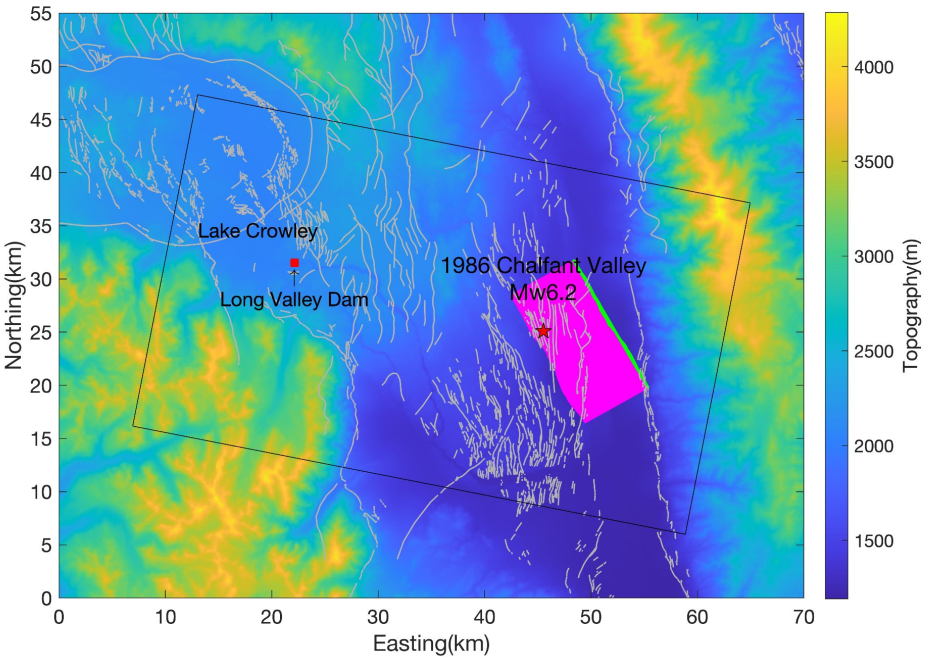
(c) GP1988



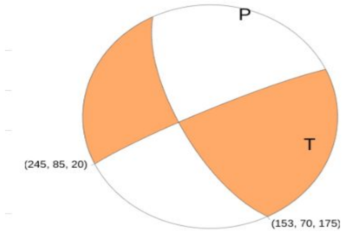


Validation event #2
1986 Mw 6.2 Chalfant Valley earthquake

- 53 km x 31.8 km x 30 km domain
- Discontinuous mesh:
  15120 x 9072 x 1152 grid points (dh=3.5m)
  5040 x 3024 x 576 (dh=10.5m)
  1680 x 1008 x 800 (dh=31.5m)
- Qs=0.075Vs $f^{0.2}$, GTL tapered to 700 m depth
- Event information
  - Time: 1986/7/21 14:42:26 UTC
  - Epicenter: Lat: 37.533°N Lon: 118.441°W
  - Depth: 10.8 km (Smith & Priestley, 2000):
  - Mw 6.2

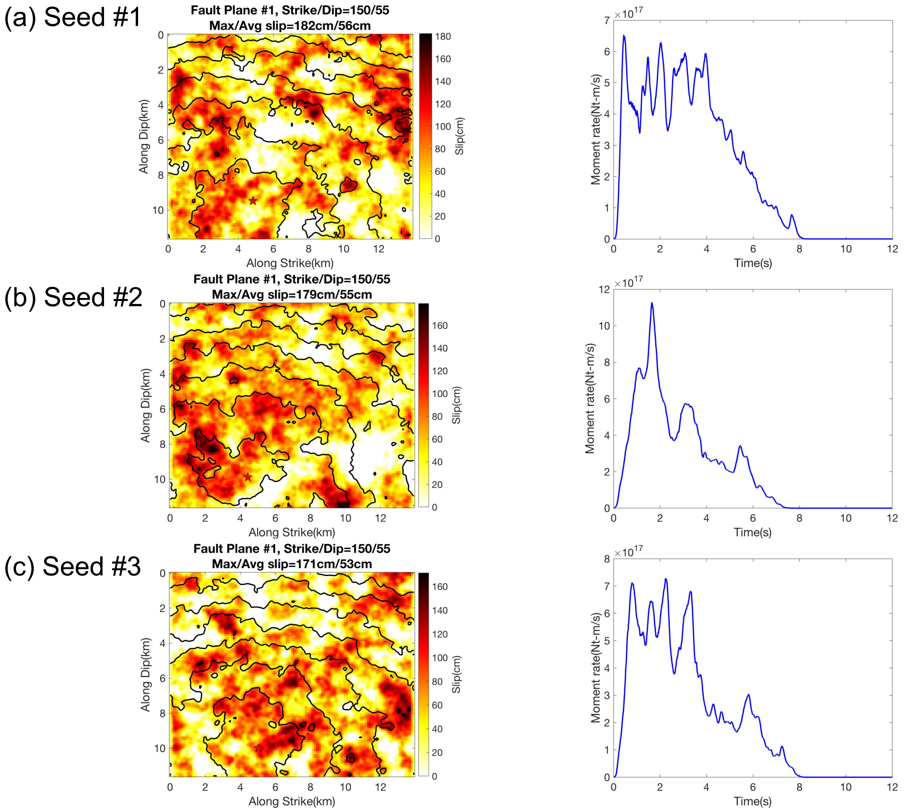


USGS Moment tensor

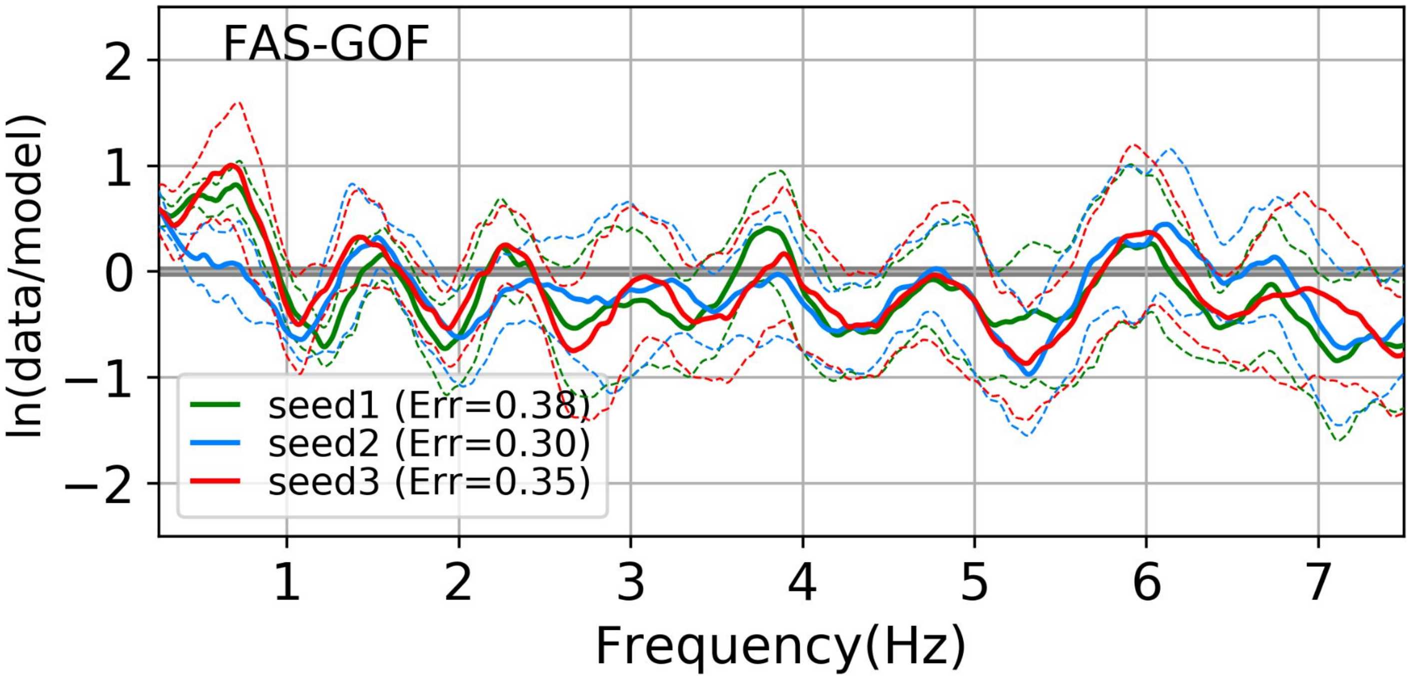


Finite-fault rupture model

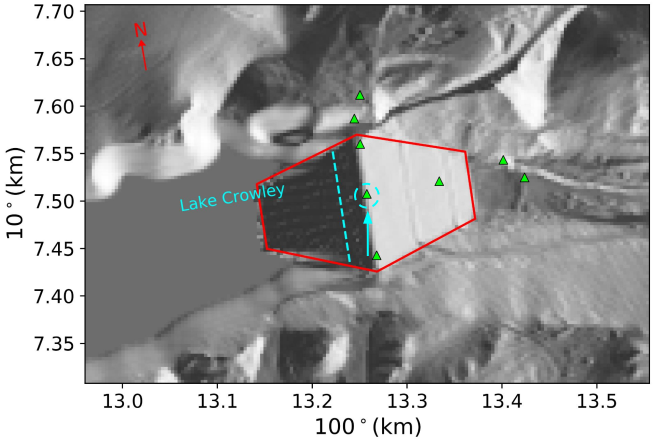
- Strike-slip strike/dip/rake=150º/55º/-180º
- Fault dimensions L=13.9 km W=11.6 km (Leonard, 2010; Smith & Priestley, 2000)
- Graves-Pitarka kinematic rupture generator (Graves & Pitarka, 2016)

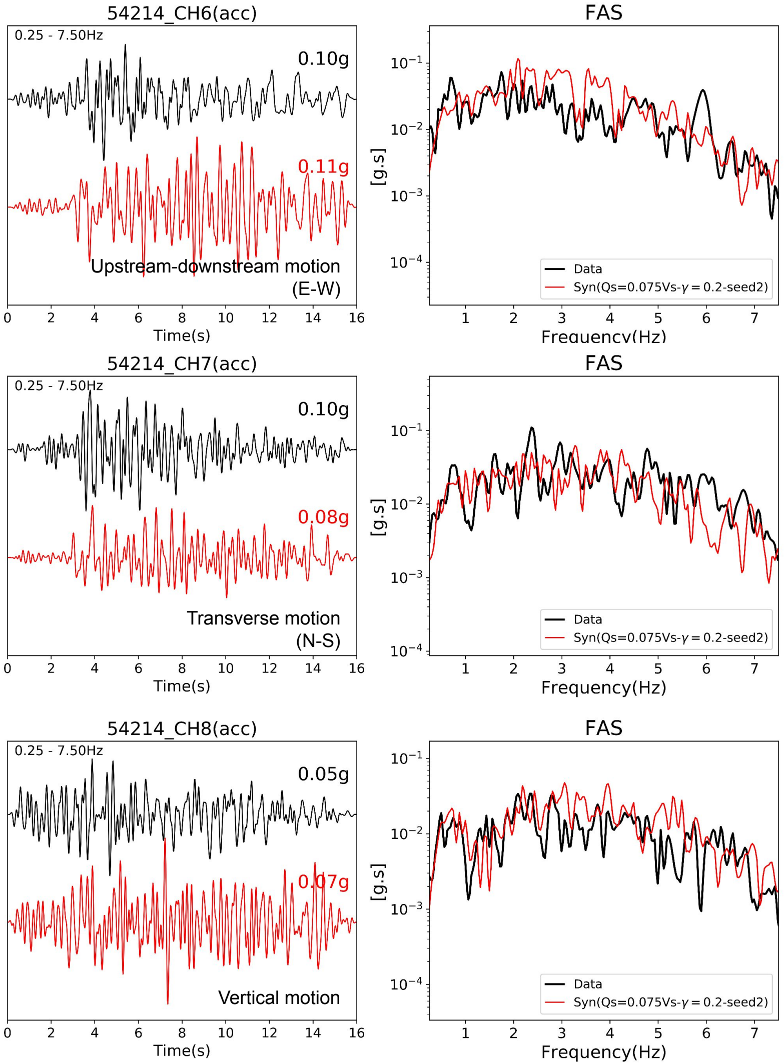


Intra-event variation?



Ground station 54933 - Acceleration
Long Valley Dam crest center

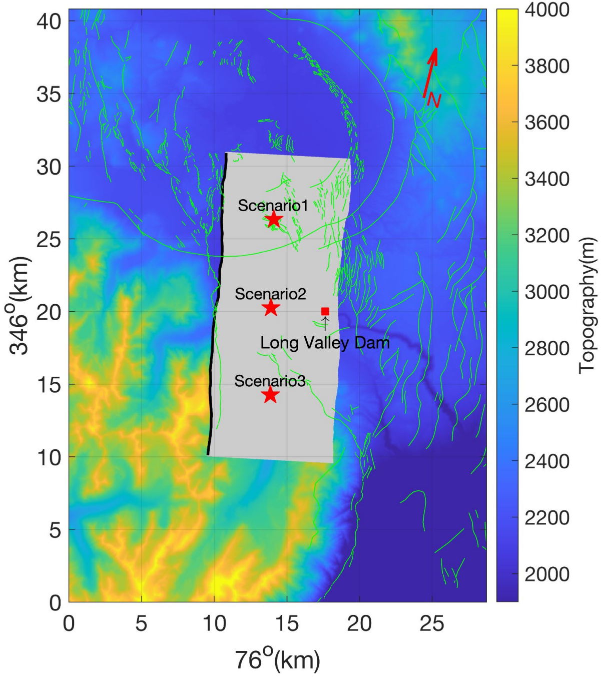


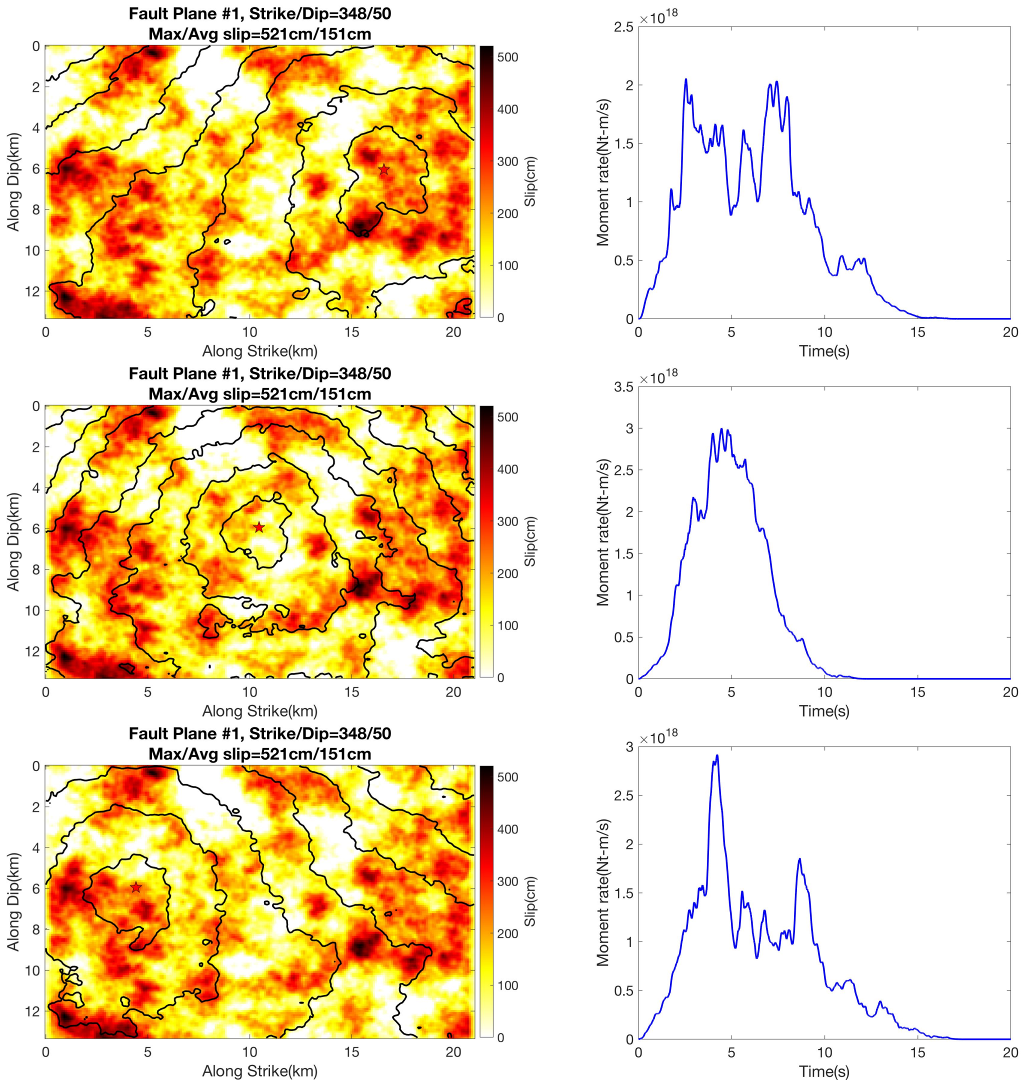


Hilton Creek Fault M6.6 Scenarios

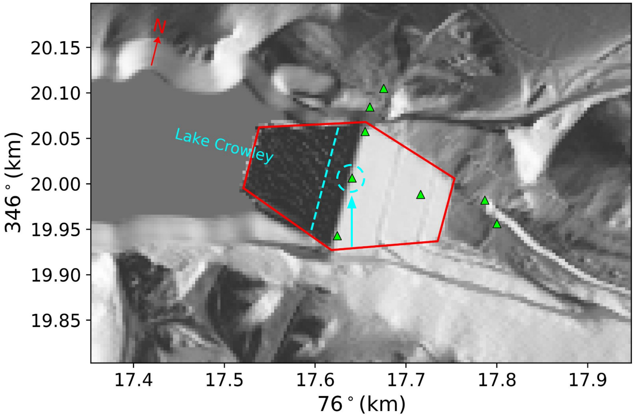
- Fault dimensions: L=21km W=13.3km
- Focal mechanism: 348º/50º/-90º
- Three rupture scenarios:

  (1) Southward (2) Bilateral (3) Northward

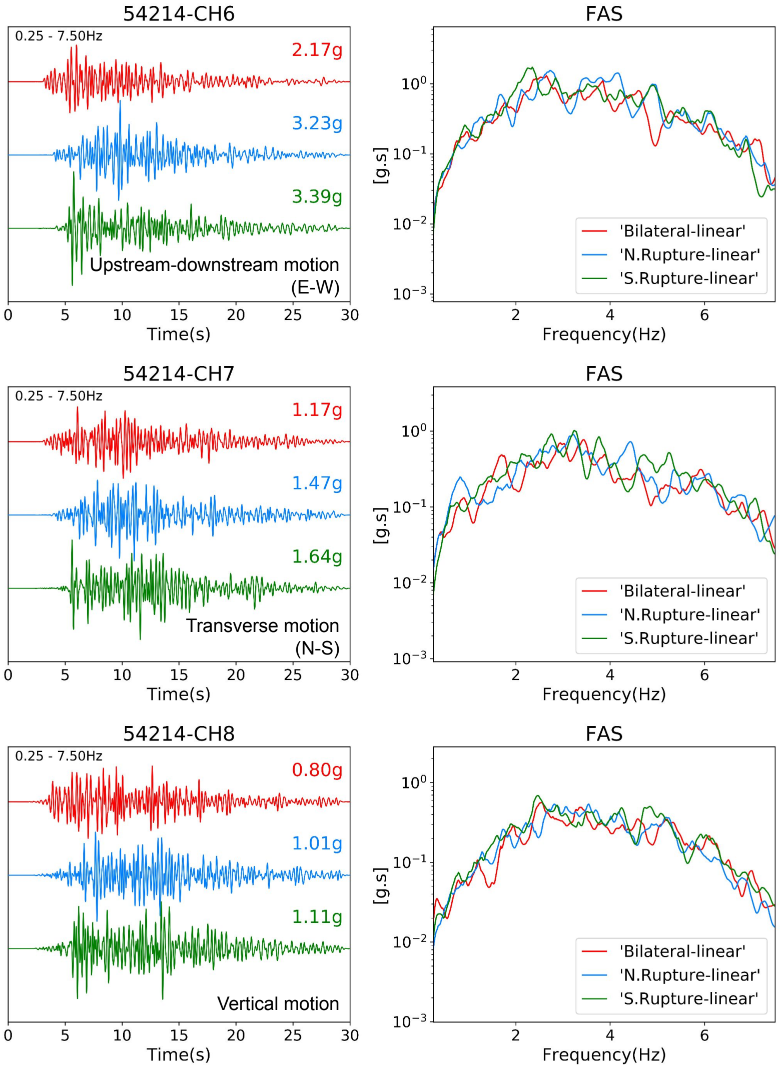




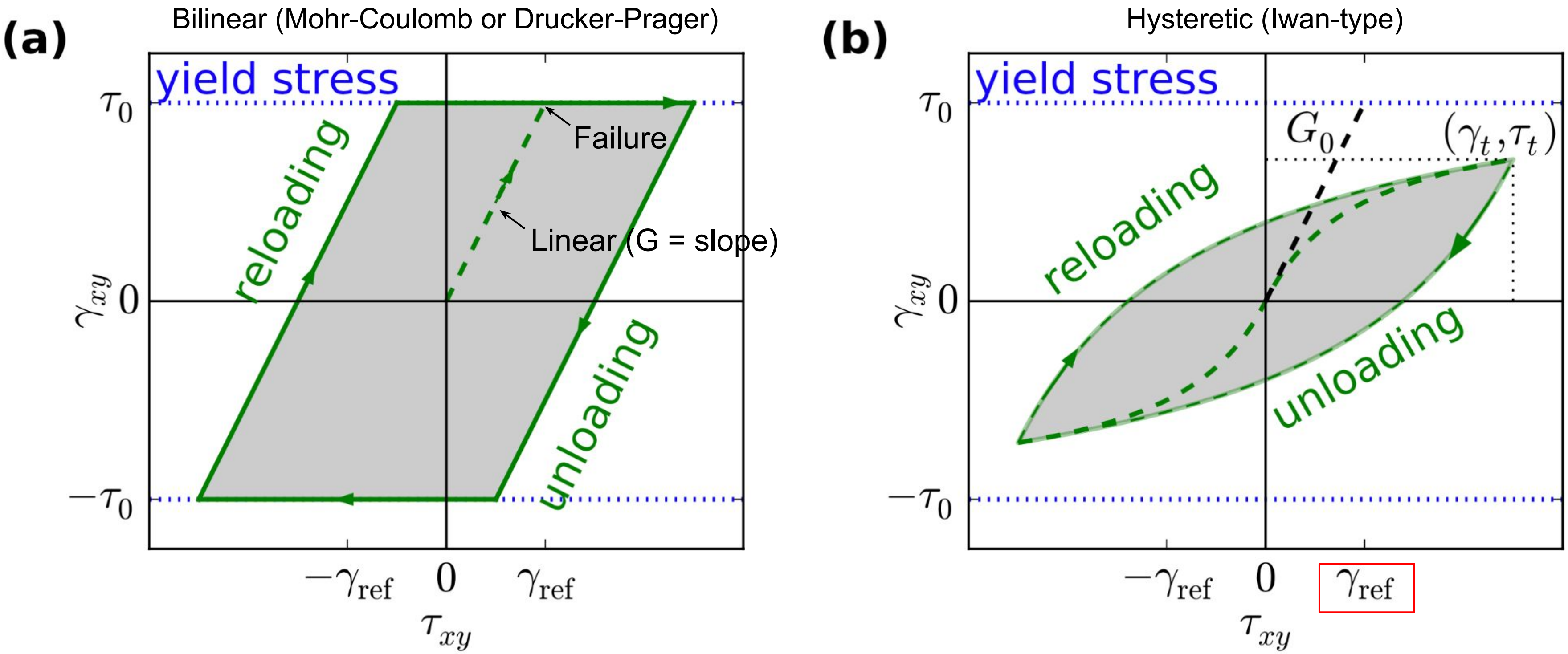
Structure array 54214 - Acceleration CH6, CH7, CH8 (dam center crest)



- **Southward** rupture produces strongest ground motions
- Strongest on upstream-downstream direction
- Different rupture types -> factor of 1.5 difference



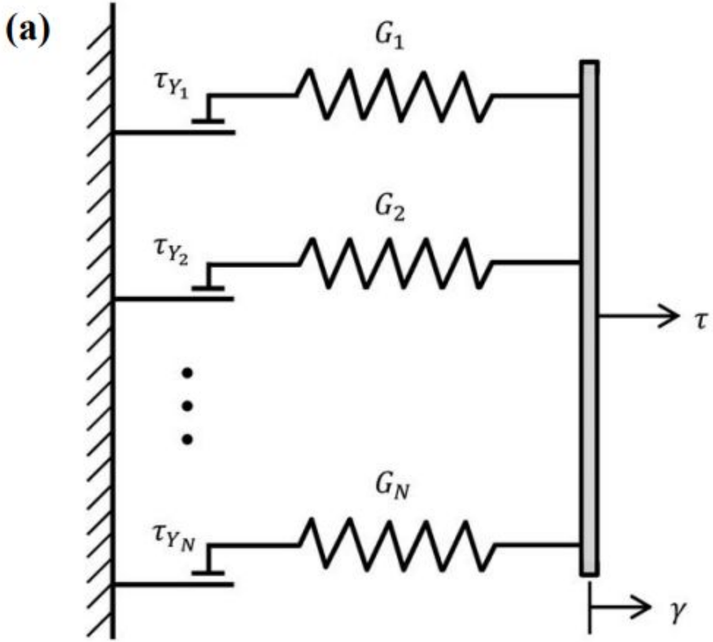
Nonlinear models

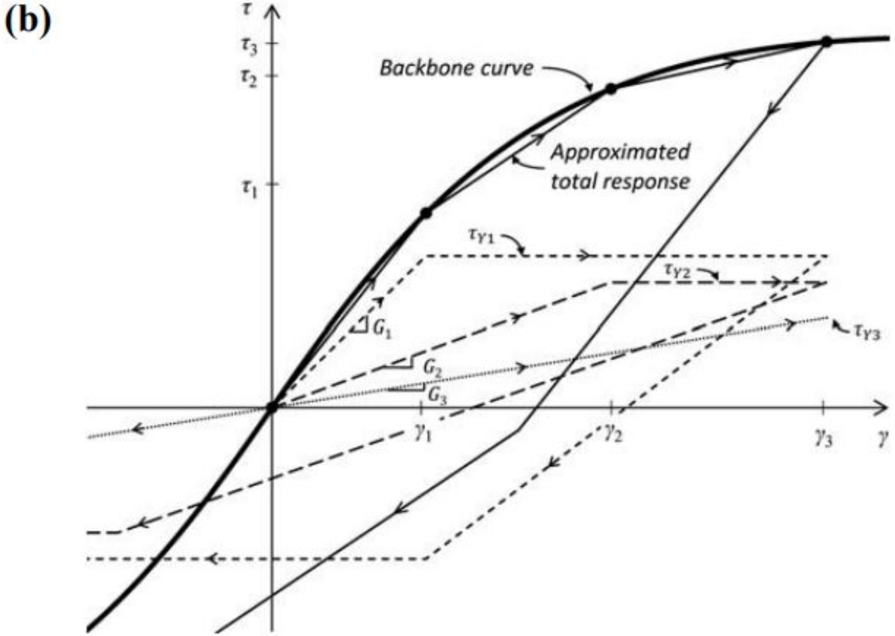


Slope of secant line of the stress-strain curve is shear modulus

The overlay method

Spring sliders in parallel series





$G_1+G_2+G_3 \ldots +G_N=G_0$

(Kaklamanos et al., 2015)

Reference strain: $\gamma_r = \dfrac{\tau_0}{G_0}$

Yield stress:

$$\tau_0 = C\cos(\phi) - (\sigma_m - P)\sin(\phi)$$

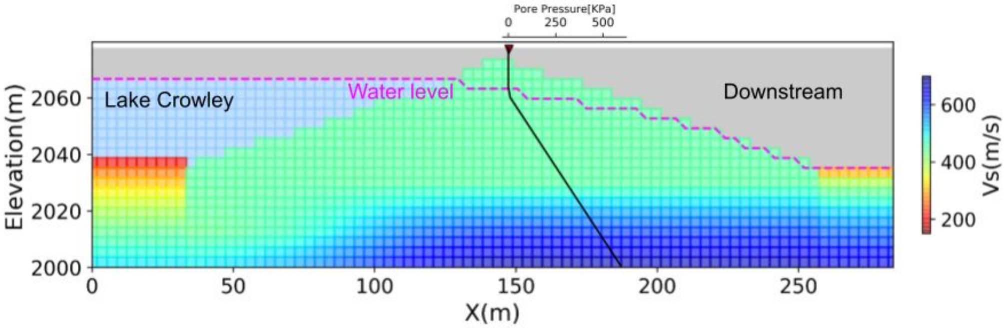
Cohesion

Friction angle

Mean stress

Fluid pressure

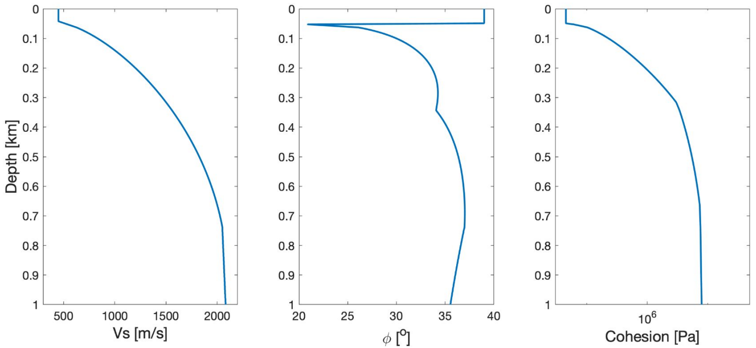
Hydrostatic condition for pore pressure:



Principal stresses:

$$\sigma_1 = \sigma_v$$
$$\sigma_2 = 0.8\sigma_1 \qquad \text{(Normal faulting tectonic setting)}$$
$$\sigma_3 = 0.6\sigma_1$$
$$\sigma_m = 1/3\,(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})$$

Cohesion and friction angle:



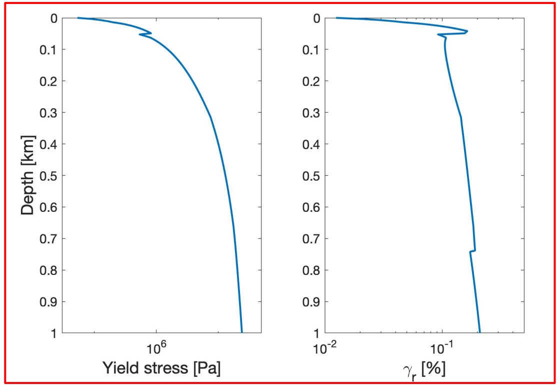
Inside LVD:

$$(c = 45KPa, \phi = 39^o)$$

(Griffiths & Prevost, 1988)

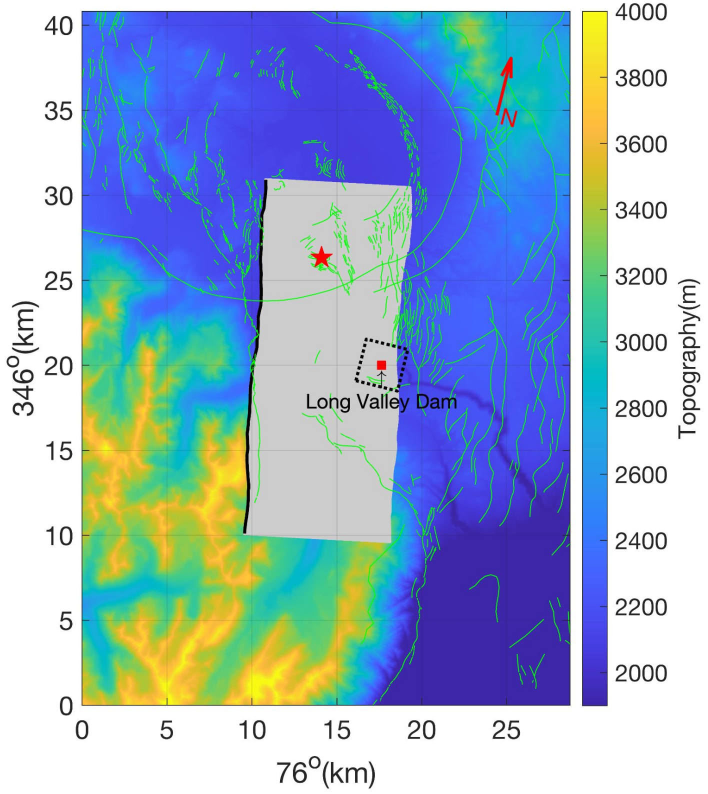
Outside LVD:

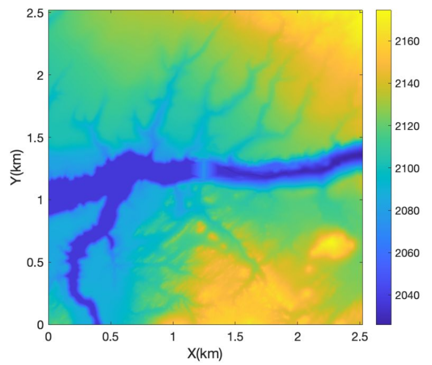
- Hoek-Brown failure criterion
- Geological Strength Index (GSI) based on shear wave speed

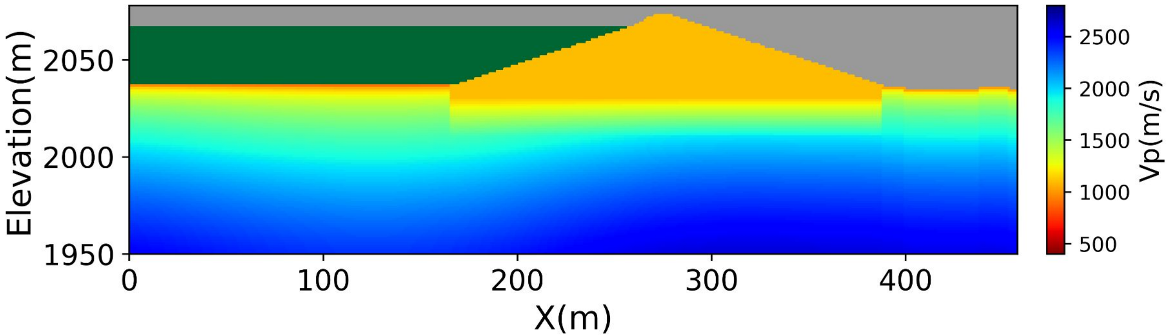


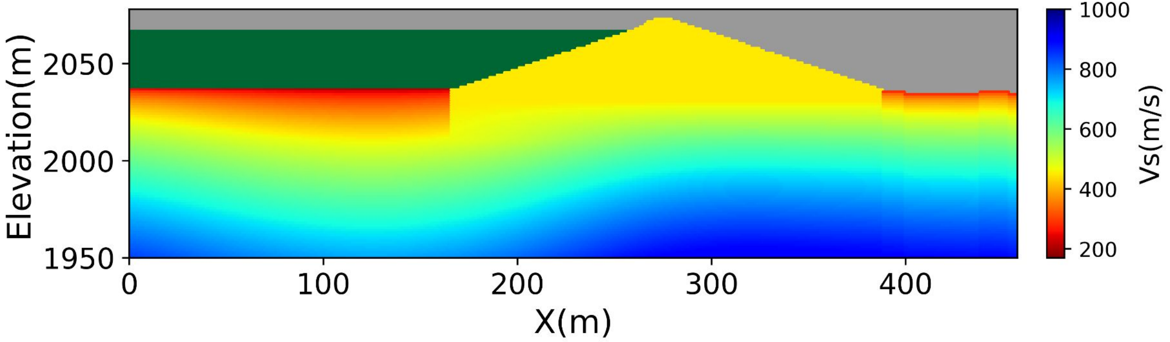
Plane wave calculation

- Smaller domain
- 1.25m grid spacing
- 10 yield surfaces







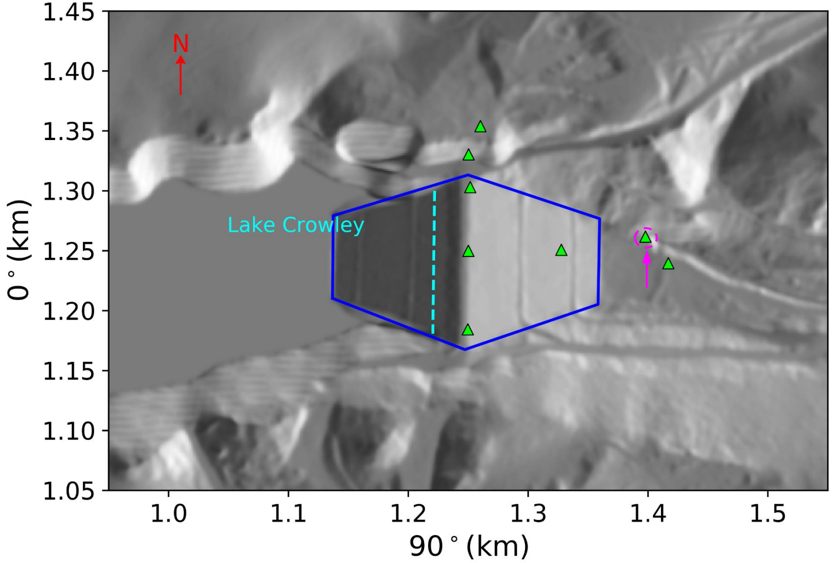


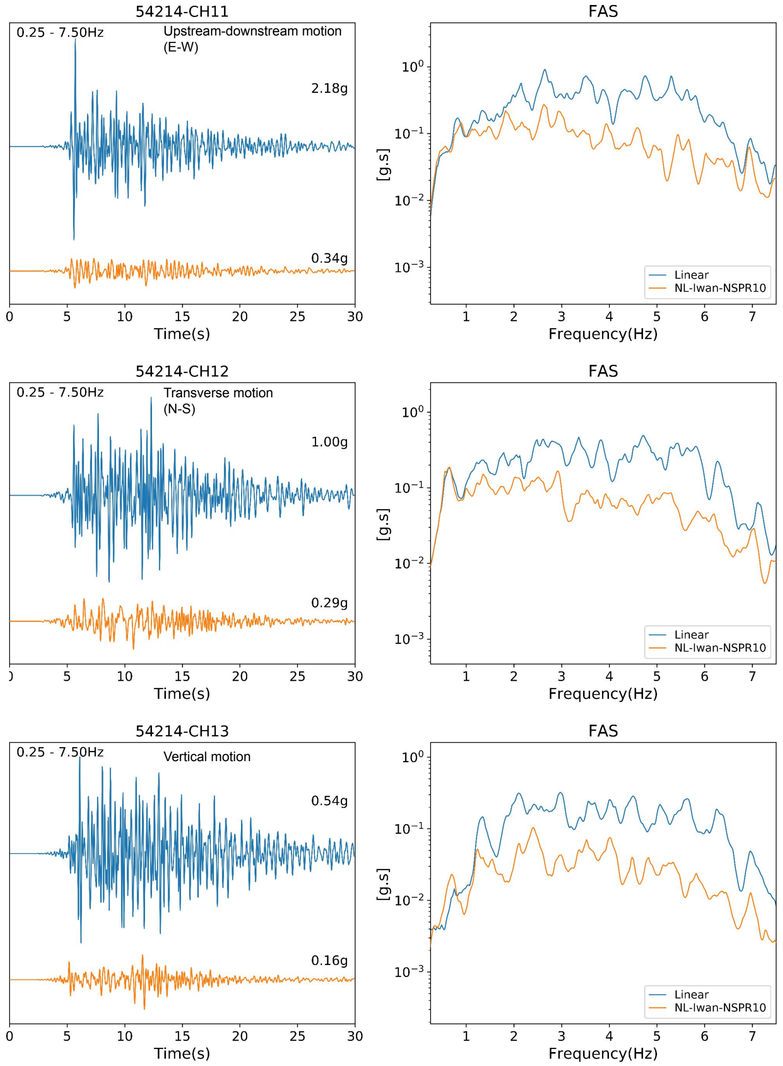
54214 CH11,12,13 (Downstream base)

Linear vs Nonlinear-Iwan simulation

Planewave (10 surfaces)

Homogeneous core with Vs=450 m/s



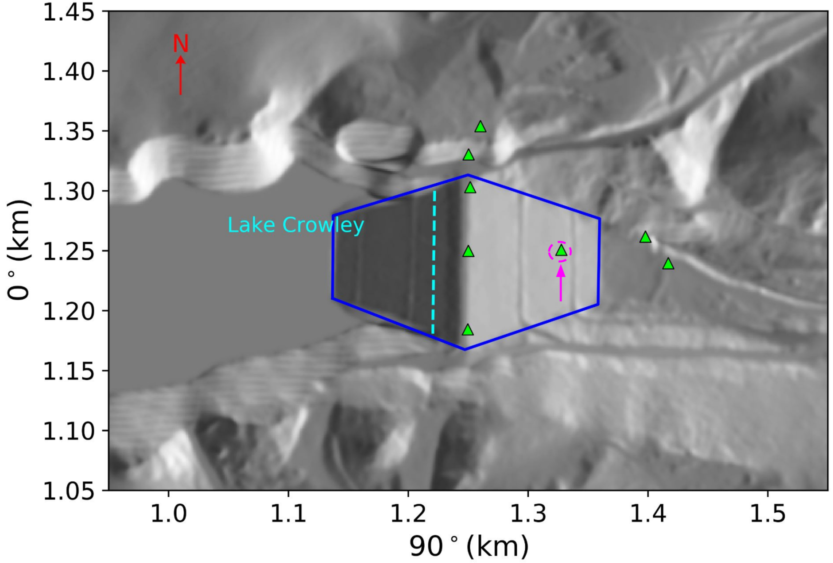


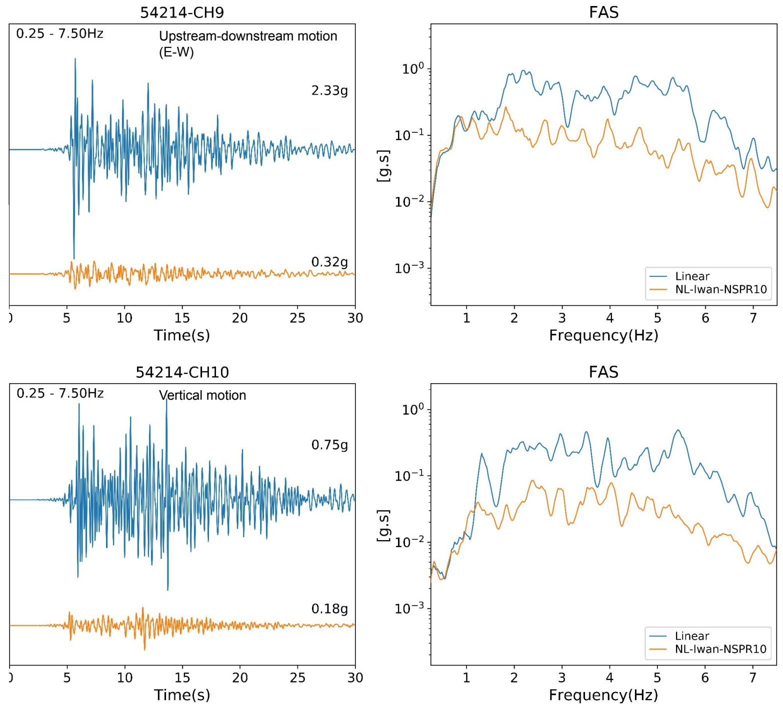
54214 CH9,10 (Downstream face)

Linear vs Nonlinear-Iwan simulation

Planewave (10 surfaces)

Homogeneous core with Vs=450 m/s



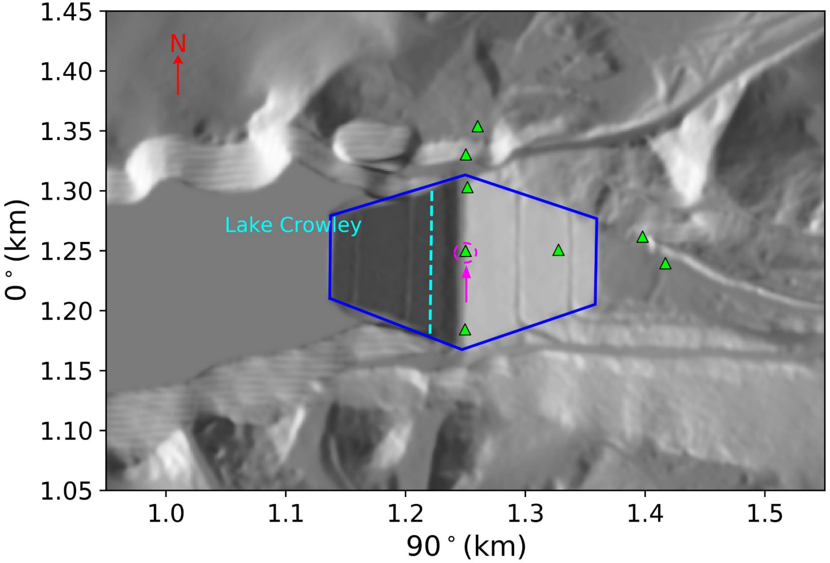


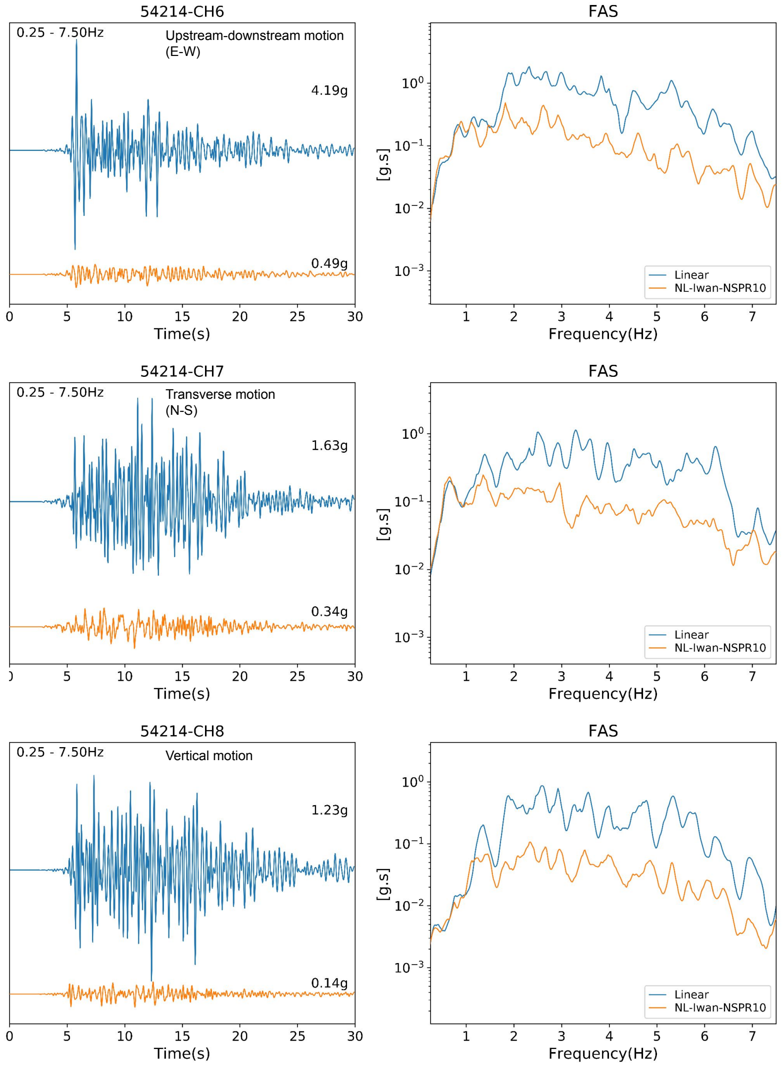
54214 CH6,7,8 (Crest center)

Linear vs Nonlinear-Iwan simulation

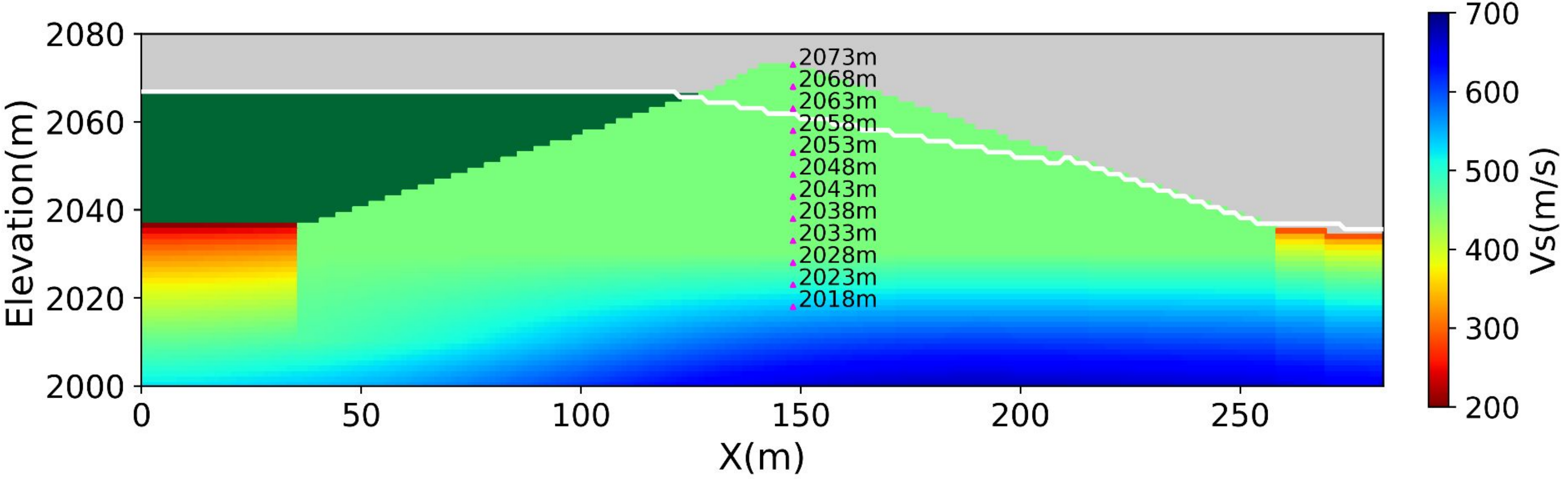
Planewave (10 surfaces)

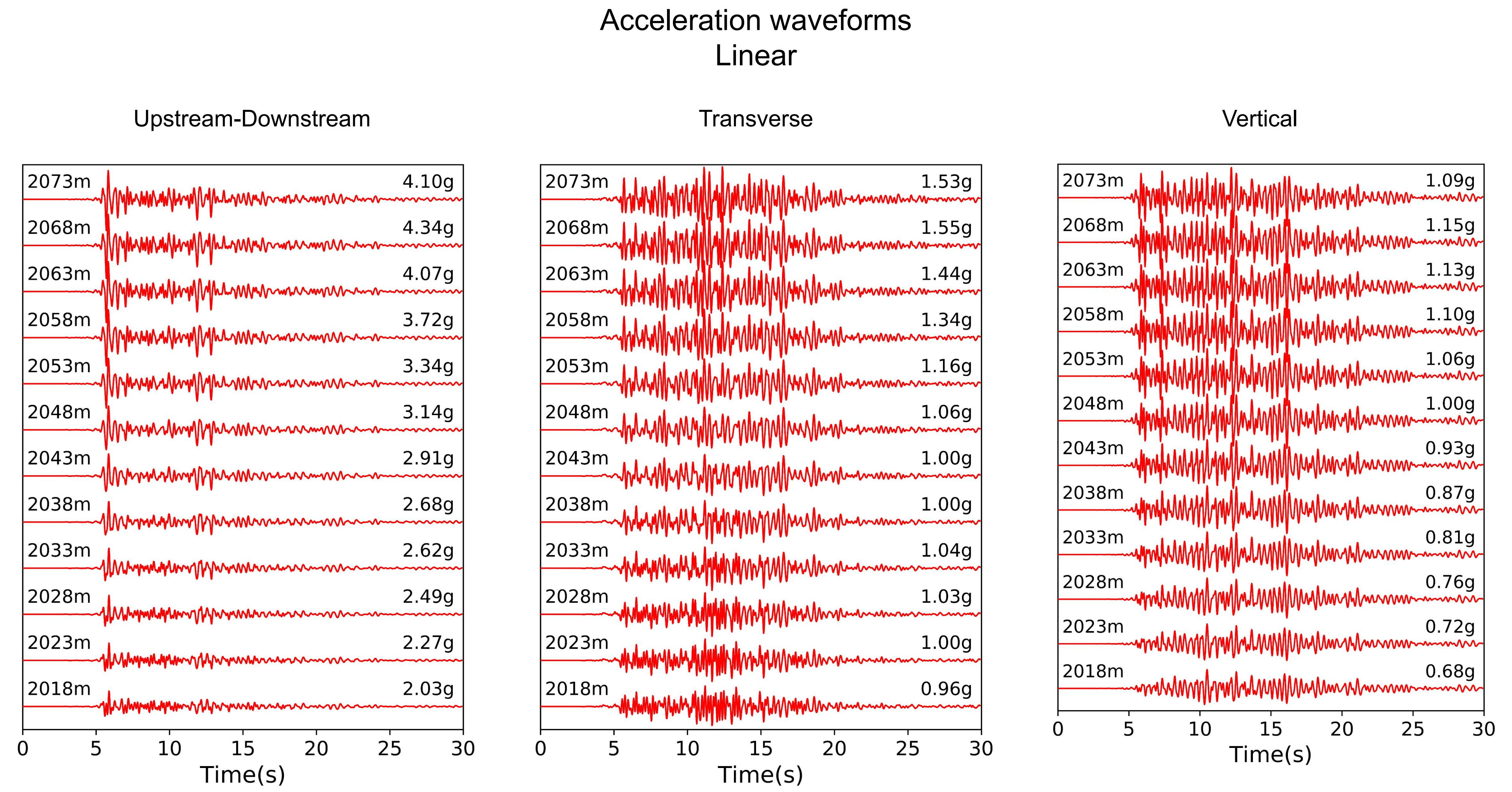
Homogeneous core with Vs=450 m/s



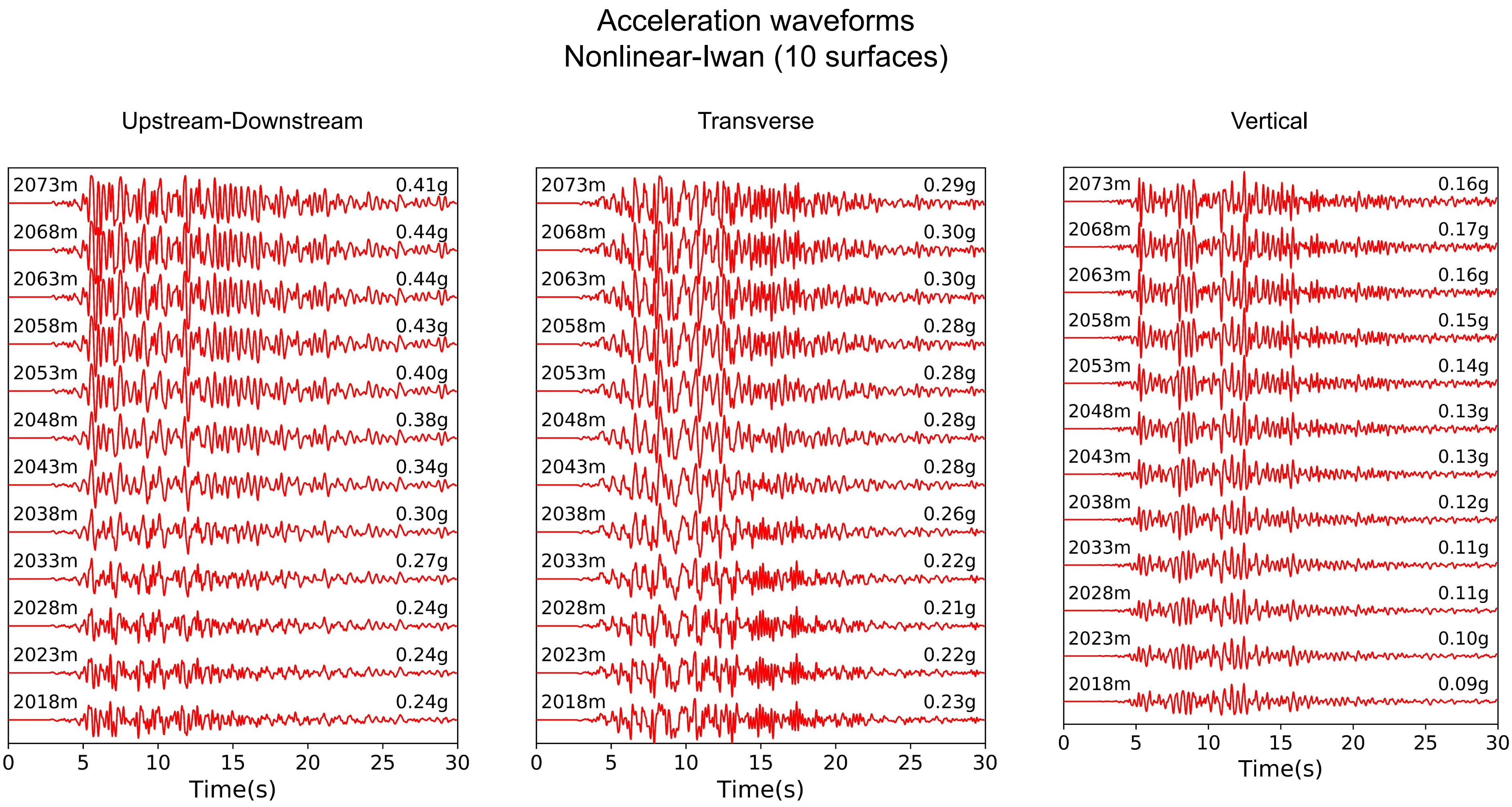


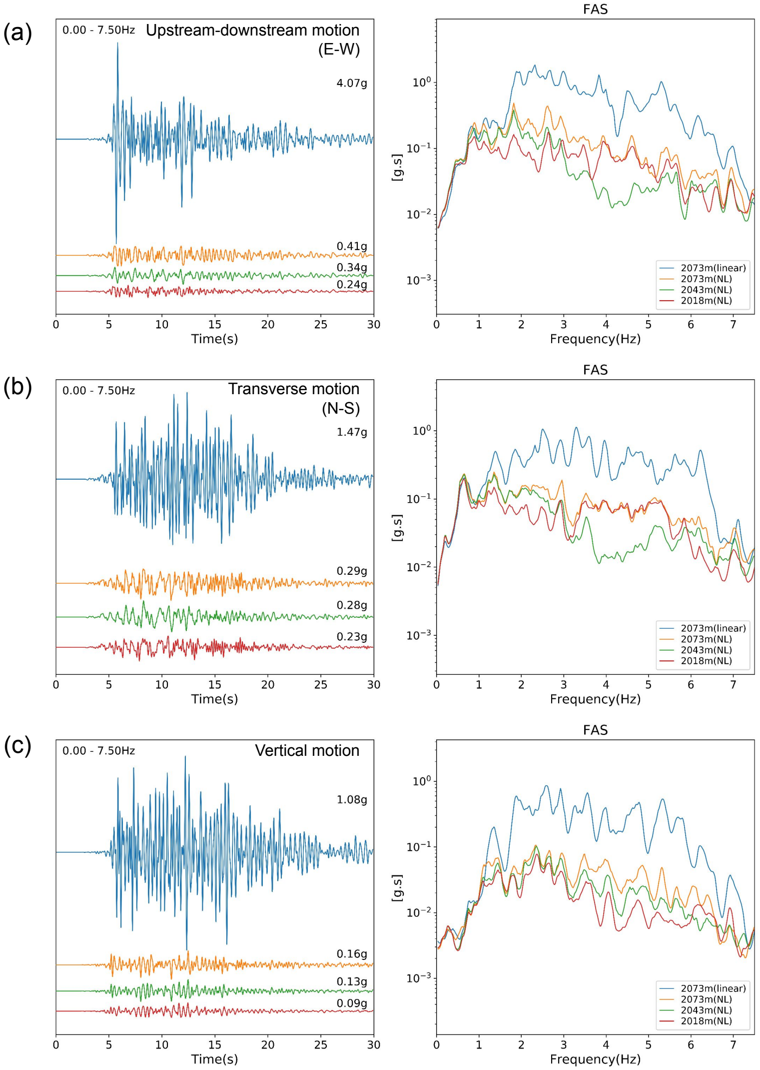
Vertical synthetic array





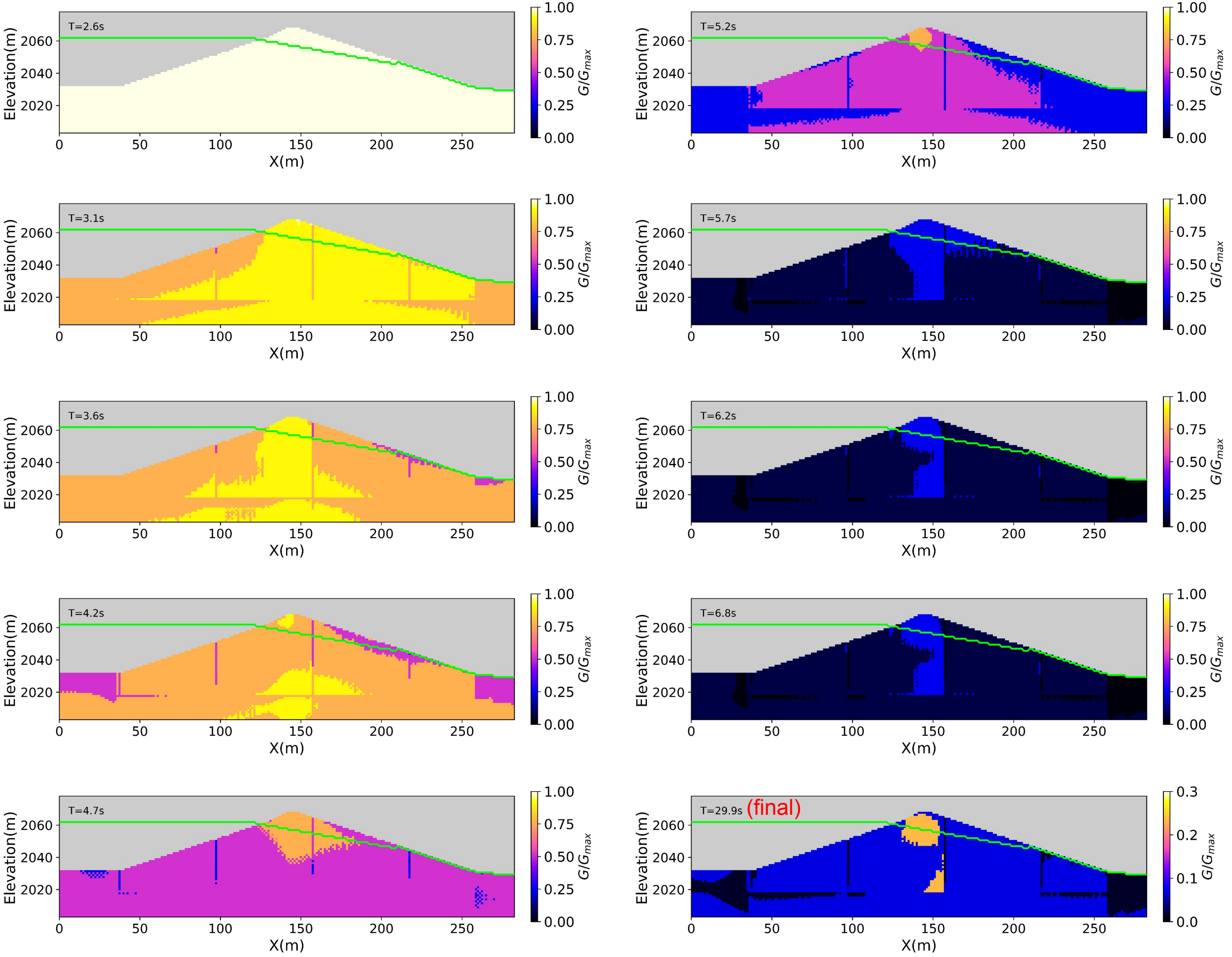
Acceleration waveforms
Linear
Upstream-Downstream
Transverse
Vertical
2073m 4.10g
2068m 4.34g
2063m 4.07g
2058m 3.72g
2053m 3.34g
2048m 3.14g
2043m 2.91g
2038m 2.68g
2033m 2.62g
2028m 2.49g
2023m 2.27g
2018m 2.03g
2073m 1.53g
2068m 1.55g
2063m 1.44g
2058m 1.34g
2053m 1.16g
2048m 1.06g
2043m 1.00g
2038m 1.00g
2033m 1.04g
2028m 1.03g
2023m 1.00g
2018m 0.96g
2073m 1.09g
2068m 1.15g
2063m 1.13g
2058m 1.10g
2053m 1.06g
2048m 1.00g
2043m 0.93g
2038m 0.87g
2033m 0.81g
2028m 0.76g
2023m 0.72g
2018m 0.68g
0 5 10 15 20 25 30
Time(s)

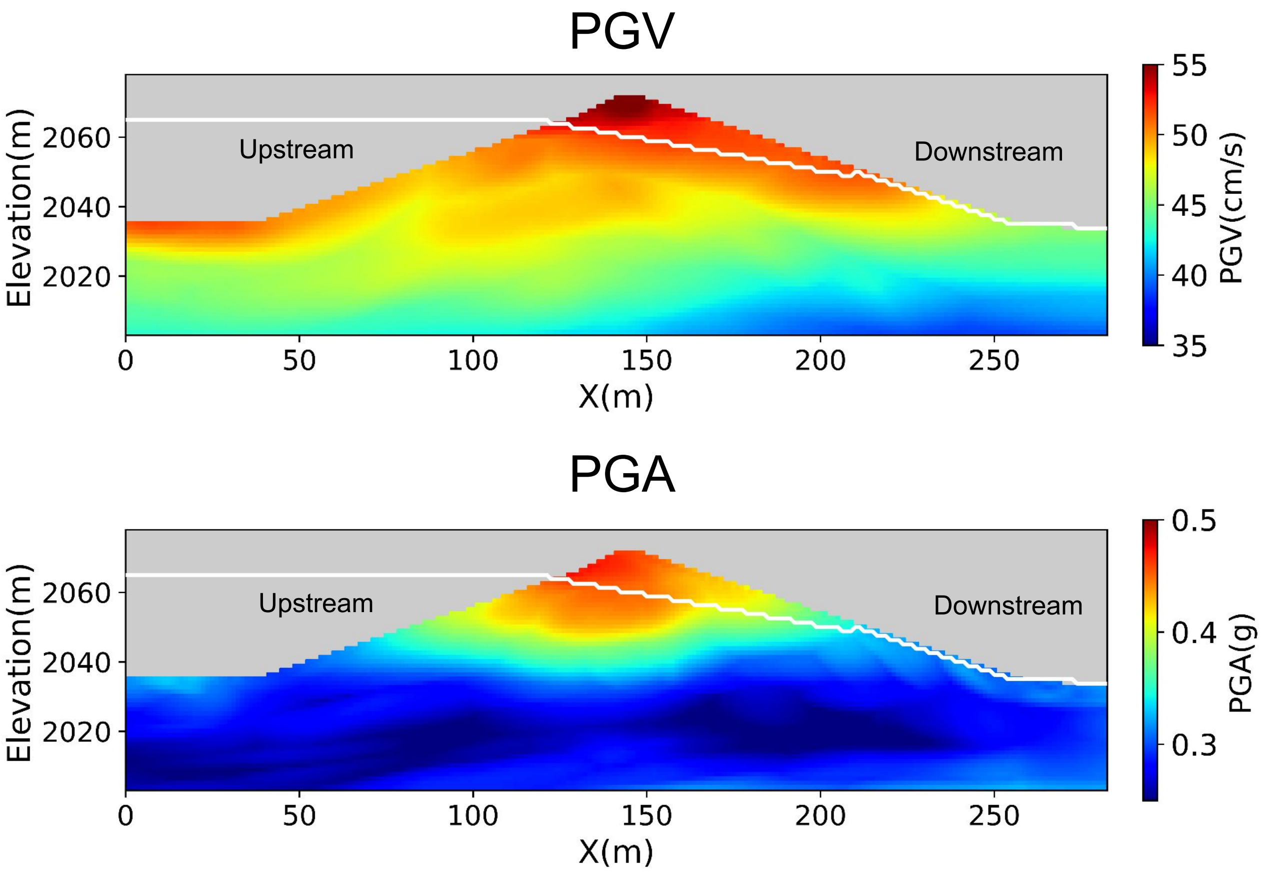

Acceleration waveforms
Nonlinear-Iwan (10 surfaces)
Upstream-Downstream
Transverse
Vertical
2073m
2068m
2063m
2058m
2053m
2048m
2043m
2038m
2033m
2028m
2023m
2018m
0.41g
0.44g
0.44g
0.43g
0.40g
0.38g
0.34g
0.30g
0.27g
0.24g
0.24g
0.24g
0.29g
0.30g
0.30g
0.28g
0.28g
0.28g
0.28g
0.26g
0.22g
0.21g
0.22g
0.23g
0.16g
0.17g
0.16g
0.15g
0.14g
0.13g
0.13g
0.12g
0.11g
0.11g
0.10g
0.09g
0
5
10
15
20
25
30
Time(s)



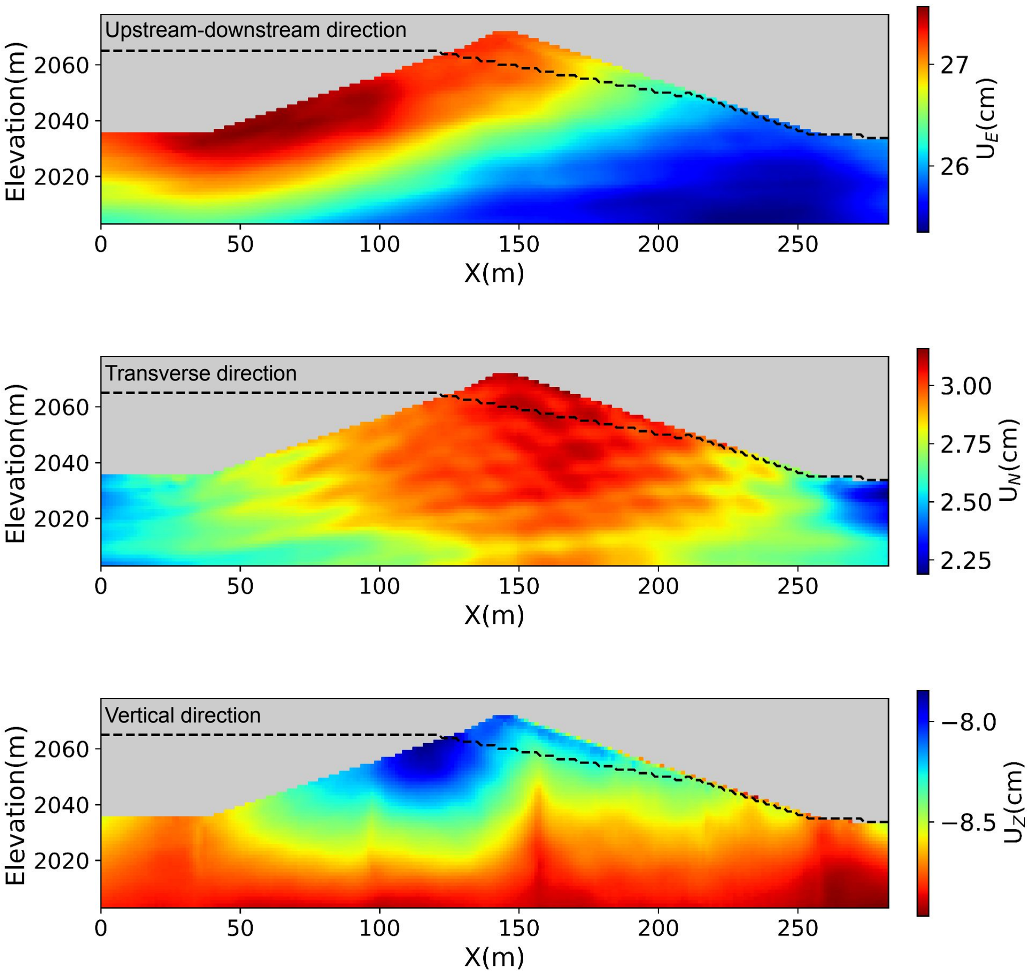
(a)
0.00 - 7.50Hz
Upstream-downstream motion
(E-W)
4.07g
0.41g
0.34g
0.24g
Time(s)
FAS
[g.s]
Frequency(Hz)
2073m(linear)
2073m(NL)
2043m(NL)
2018m(NL)
(b)
0.00 - 7.50Hz
Transverse motion
(N-S)
1.47g
0.29g
0.28g
0.23g
Time(s)
FAS
[g.s]
Frequency(Hz)
2073m(linear)
2073m(NL)
2043m(NL)
2018m(NL)
(c)
0.00 - 7.50Hz
Vertical motion
1.08g
0.16g
0.13g
0.09g
Time(s)
FAS
[g.s]
Frequency(Hz)
2073m(linear)
2073m(NL)
2043m(NL)
2018m(NL)

G/Gmax (Iwan-10 surfaces)




PGV
Upstream
Downstream
Elevation(m)
2060
2040
2020
0
50
100
150
200
250
X(m)
55
50
45
40
35
PGV(cm/s)
PGA
Upstream
Downstream
Elevation(m)
2060
2040
2020
0
50
100
150
200
250
X(m)
0.5
0.4
0.3
PGA(g)

Displacement



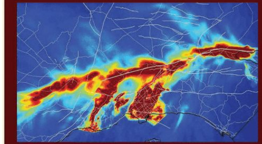
Doctoral Studies in Earthquake Science & Applied Geophysics:

SDSU/UCSD Joint PhD Prgogram in Geophysics

San Diego State University & University of California San Diego are accepting Fall 2023 applications for the SDSU/UCSD Joint Doctoral Program in Geophysics.

The UCSD/SDSU Joint Program is a collaboration between geophysicists at UCSD's Scripps Institution of Oceanography and SDSU's Department of Geological Sciences. The Joint Program was inaugurated in Fall 2010.

The UCSD core Geophysics curriculum provides students the foundation for advanced coursework and dissertation research that may be undertaken with participating faculty at both universities.

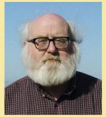


The Joint Program addresses fundamental science related to earthquake hazards, energy and the environment, using tools from geology, terrestrial and marine geophysics, and advanced computation. Areas of specialization include: the physics of earthquakes and earthquake hazards; the multiscale structure and dynamics of fault systems; quantitative paleoseismology and neotectonics; and high-performance computational seismology.

For further information see:
www.geology.sdsu.edu/jdp

Apply by December 15, 2022:
www.calstate.edu/apply

FACULTY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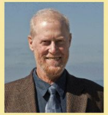
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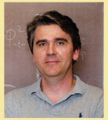
Steve Constable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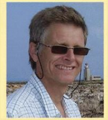
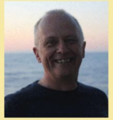

Peter Gerstotf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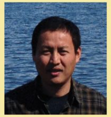
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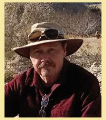
Kim Bak Olsen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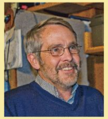
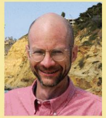

David Sandwell


Peter Shearer


Frank Vernon


Matthew Weingarten

send inquiries to:

Kim Bak Olsen
kbolsen@sdsu.edu

Department of Geological Sciences
San Diego State University