Caltech

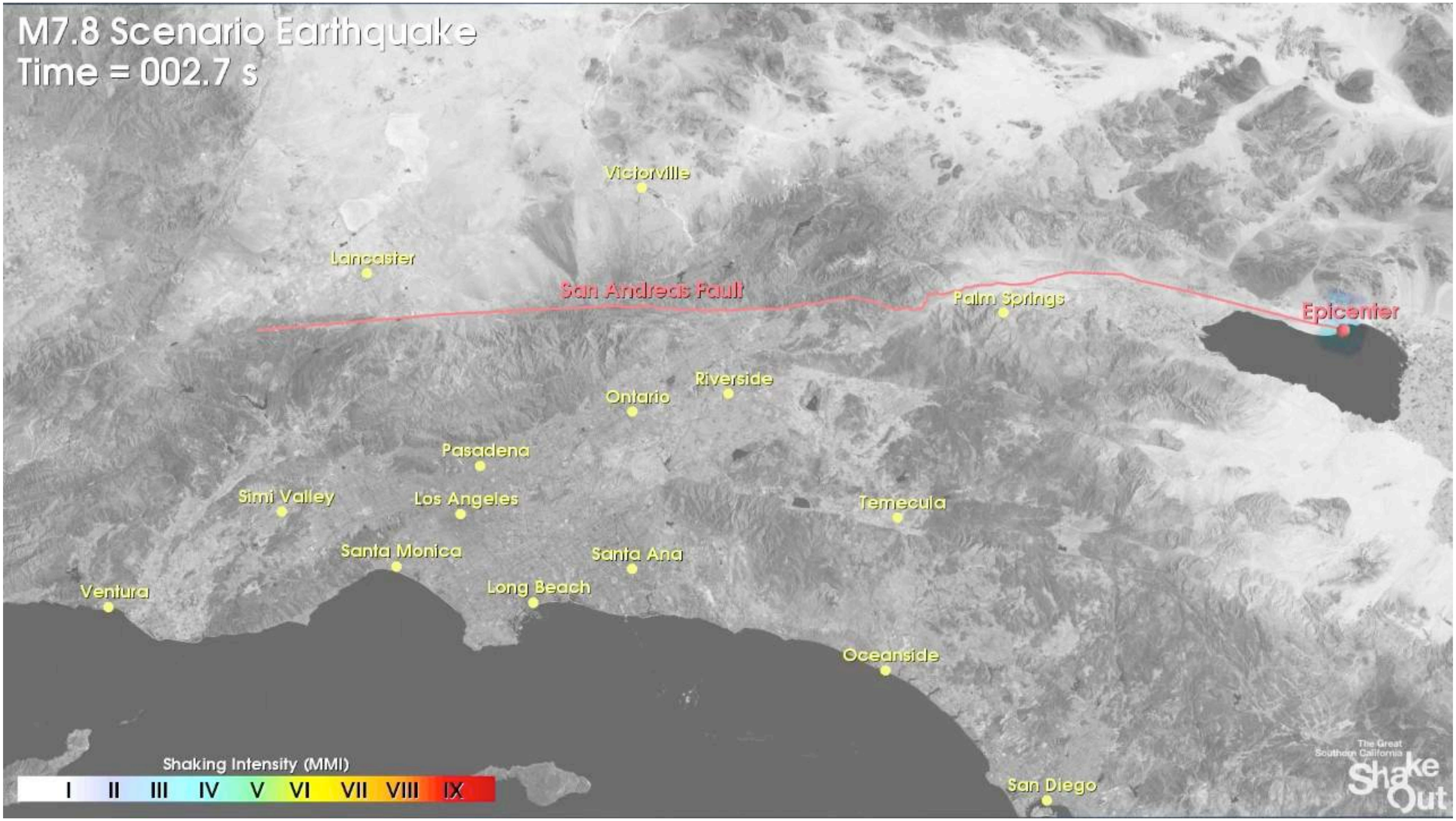
On seismic waves and convex features: Topography effects and their nonlinear dependence on soil layering

Domniki Asimaki & Kami Mohammadi

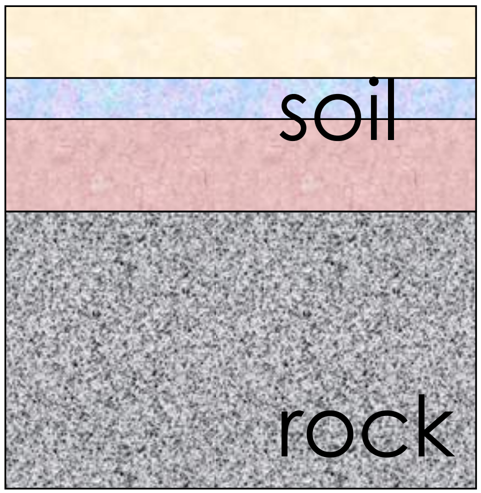
Mechanical and Civil Engineering
California Institute of Technology

Vamvatsikos & Friends, Hydra, June 2016

Earthquake simulations in the 21st century

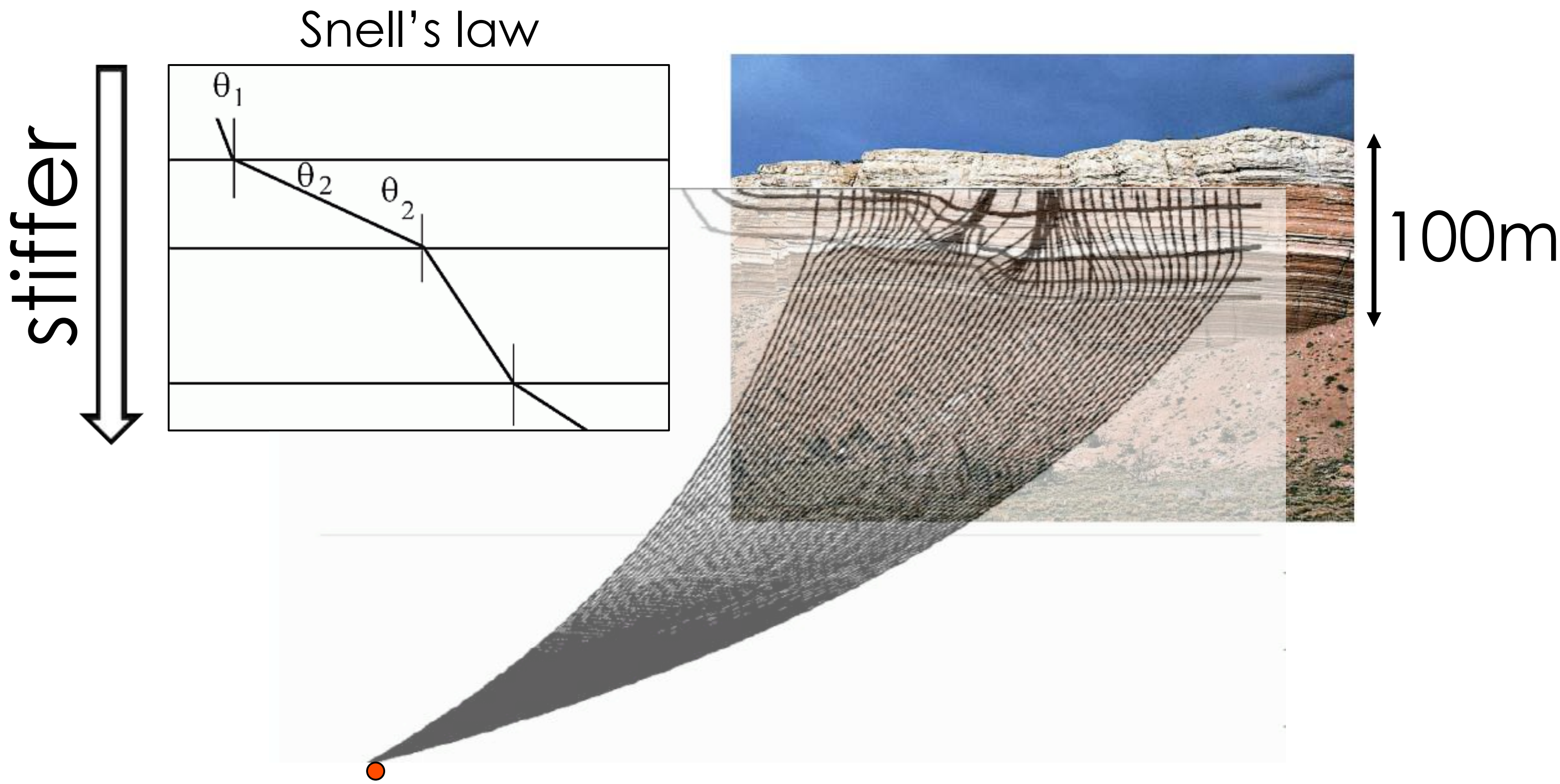


For engineers & seismologists…



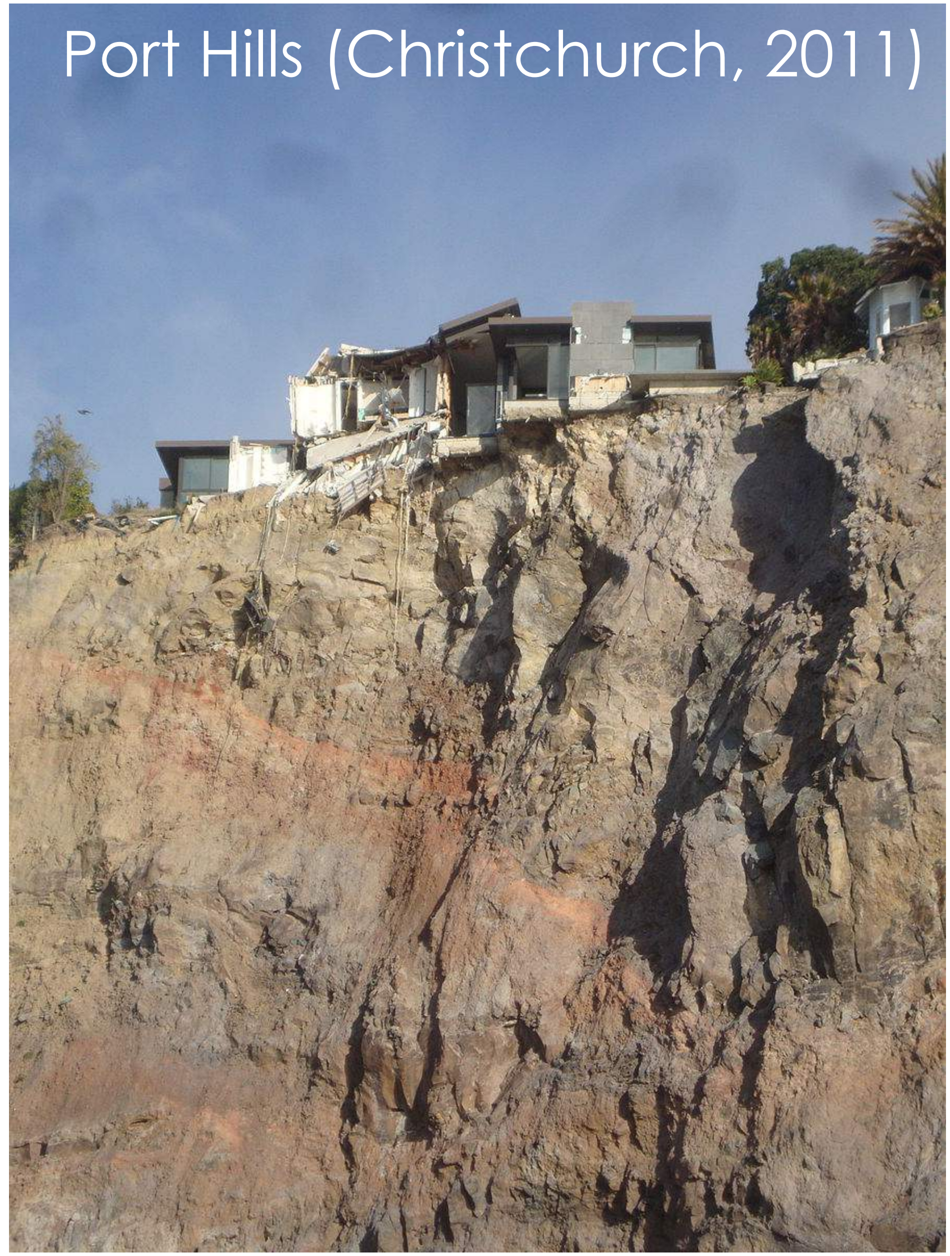
…the world is (usually) flat

Which is not always a bad idea



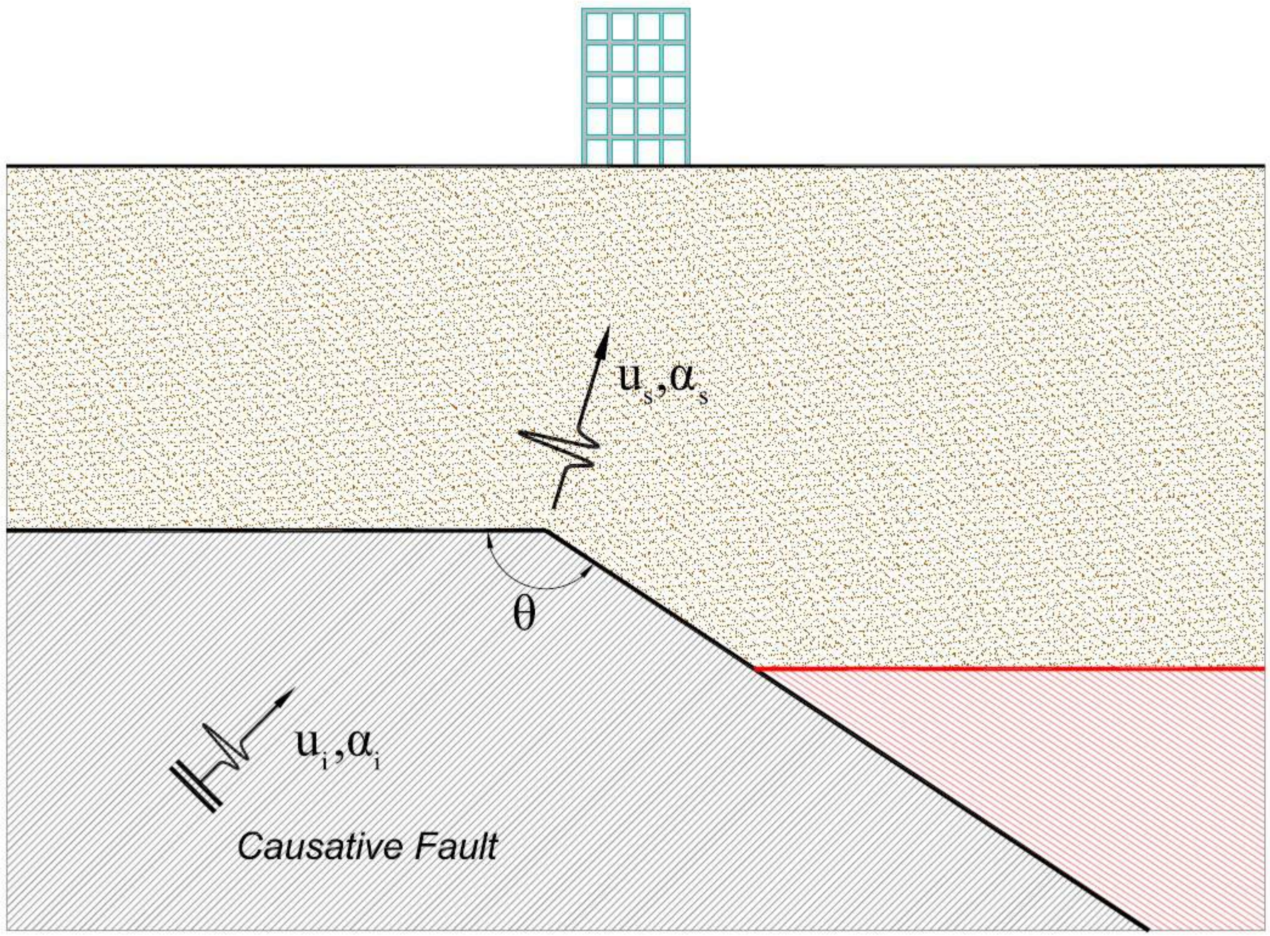
Source depth: 20-50km


Hotel Montana (Haiti, 2010)
http://web.ics.purdue.edu/~ecalais/haiti/natureG/


Port Hills (Christchurch, 2011)

Ayadan & Ulusay (2015)

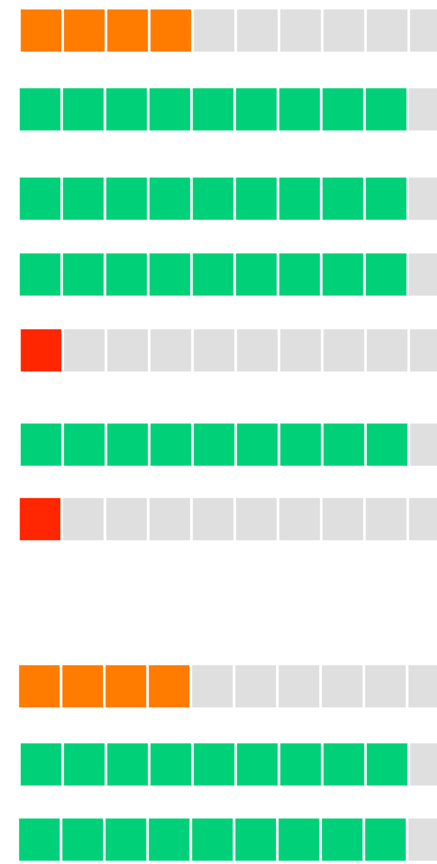
Meet the infinite wedge



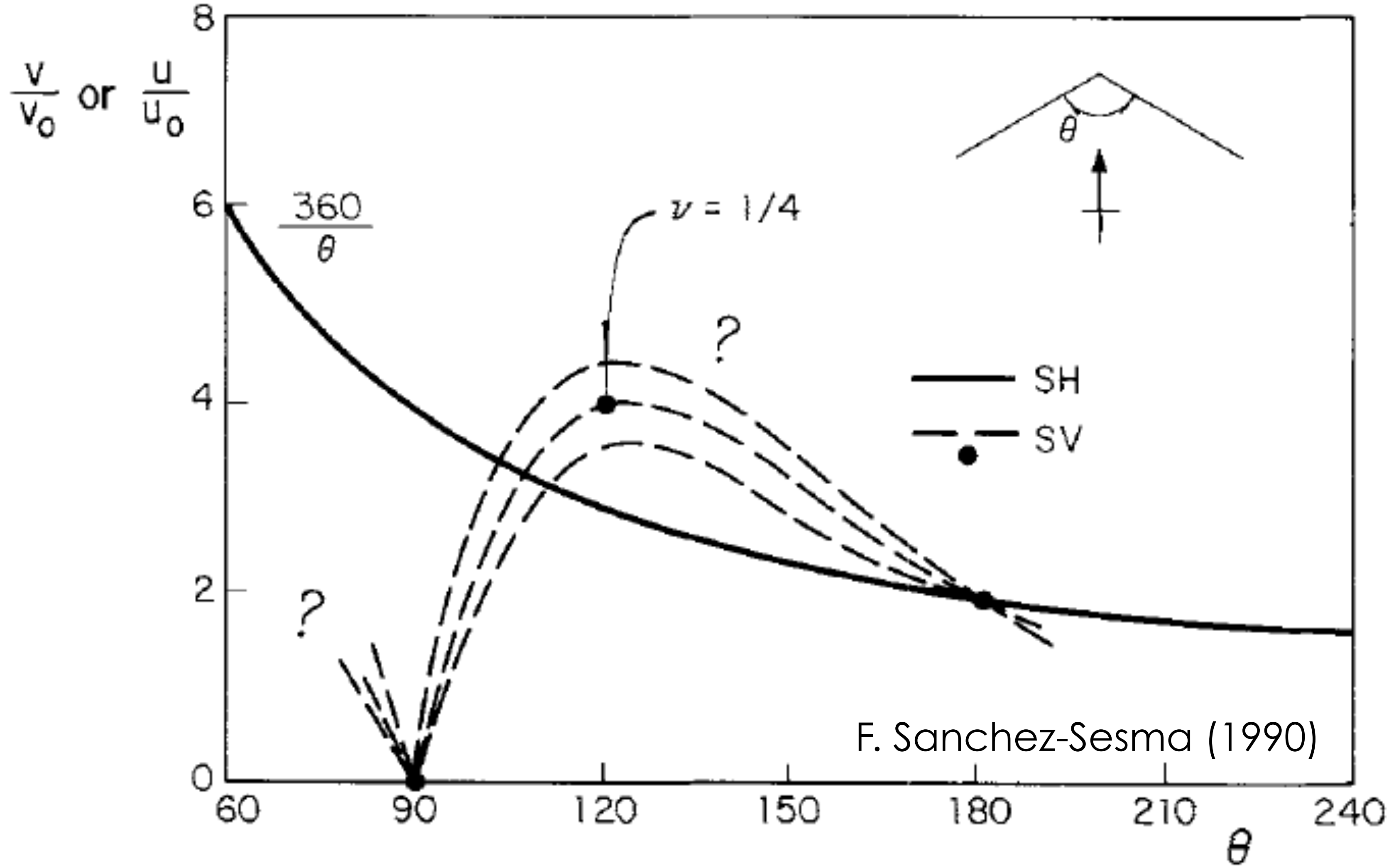
Continental margins, mountain roots, crustal discontinuities…

Focusing effects literature

- **Nucleation** Interior: Elastodynamics
  Exterior: Acoustics, Electromag.
- **Propagation** Rayleigh waves
  Body Waves: Scalar (SH)
  → **Vector (P and SV)**
- **Material** Homogeneous
  Layered →
- **Solution** (Semi) analytical: Simple Geometry
  Experimental: Rayleigh Wave
  Numerical: FDM, FEM, BEM

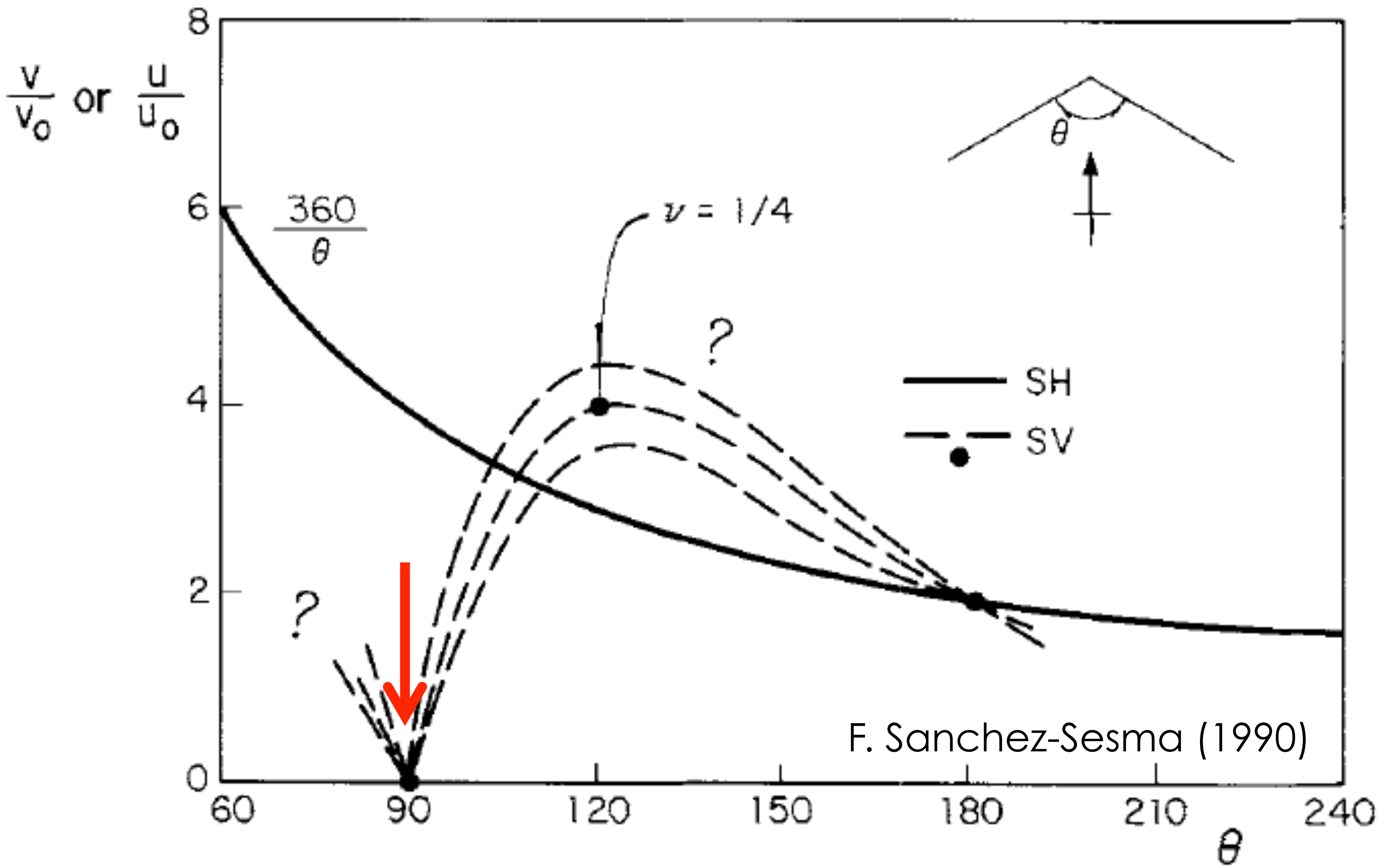


Geometric Solution of Infinite Wedge

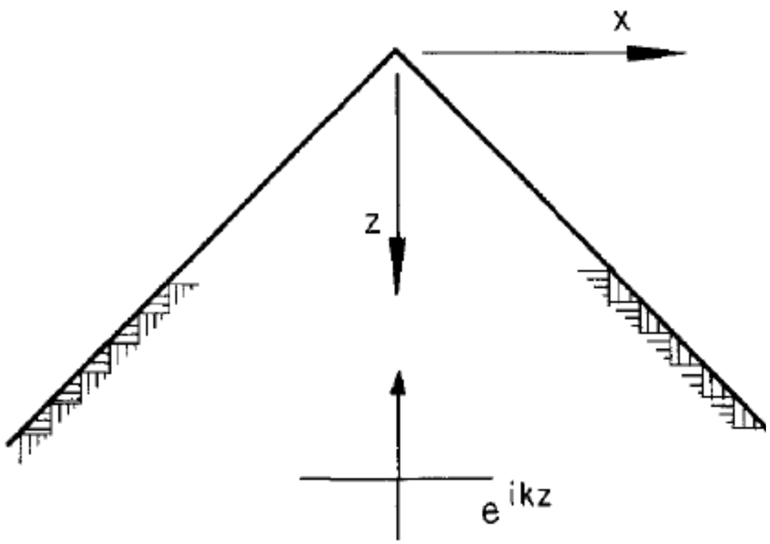


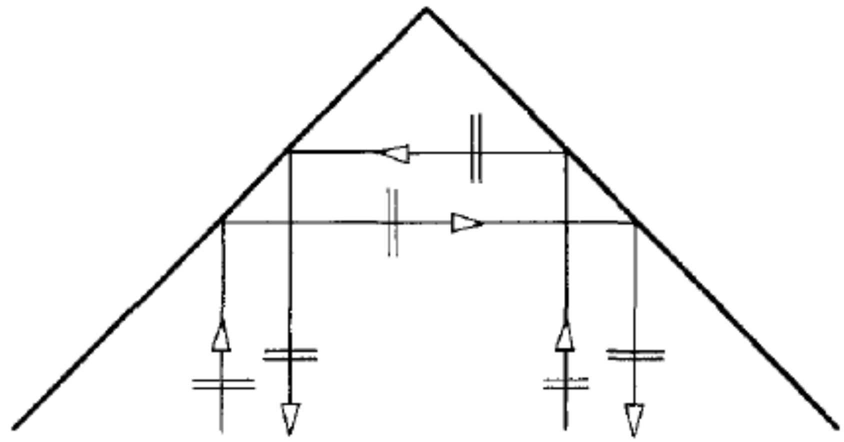
F. Sanchez-Sesma (1990)

Closed form solution of 90° wedge



Closed form solution of 90° wedge

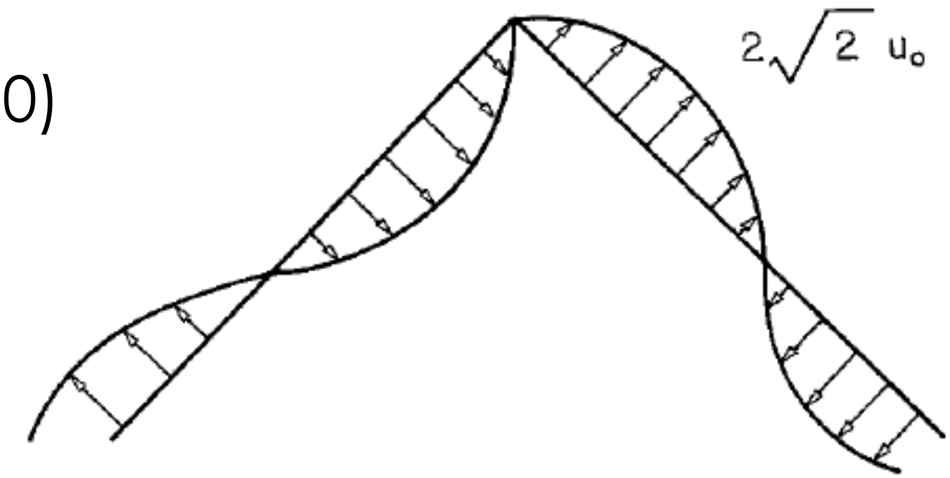




F. Sanchez-Sesma (1990)

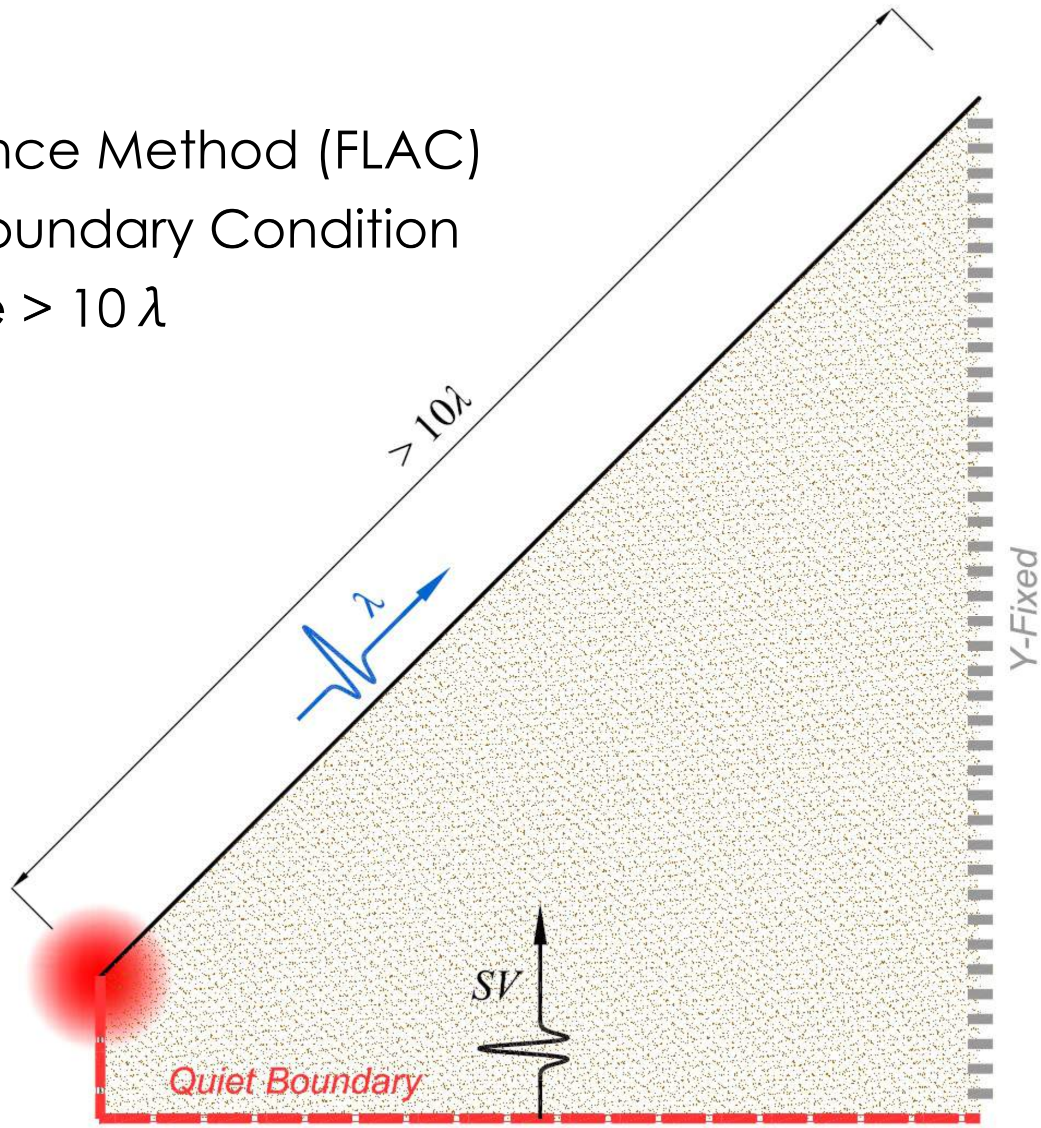
Poisson's ratio ν=1/4

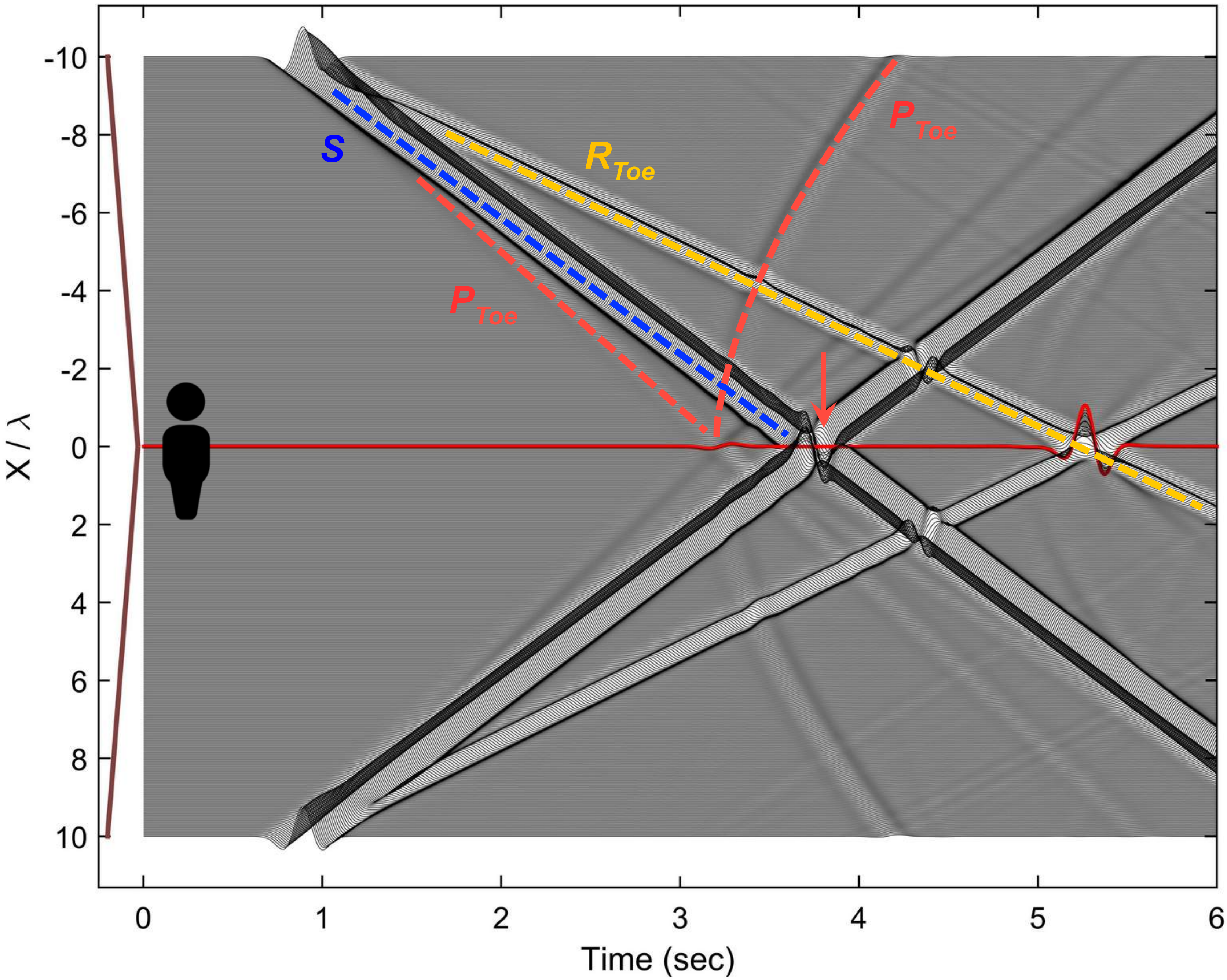
Internal angle 90°



"Infinite" wedge numerical simulations

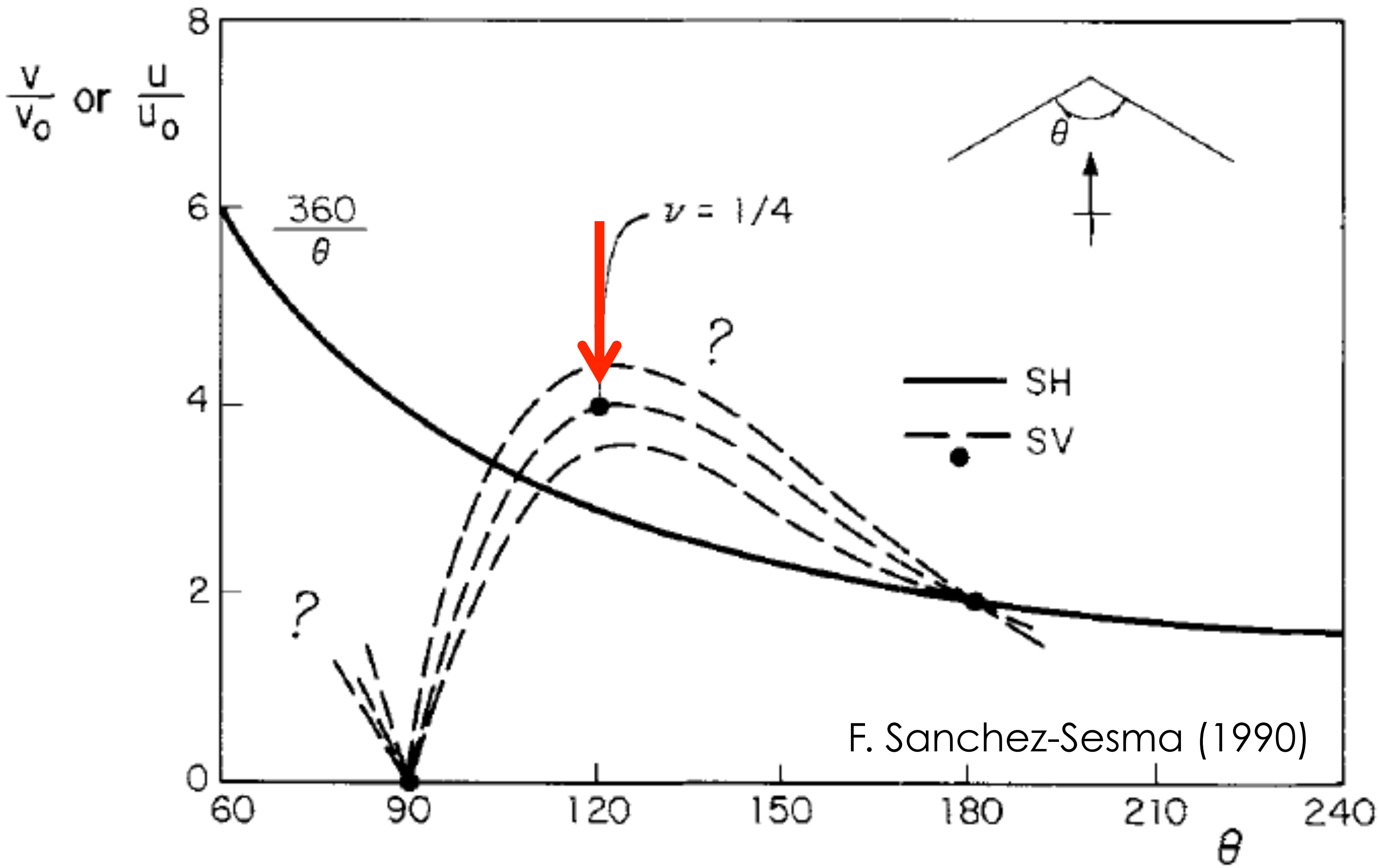
- Explicit Finite Difference Method (FLAC)
- Quiet (Absorbing) Boundary Condition
- Infinite = Model face > 10 λ

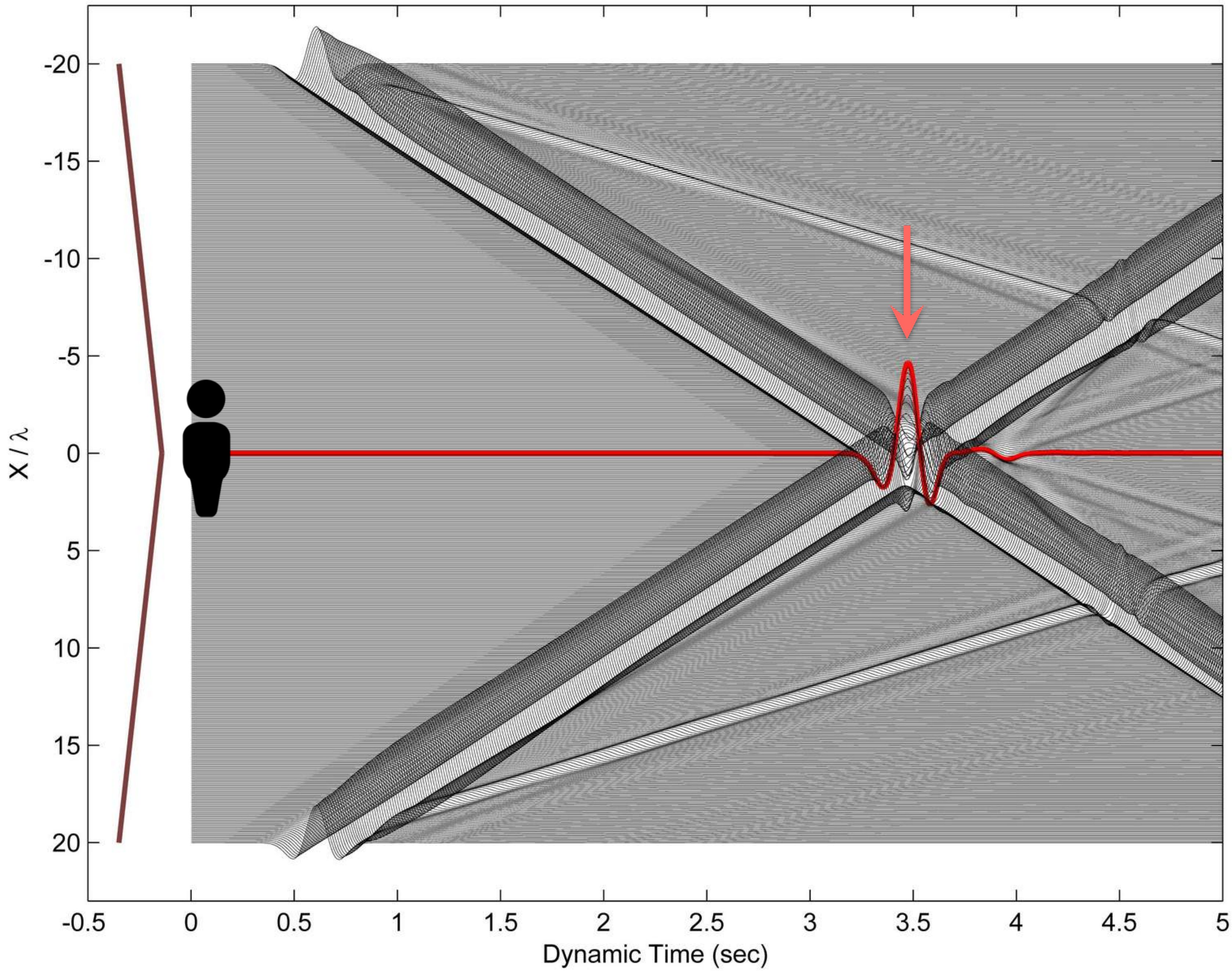




S
R_Toe
P_Toe
P_Toe
X / λ
Time (sec)
-10
-8
-6
-4
-2
0
2
4
6
8
10
0
1
2
3
4
5
6

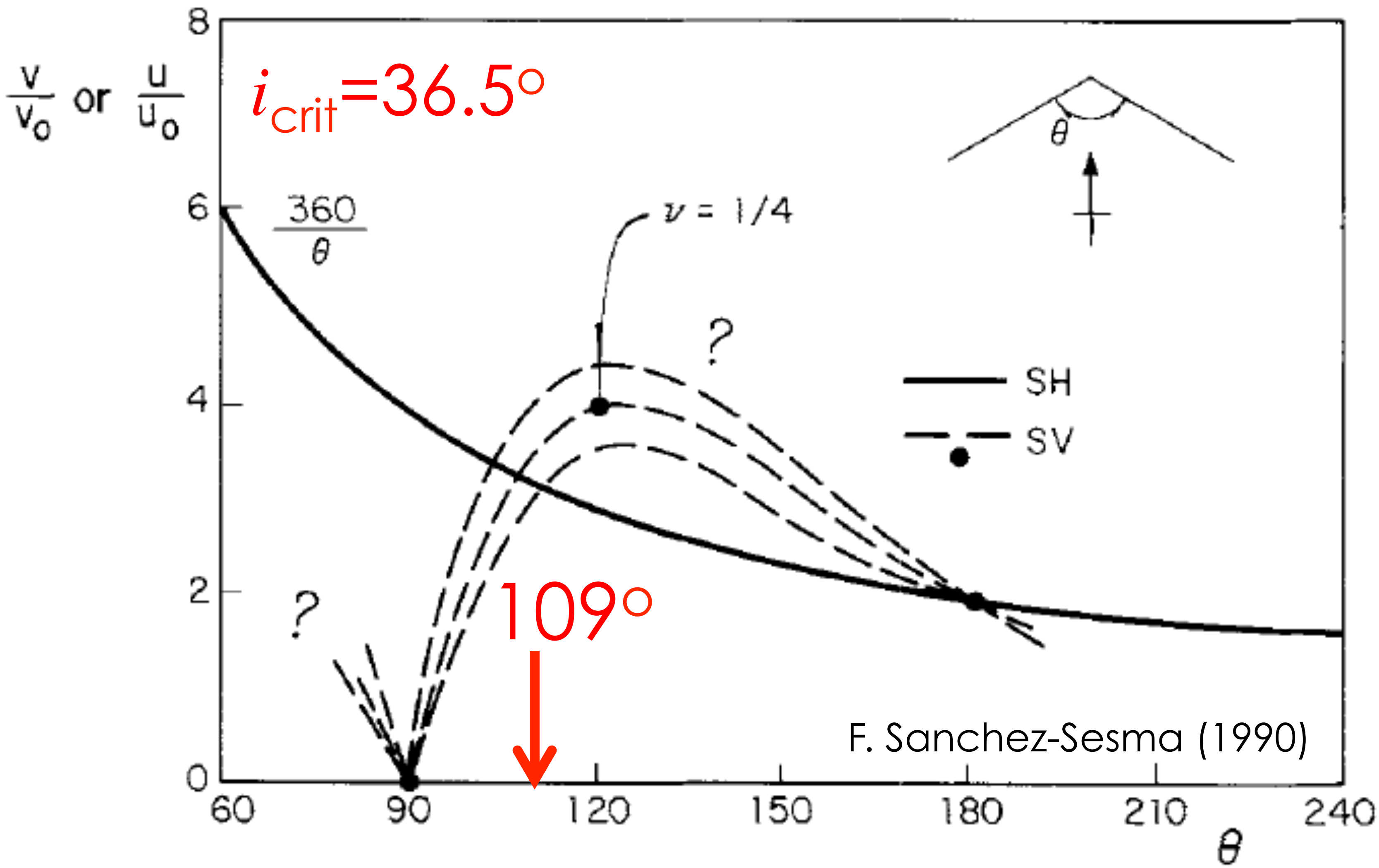
Geometric Solution of Infinite Wedge



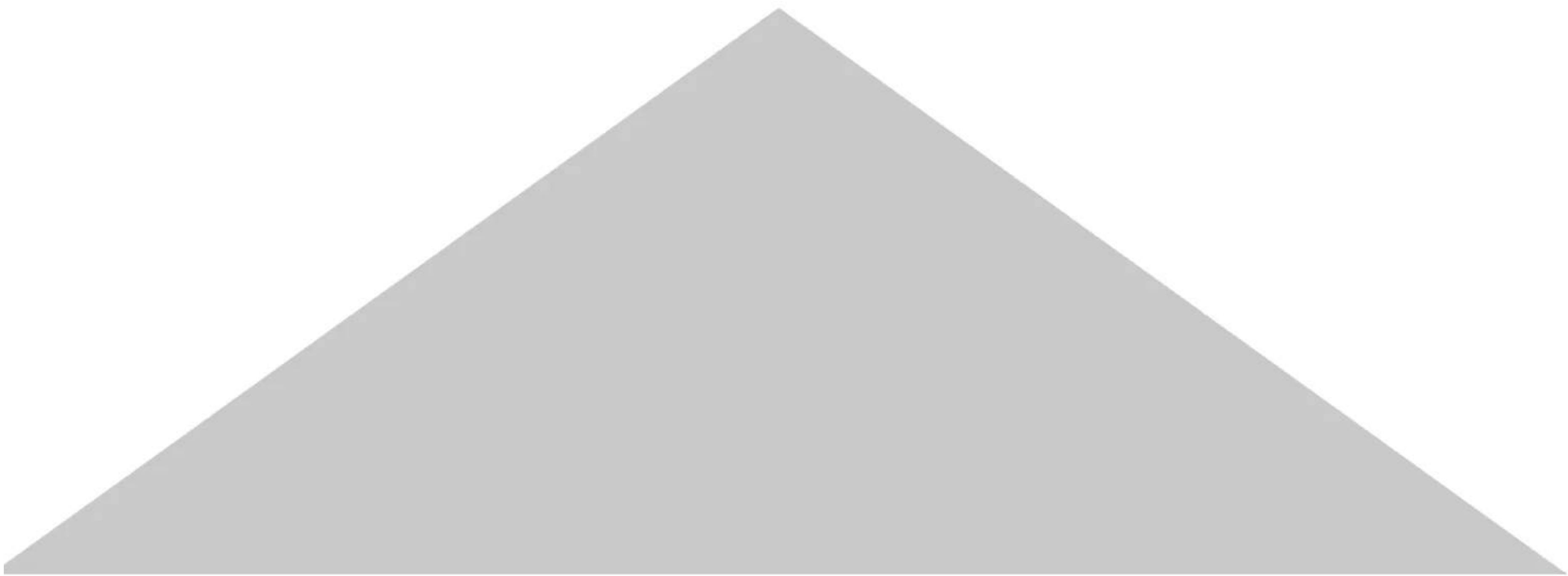


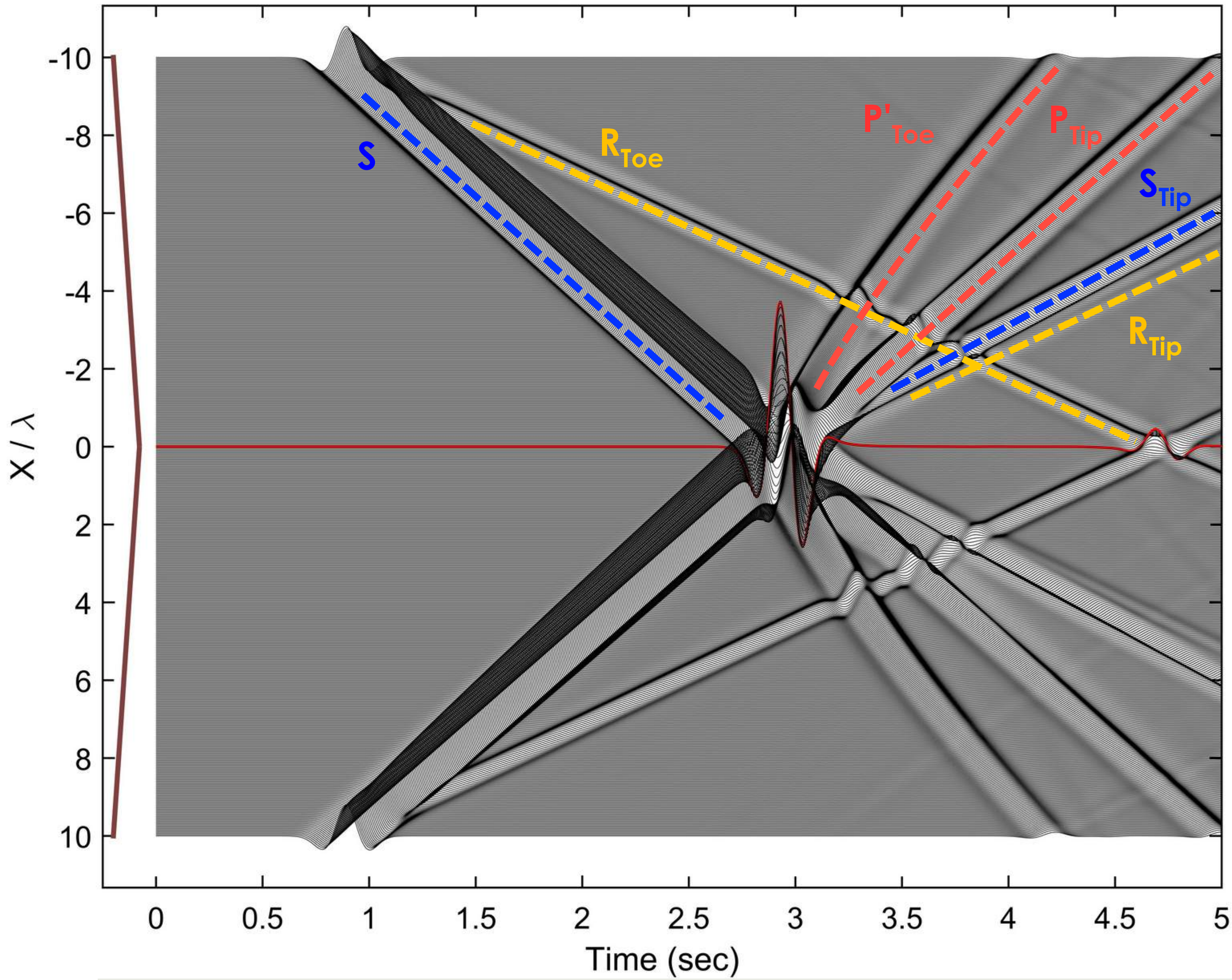
-20
-15
-10
-5
0
5
10
15
20
X / λ
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Dynamic Time (sec)

Critical angle: a special case

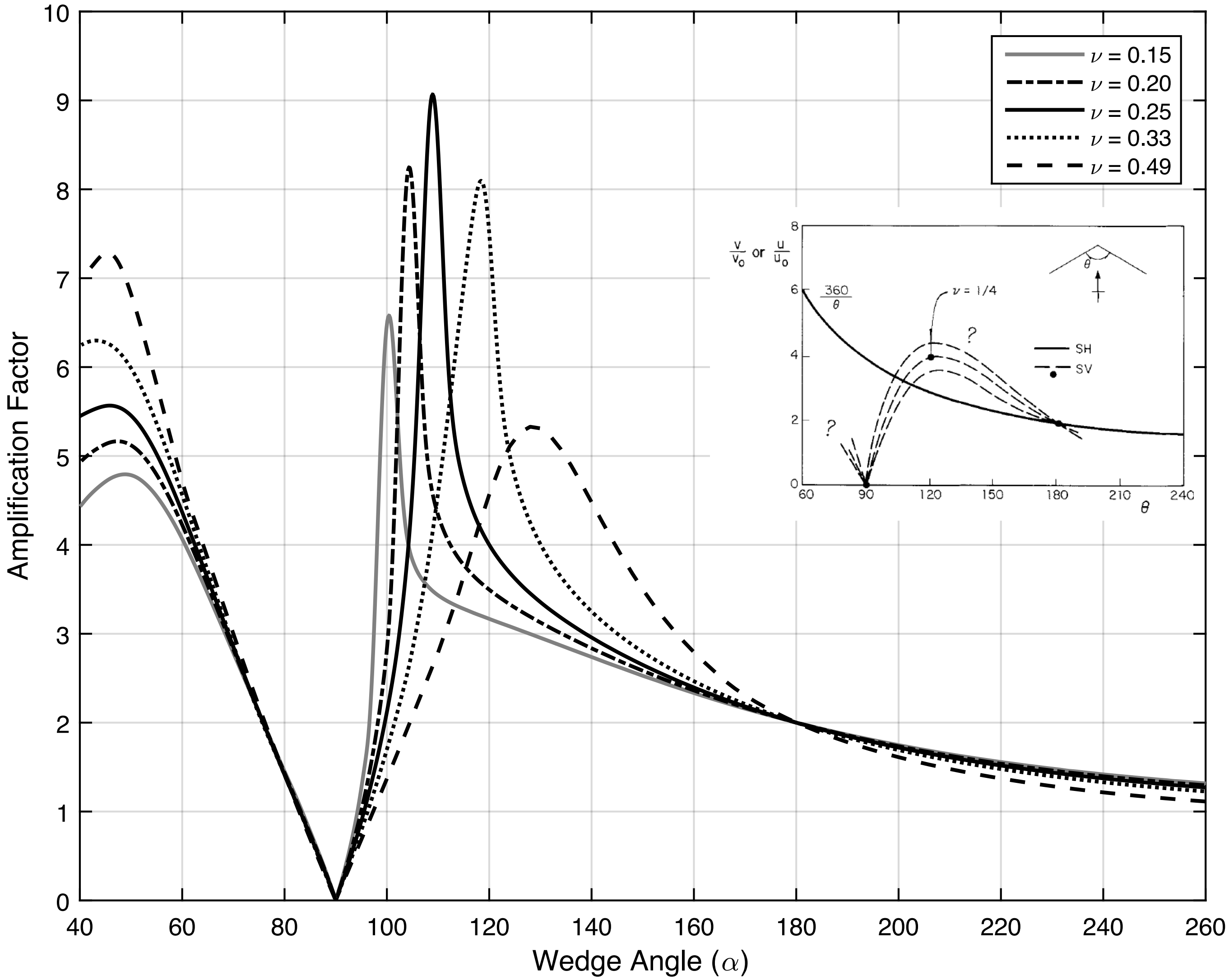


Numerical simulation of θ_{crit} wedge



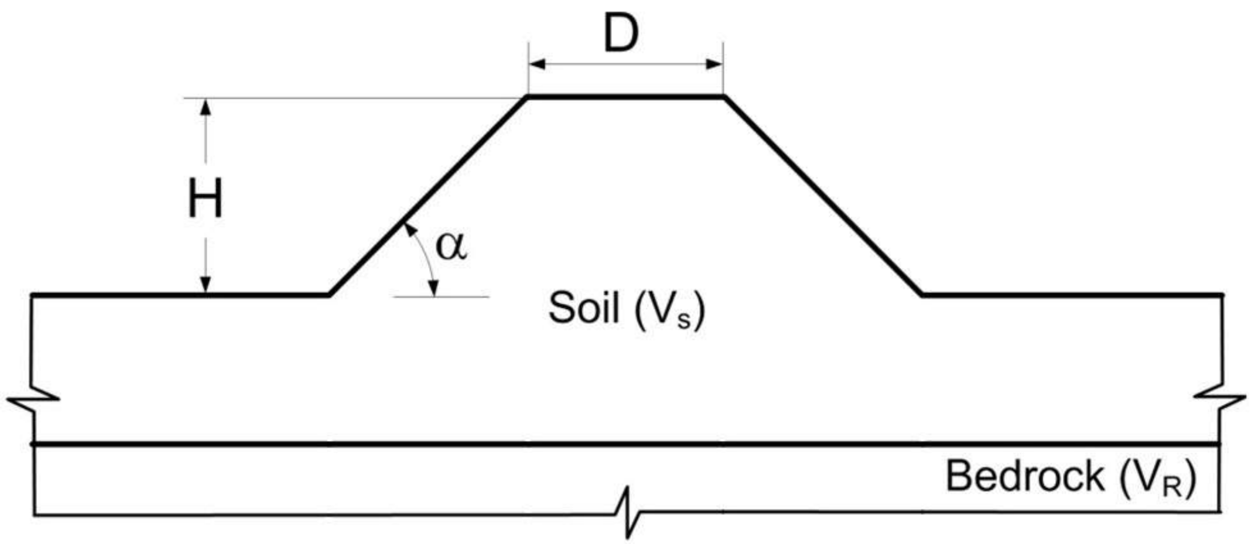

S
R_{Toe}
P'_{Toe}
P_{Tip}
S_{Tip}
R_{Tip}
X / λ
Time (sec)
-10
-8
-6
-4
-2
0
2
4
6
8
10
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

Infinite wedge vs. Poisson's ratio



2D topography effects

Geometry parameterization



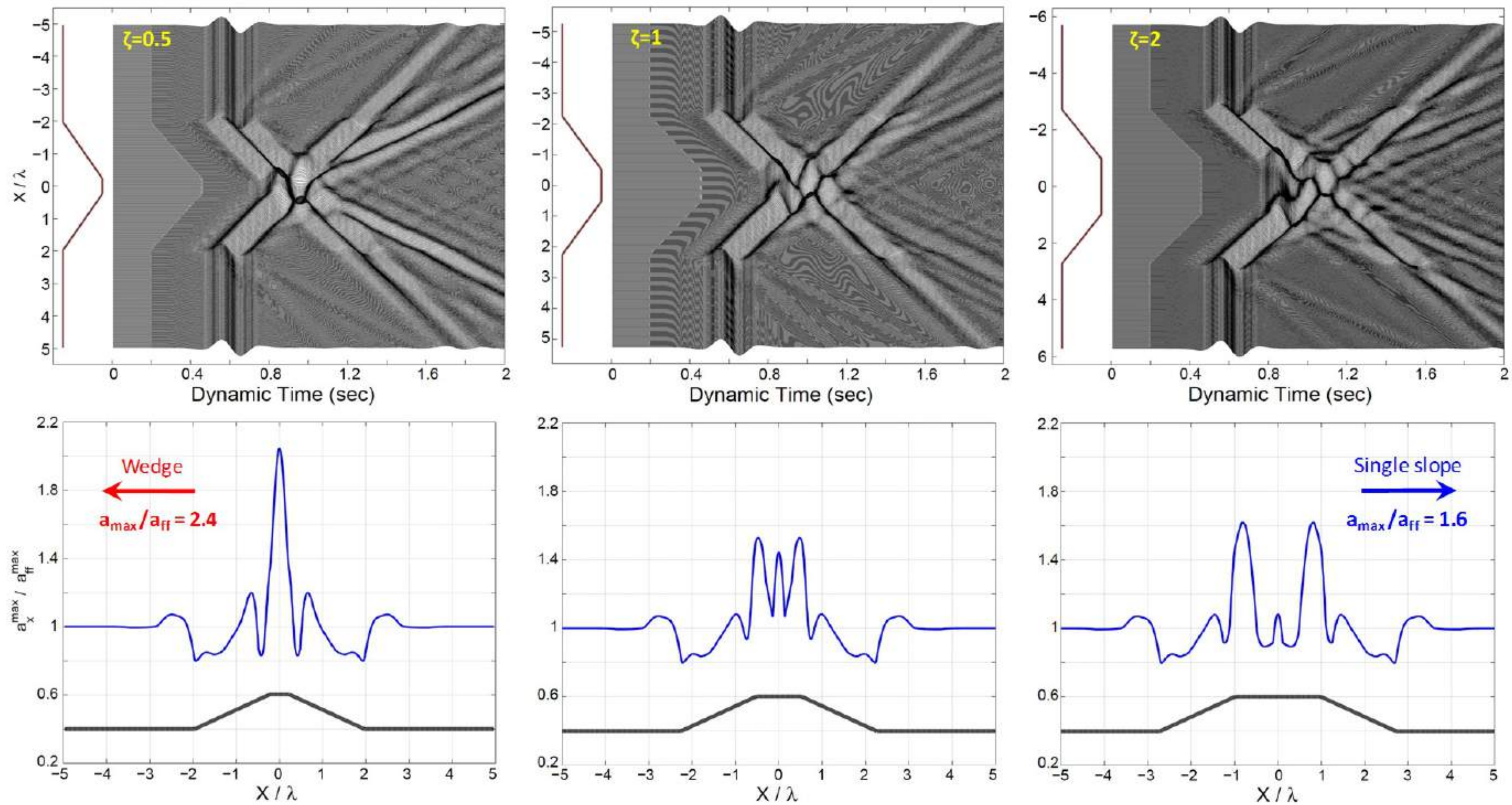
Slope angle: α [°]

Dimensionless height: $\boldsymbol{\eta = H/\lambda}$

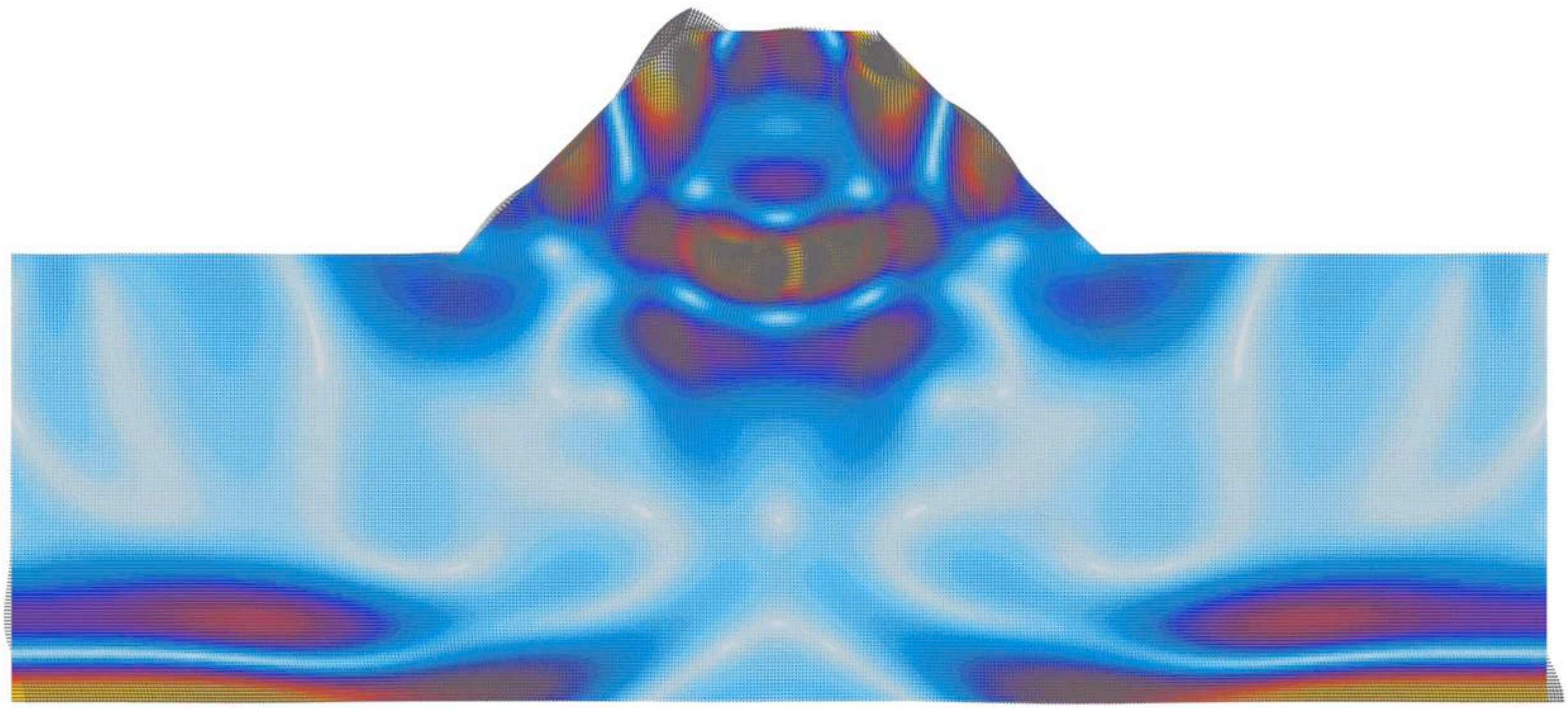
Dimensionless width: $\boldsymbol{\zeta = D/\lambda}$

Excitation: Vertical SV (horizontal motion) Ricker, f_0

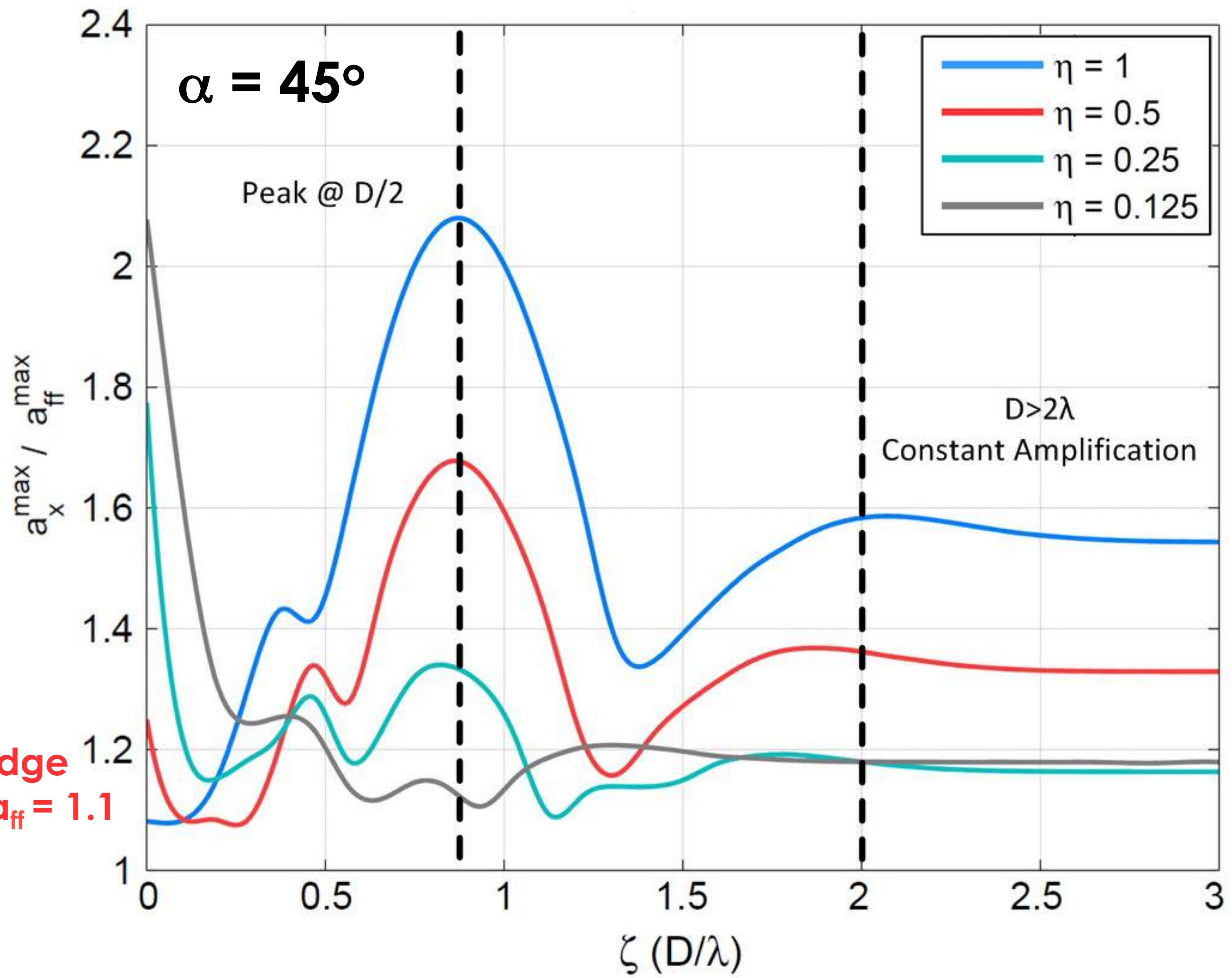
Dam: α = 30°; η=1.0



Homogeneous feature



Unified representation of convex features

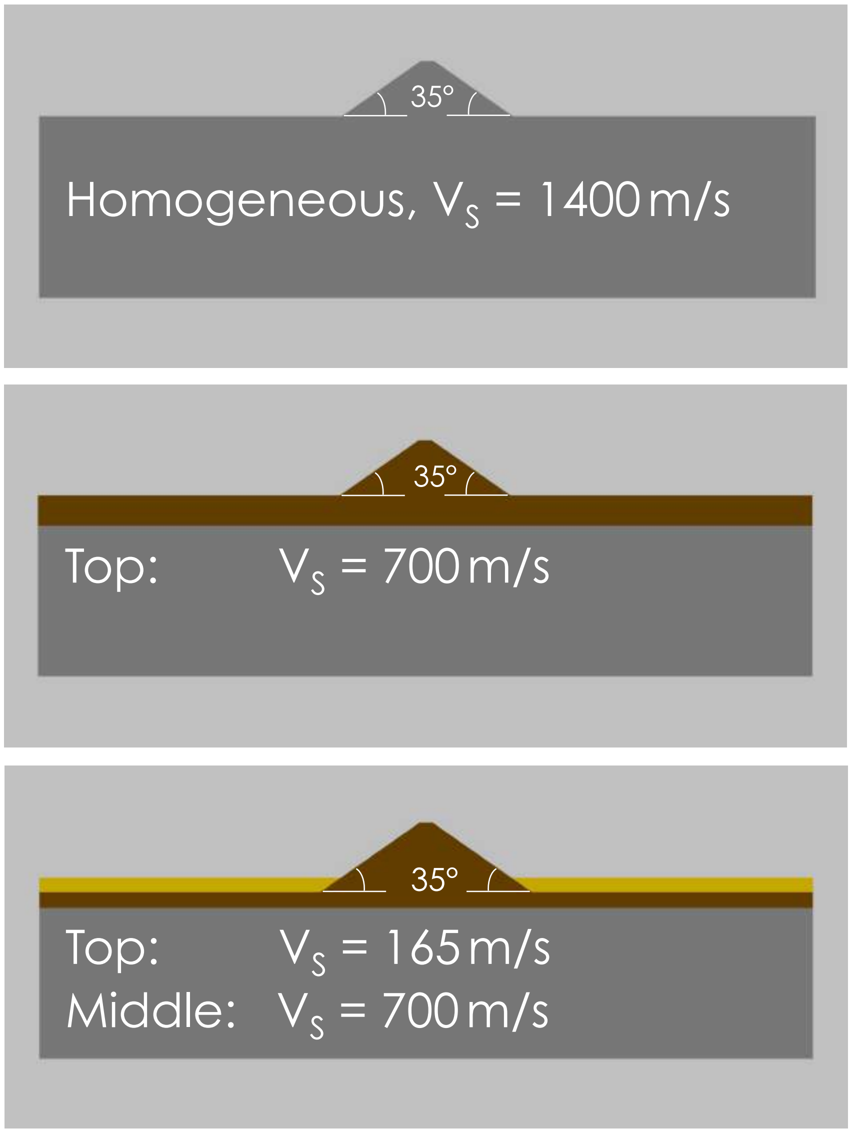


Single Slope
$a_{max}/a_{ff} = 1.5$

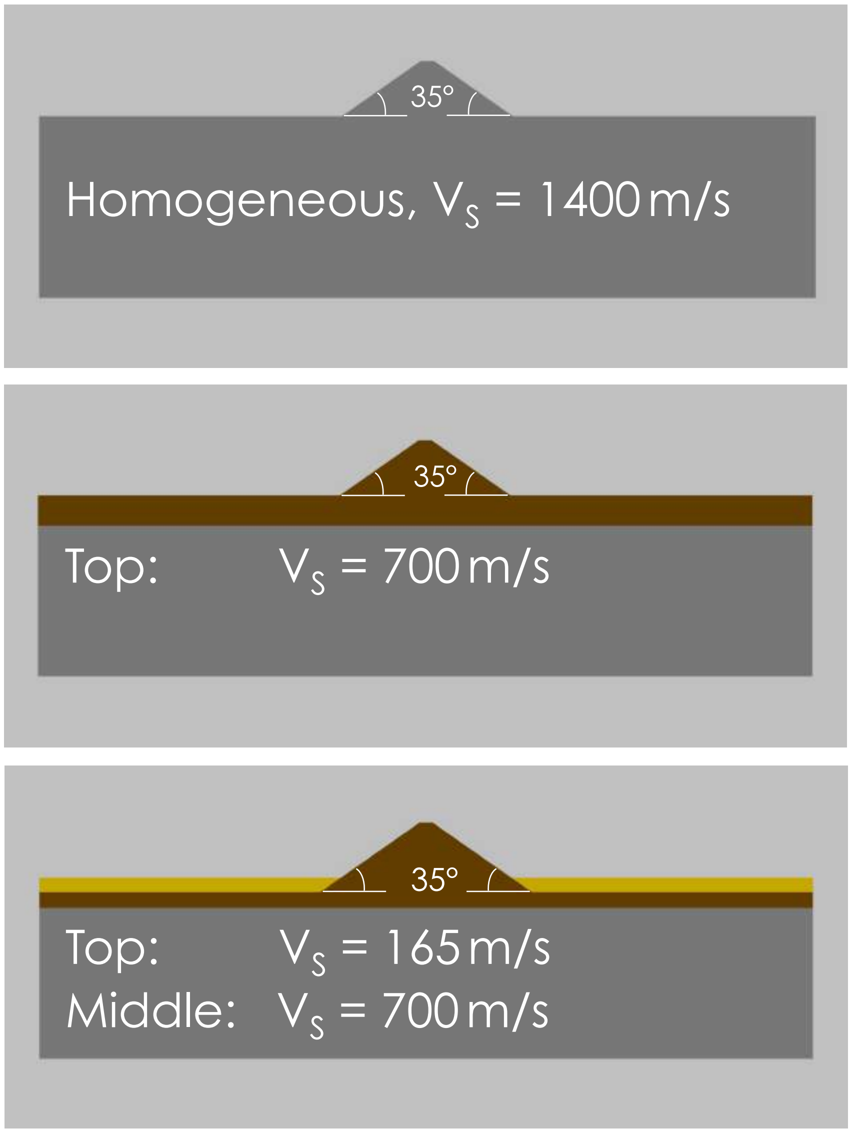
Wedge
$a_{max}/a_{ff} = 1.1$

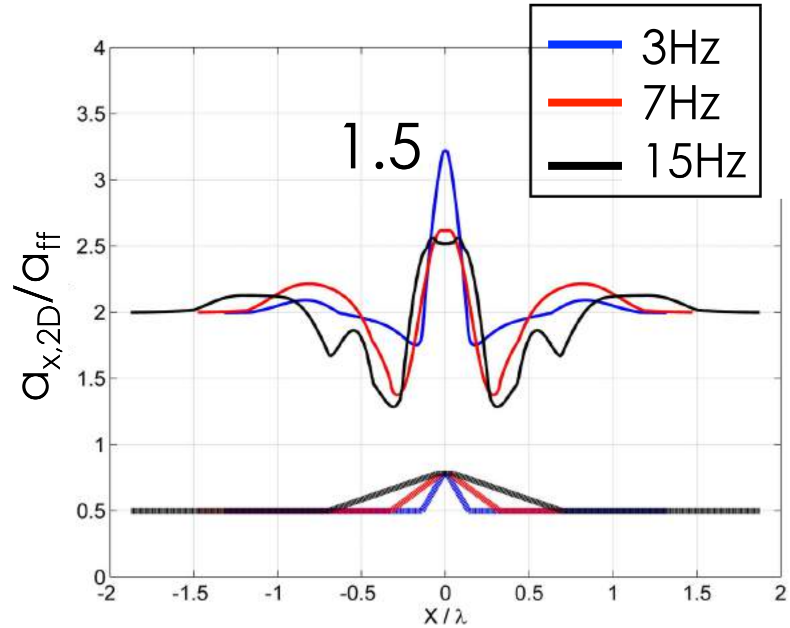
3D site effects: soil + geometry

Soil or topography effects?

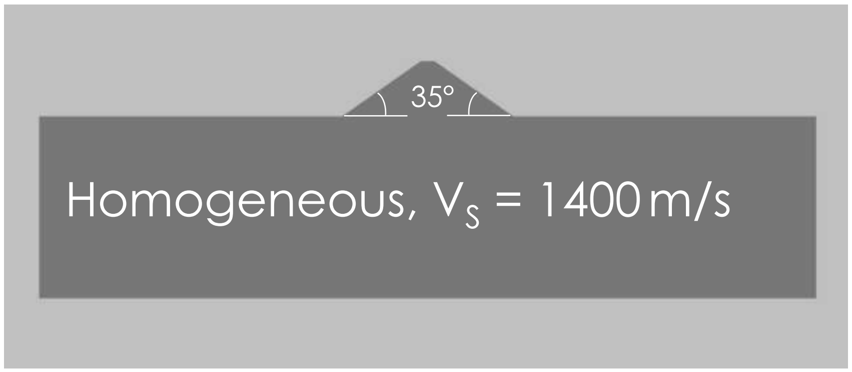


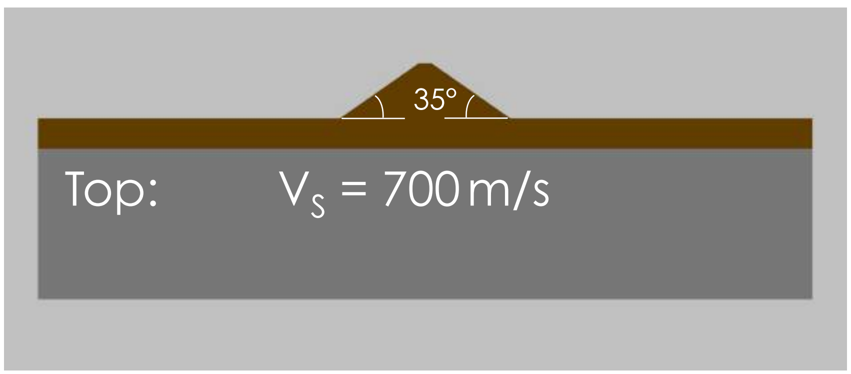
Horizontal motion ($a_{x,2D}$)

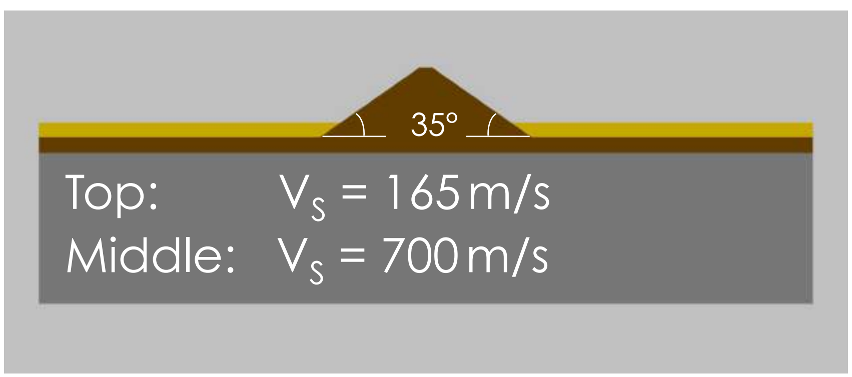


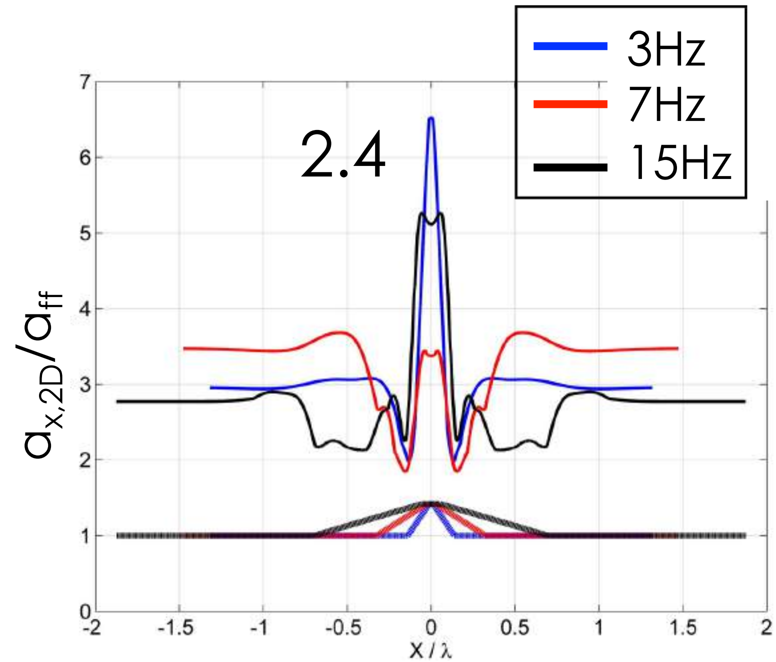


Horizontal motion ($a_{x,2D}$)

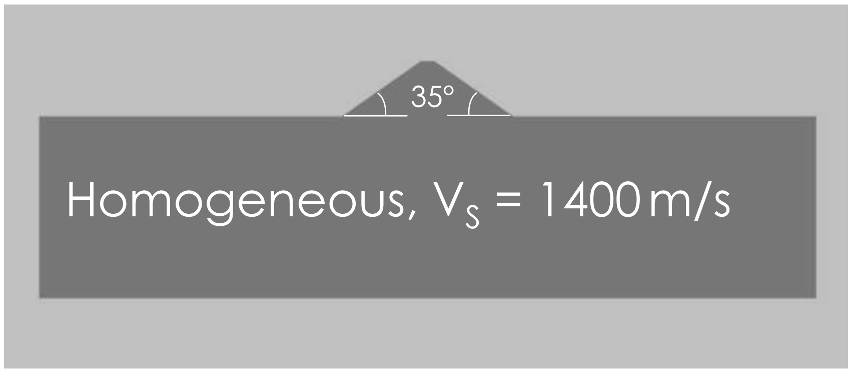


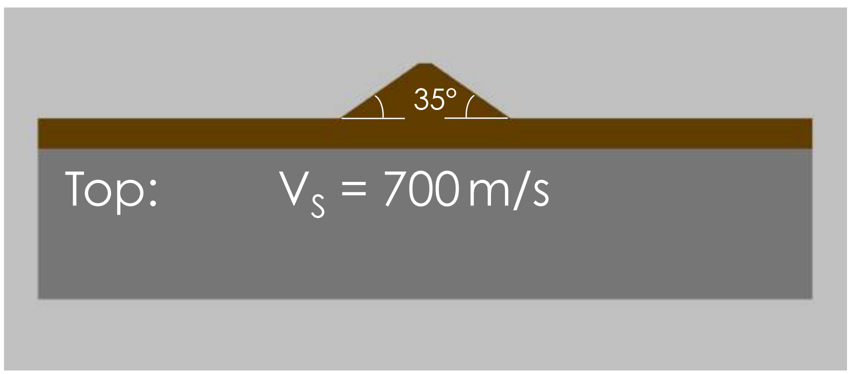


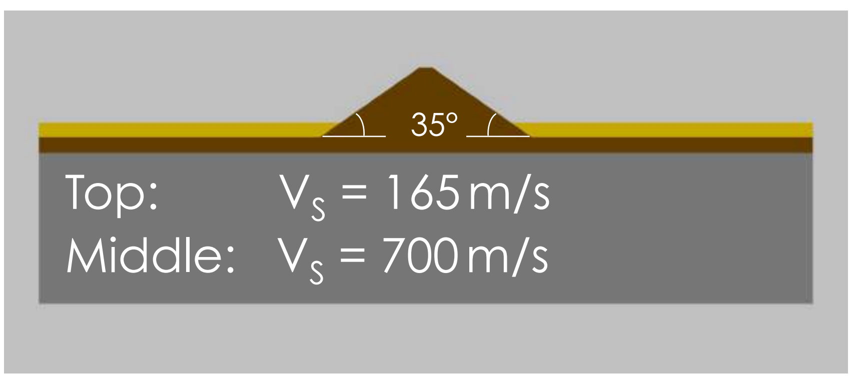


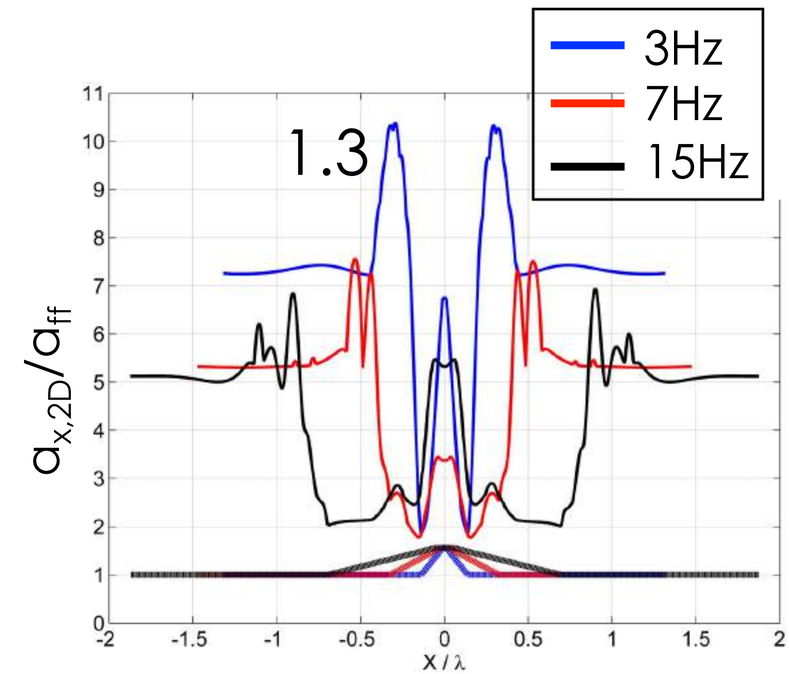


Horizontal motion ($a_{x,2D}$)

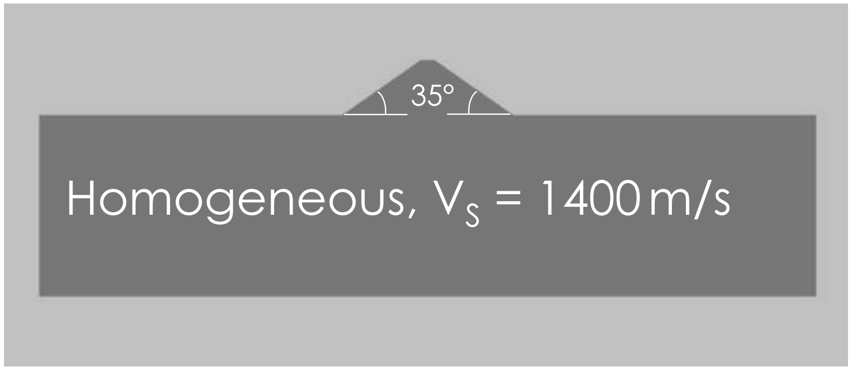


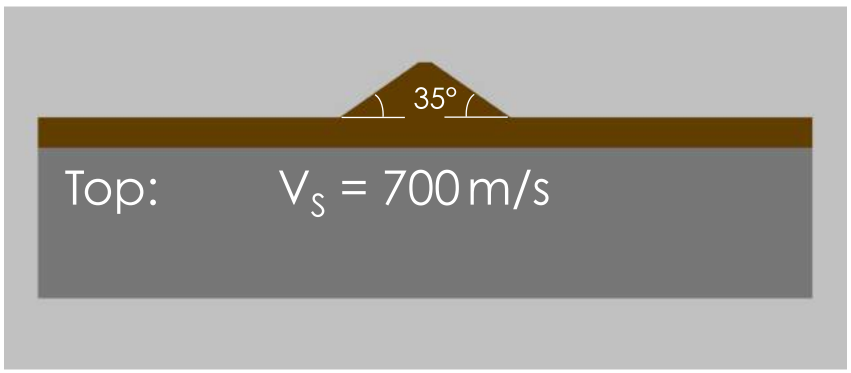


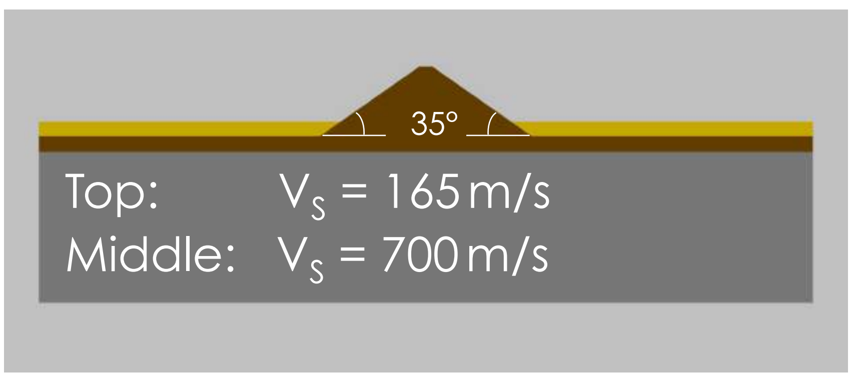


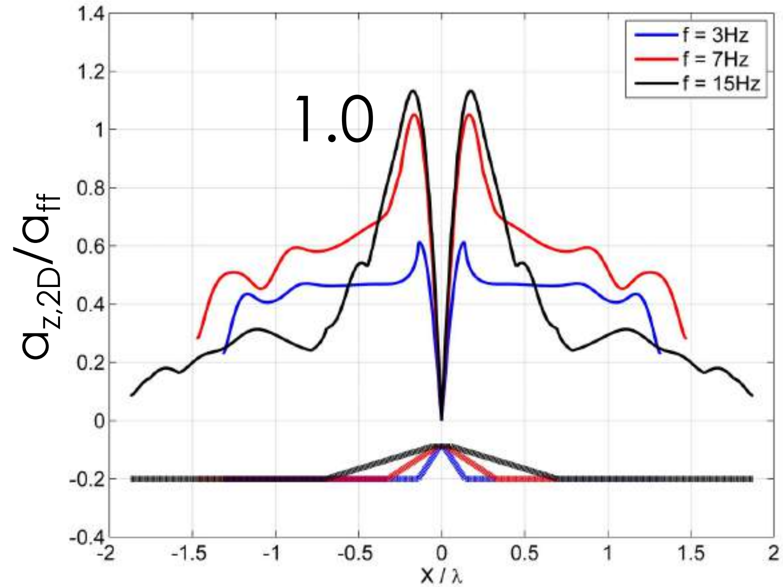


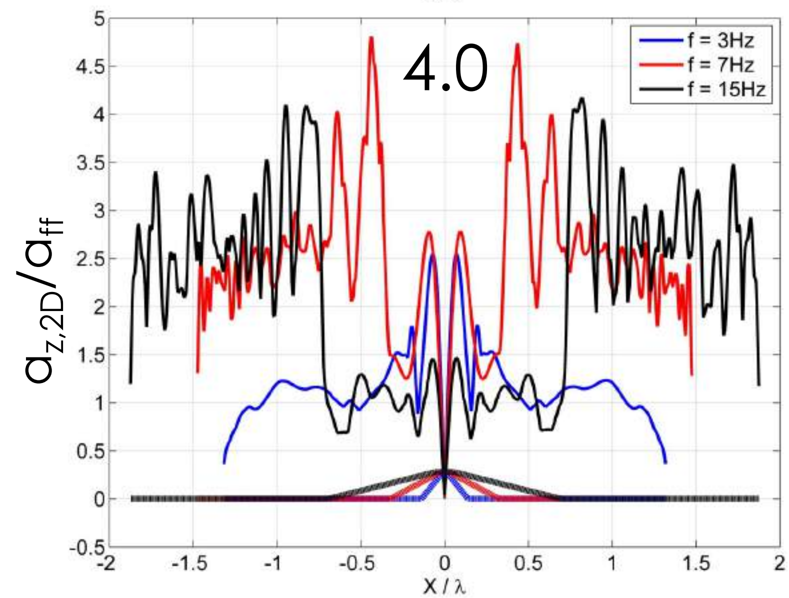
Vertical motion ($a_{z,2D}$)



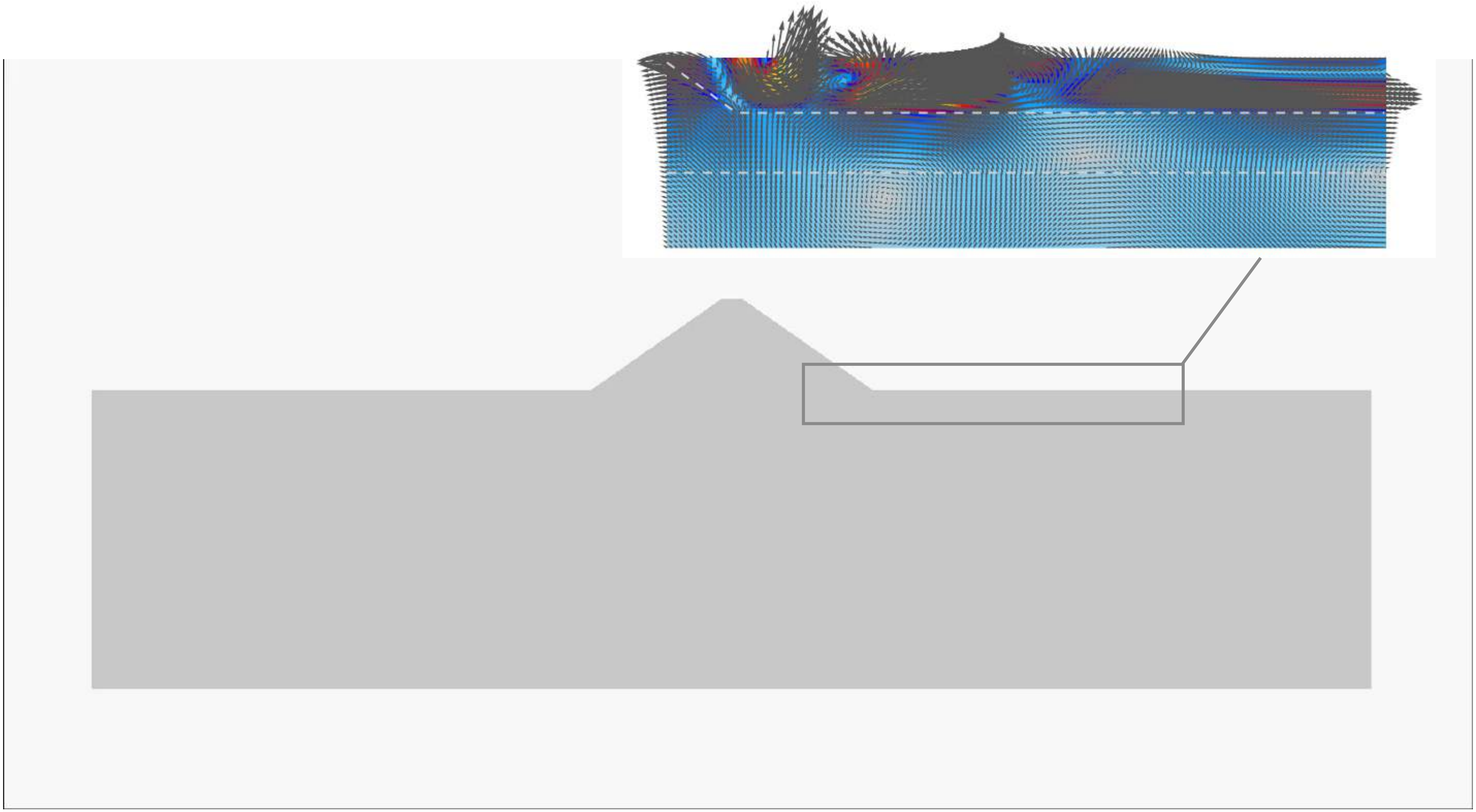






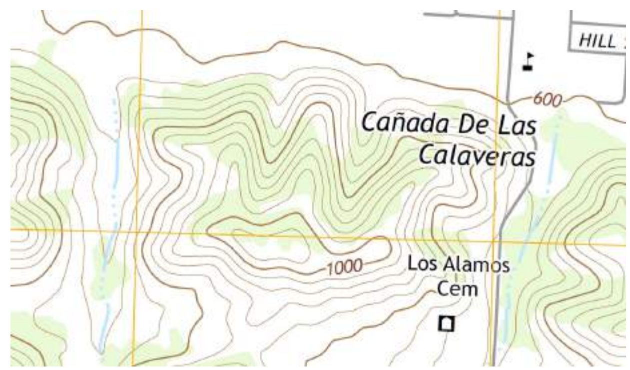


Topography on layered soil

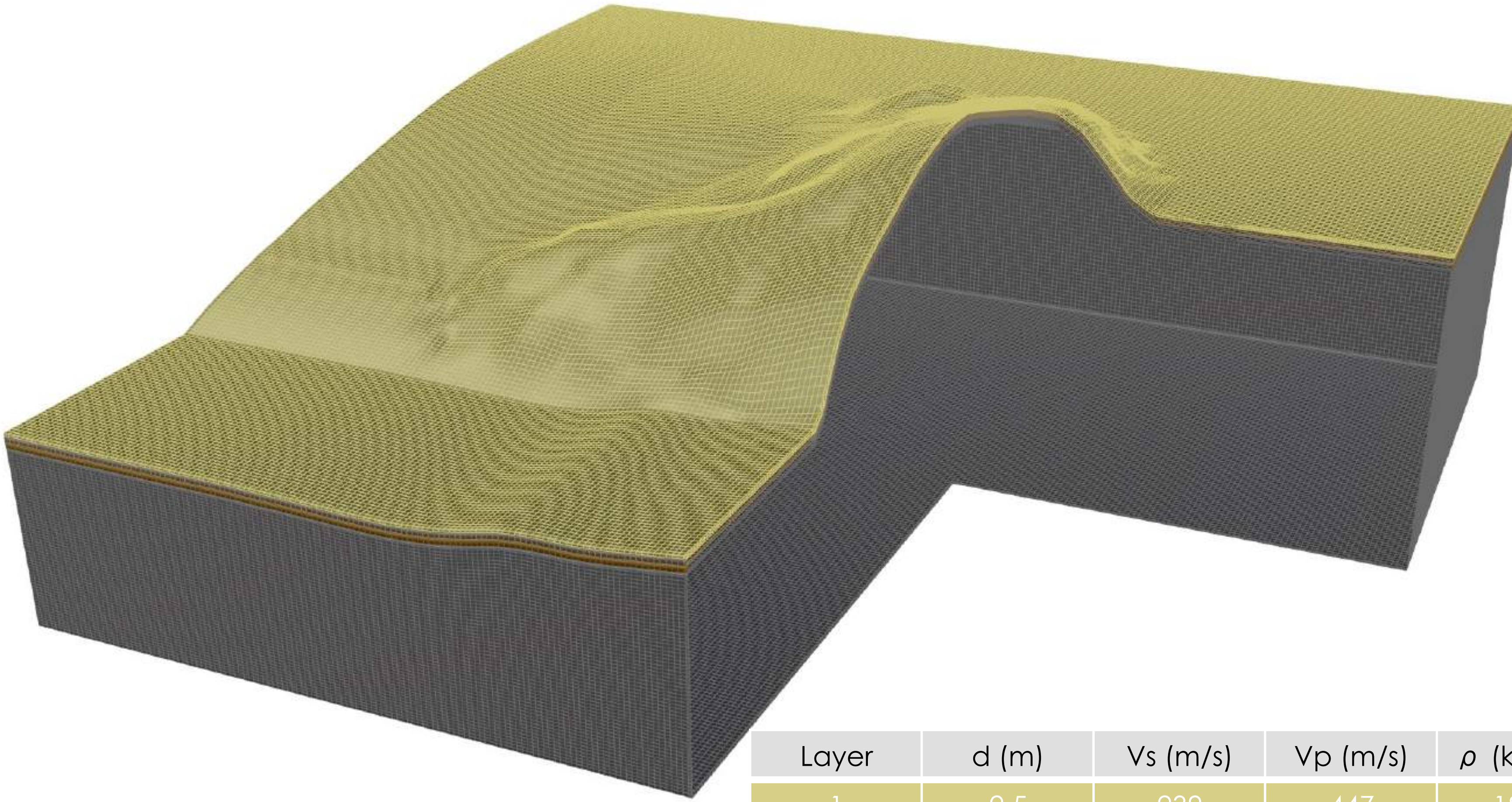


More complex (real) configurations

Strong motion stations in California

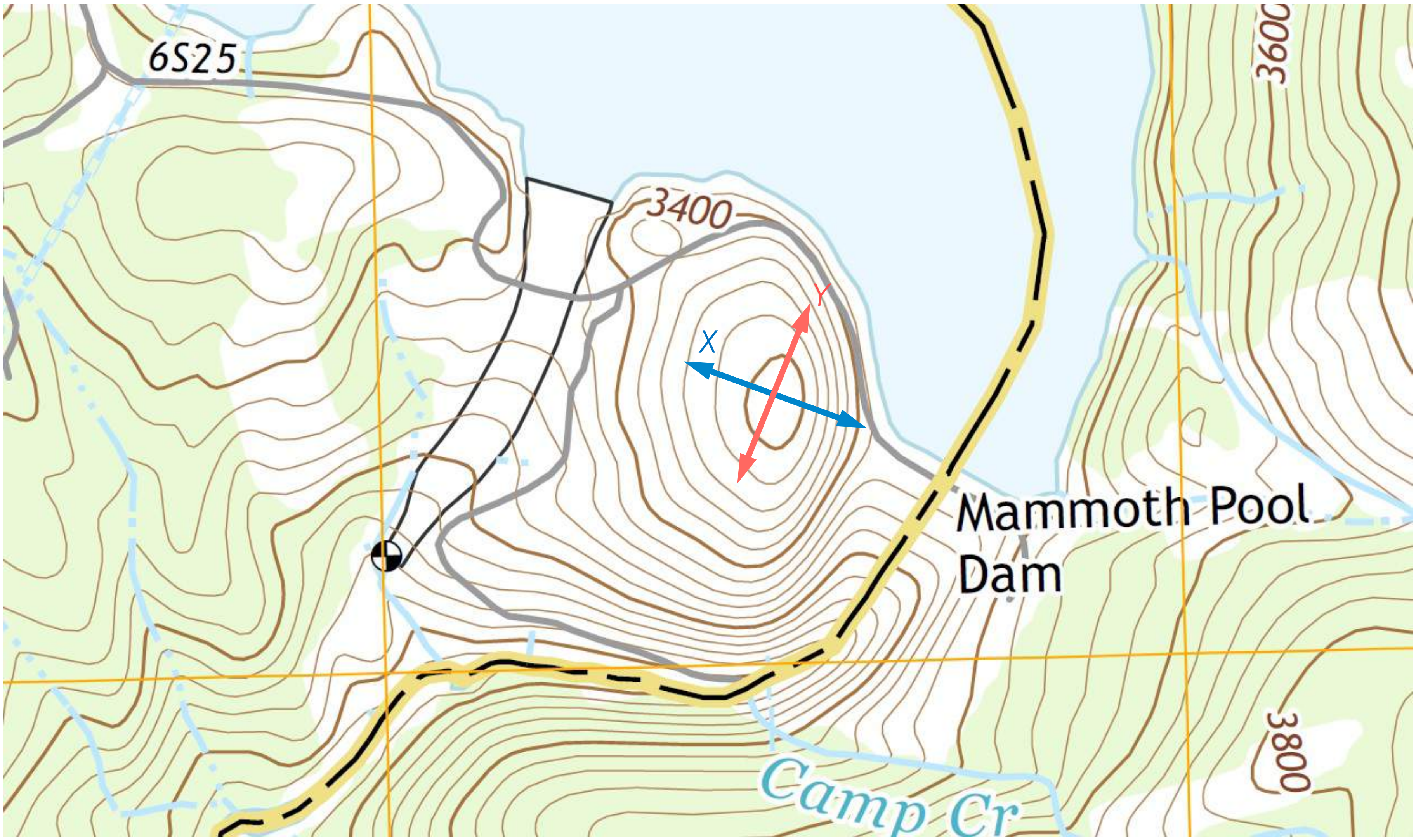


BK-KCC stratigraphy and properties

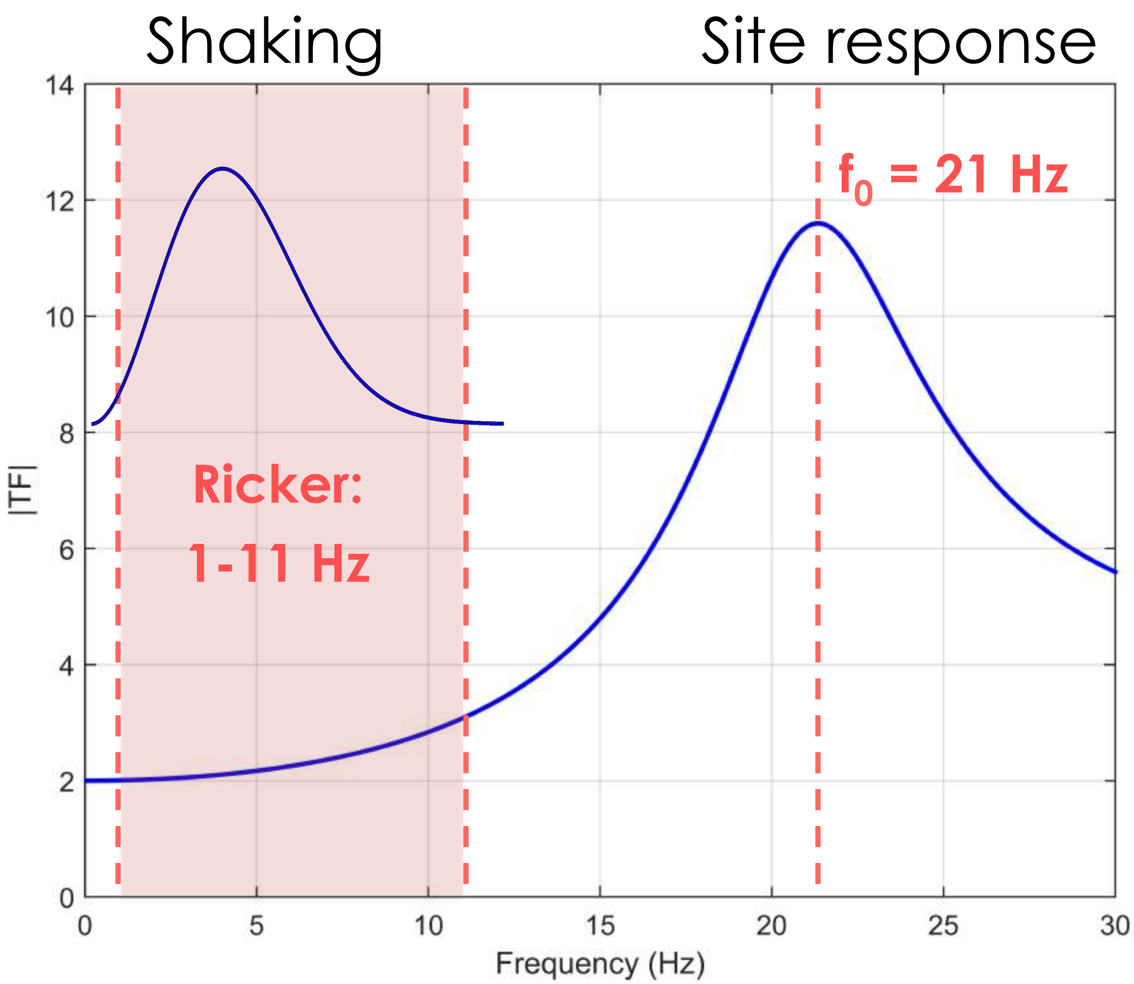


Layer	d (m)	Vs (m/s)	Vp (m/s)	ρ (kg/m^3)
1	2.5	239	447	1870
2	6.0	1072	2006	2300
3	6.0	1865	3489	2400
4	>2 λ	2445	4574	2500

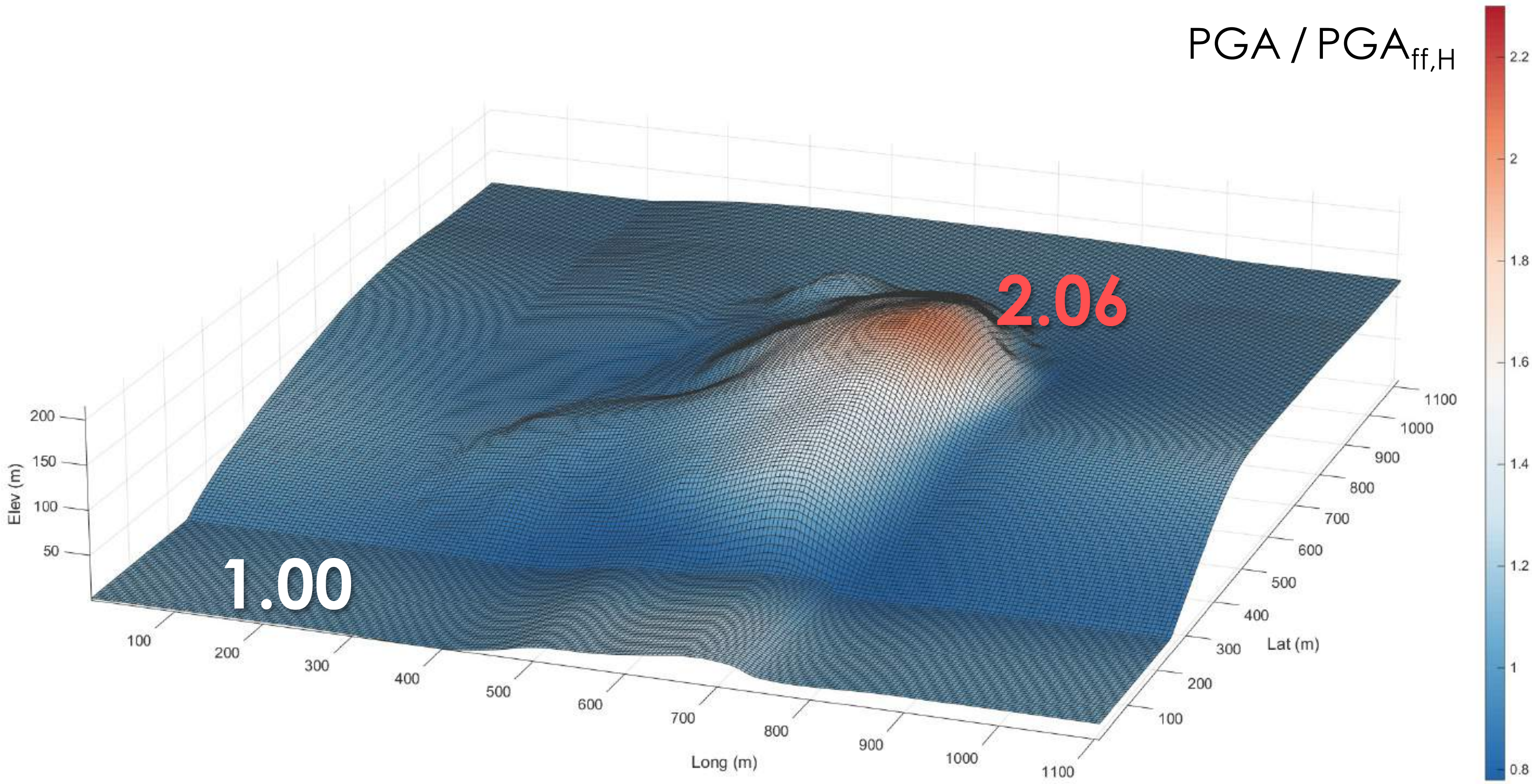
BK-KCC: Polarization scenarios



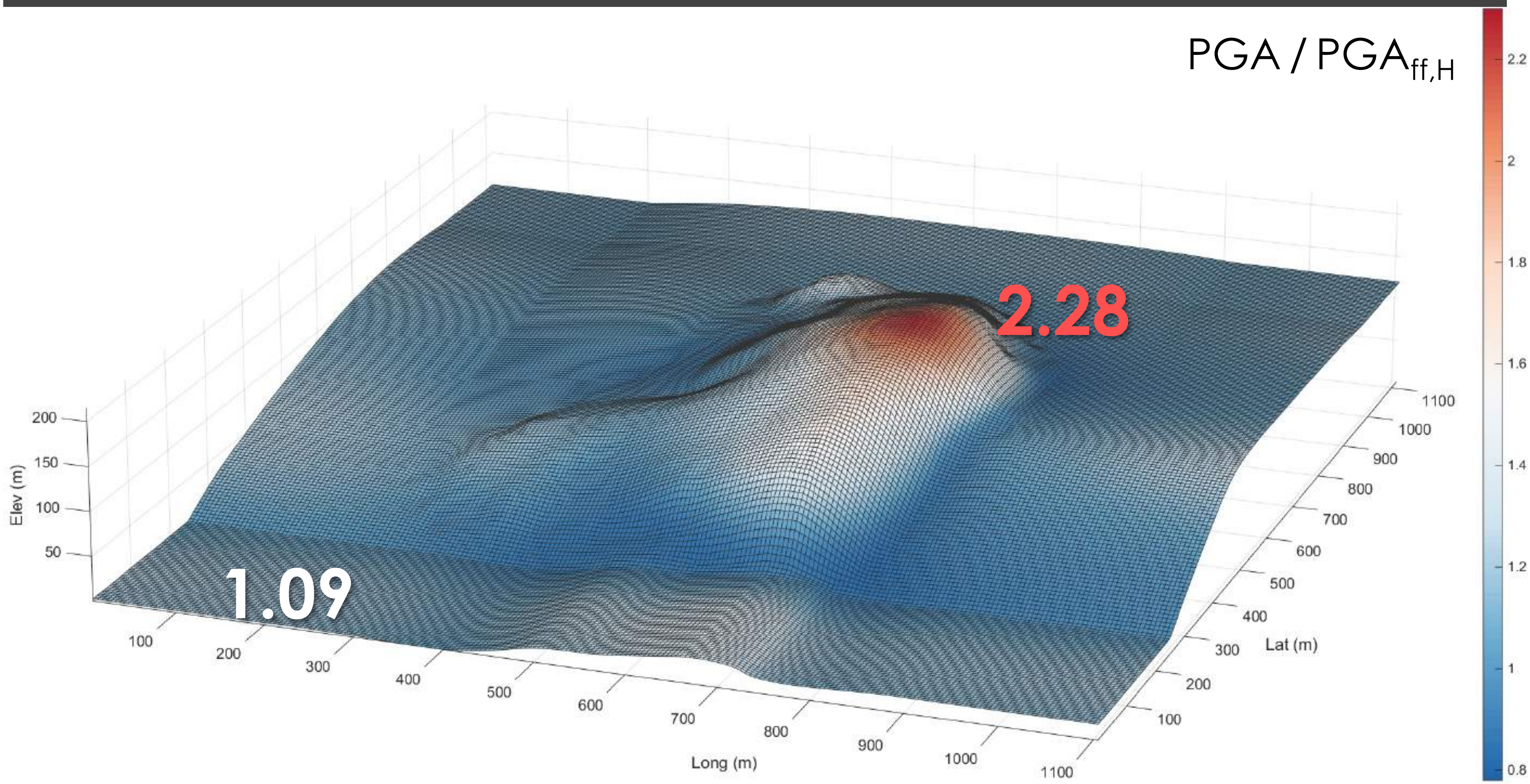
Frequency analysis



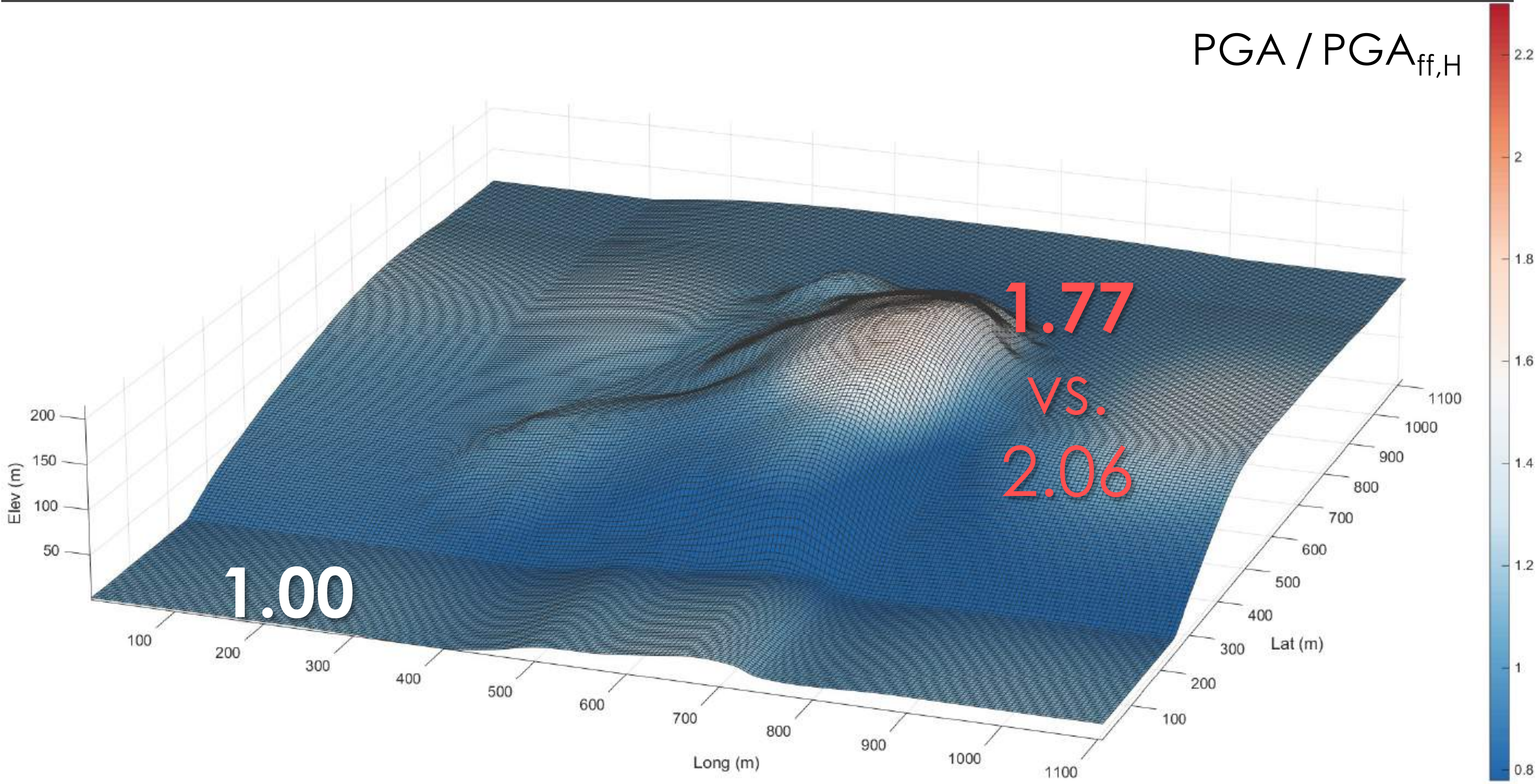
Homogeneous BK-KCC: X-polarization



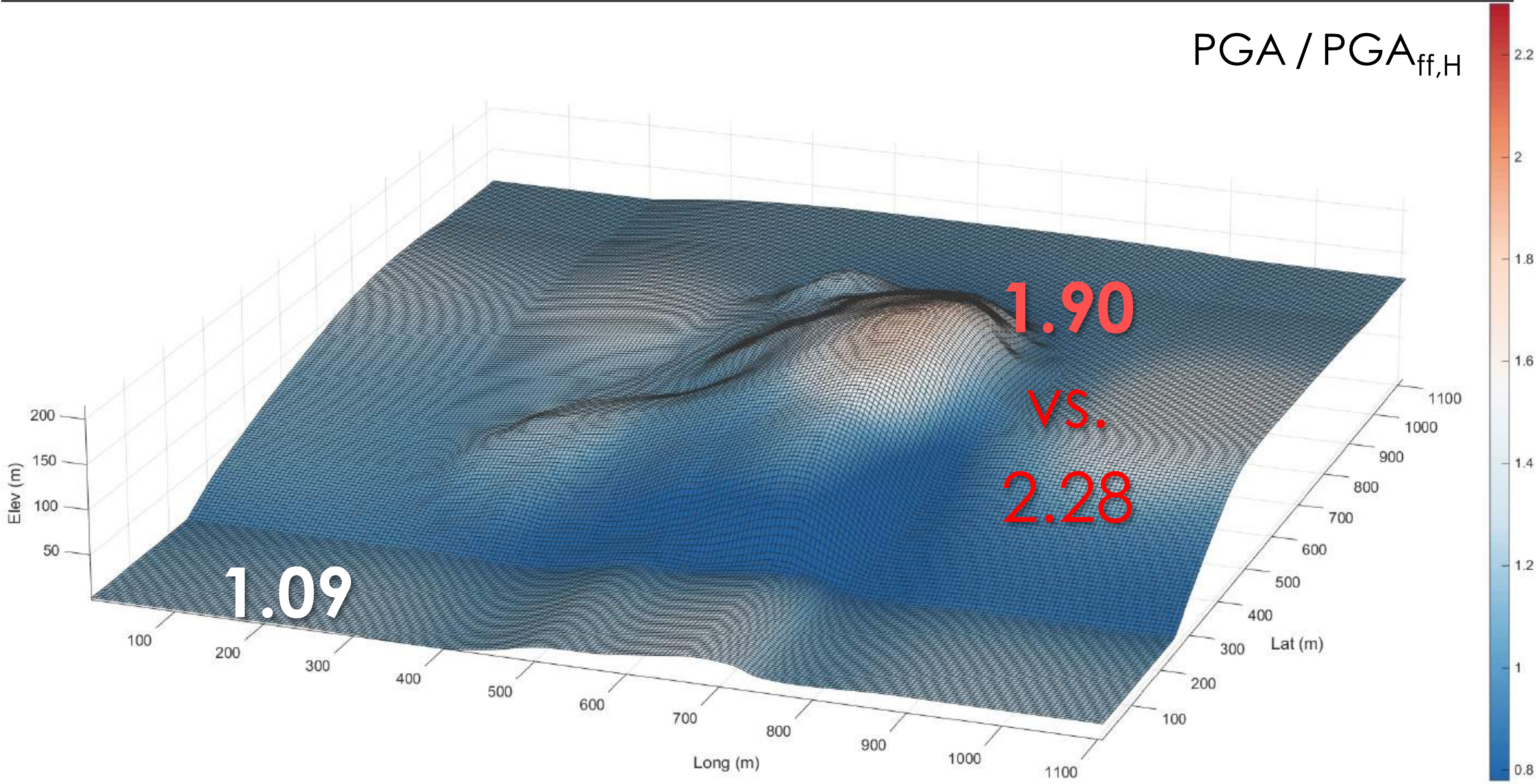
Layered BK-KCC: X-polarization



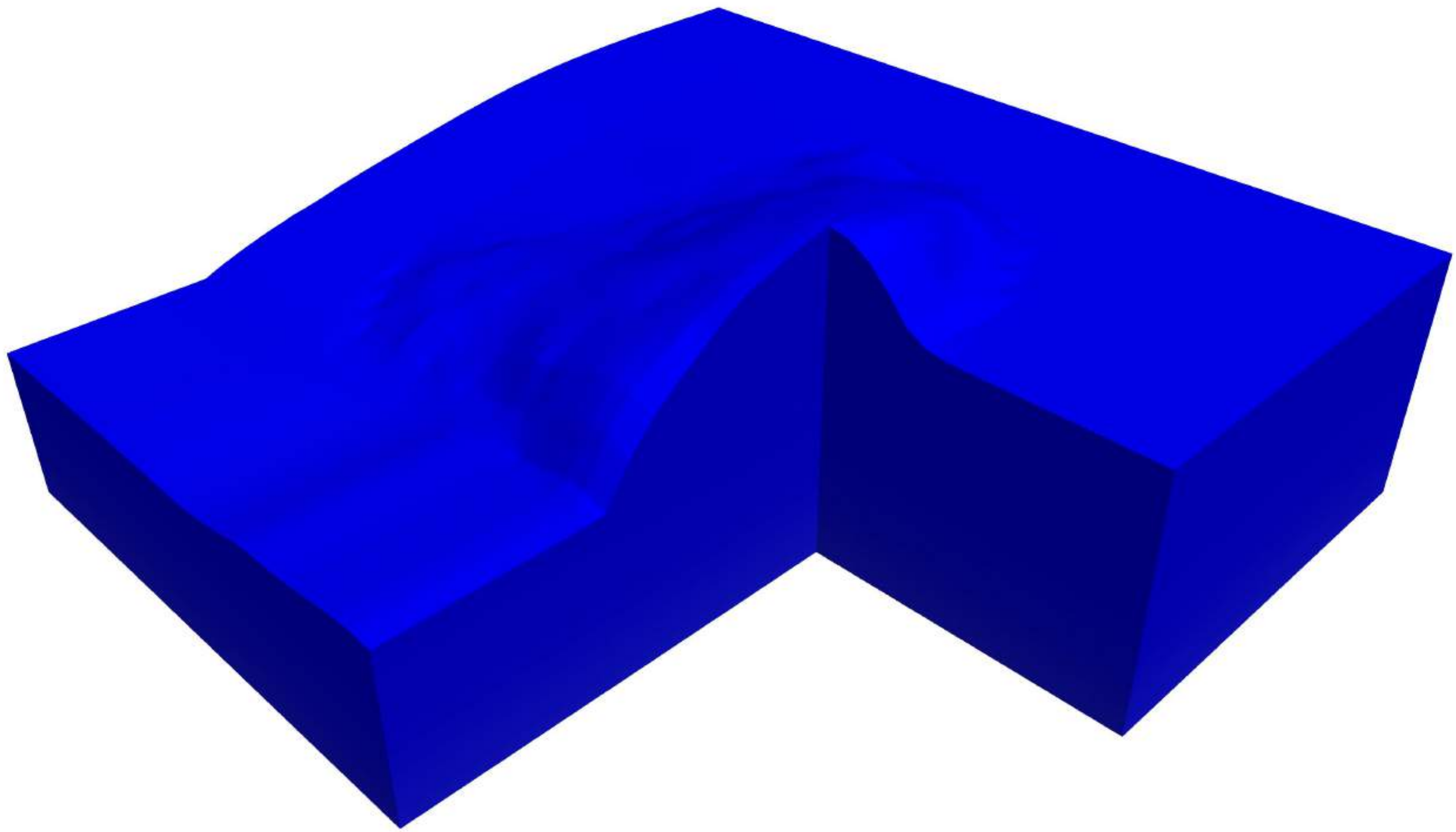
Homogeneous BK-KCC: Y-polarization



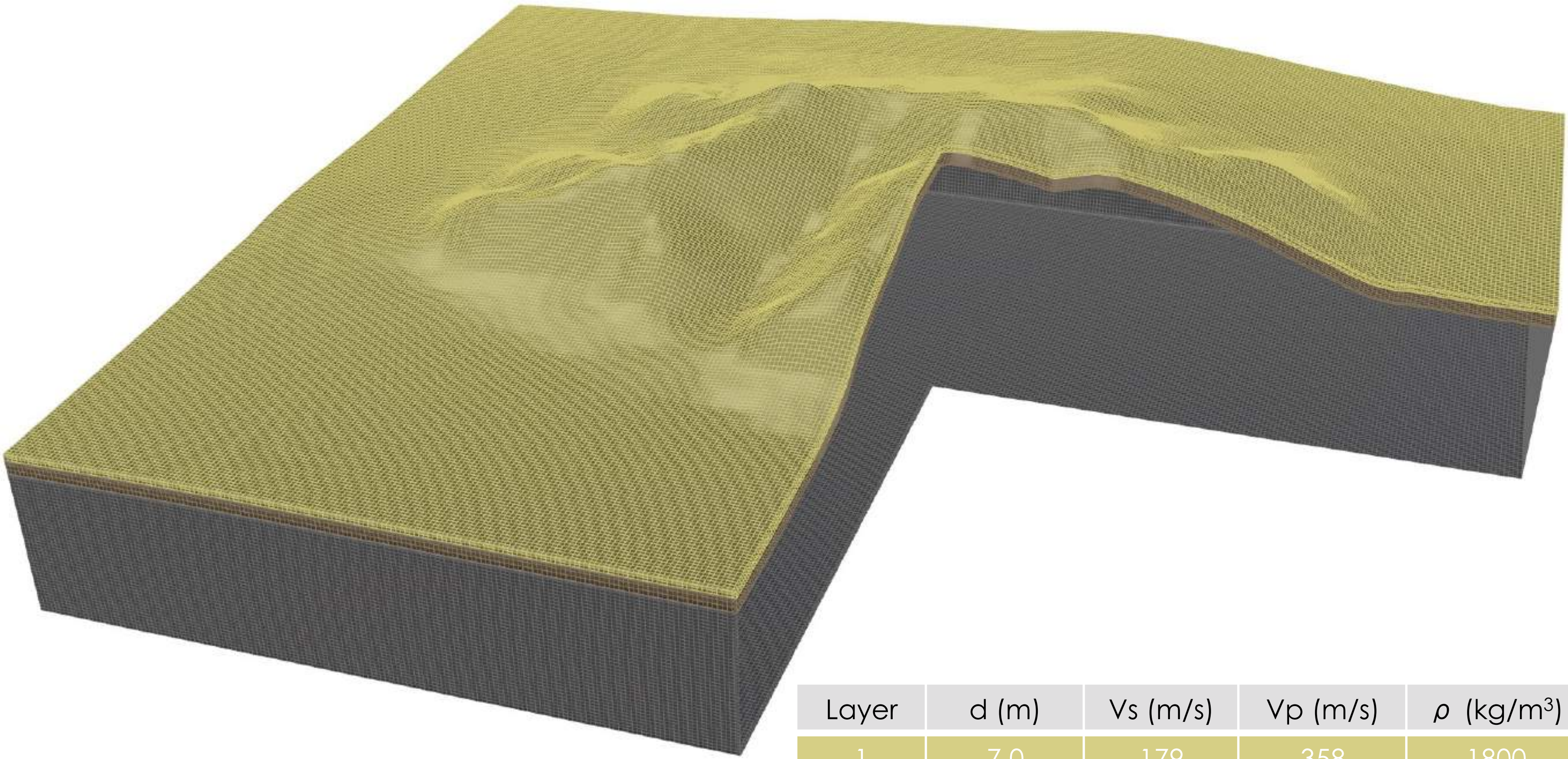
Layered BK-KCC: Y-polarization



Layered BK-KCC: x-polarization

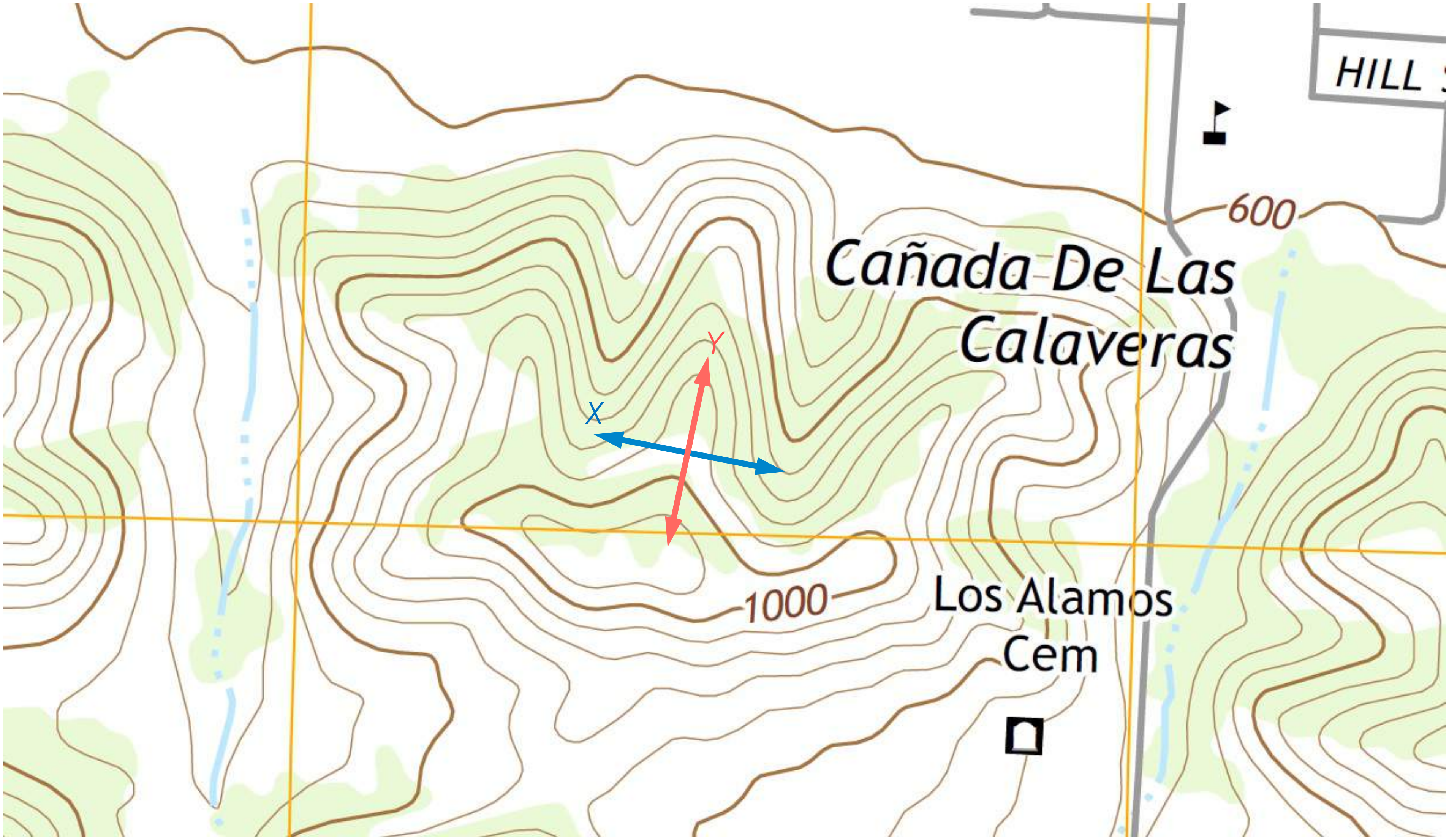


Los Alamos cemetery (CI-LCP)

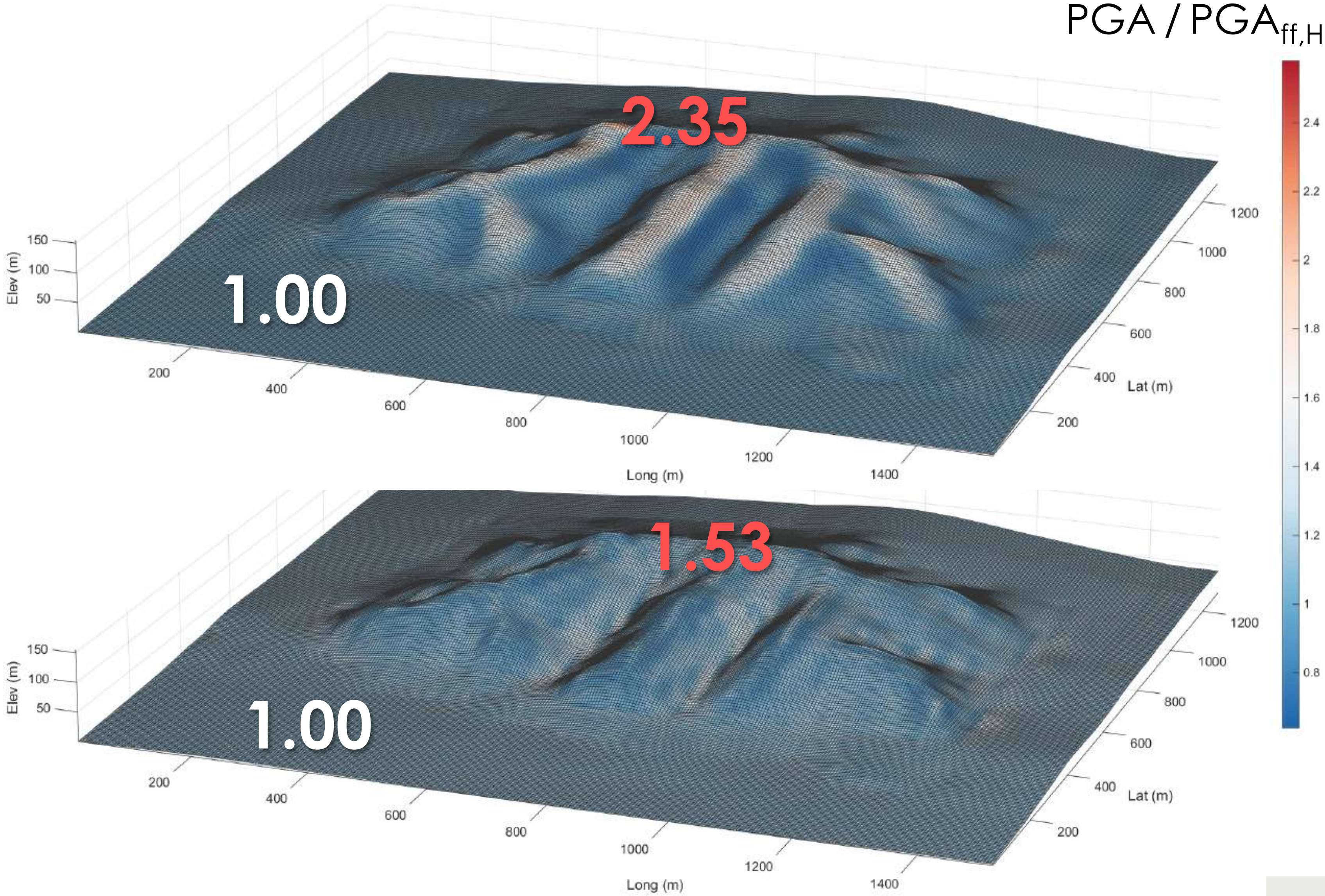


Layer	d (m)	Vs (m/s)	Vp (m/s)	ρ (kg/m^3)
1	7.0	179	358	1800
2	14.0	255	510	1870
3	>2 λ	486	971	2000

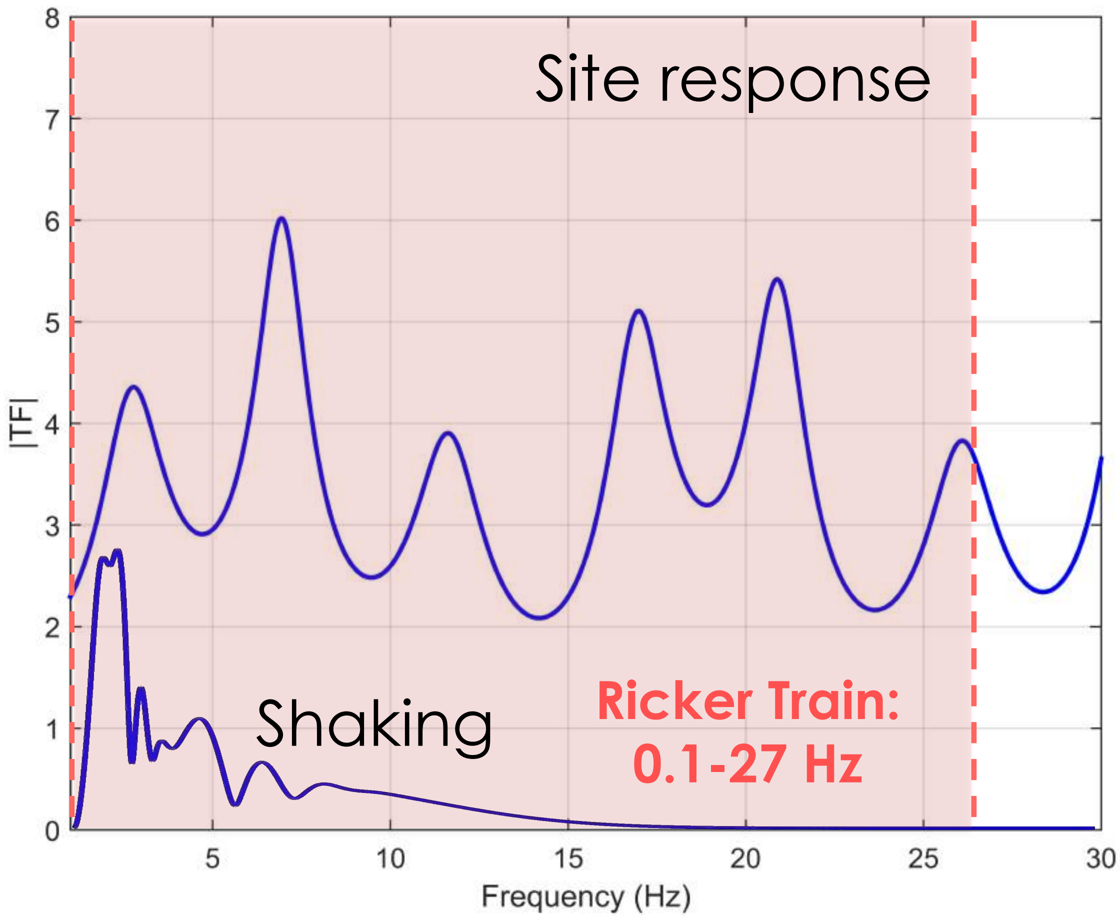
CI-LCP: Polarization scenarios



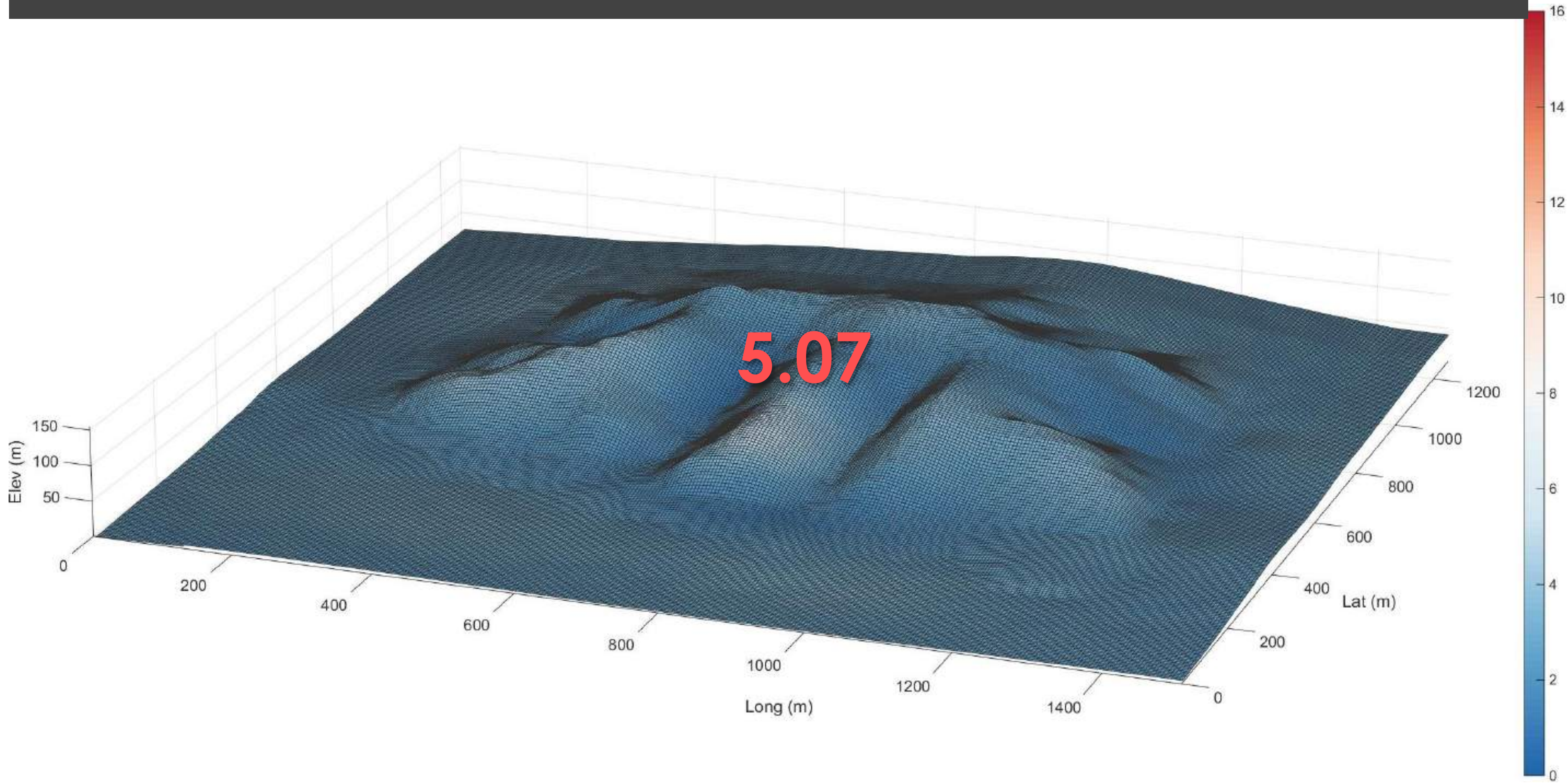
CI-LCP: Homogeneous vs. Layered



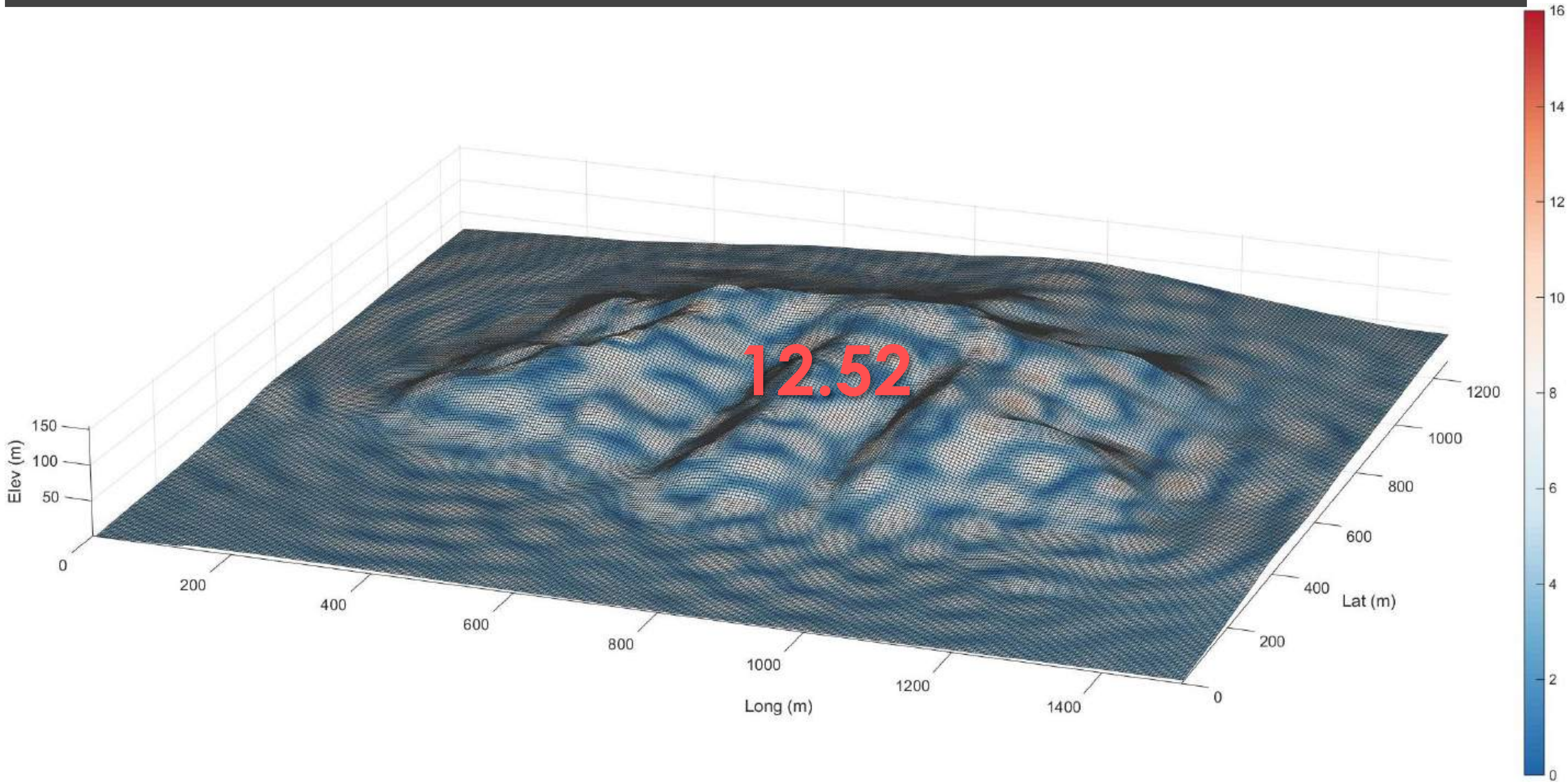
Frequency analysis



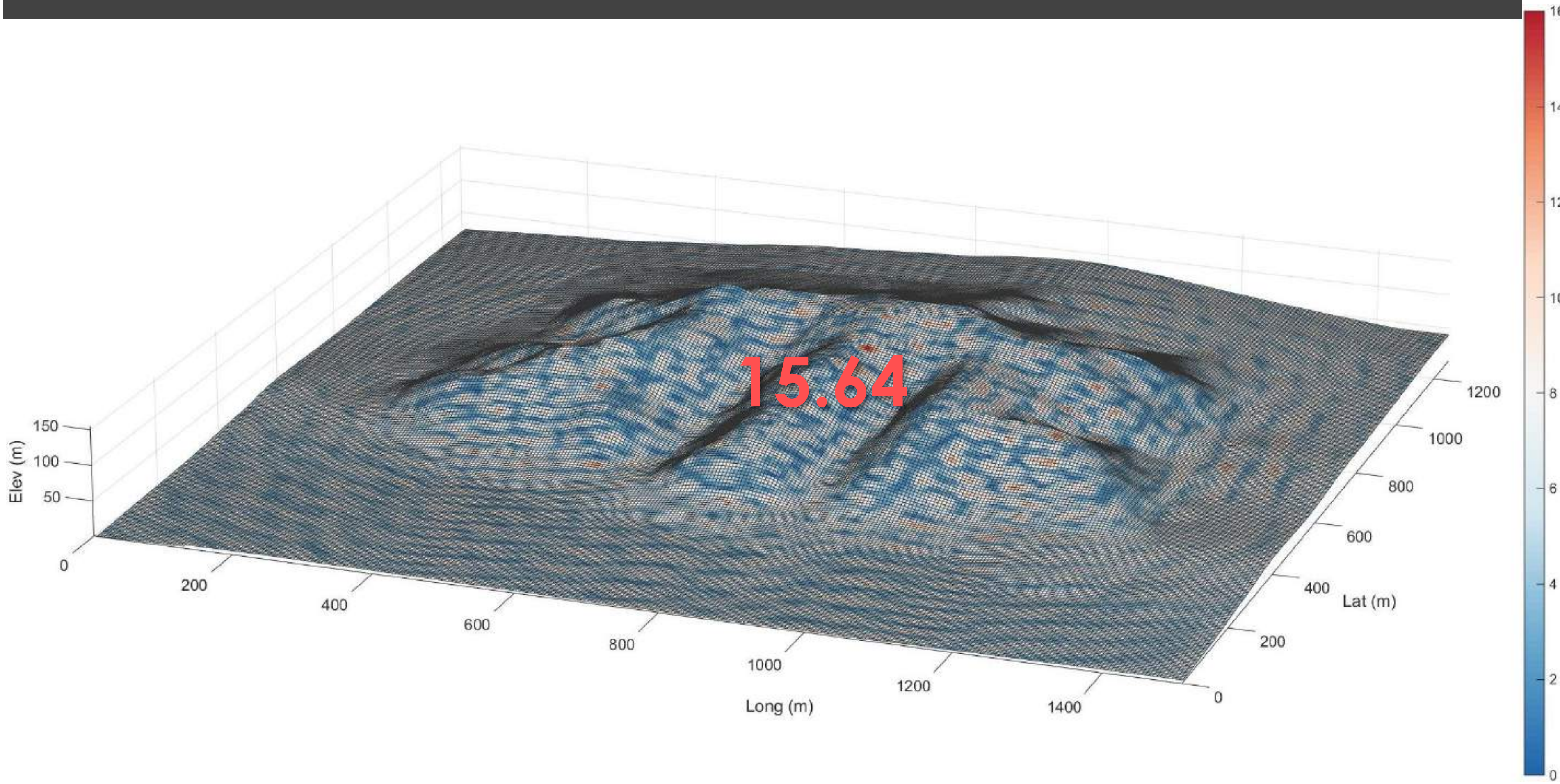
Transfer function amplitude @ f = 1Hz



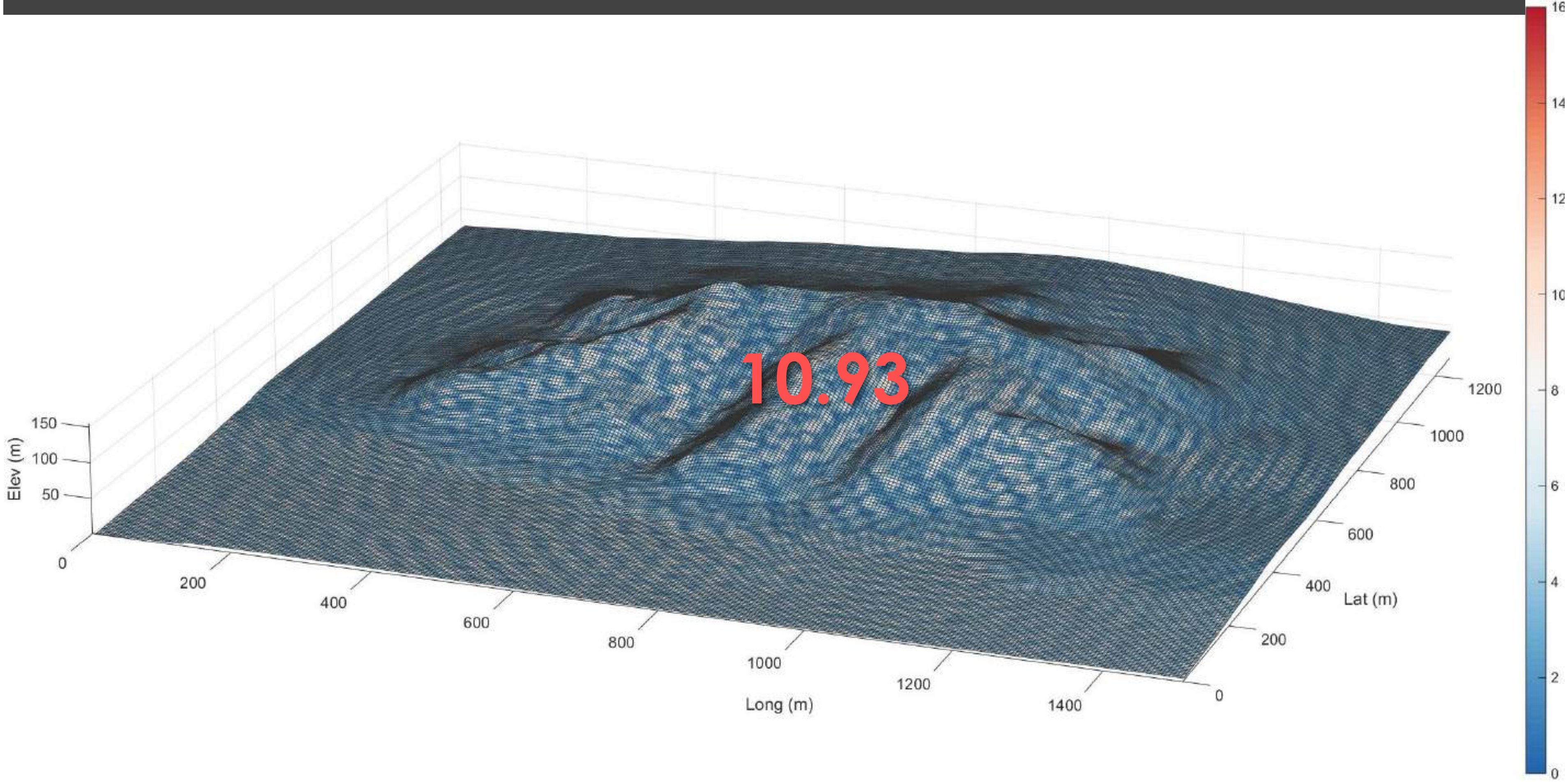
Transfer function amplitude @ f = 3.5Hz



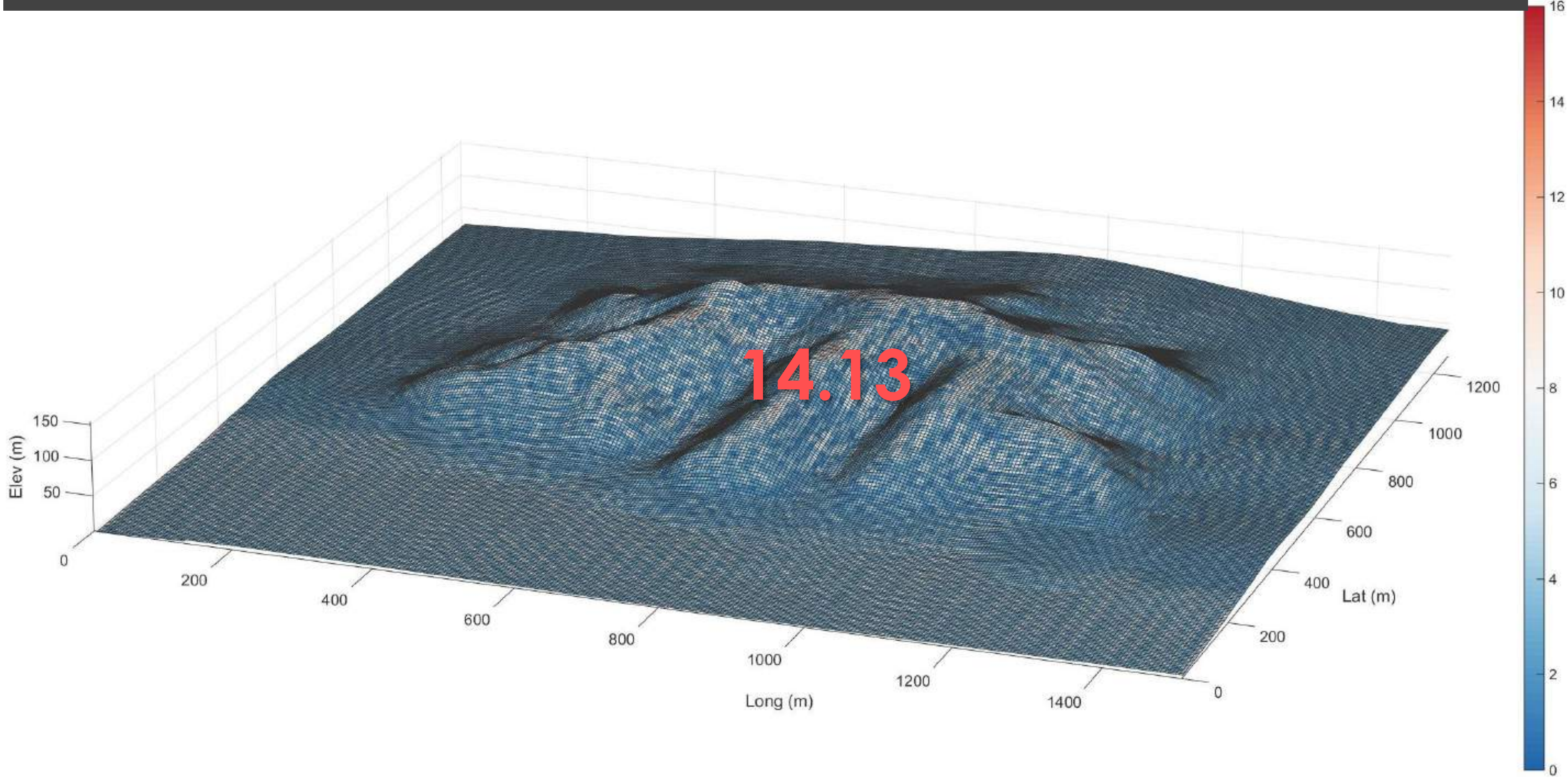
Transfer function amplitude @ f = 7Hz



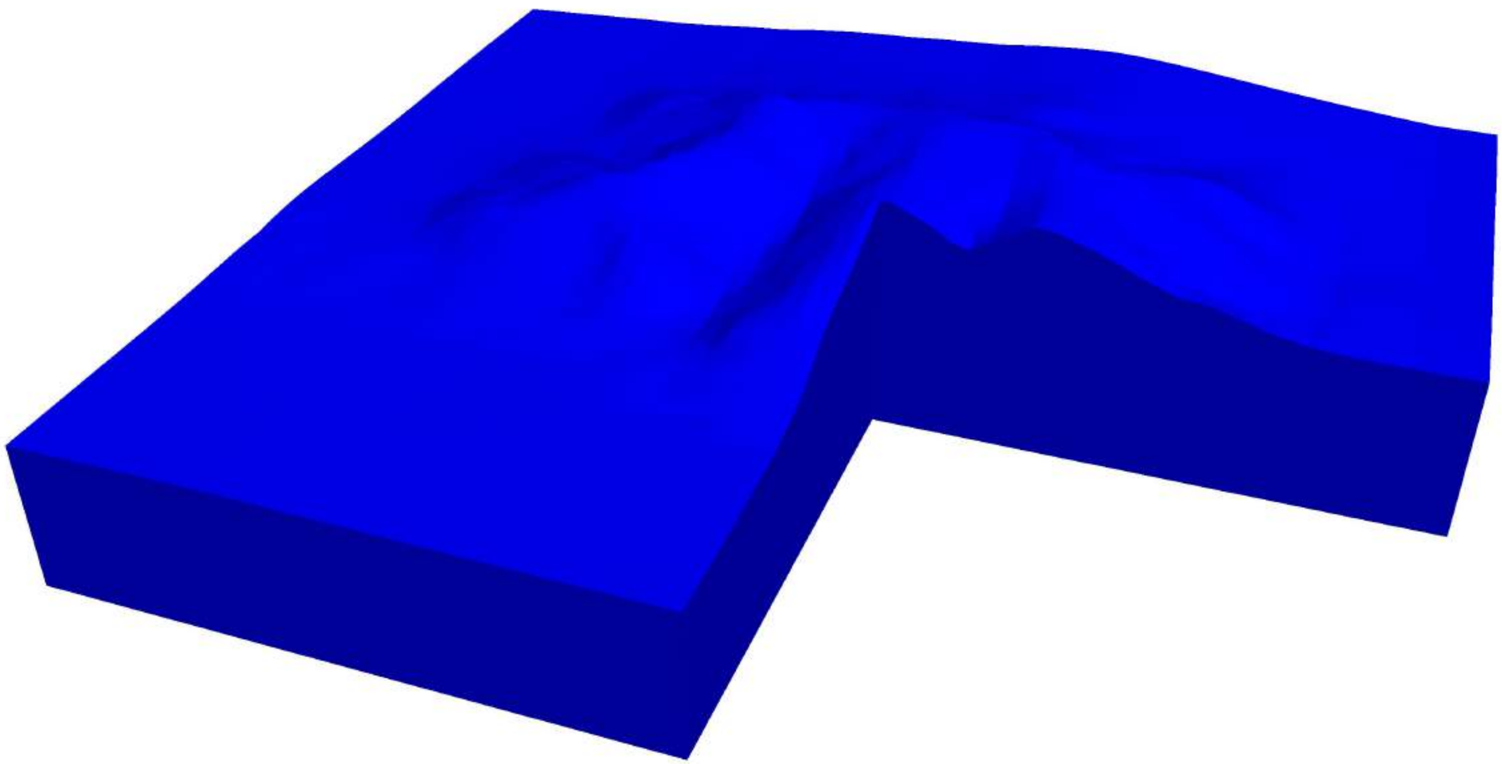
Transfer function amplitude @ f = 10Hz



Transfer function amplitude @ f = 15Hz

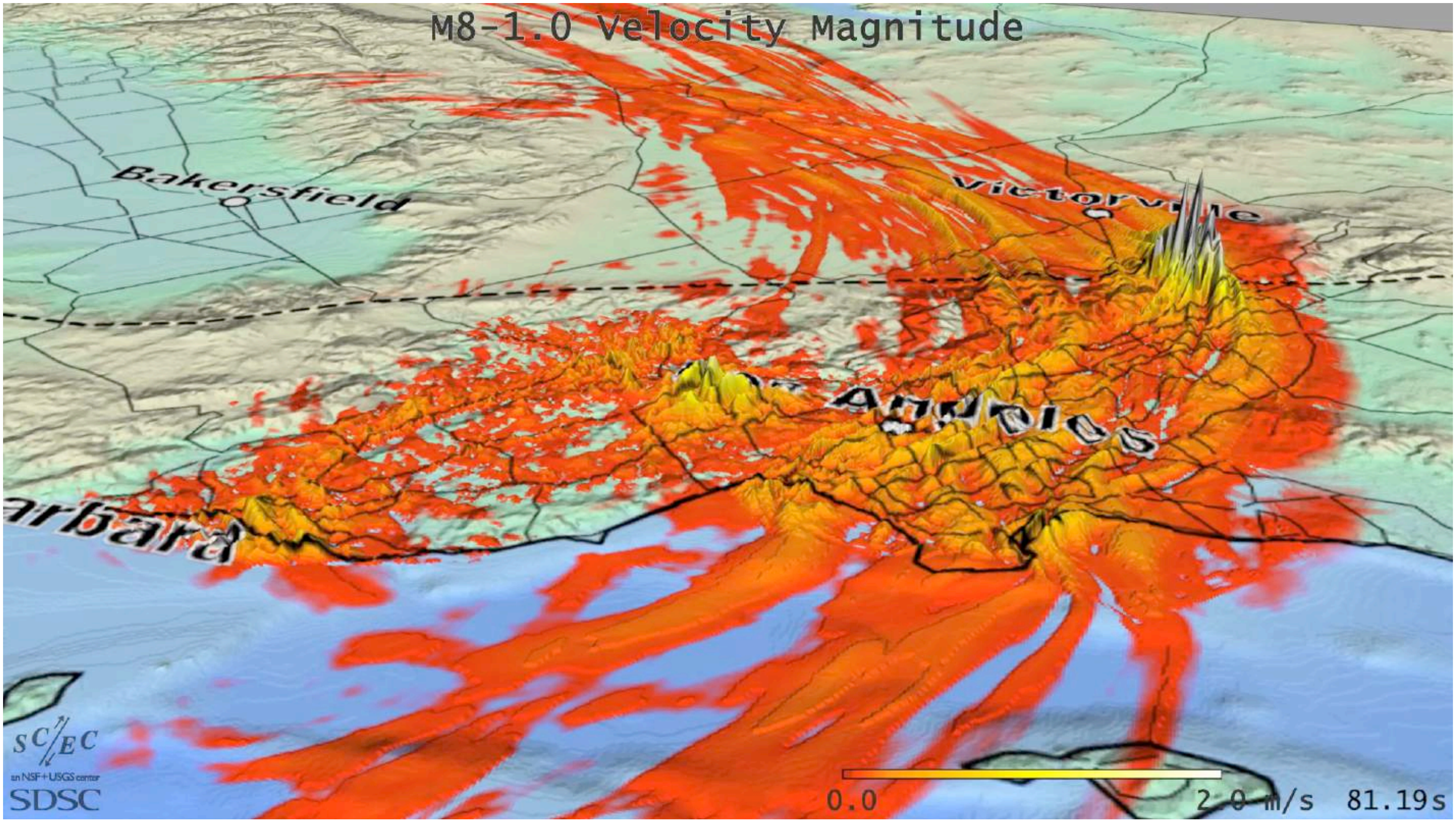


Layered CI-LCP: Ricker train

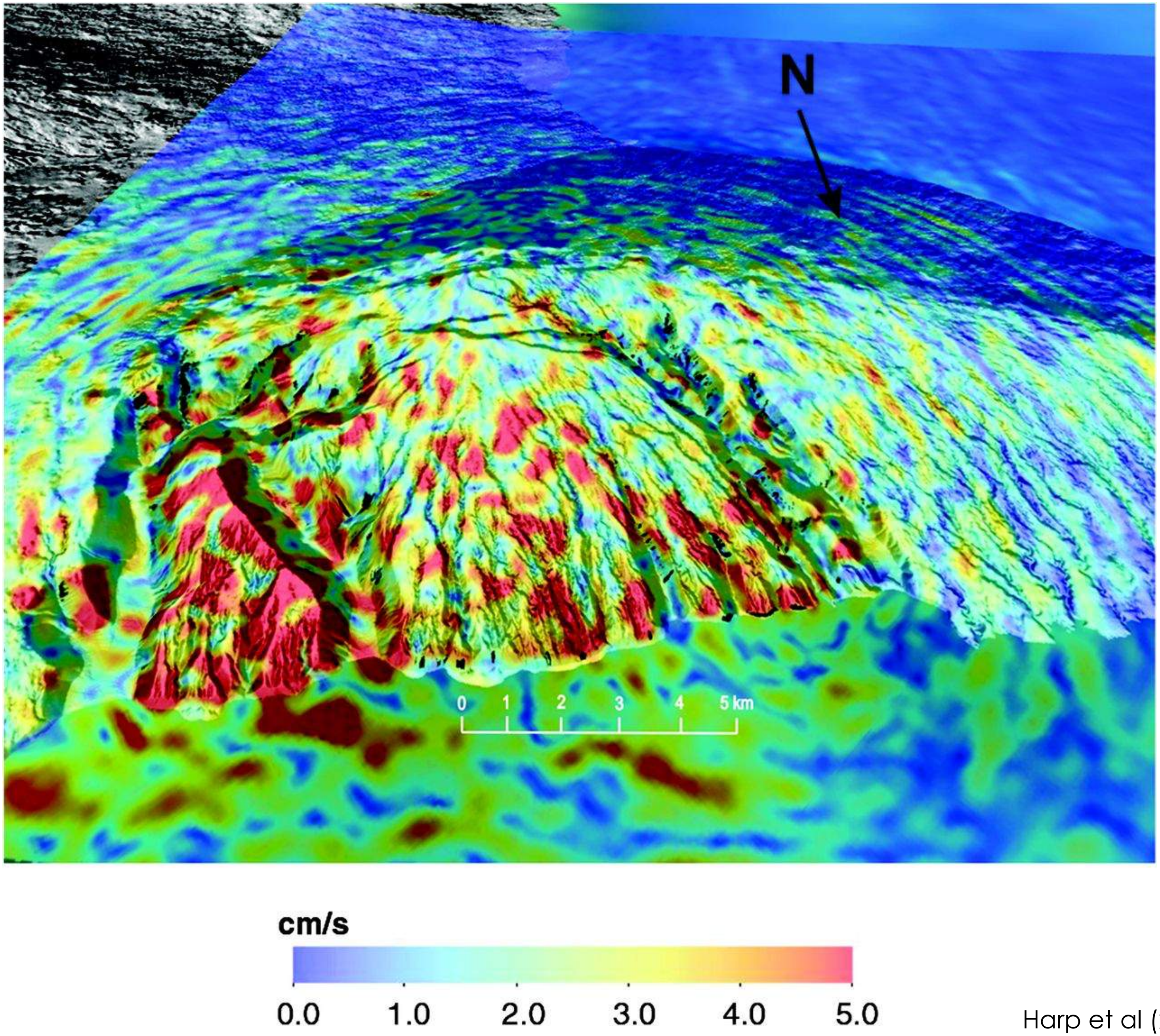


What about uncertainty & risk?

Topography in physics-based simulations

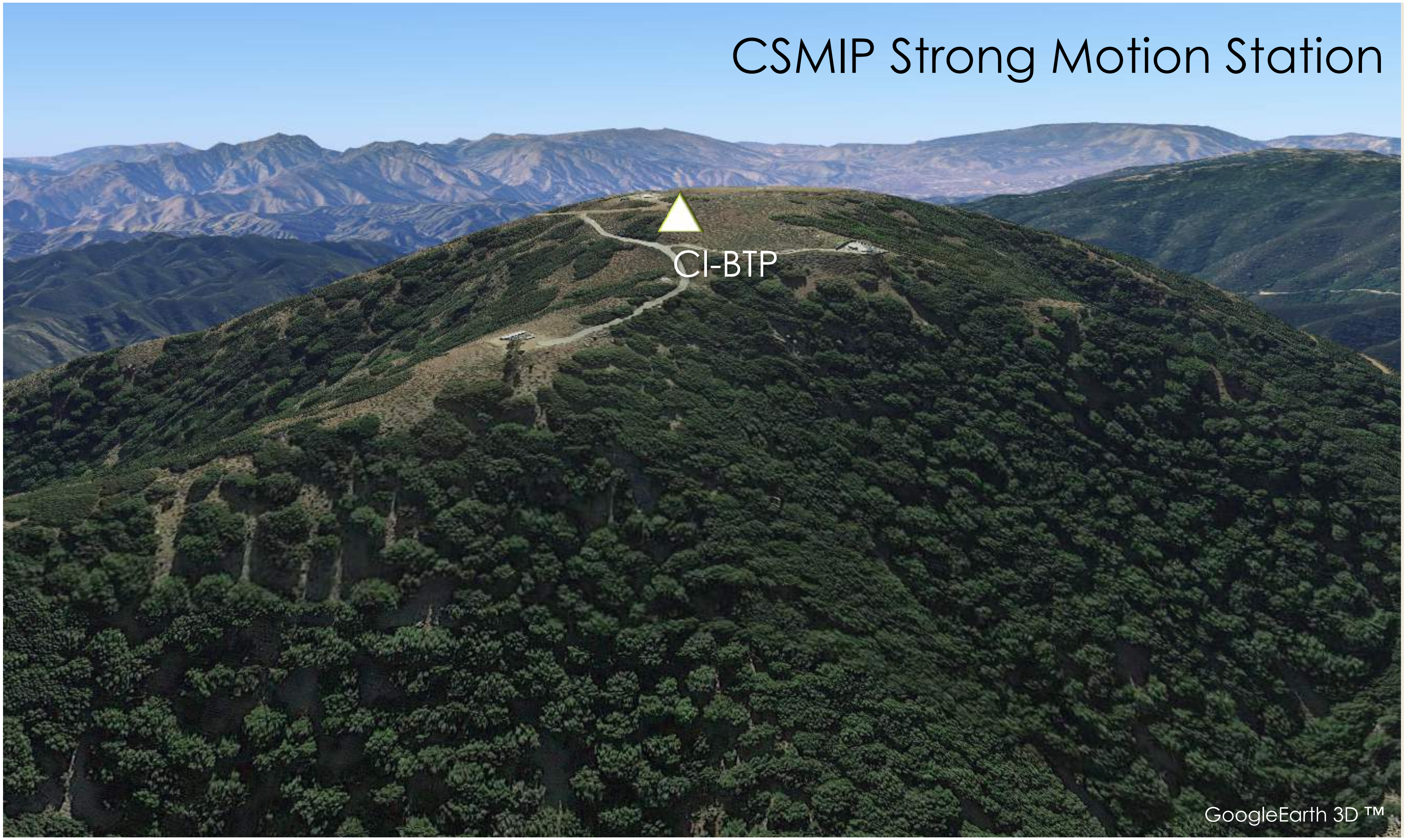


http://scec.usc.edu/scecpedia/M8

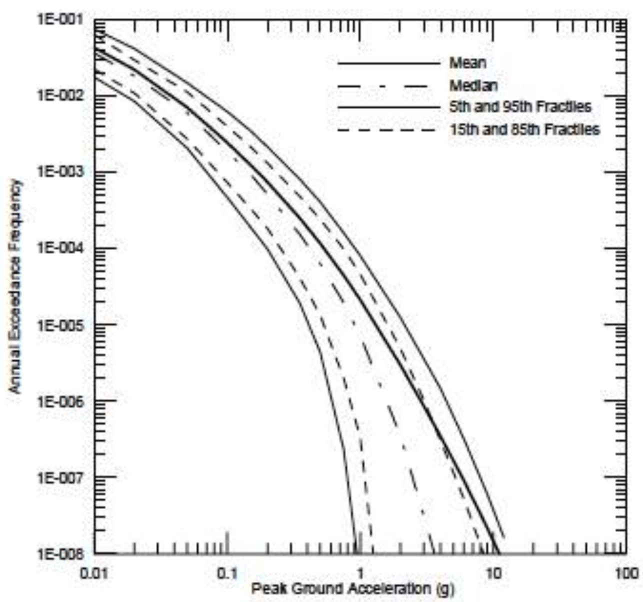


Harp et al (2014) BSSA

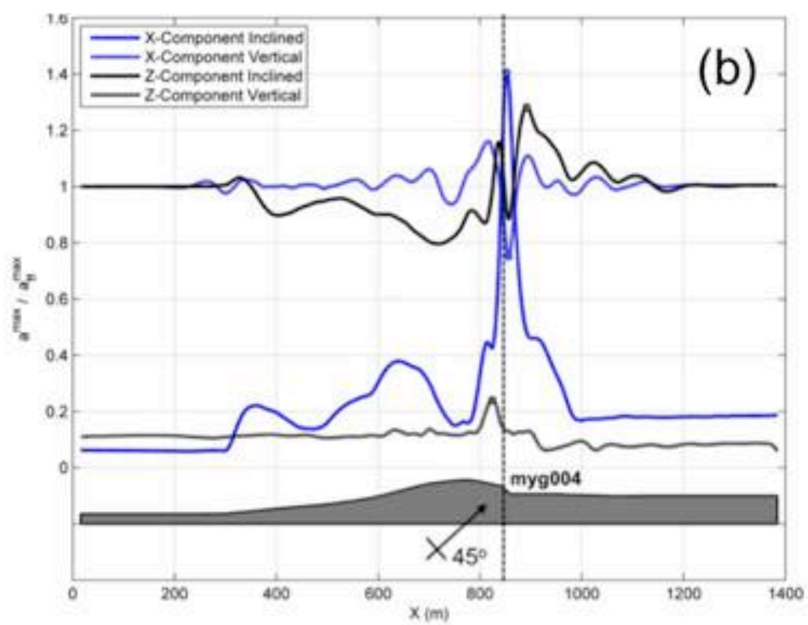
Are GMPEs biased?



Extreme ground motions & physical limits

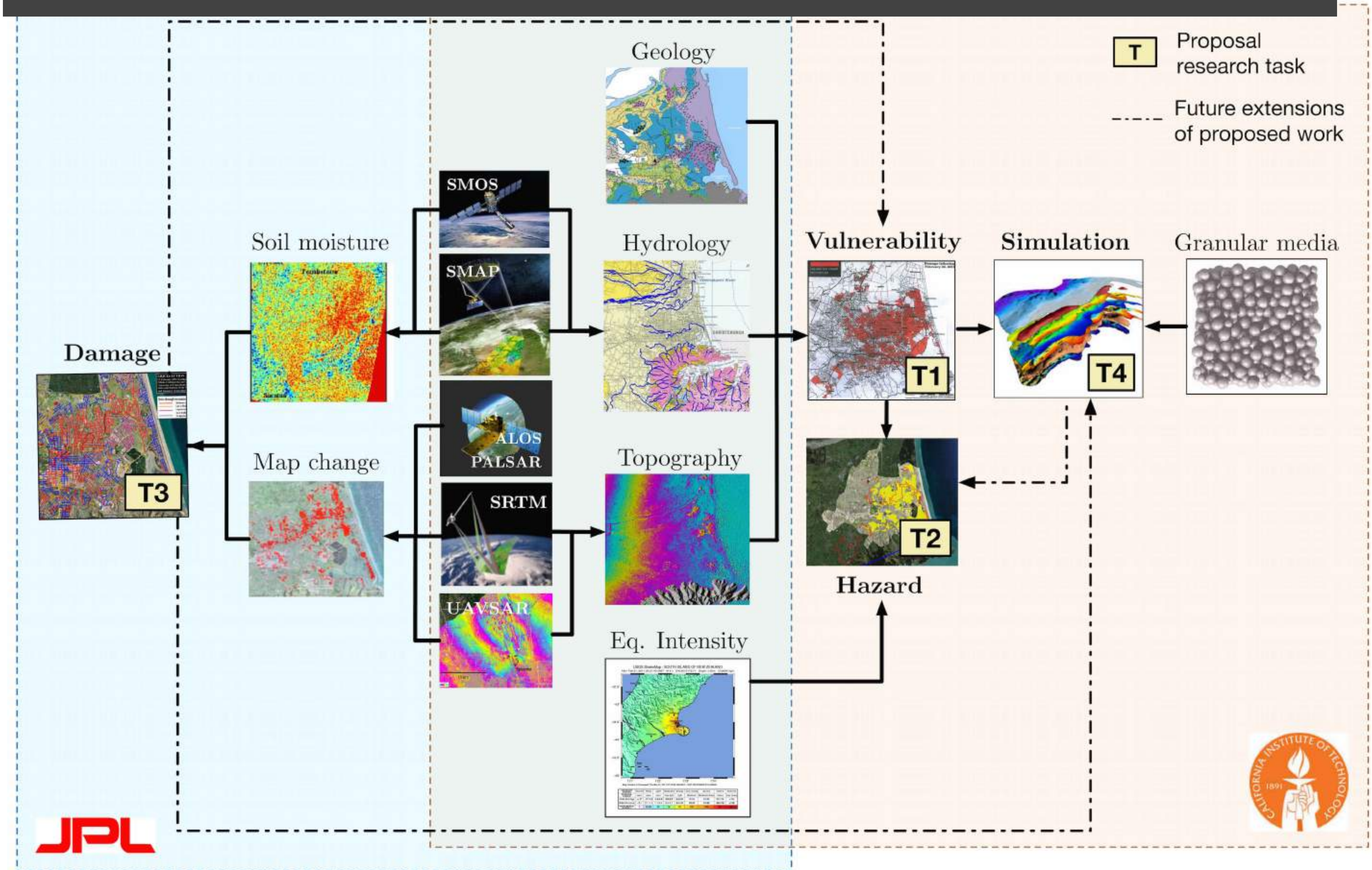


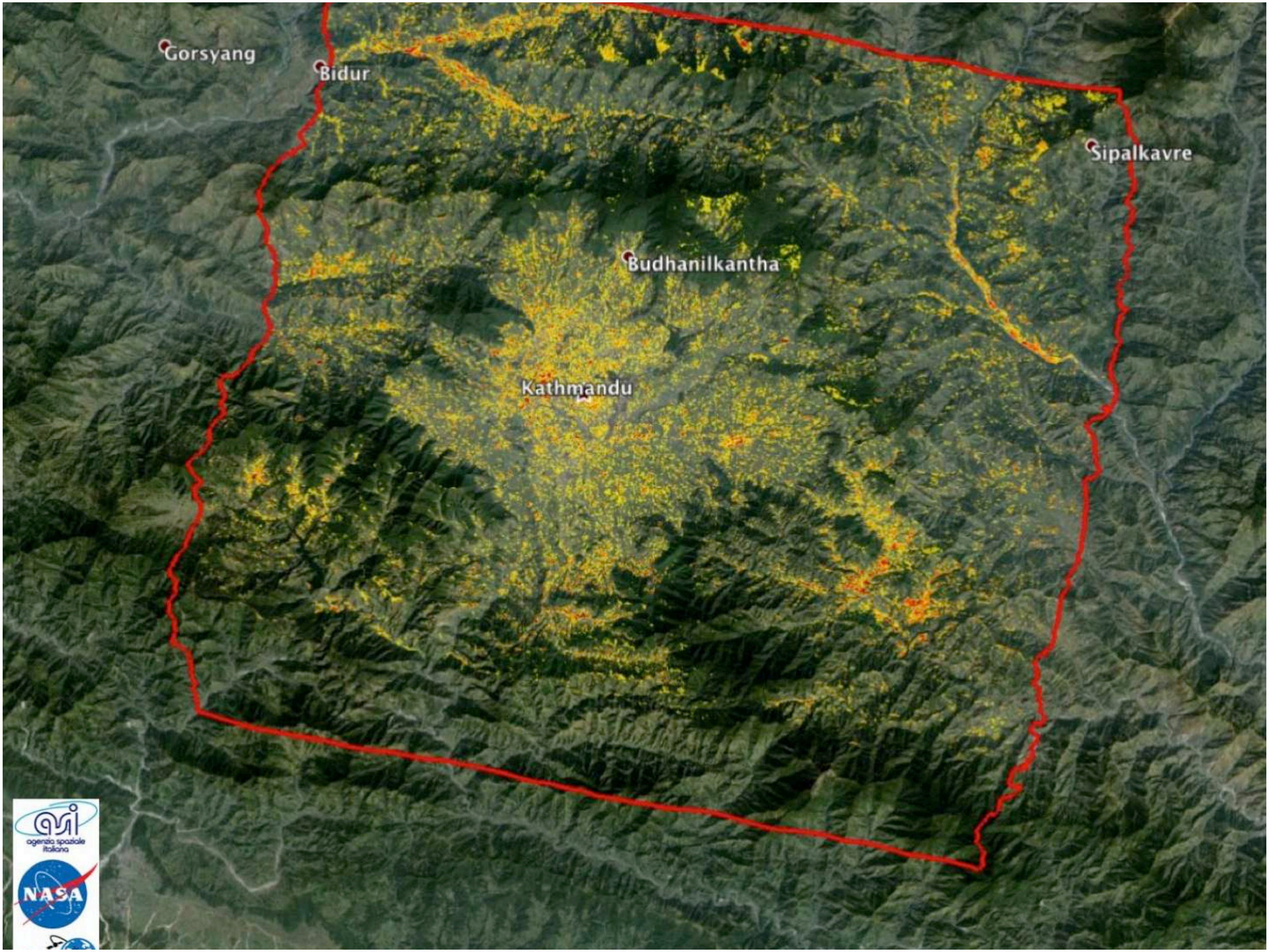
PGA = 2.79g



Assimaki, Mohammadi, Wu and Peng (2012)

Physics-based multi-hazard assessment




Gorsyang
Bidur
Sipalkavre
Budhanilkantha
Kathmandu
agenzia spaziale italiana
NASA

To summarize, we're just getting started…

3 'facts'

- The world isn't flat
- Topo-effects are not "topography" effects
- Topo-effects are frequency-dependent & nonlinear

5 open questions

- Integration in regional models of simulated GMs?
- Parameterization in GMPEs?
- Prediction of extreme ground motions?
- Seismology-geology-hydrology coupled hazards
- Design of dams / embankments / retaining walls ?

Questions?