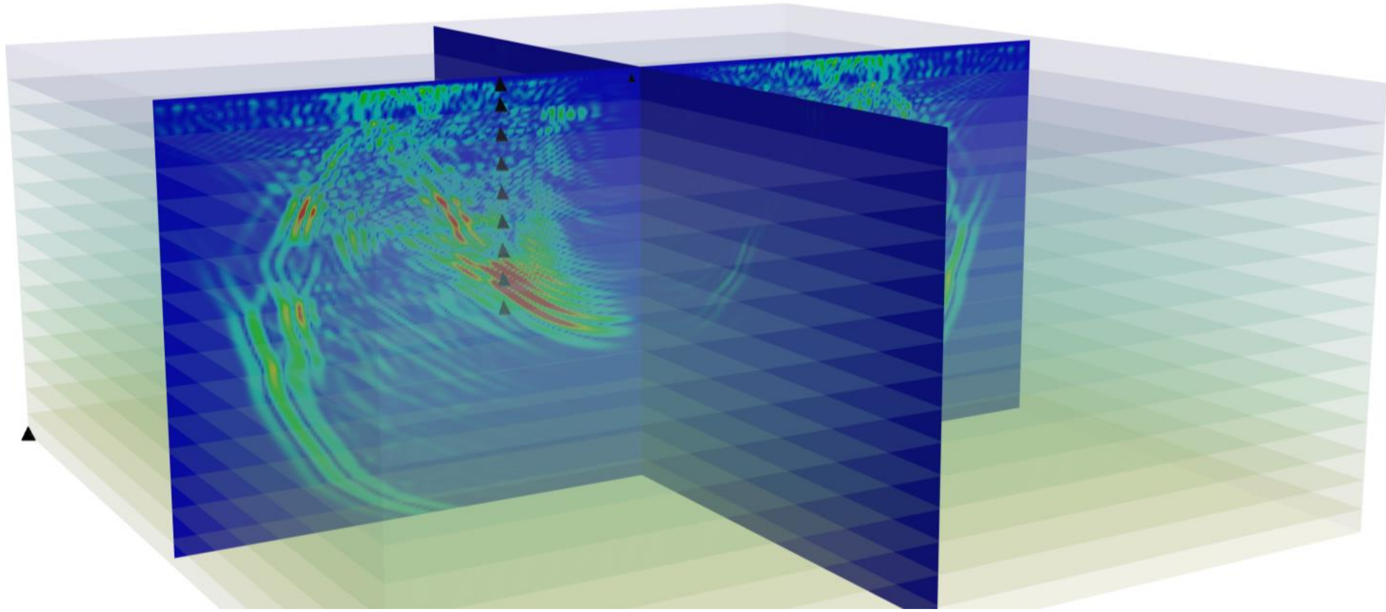
The wavefield of an SCPTu test

Not as simple as you think

Lindsay Linzer

26 June 2025



srk consulting

Talk outline

Wave3D

- Developed at COMRO / Miningtek from 1989 onwards
- 3D elastodynamic seismic wave modelling code

mXrap

- Developed at Australian Centre for Geomechanics from 2000 onwards
- Software platform that provides geotechnical engineers with many data analysis, monitoring and investigation tools

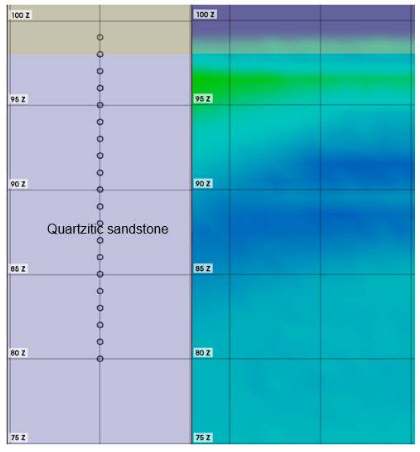
SCPTu tests

- Seismic Cone Penetration Tests
- Developed in the mid-1980s to record shear wave velocity data during Cone Penetration Tests (CPT)
- Widely used in geotechnical investigations of soil to determine Vs profile and elastic moduli

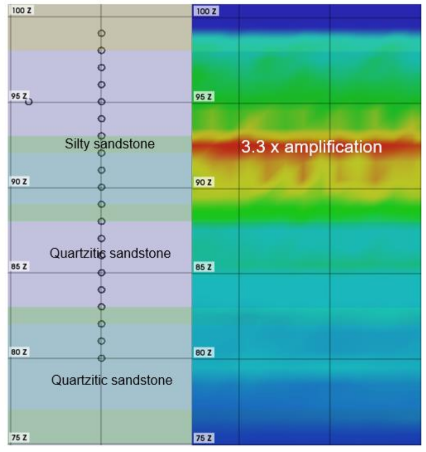
Wave3D

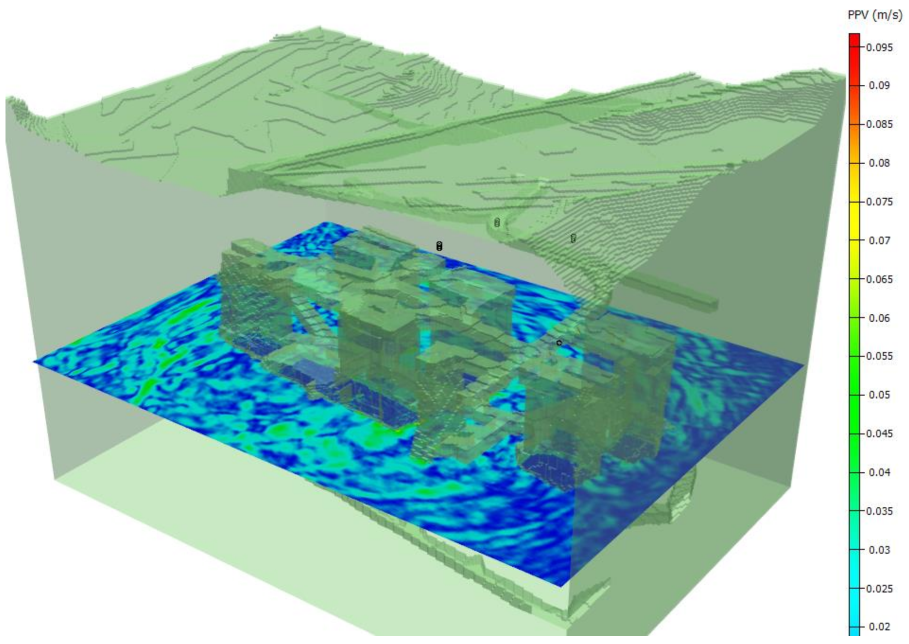
- Developed for rockburst research for deep level mining at COMRO/CSIR
- Authors: Peter Cundall (1989 / 1990), John Napier (1990) , Mark Hildyard & Cundall (1990-1995), Hildyard now main developer
- 3D dynamic code, finite-difference method, 4^{th} order
- Very efficient due to orthogonal staggered grid
- Unique ability to model voids
- Recently developed a blast modelling capability for open pits, civil engineering projects
- Proving to be an extremely useful tool in blast design, for near- and far-field problems

Half space model

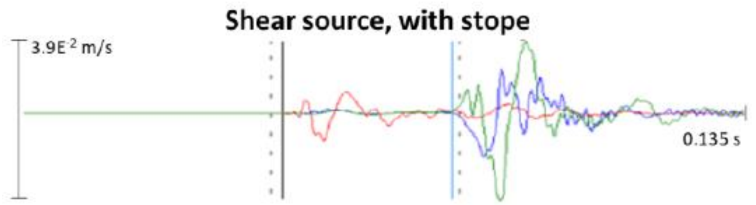


Layered model

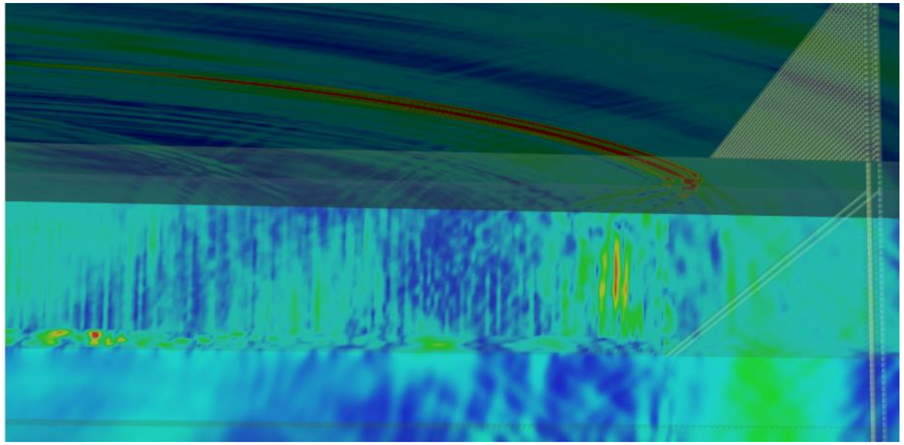




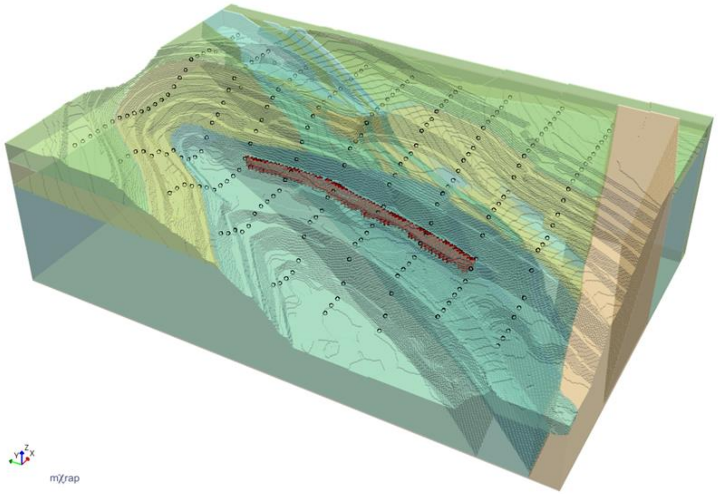
Wide range of studies



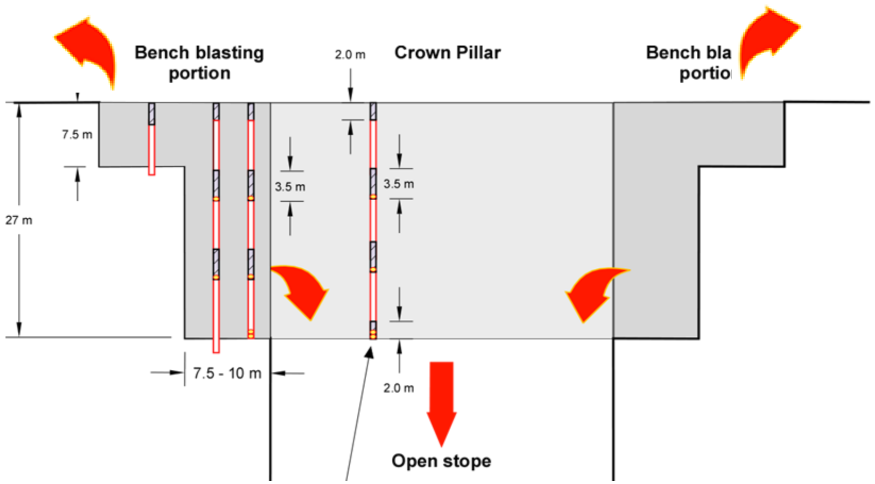
Large number of underground seismic research studies, simulated rockburst experiment



Design of vibration barriers for blast protection of sensitive structures



Forensic studies of blast triggered failures in open pits

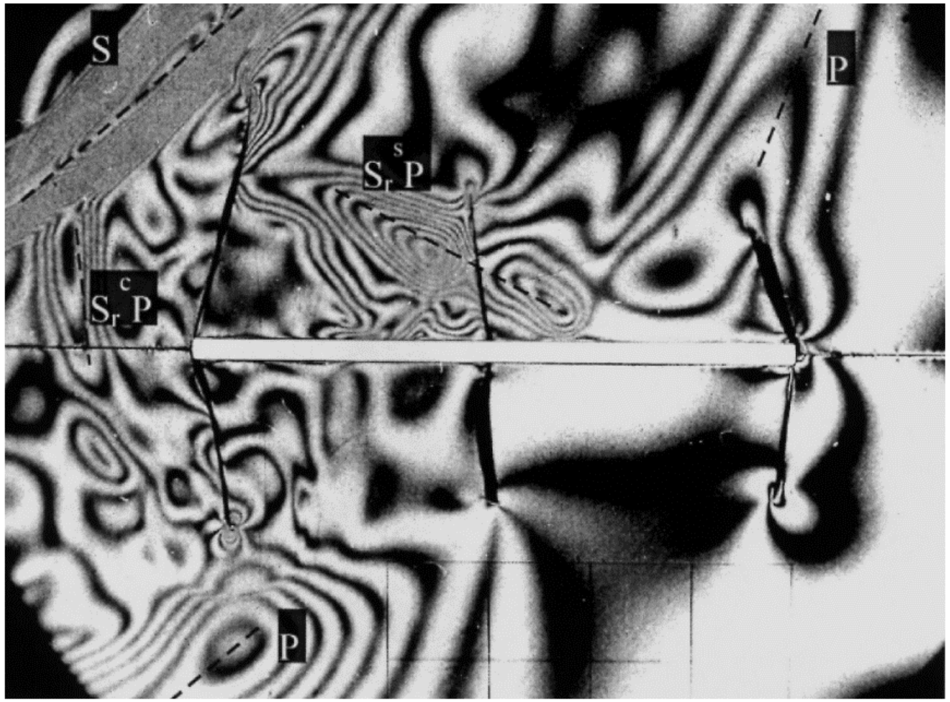


Design and testing of complex blasting patterns

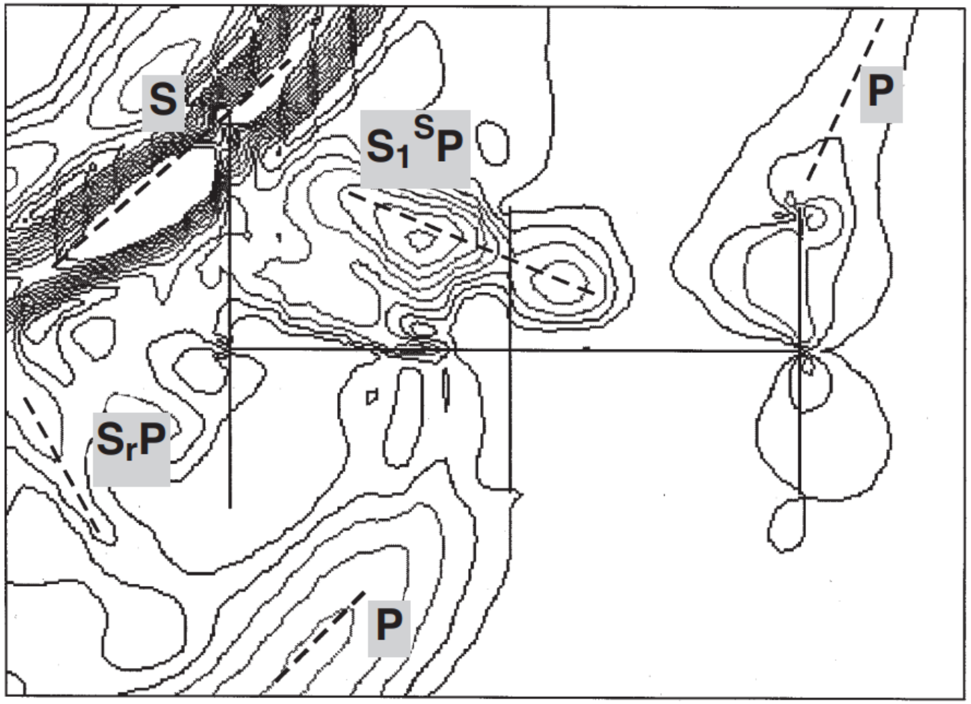
Many other applications: vibrations due to pile-driving, detecting cracks in rails, SCPTu …

Wave3D – Physical models compared to Wave2D

Effect of a stope and high angled fractures - refraction, reflection, diffraction, scattering, wave phase conversion…



Physical model



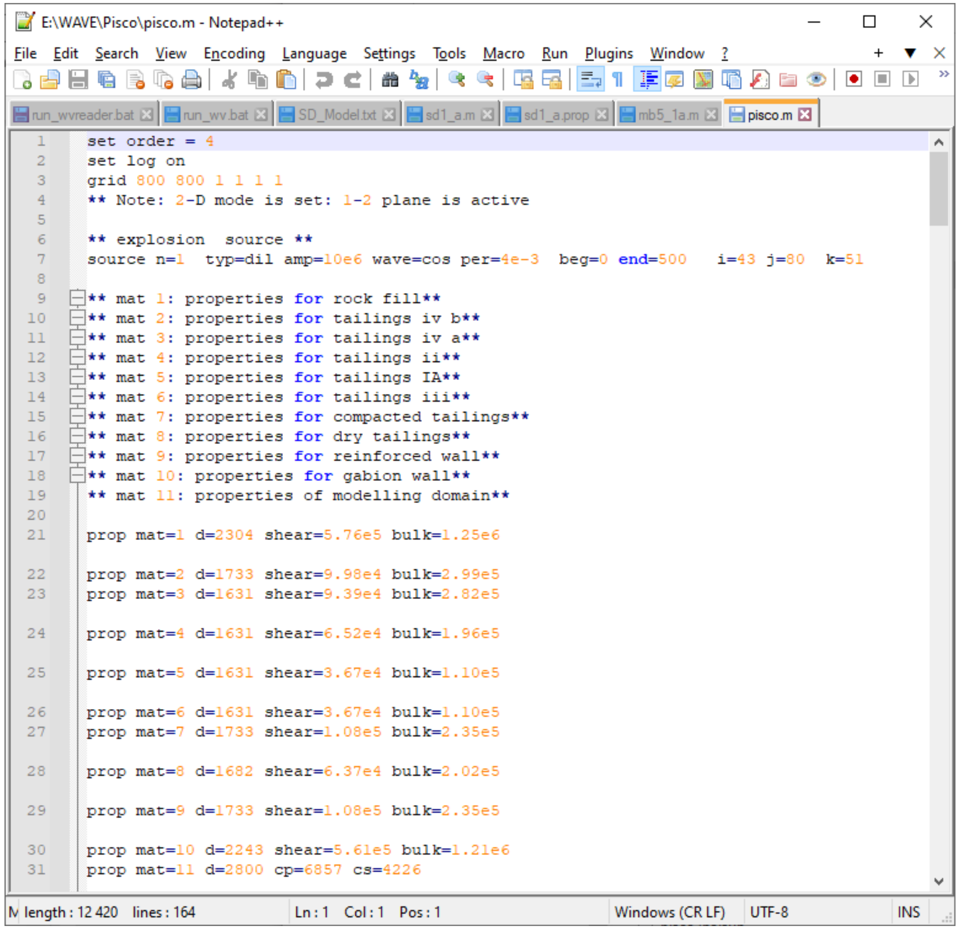
2D WAVE model

Photodynamic experiment to investigate effects of high angle fractures using stress wave induced birefringence

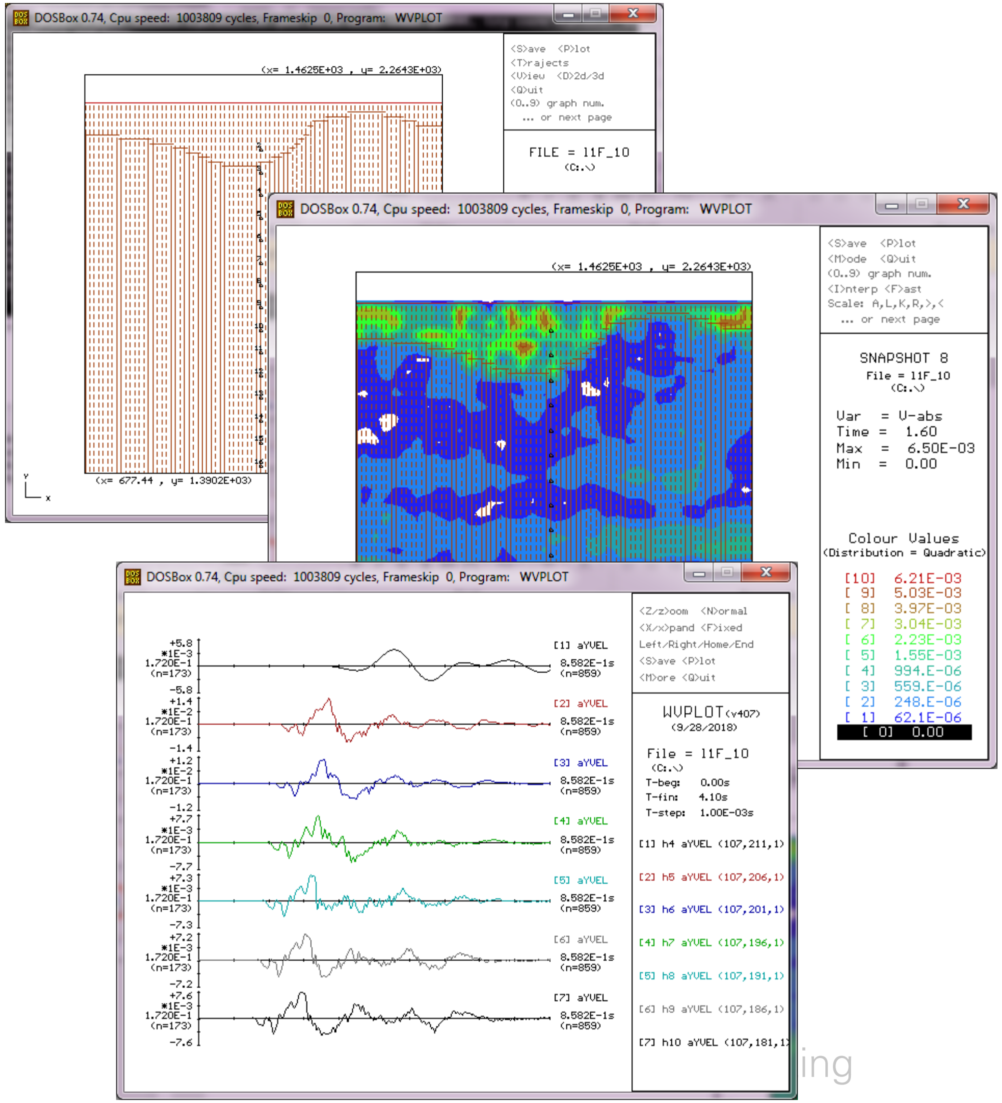
Daehnke, A. (1998). Stress wave and fracture propagation in rock, PhD Thesis, 409pp

Original WAVE3D model builder & post processor

Model building by hand in text editor



Post processing in WVPLOT (16 bit Turbo Pascal)



mXrap

ACG AUSTRALIAN CENTRE FOR GEOMECHANICS

CSIRO | The University of Western Australia | Joint Venture

- mXrap is a software platform that provides geotechnical engineers with many data analysis, monitoring and investigation tools
- mXrap users can also develop their own apps using the in-built app editor
- Initially developed for mining seismology but usage has extended to many other domains

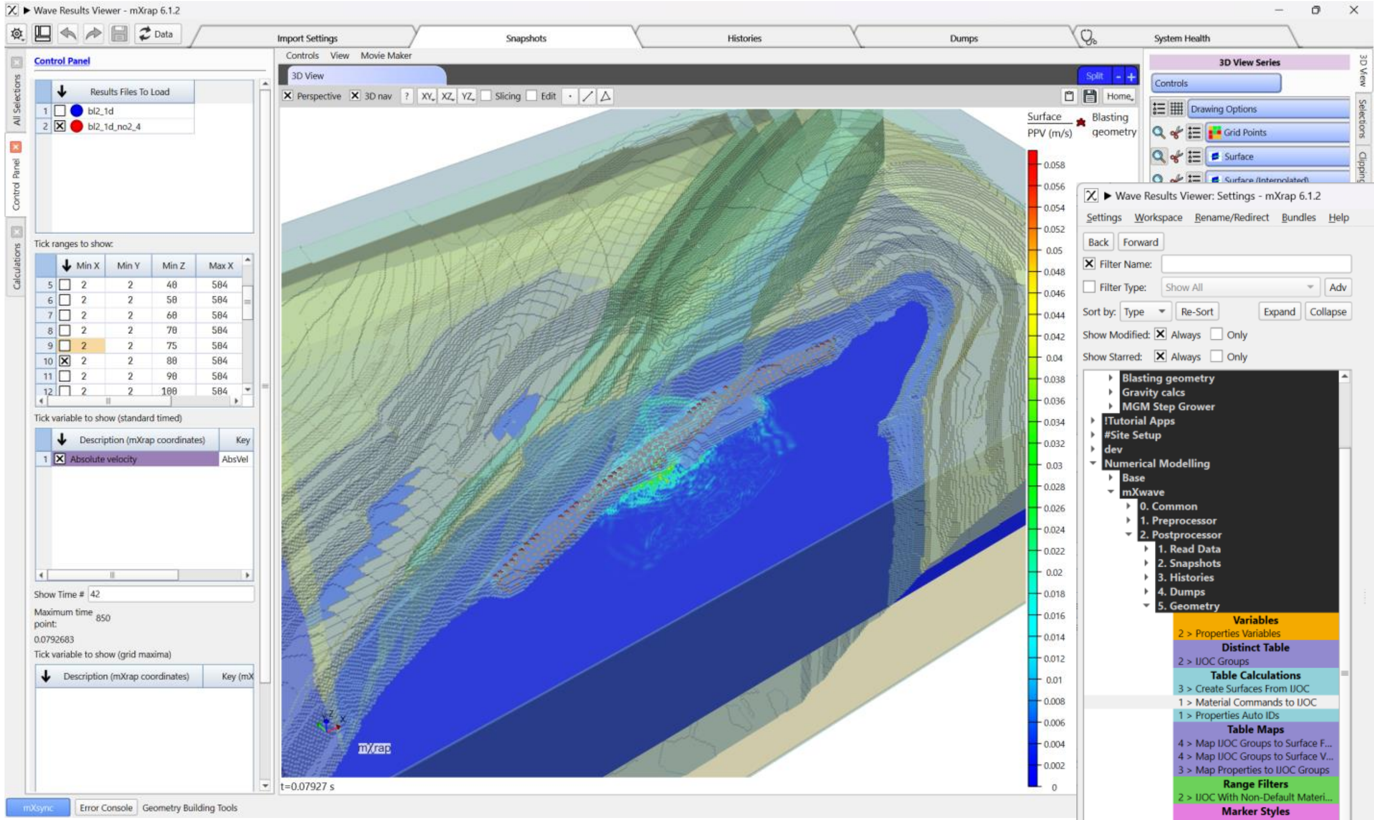
Consortium Members

Research Licence Holders

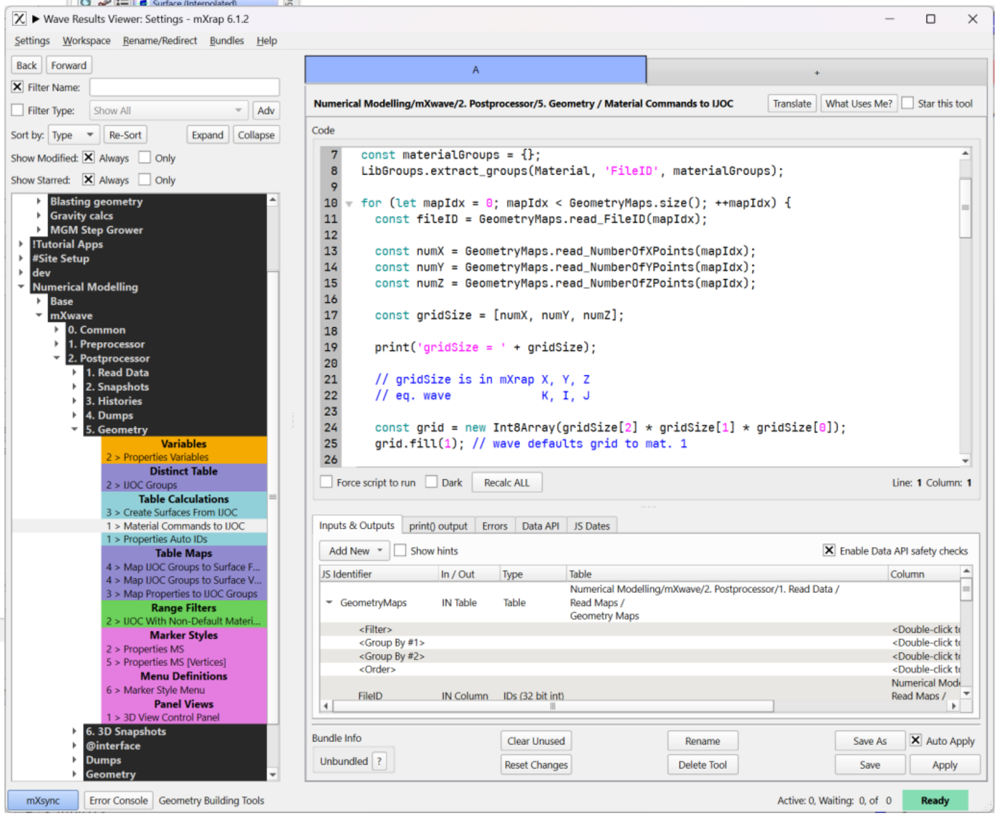
Consulting Licence Holders

mXrap
Wave3D model builder

Build complex 3D models from DXF files

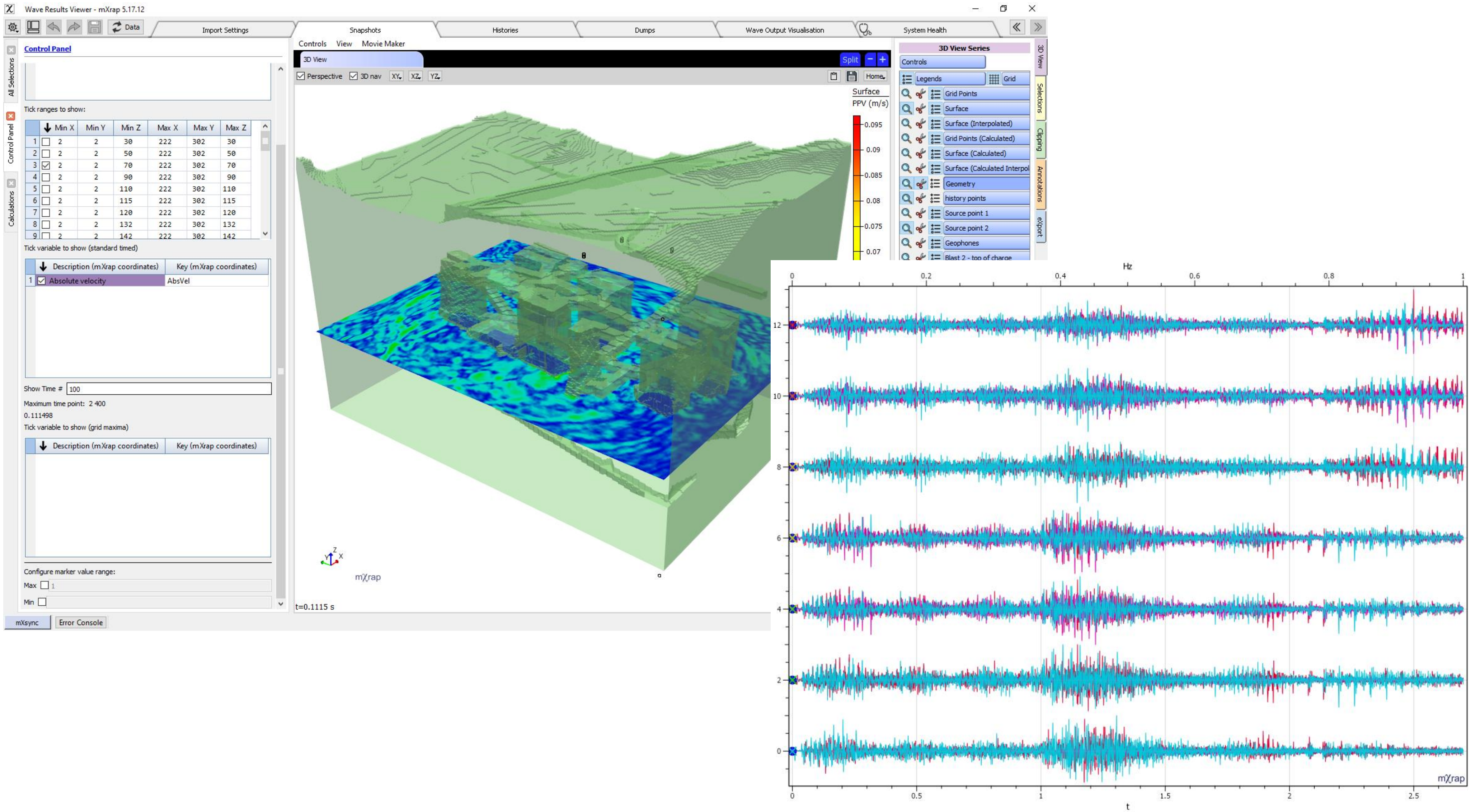


JS scripting to build custom apps



mXrap

Wave3D post-processor



SCPTu tests

- Methodology has been developed and used extensively for more than three decades for the in-situ measurement of shear wave velocity (Vs)

- Small strain Shear Modulus

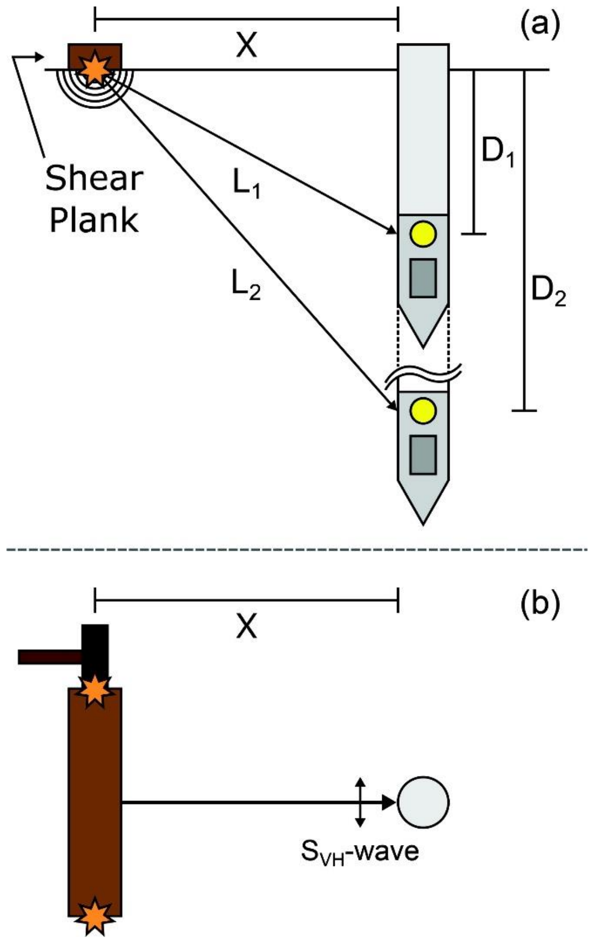
$$G_0 = \rho V_s^2$$

- Poisson's ratio

$$\vartheta = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - V_s^2\right)}$$

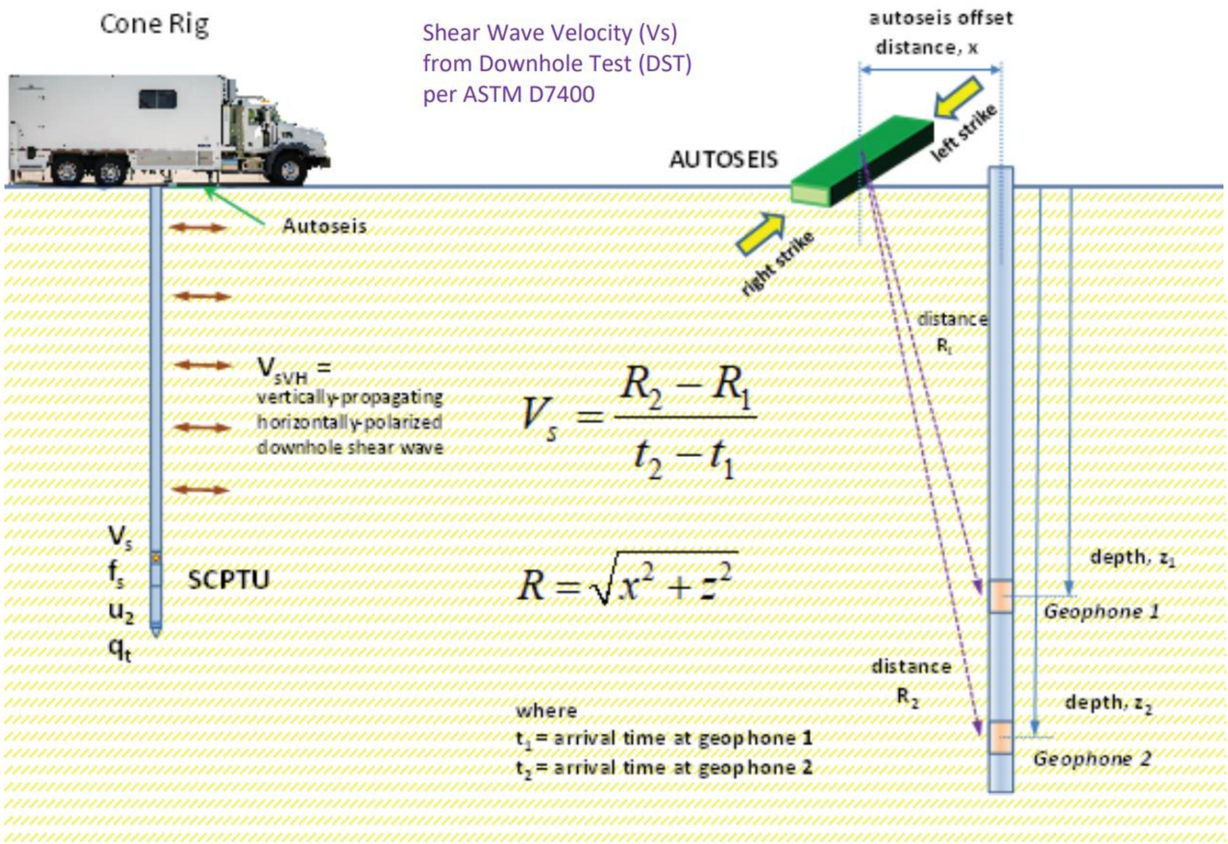
- Small strain Young's Modulus

$$E_0 = 2G_0(1 + \vartheta)$$

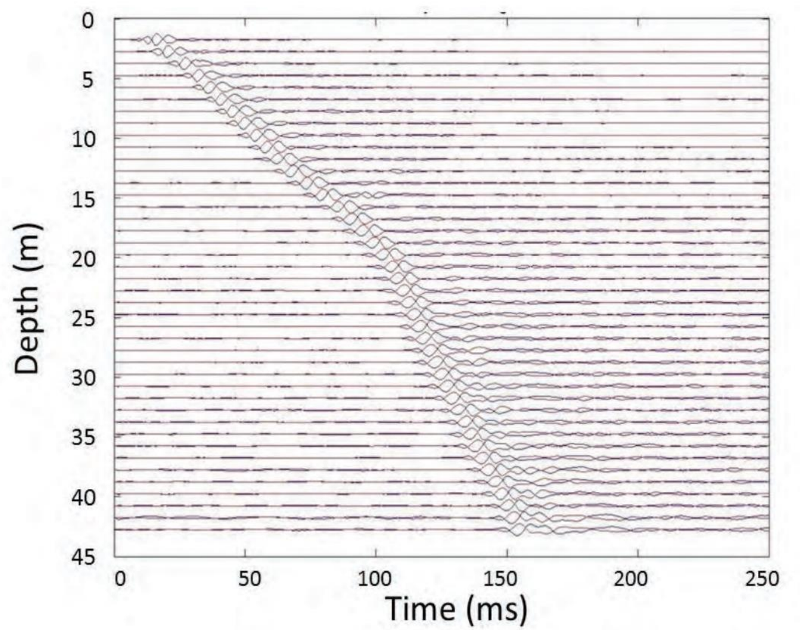


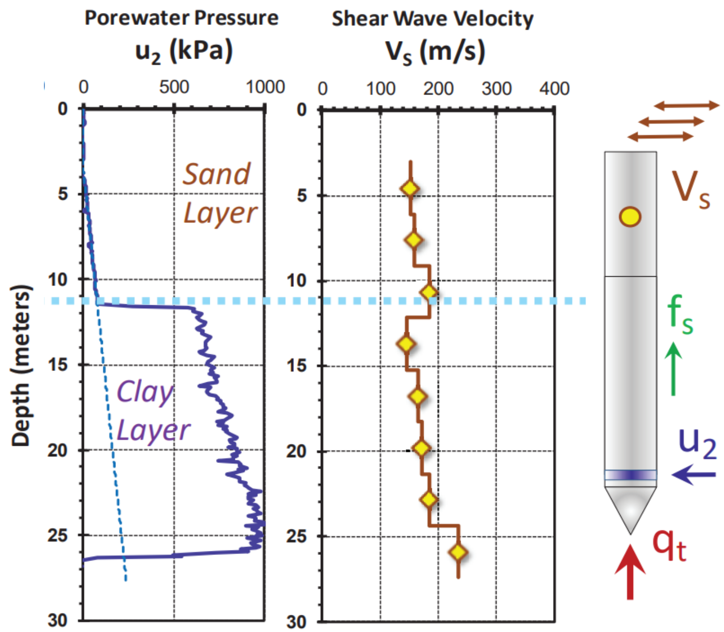
https://cdnsciencepub.com/doi/10.1139/cgj-2018-0689

SCPTu field setup



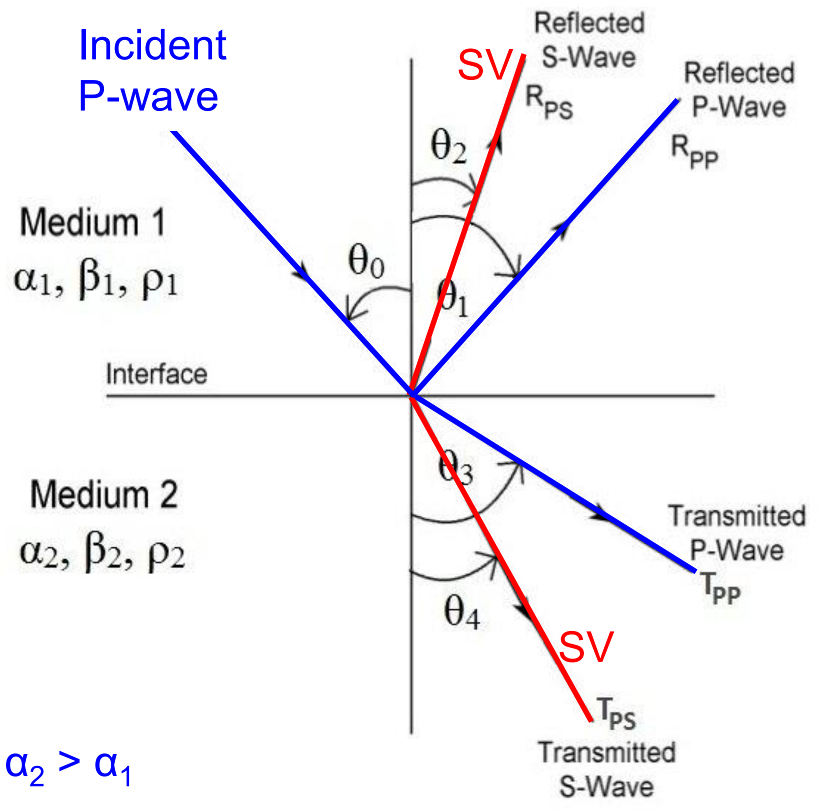
ConeTec_CPT_Design_Parameter_Manual-2023_First_Edition-2023-04-24_rev1.1_print ready_EN.pdf



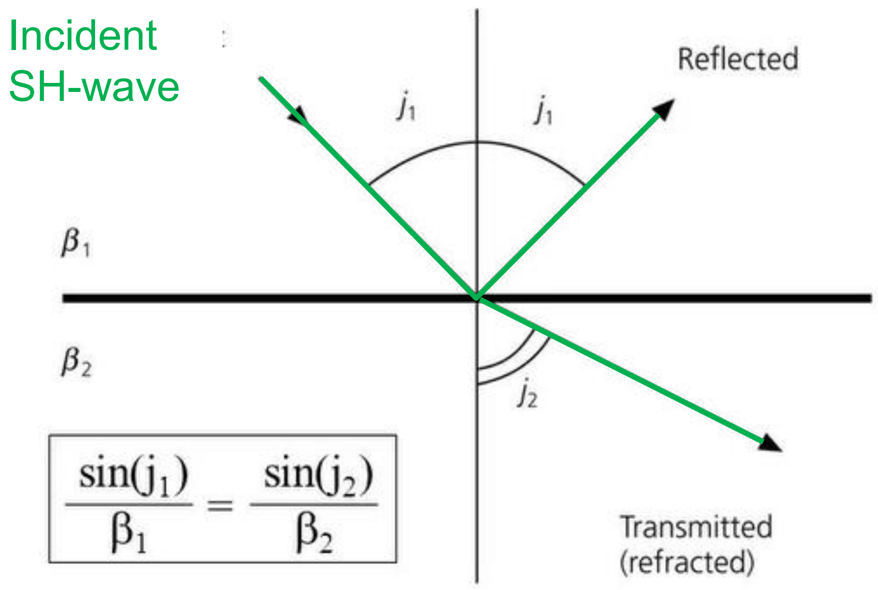


Reason for SH source

Fewer phase conversions at interfaces



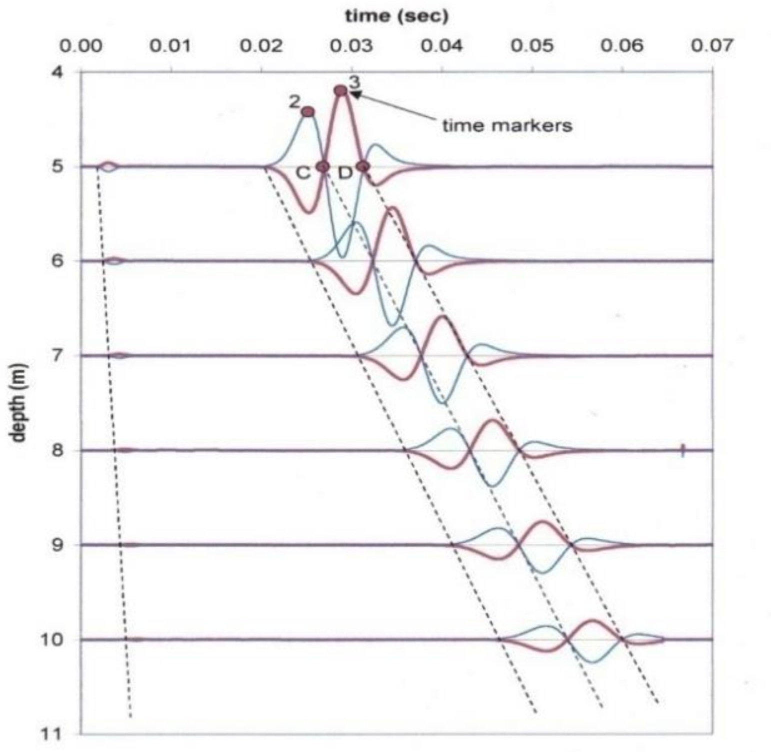
Apply Snell's law to determine the refraction angles at layer interfaces and to reproduce the refracted paths



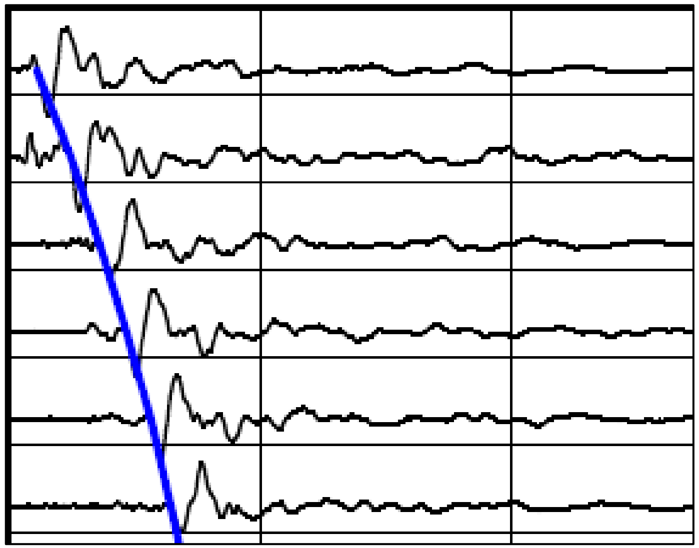
SCPTu data processing

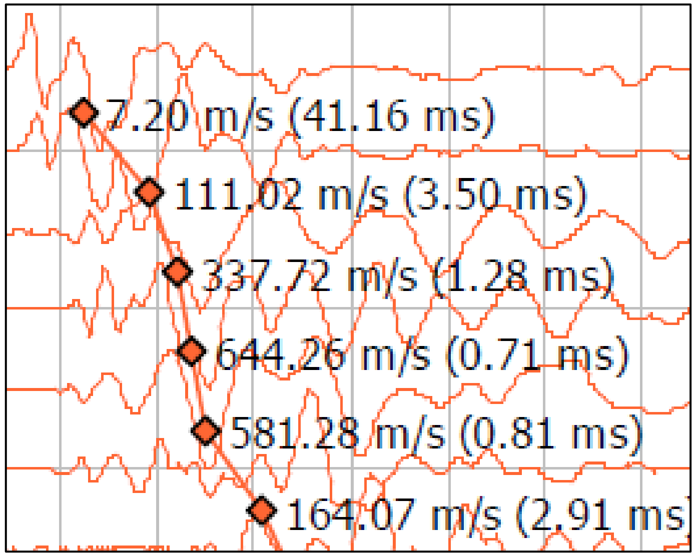
S-wave arrival time picking

Ideal seismograms



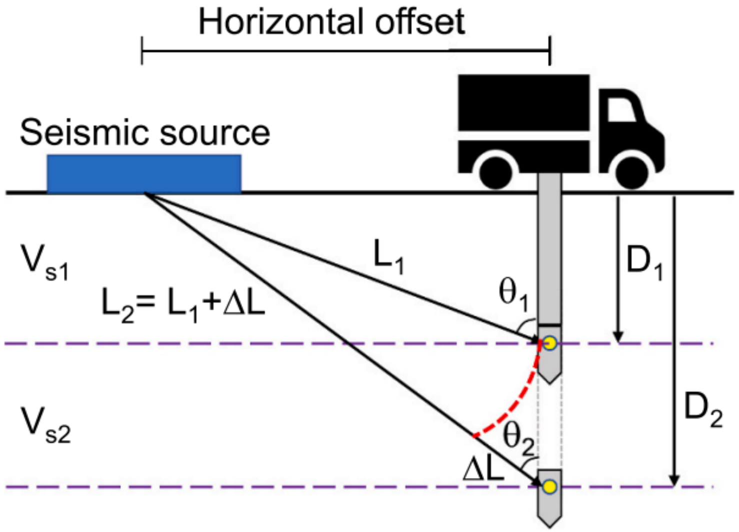
Actual seismograms





SCPTu data processing
Velocity determination

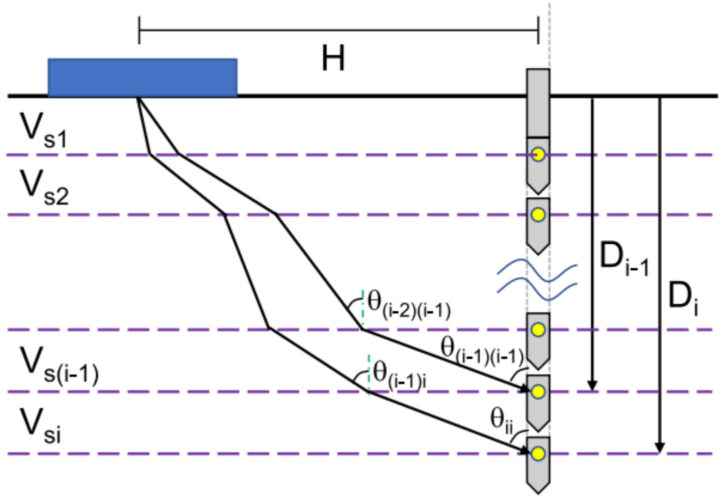
Slope and interval method



$$t_{i,equiv} = t_i cos\theta_i = t_i \frac{D_i}{L_i}$$

$$V_s = \frac{D_i - D_{i-1}}{t_{i,equiv} - t_{i-1,equiv}}$$

Refracted ray path method



$$\frac{sin\theta_{1i}}{V_{s1}} = \frac{sin\theta_{2i}}{V_{s2}} = \ldots = \frac{sin\theta_{ji}}{V_{sj}} = \ldots = \frac{sin\theta_{ii}}{V_{si}}$$

$$H = D_1 tan\theta_{1i} + (D_2 - D_1) tan\theta_{2i} + \ldots + (D_i - D_{i-1}) tan\theta_{ii}$$

$$t_i = \frac{D_1/cos\theta_{1i}}{V_{s1}} + \frac{(D_2 - D_1)/cos\theta_{2i}}{V_{s2}} + \ldots + \frac{(D_i - D_{i-1})/cos\theta_{ii}}{V_{si}}$$

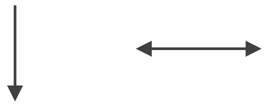
Modified refracted ray path method for determination of shear wave velocity profiles using seismic cone - ScienceDirect

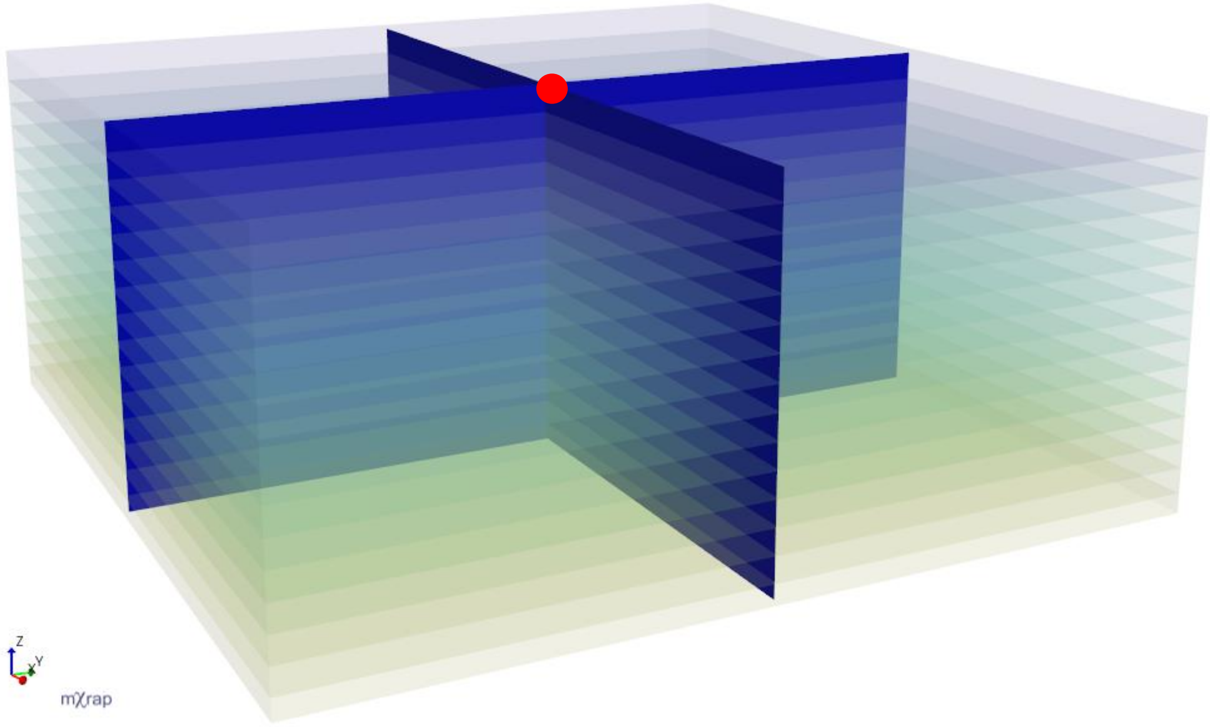
Thoughts on SH sources in a TSF scenario

- There's a free surface and the tailings material is not homogenous and layered
  - Free surface → Rayleigh waves
  - Free surface + layering → Love waves
- Surface waves are dispersive i.e. their velocity varies with frequency, and different frequencies travel at different depths
- Possibility that less energy travels to depth because a large proportion results in surface waves and travels horizontally
- SH source → asymmetrical wavefield
- Maybe an explosive (P-wave, vertical hammer blow) source is better / less complicated?
- The use of uniaxial geophones is limiting

3D model, Vs from SCPTu test

- Compare a vertical hammer blow source to an SH source
- Model with/out layering



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prop mat=8 d=1700  cp=476 cs=275
prop mat=9 d=1700  cp=468 cs=270
prop mat=10 d=1700 cp=544 cs=314
prop mat=11 d=1700 cp=504 cs=291
prop mat=12 d=1700 cp=509 cs=294
prop mat=13 d=1700 cp=549 cs=317
prop mat=14 d=1700 cp=407 cs=235
prop mat=15 d=1700 cp=310 cs=179
prop mat=16 d=1700 cp=383 cs=221
prop mat=17 d=1700 cp=386 cs=223
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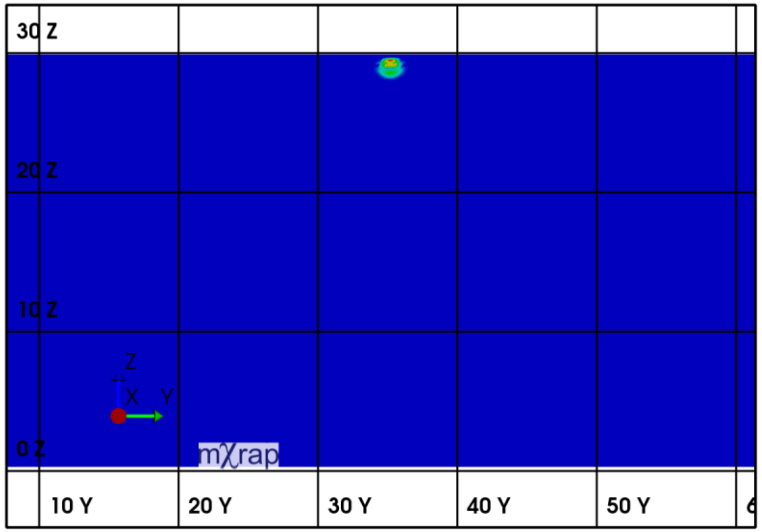
Vertical hammer blow (normal stress S22)



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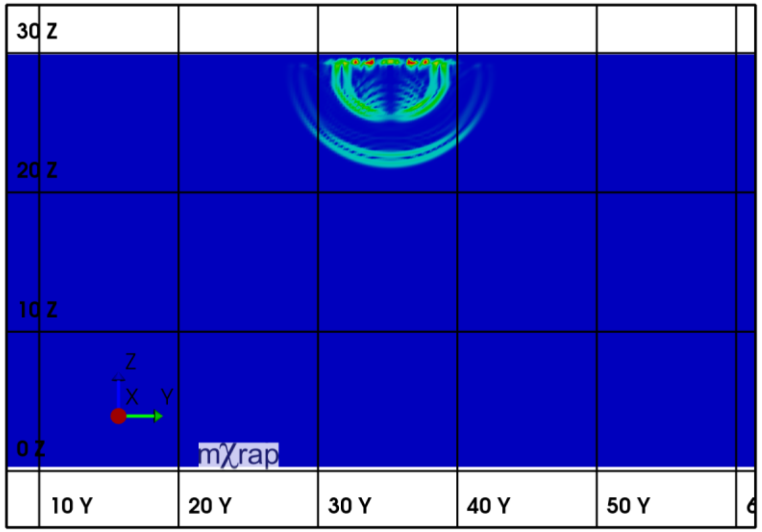

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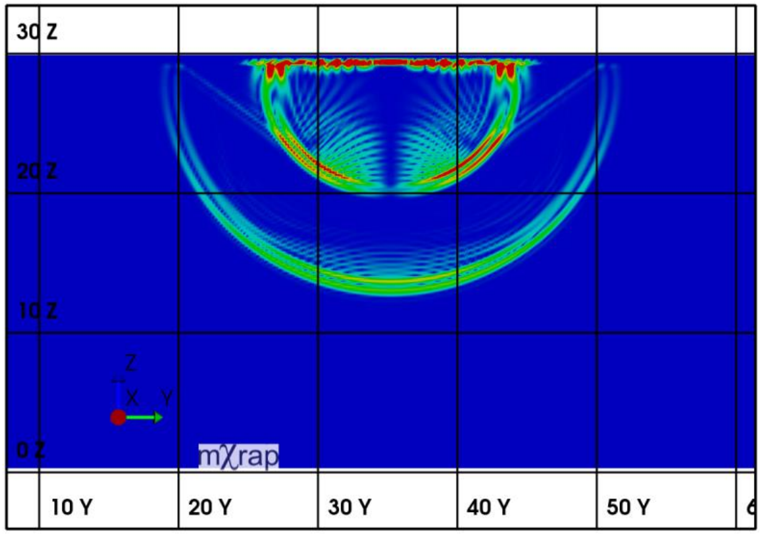

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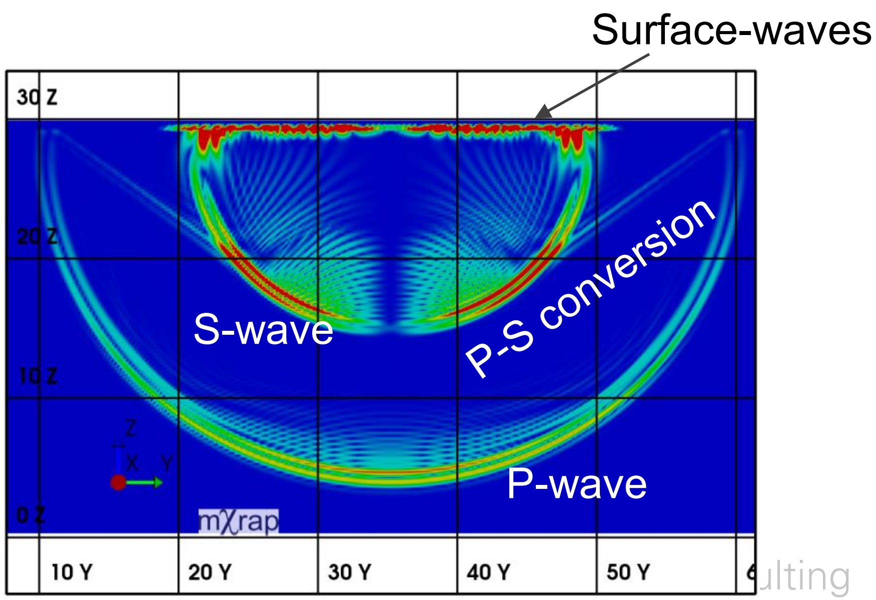

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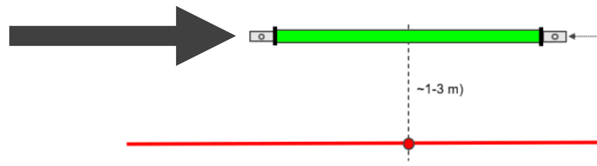
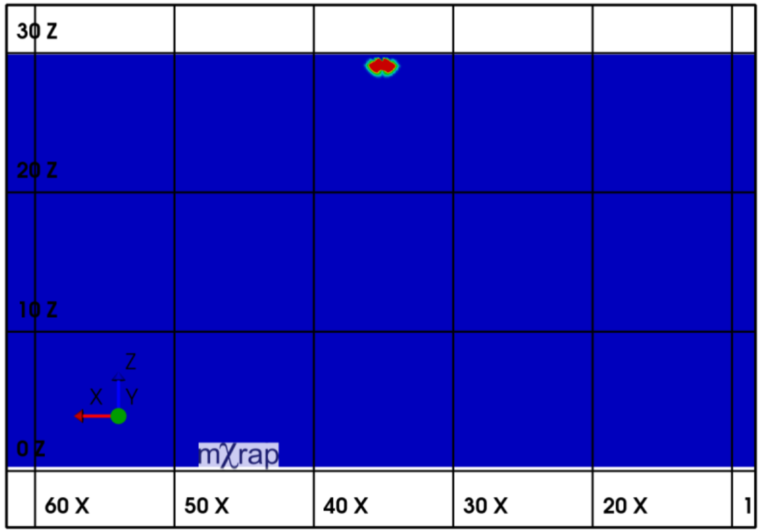
SH hammer blow (shear stress S23)

Axis parallel to long axis of source





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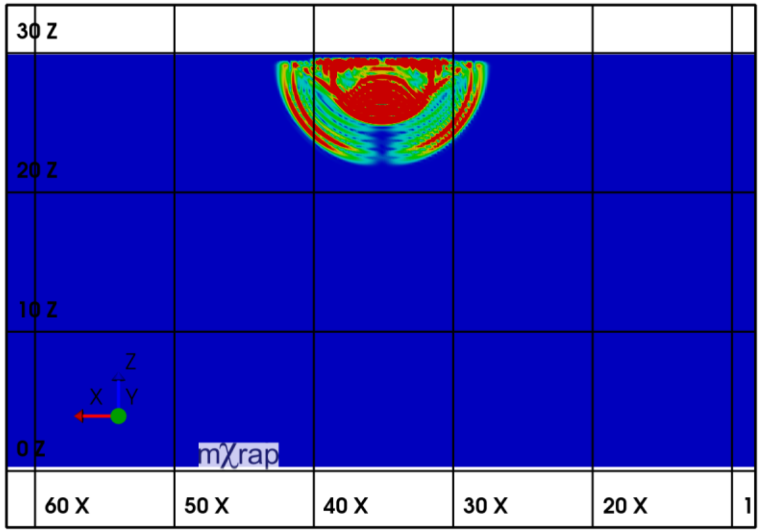

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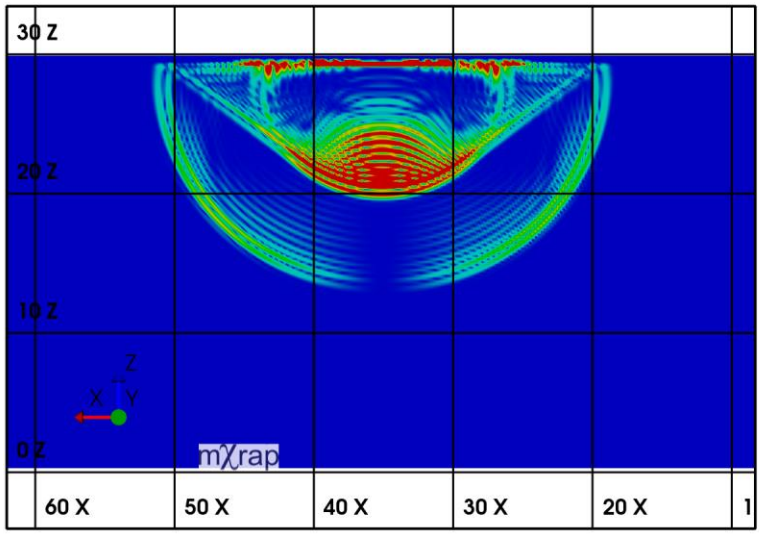

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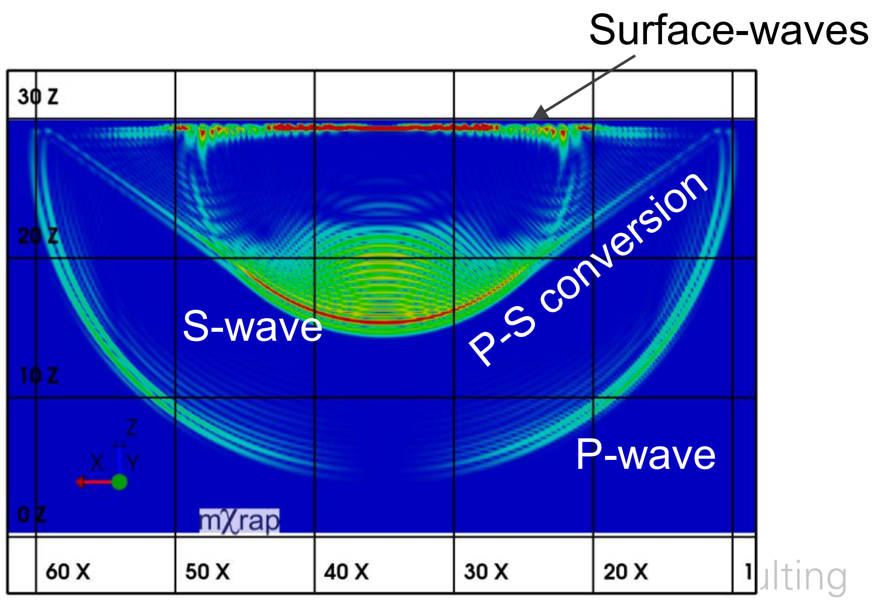

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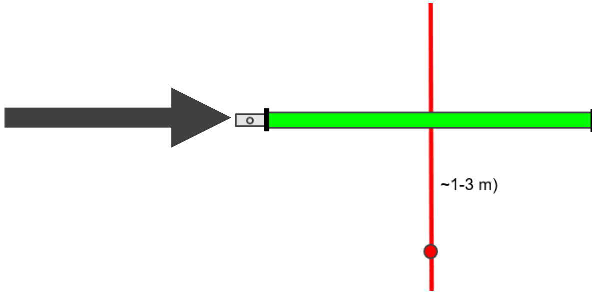
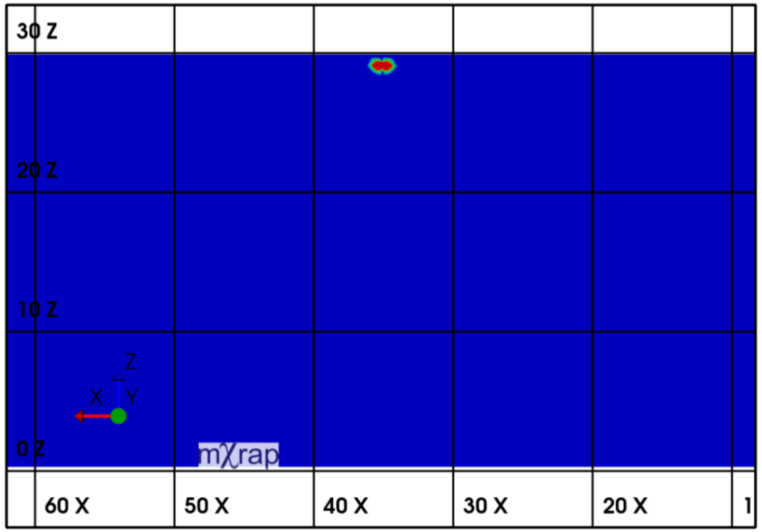
SH hammer blow (shear stress S23)

Axis orthogonal to long axis of source, no layering





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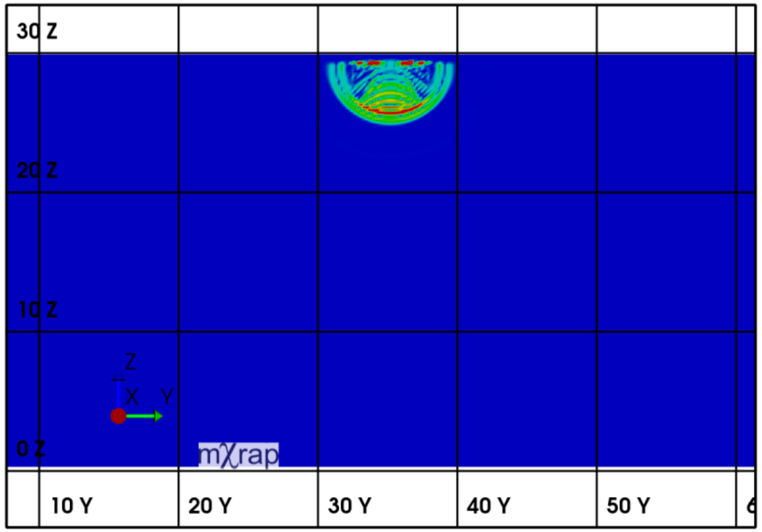

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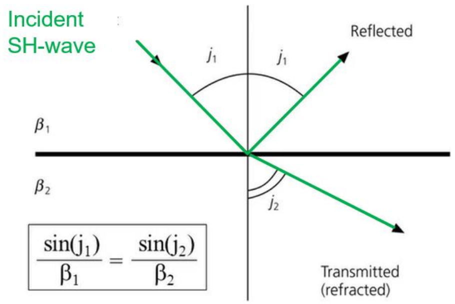

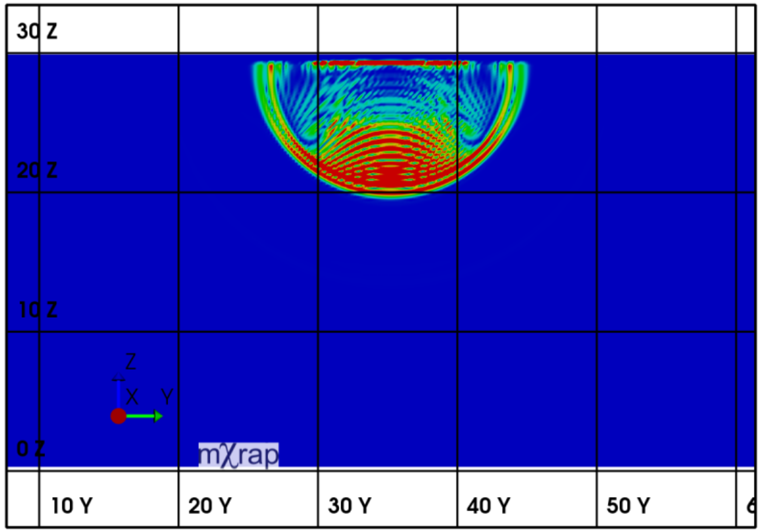

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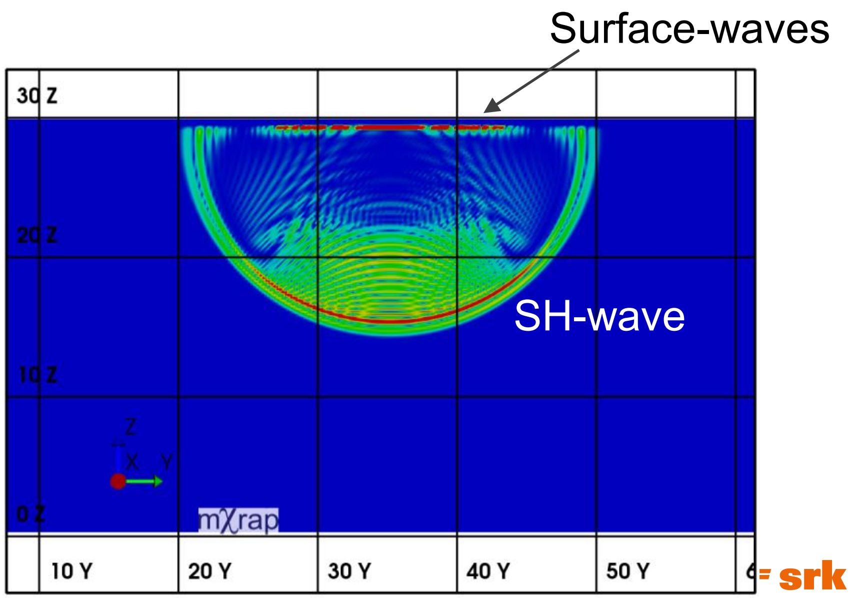
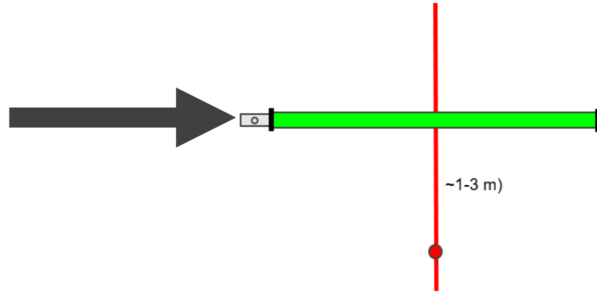
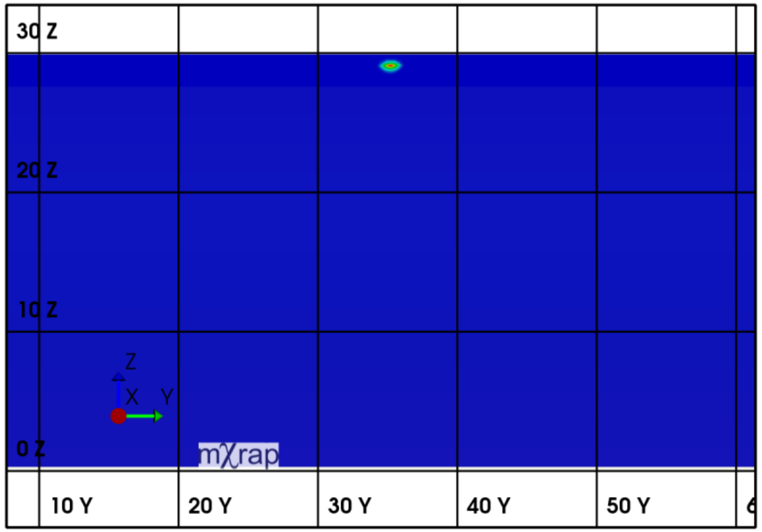


t=0.05311 s

SH hammer blow (shear stress S23)

Axis orthogonal to long axis of source + layering





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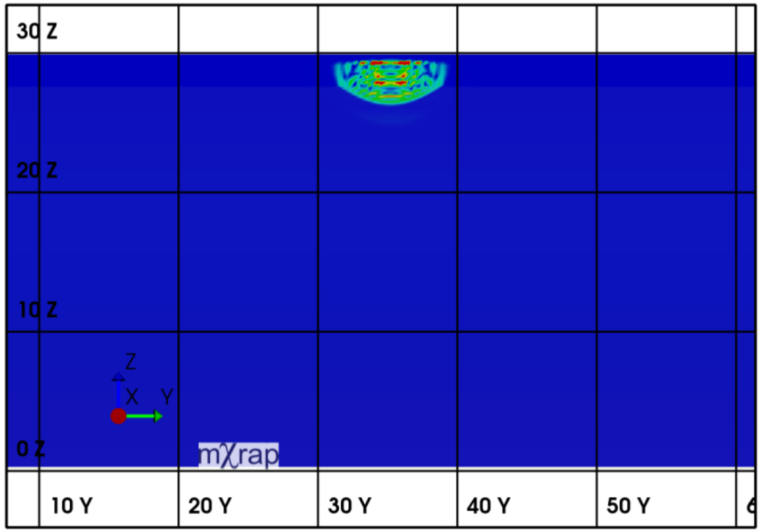

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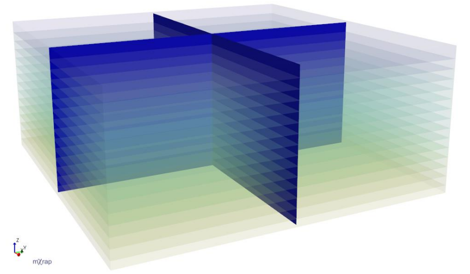

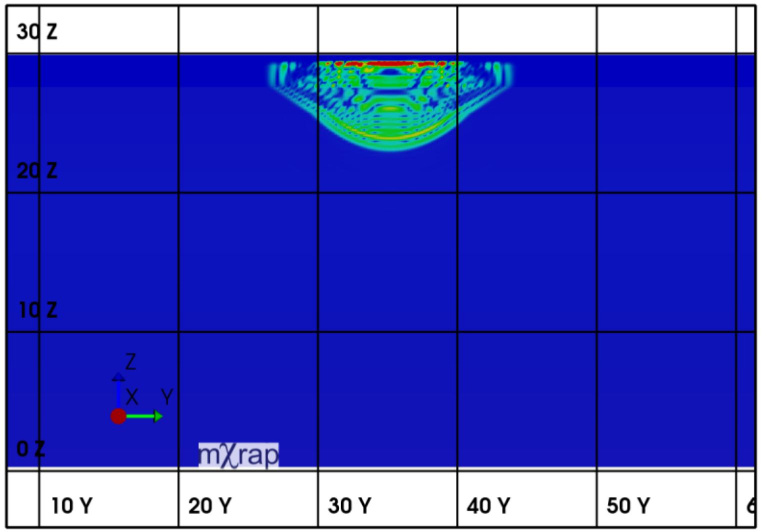

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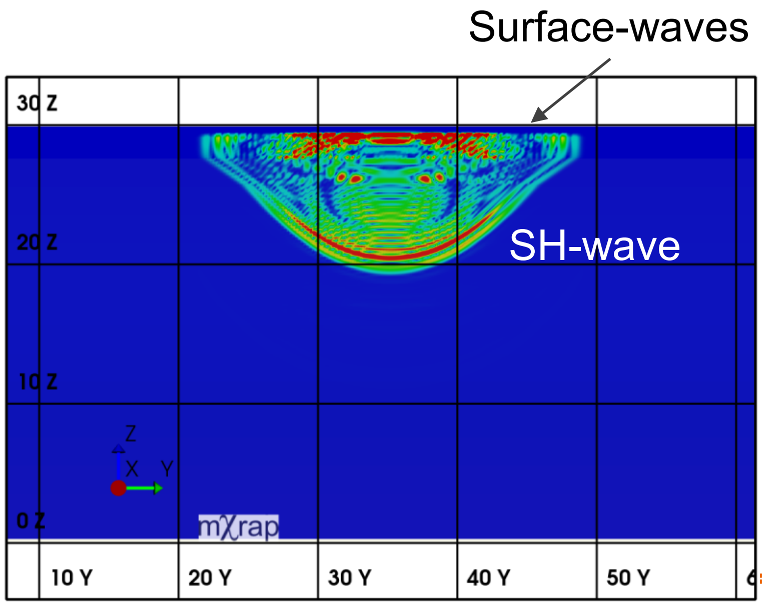

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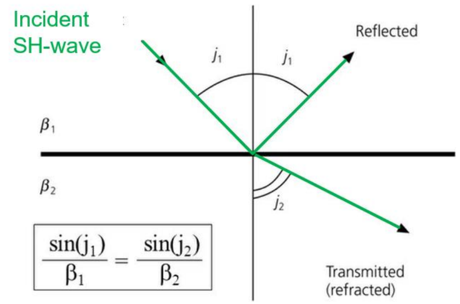
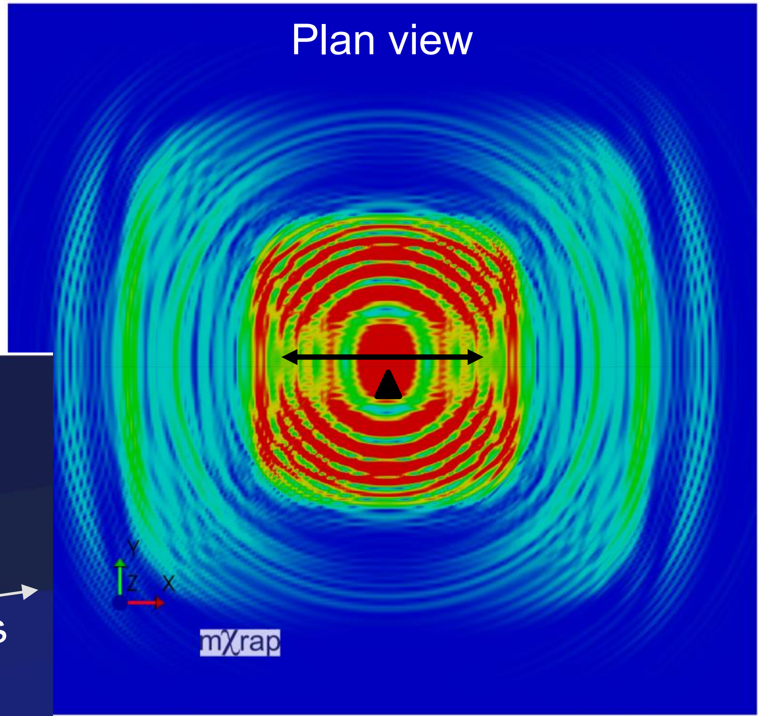
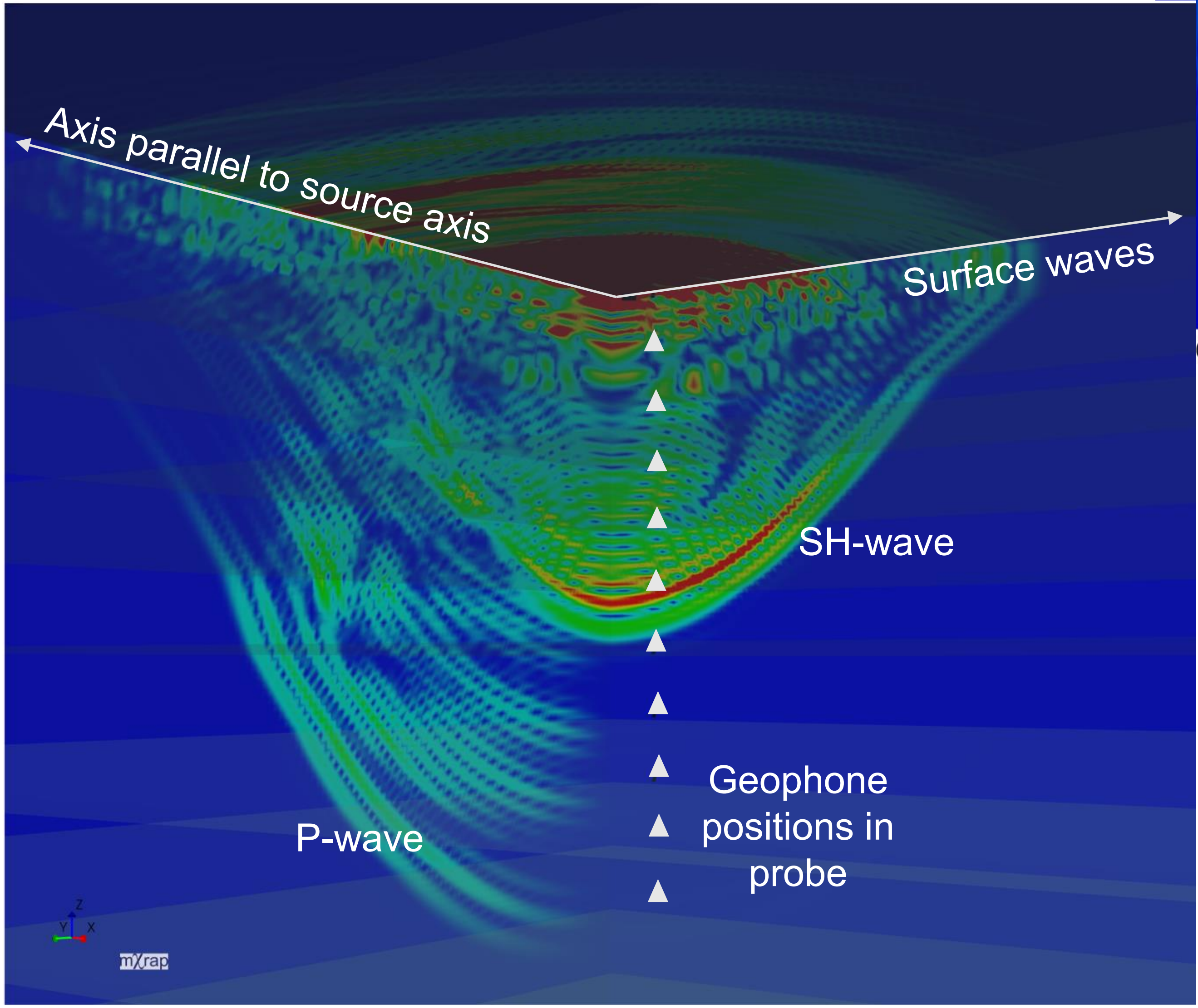


SH hammer blow source + layering



0531 s



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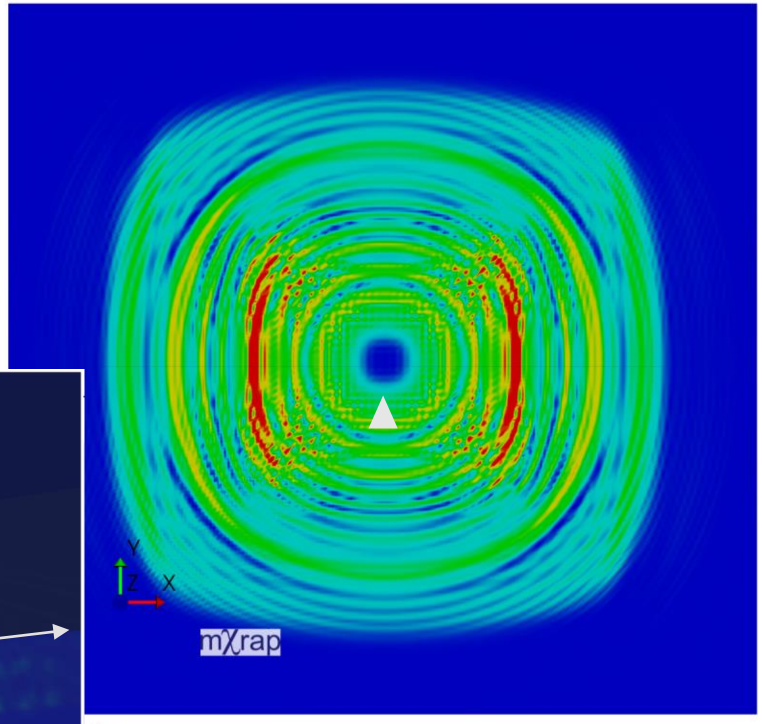
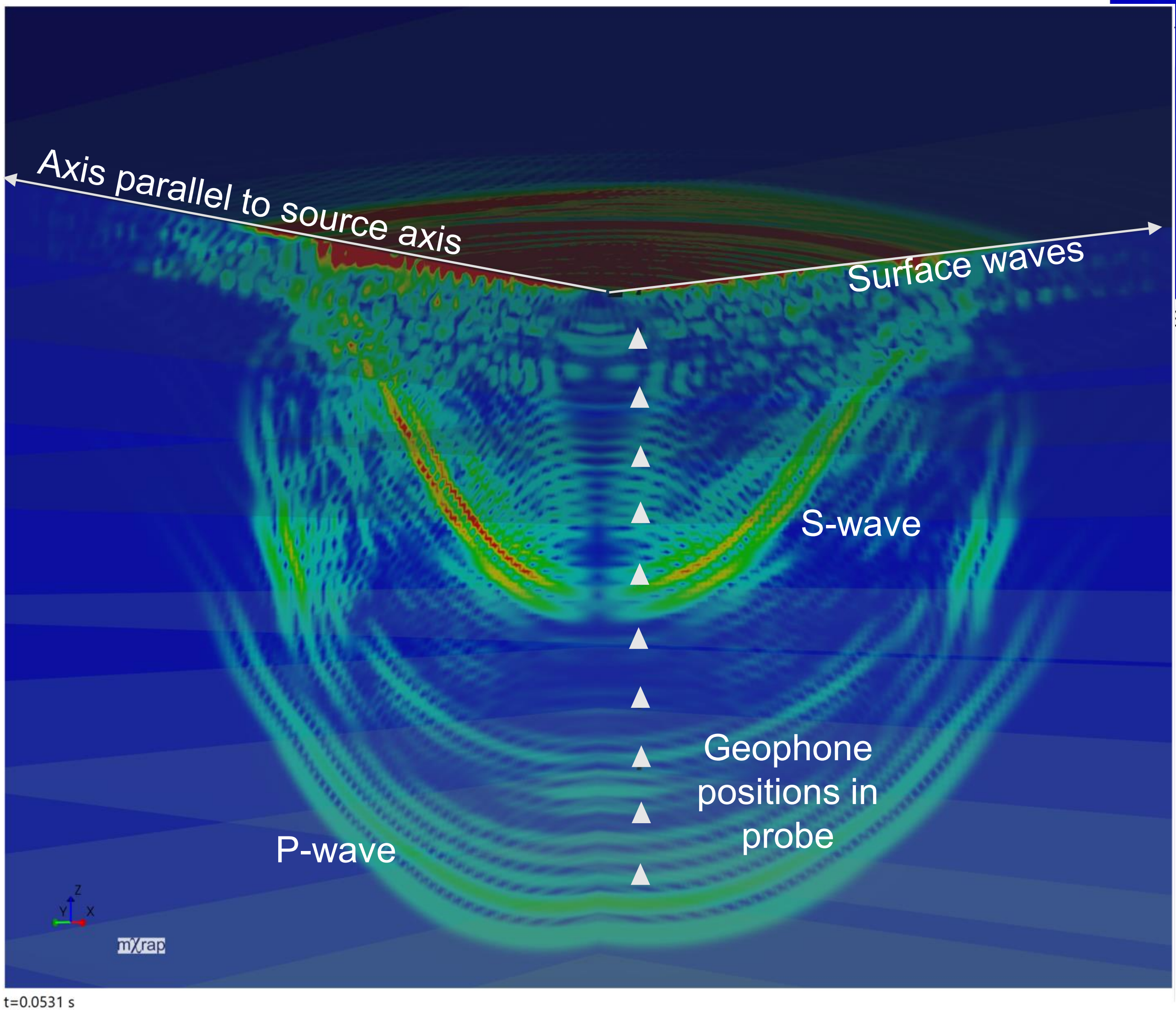
Vertical hammer blow + layering





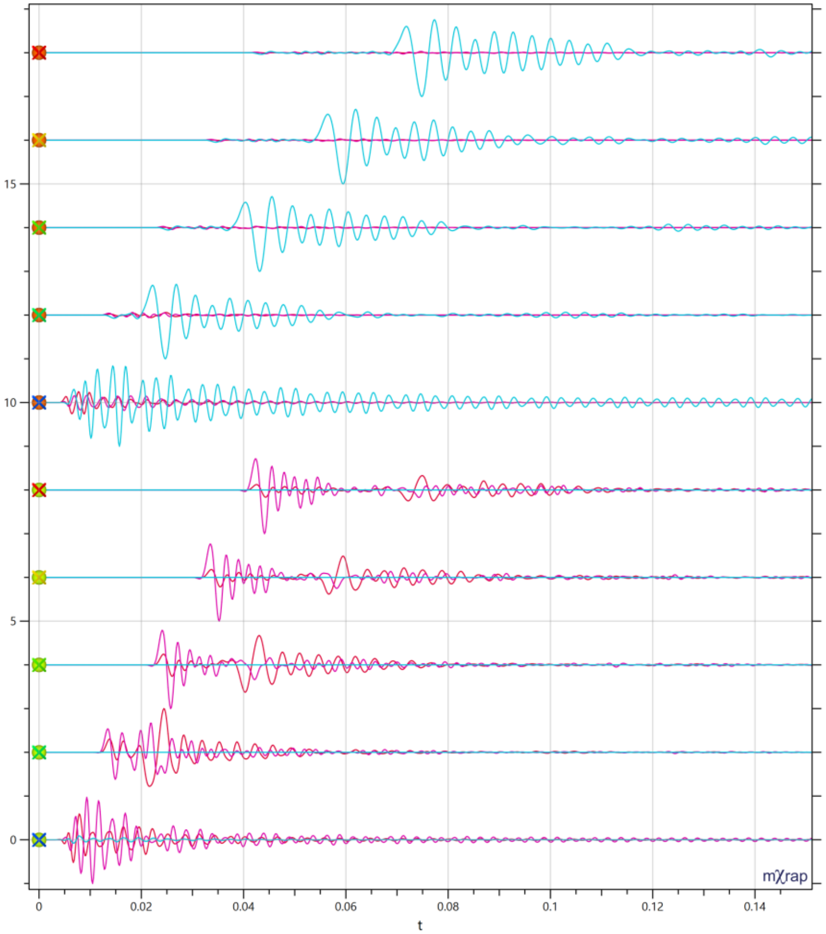
Seismograms for SH and vertical hammer blow

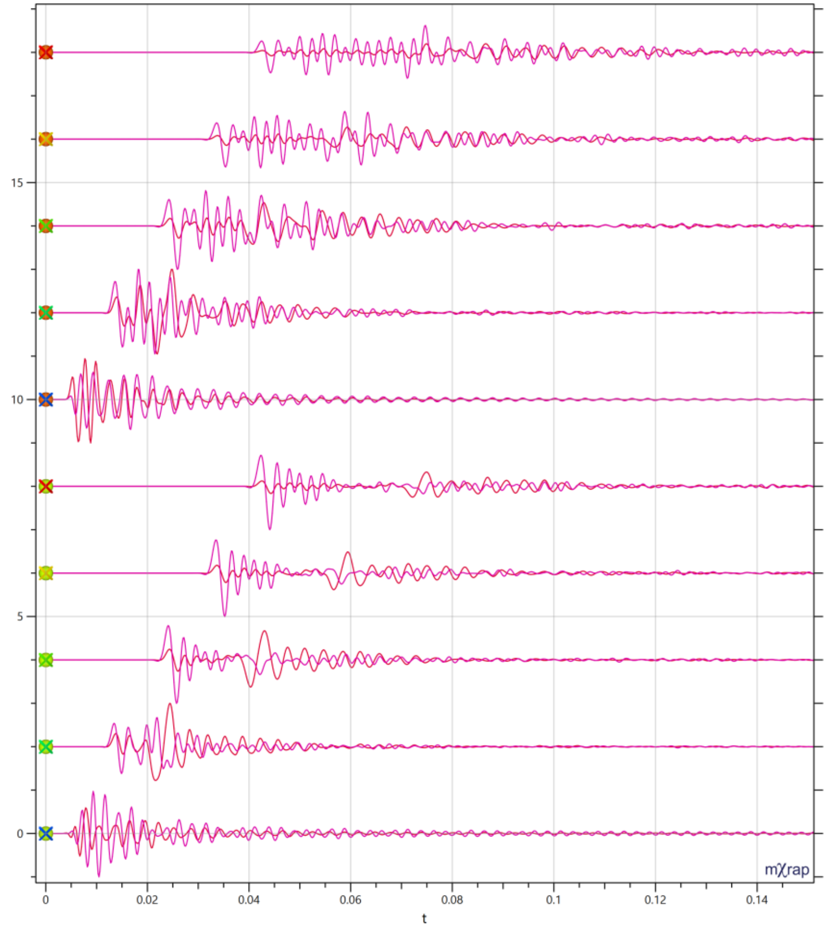
All components

Minus x-component

SH source

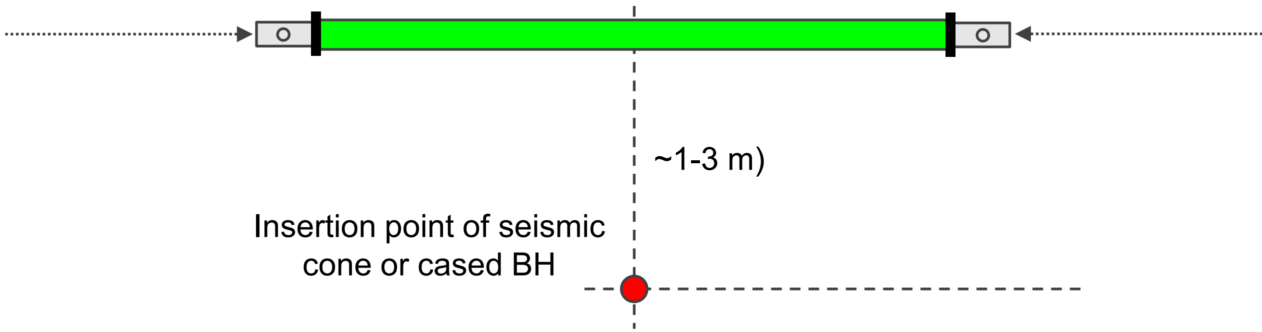
Vertical source





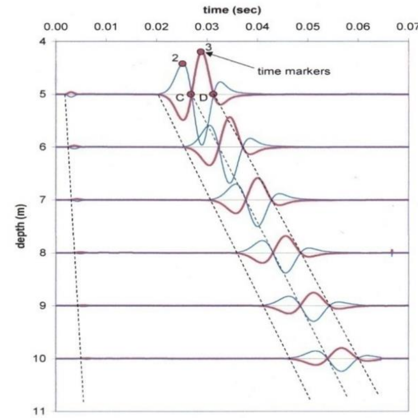
P-waves easier to identify for vertical source, S-waves easier for deeper geophones as phases separate

Summary

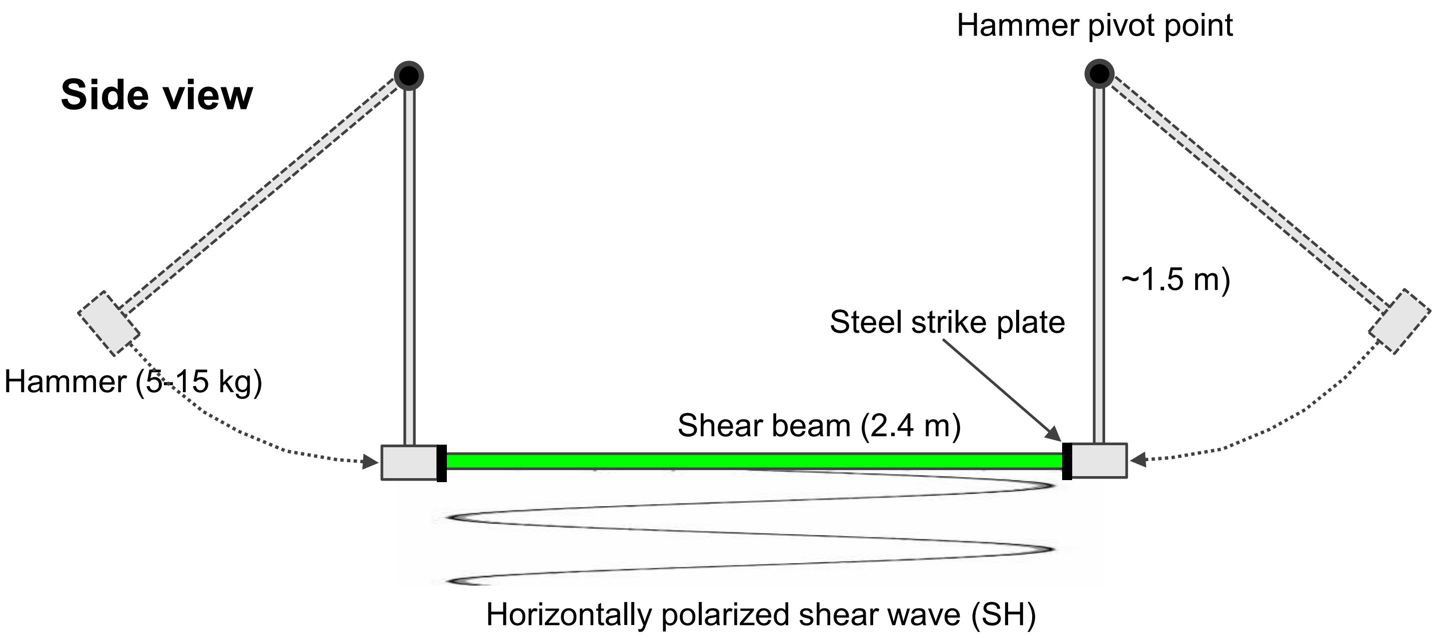


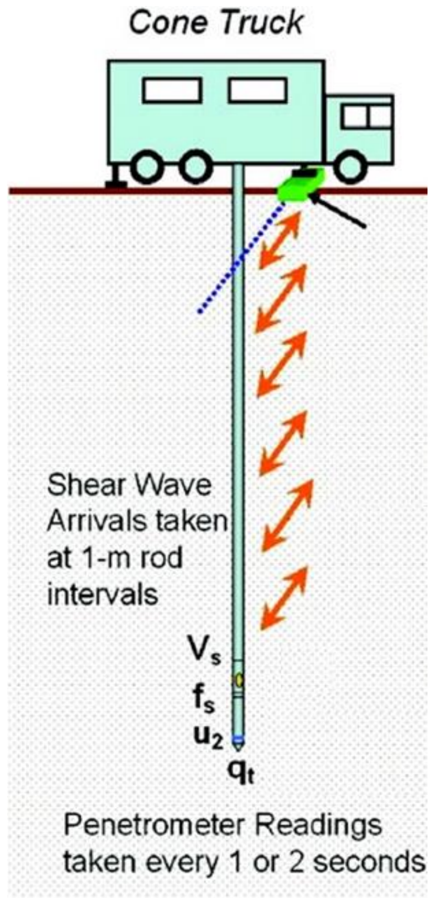
- Noisy near surface seismograms are not just because of rod noise – complex wave conversions are taking place along the interface e.g. surface waves
- P-waves easier to pick in the near surface, while S-waves become clearer with longer travel times
- Most probes seem to only house uniaxial geophones. Triaxials would be enormously beneficial because this will enable tensor rotations to maximise both P and S-waves, making picking much easier
- Cables can carry more than one signal through multiplexing, so extra cables will not be needed
- Radiation pattern produced by SH source is asymmetric, making positioning of the probe relative to long axis of the SH source critical
- Vertical hammer blow sources produce stronger P-waves, are symmetrical and produce S-waves. Less sensitive to positioning of probe, might be easier to process

ASTM standard D 7400 – 08
Source specs



Side view





Plan view