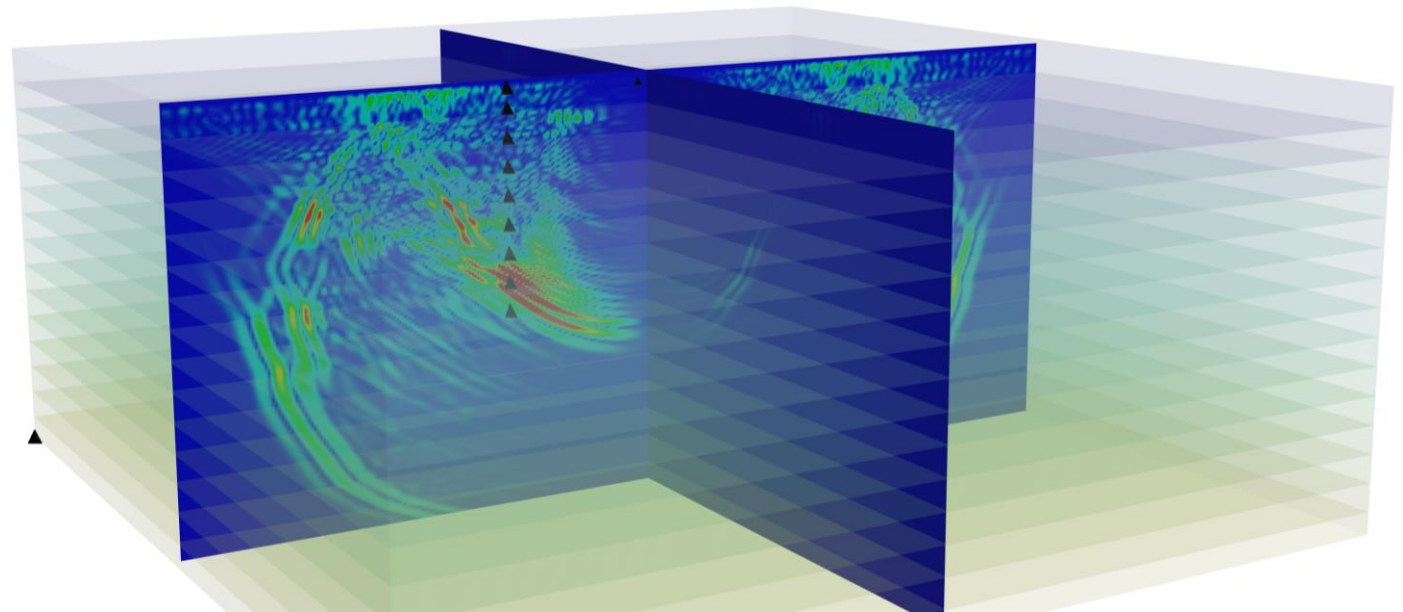


The wavefield of an SCPTu test

Not as simple as you think

Lindsay Linzer

26 June 2025



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

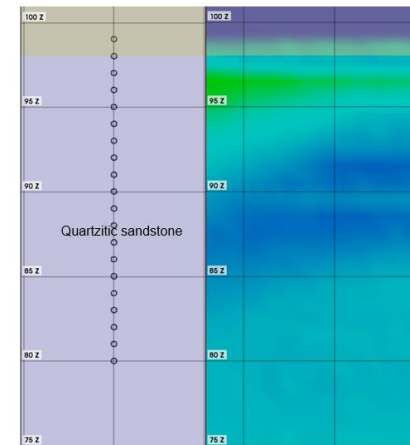
SCPTu tests

- 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 V_s profile and elastic moduli

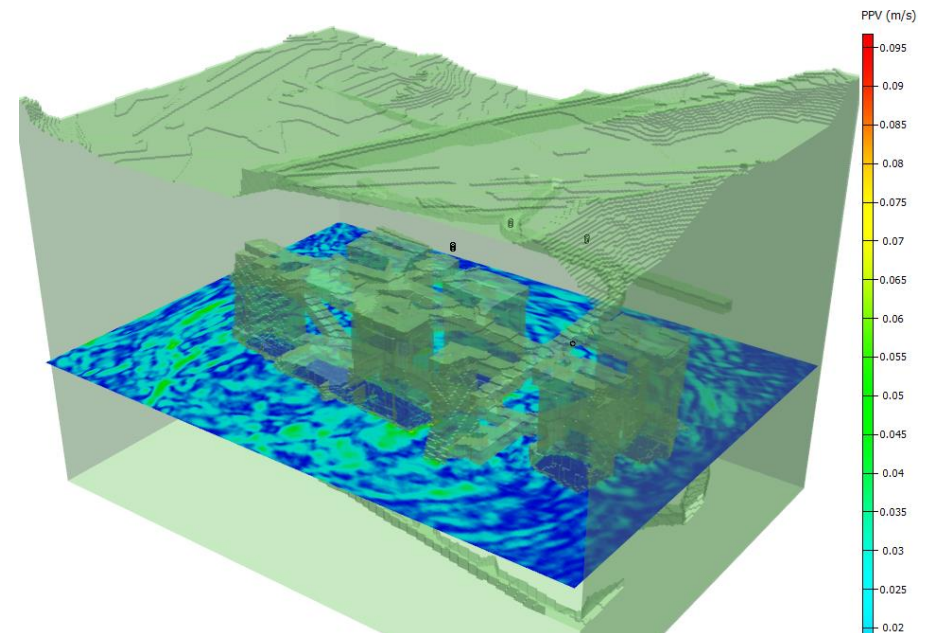
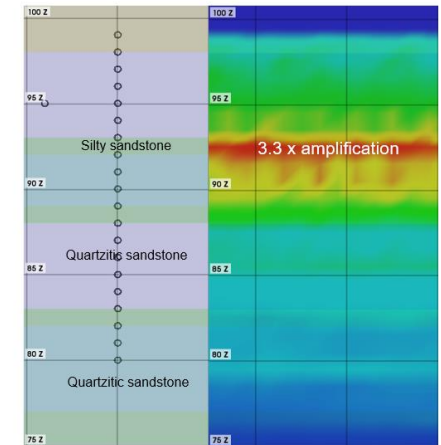
Wave3D

- 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, 4th 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

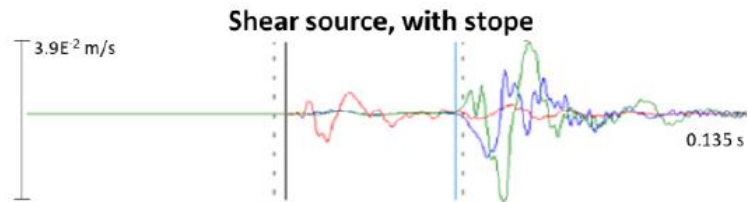
Half space model



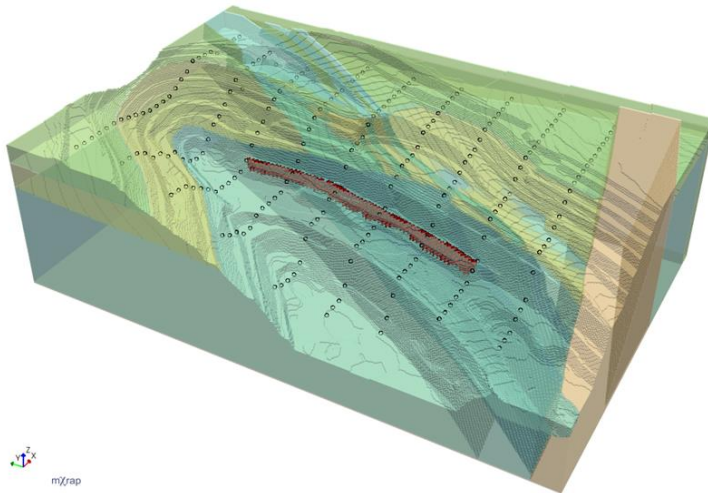
Layered model



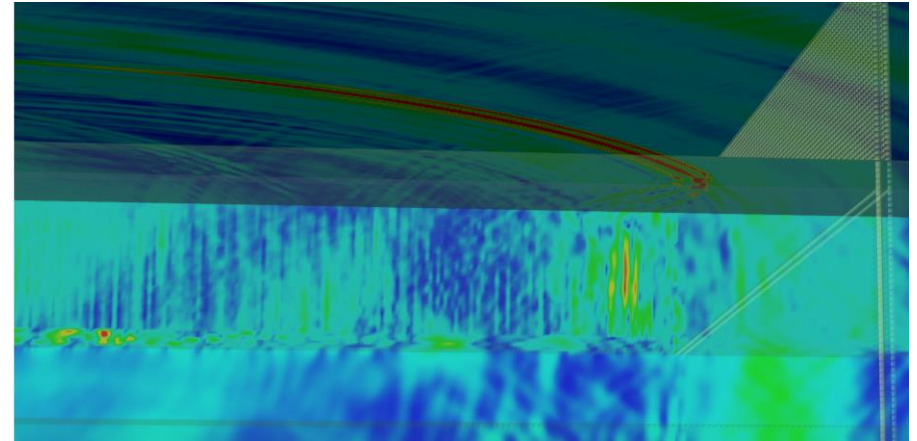
Wide range of studies



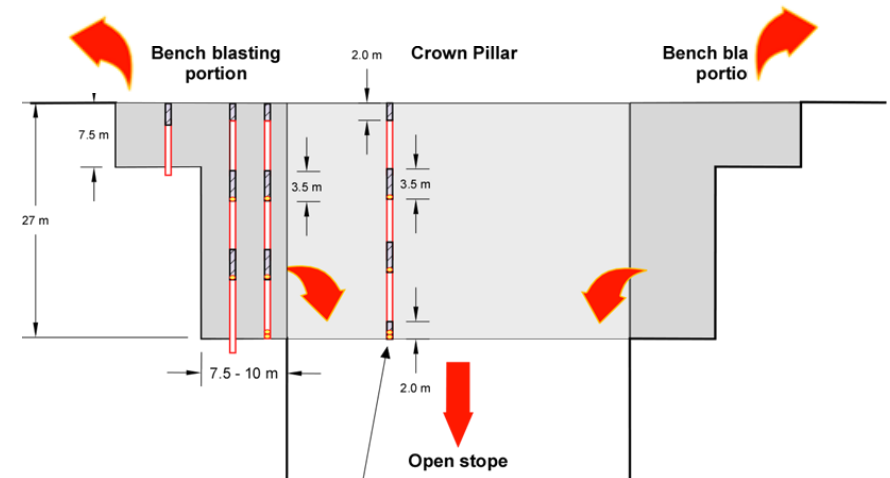
Large number of underground seismic research studies, simulated rockburst experiment



Forensic studies of blast triggered failures in open pits



Design of vibration barriers for blast protection of sensitive structures

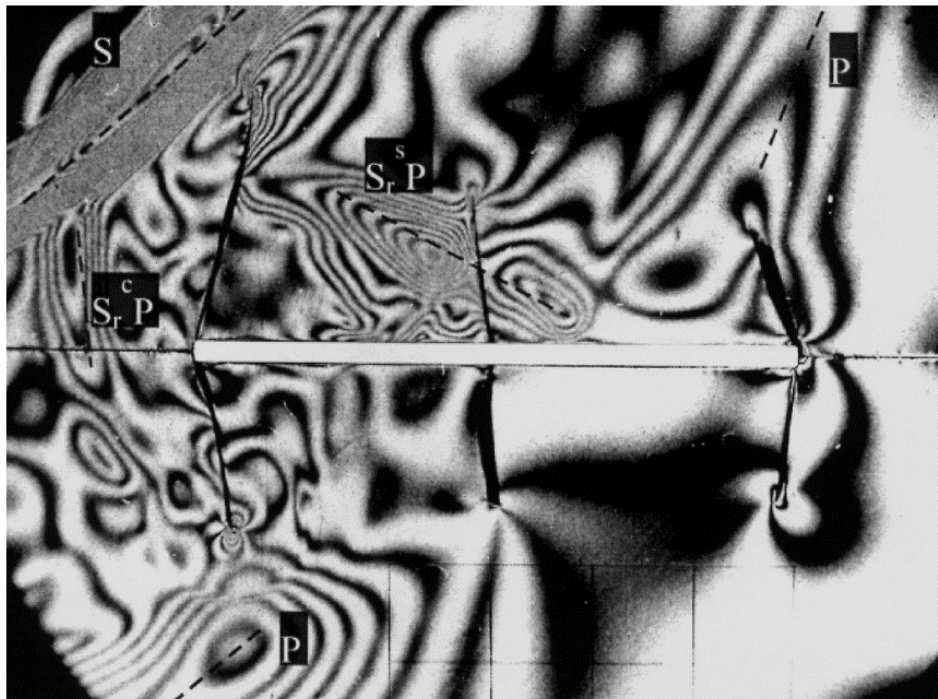


Design and testing of complex blasting patterns

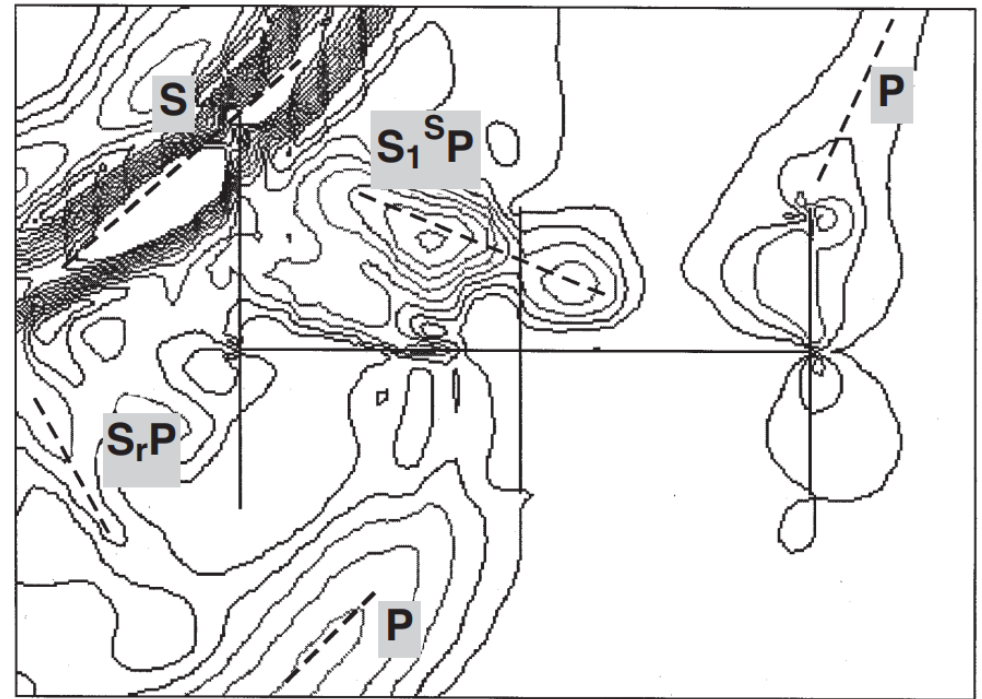
Many other applications: vibrations due to pile-driving, detecting cracks in rails, SCPTu ...

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

```
E:\WAVE\Pisco\pisco.m - Notepad++
File Edit Search View Encoding Language Settings Tools Macro Run Plugins Window ?
run_wvreader.bat run_wv.bat SD_Model.txt sd1_a.m sd1_a.prop mb5_1a.m pisco.m
1 set order = 4
2 set log on
3 grid 800 800 1 1 1 1
4 ** Note: 2-D mode is set: 1-2 plane is active
5
6 ** explosion source **
7 source n=1 typ=dil amp=1.0e6 wave=cos per=4e-3 beg=0 end=500 i=43 j=80 k=51
8
9 ** mat 1: properties for rock fill**
10 ** mat 2: properties for tailings iv b**
11 ** mat 3: properties for tailings iv a**
12 ** mat 4: properties for tailings ii**
13 ** mat 5: properties for tailings IA**
14 ** mat 6: properties for tailings iii**
15 ** mat 7: properties for compacted tailings**
16 ** mat 8: properties for dry tailings**
17 ** mat 9: properties for reinforced wall**
18 ** mat 10: properties for gabion wall**
19 ** mat 11: properties of modelling domain**
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21 prop mat=1 d=2304 shear=5.76e5 bulk=1.25e6
22 prop mat=2 d=1733 shear=9.98e4 bulk=2.99e5
23 prop mat=3 d=1631 shear=9.39e4 bulk=2.82e5
24 prop mat=4 d=1631 shear=6.52e4 bulk=1.96e5
25 prop mat=5 d=1631 shear=3.67e4 bulk=1.10e5
26 prop mat=6 d=1631 shear=3.67e4 bulk=1.10e5
27 prop mat=7 d=1733 shear=1.08e5 bulk=2.35e5
28 prop mat=8 d=1682 shear=6.37e4 bulk=2.02e5
29 prop mat=9 d=1733 shear=1.08e5 bulk=2.35e5
30 prop mat=10 d=2243 shear=5.61e5 bulk=1.21e6
31 prop mat=11 d=2800 cp=6857 cs=4226
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mXrap



- 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

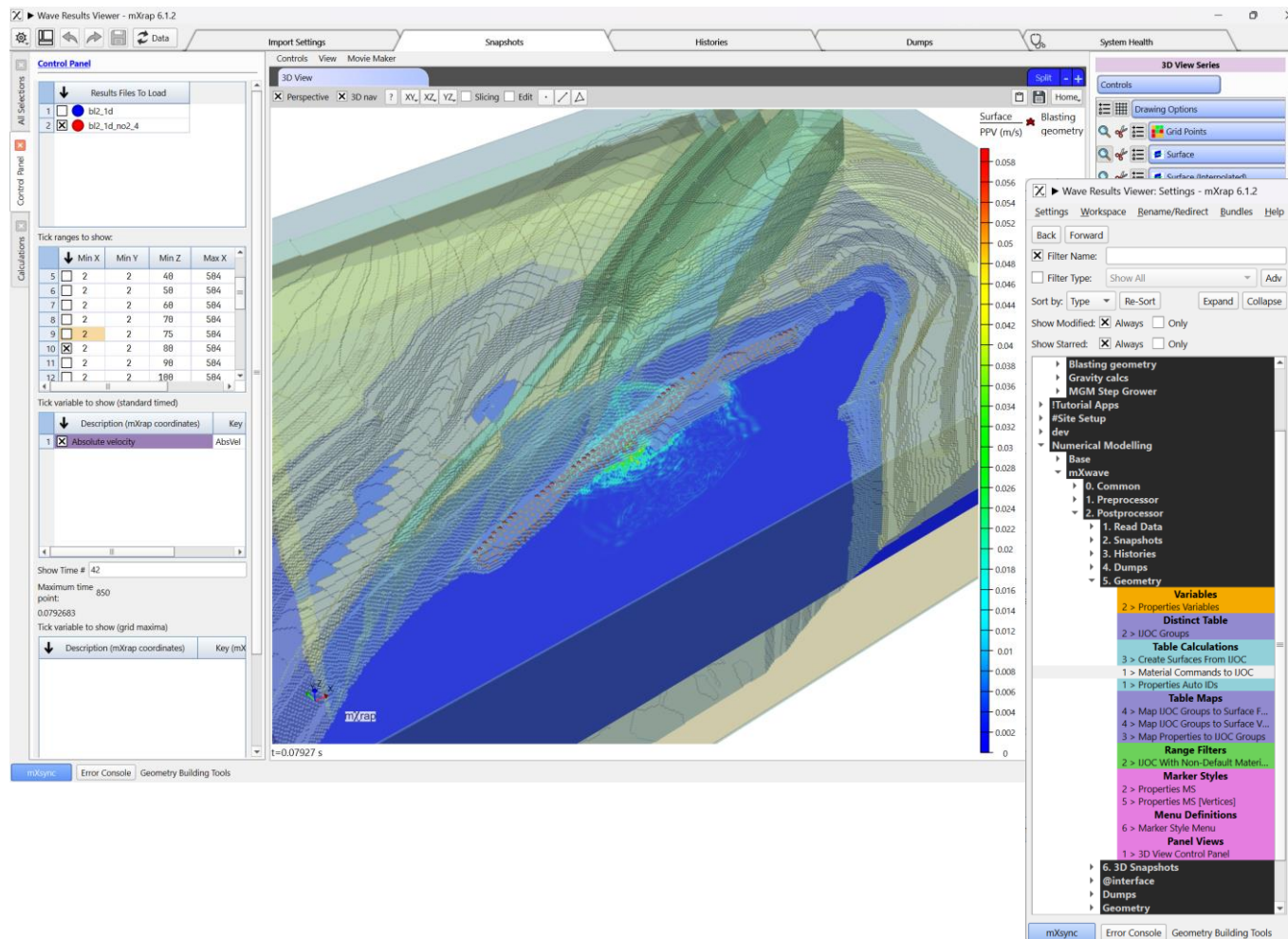


mXrap

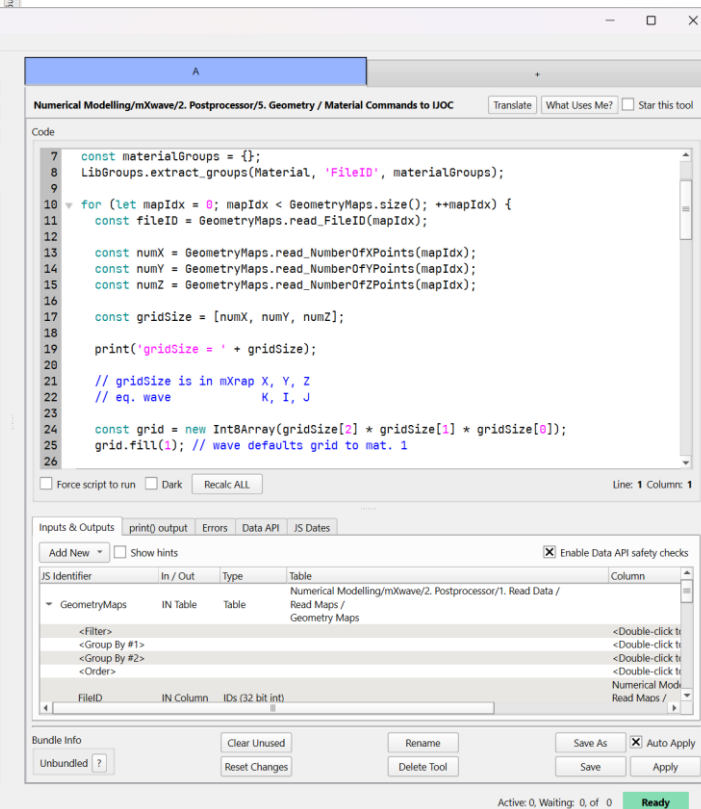
Wave3D model builder

mXrap

Build complex 3D models from DXF files



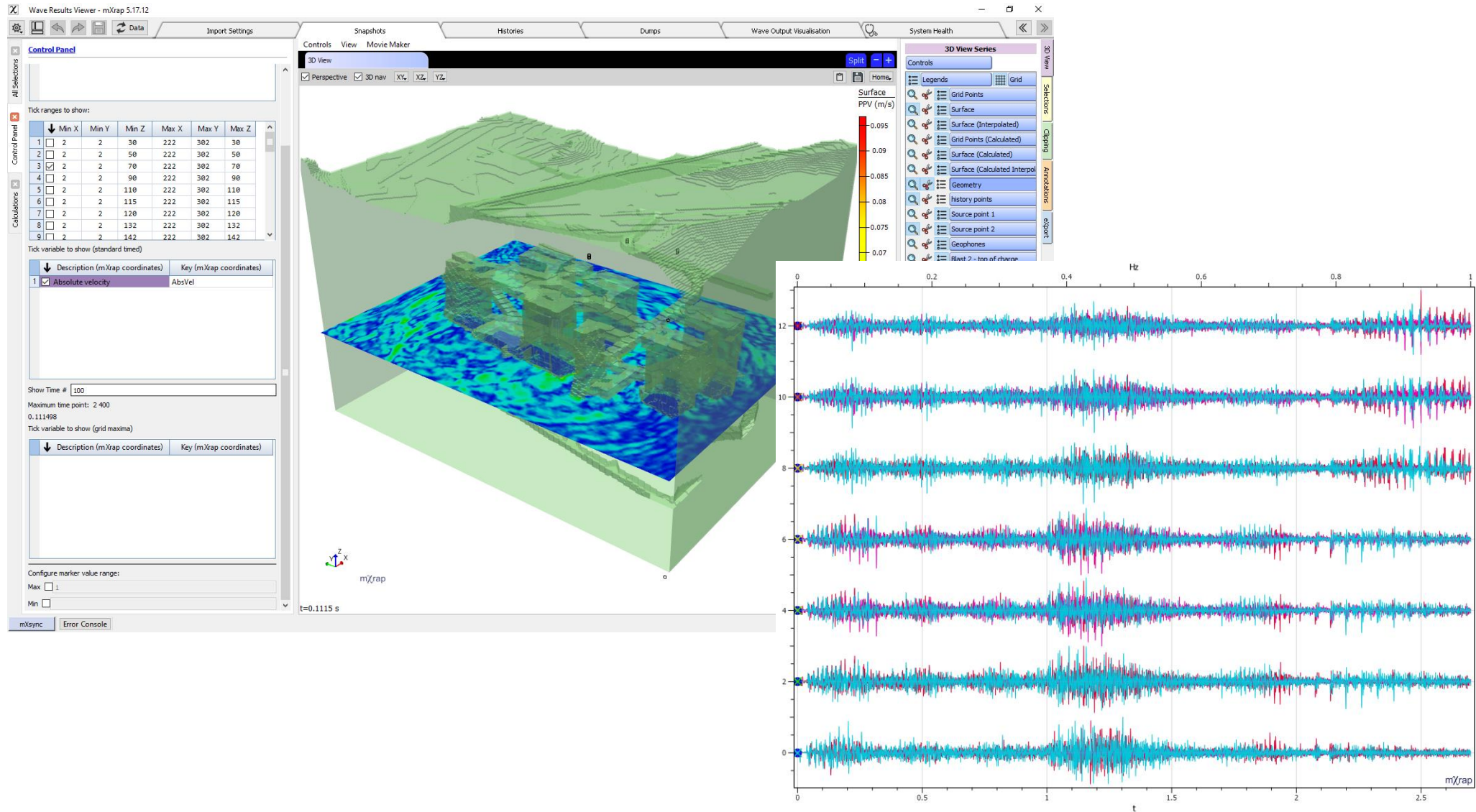
JS scripting to build custom apps



mXrap

Wave3D post-processor

mXrap



SCPTu tests

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

- Small strain Shear Modulus

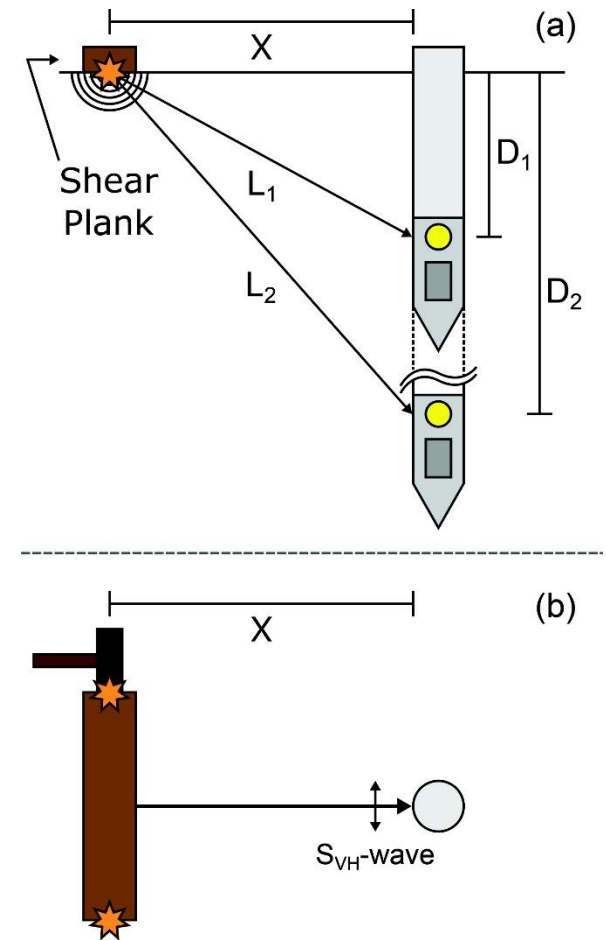
$$G_0 = \rho V_s^2$$

- Poisson's ratio

$$\nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

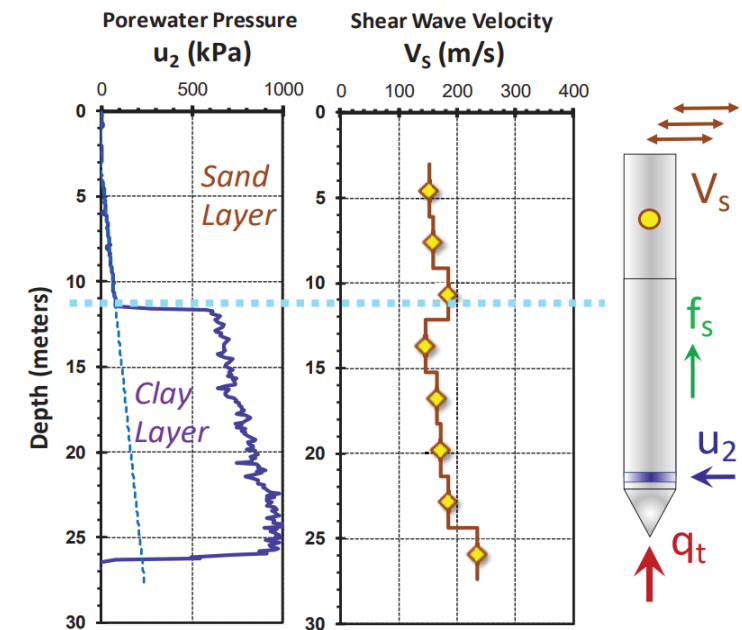
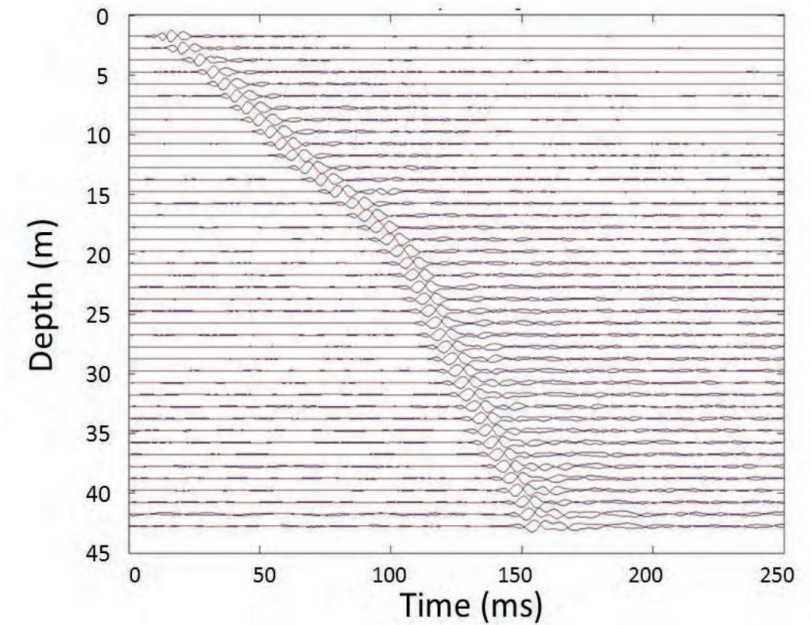
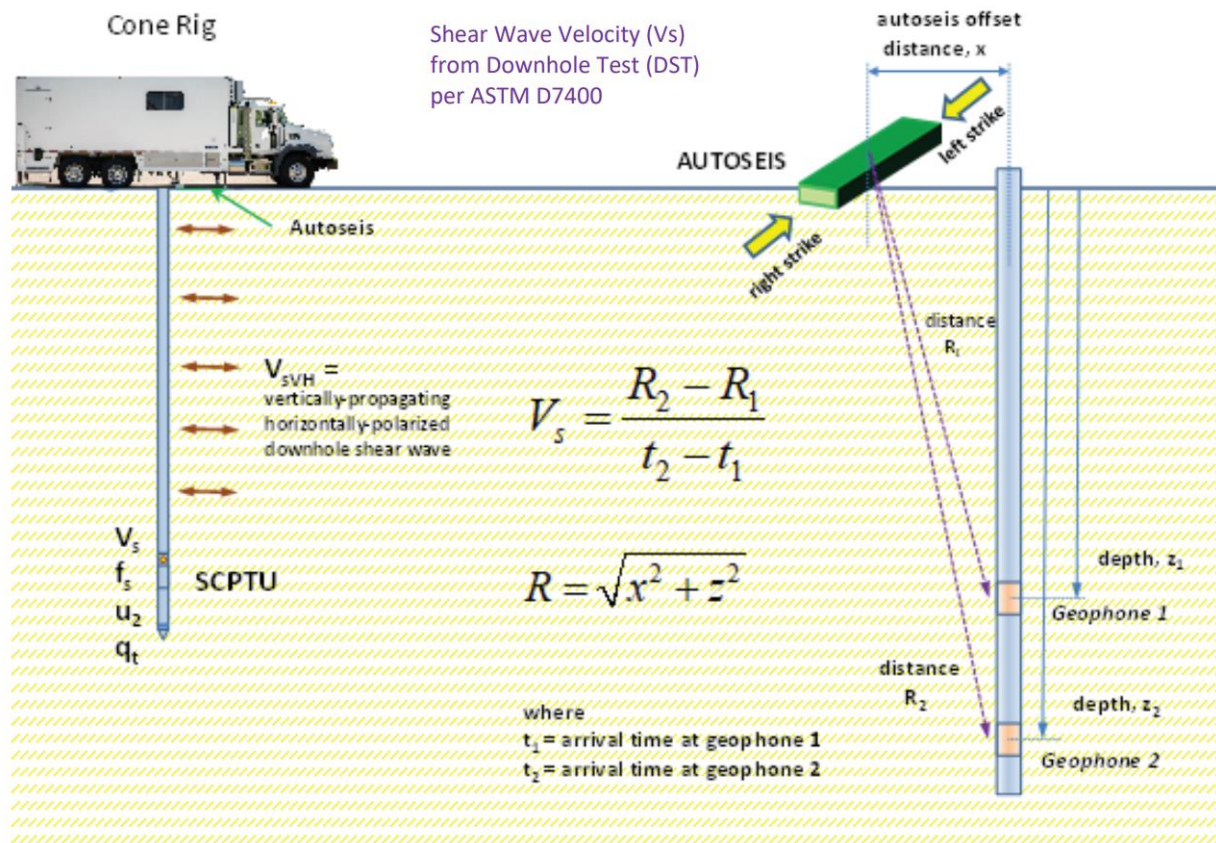
- Small strain Young's Modulus

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



<https://cdnsiencepub.com/doi/10.1139/cgj-2018-0689>

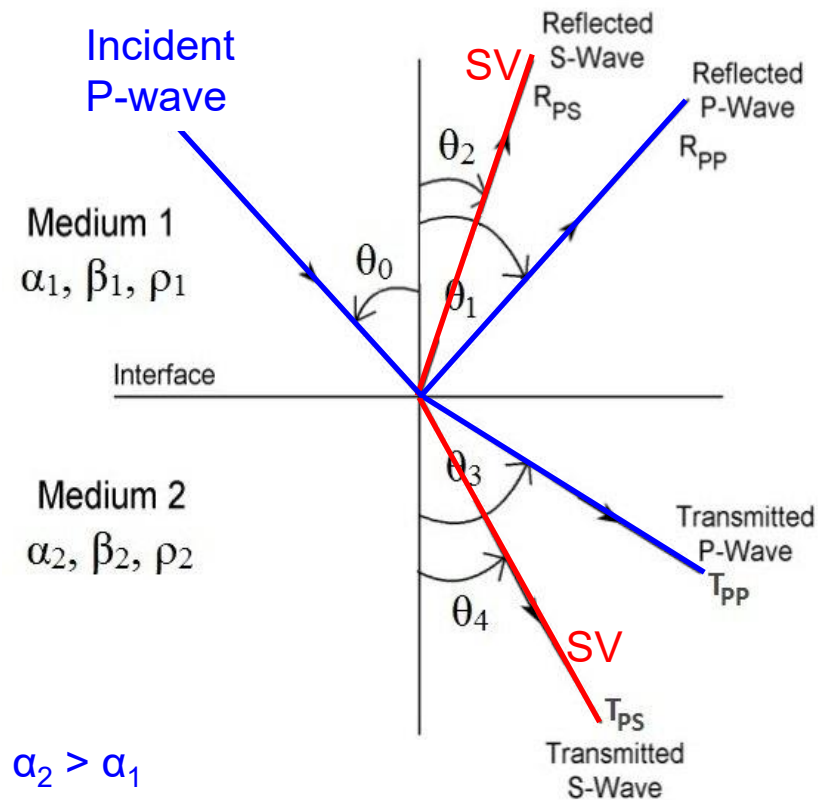
SCPTu field setup



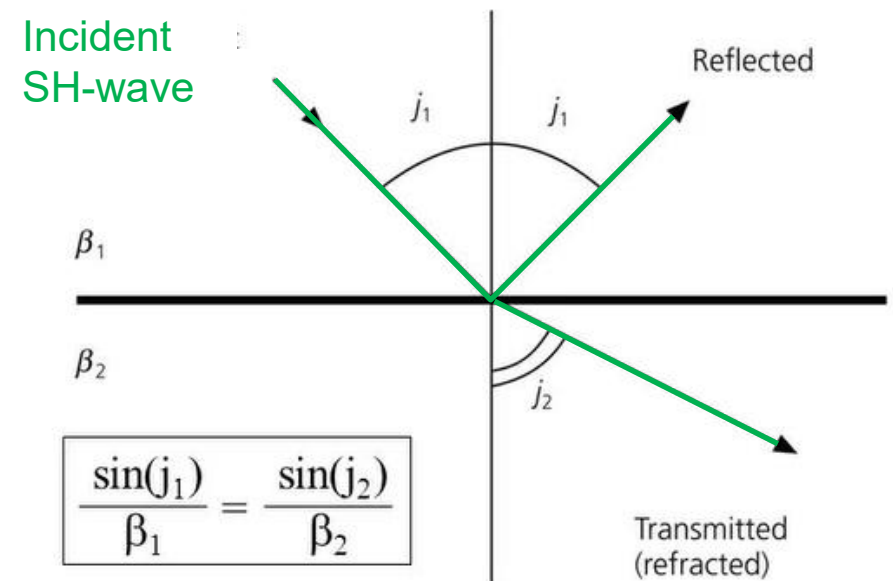
ConeTec CPT Design Parameter Manual-2023 First Edition-2023-04-24_rev1.1_print ready_EN.pdf

Reason for SH source

Fewer phase conversions at interfaces



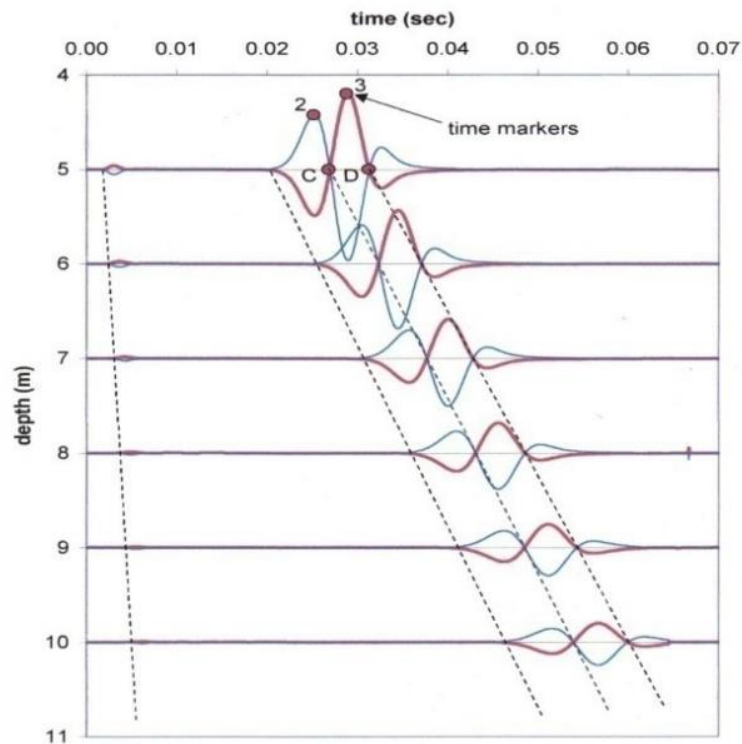
Apply Snell's law to determine the refraction angles at layer interfaces and to reproduce the refracted paths



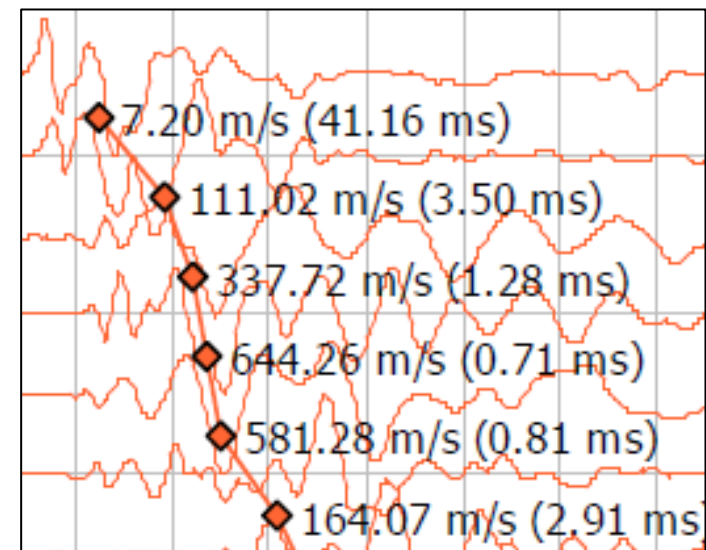
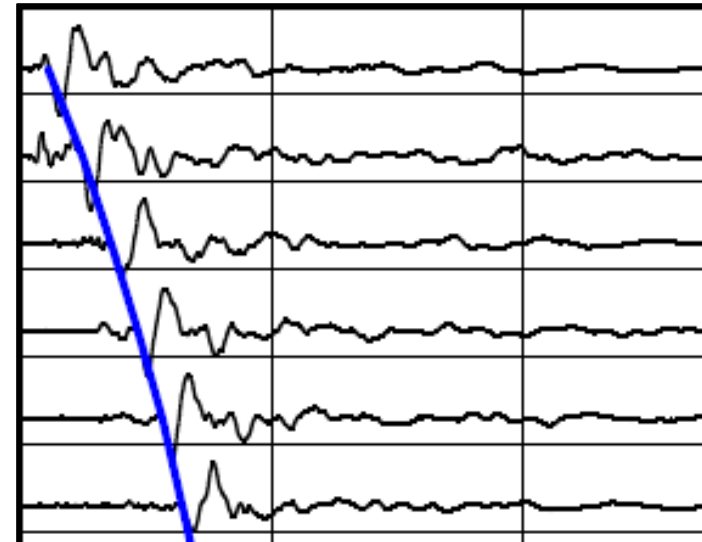
SCPTu data processing

S-wave arrival time picking

Ideal seismograms



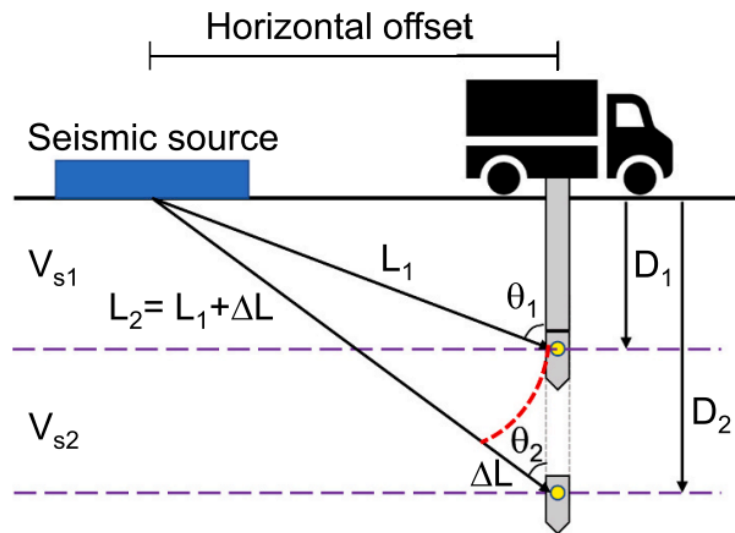
Actual seismograms



SCPTu data processing

Velocity determination

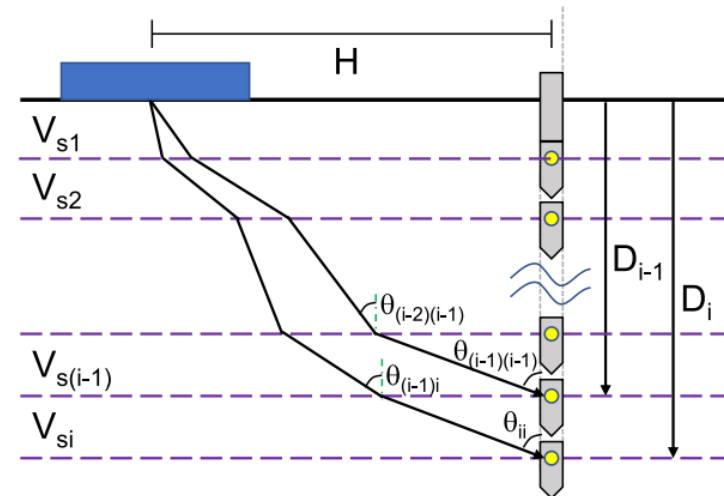
Slope and interval method



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

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

Refracted ray path method



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

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

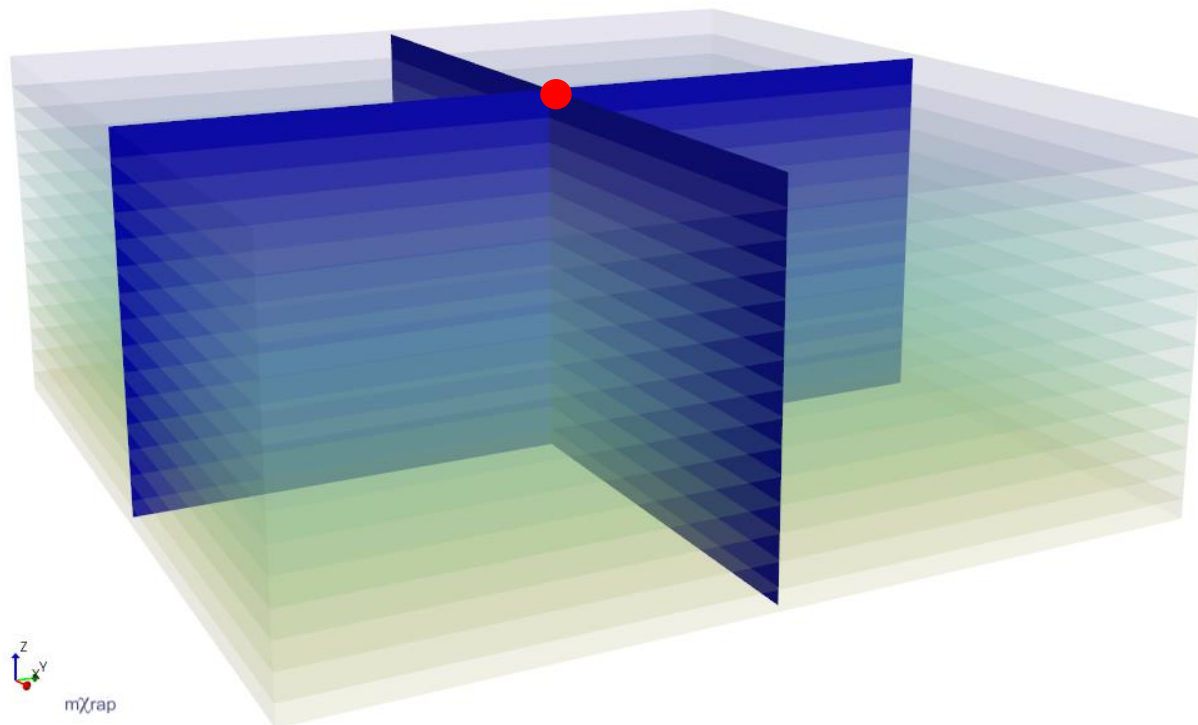
$$t_i = \frac{D_1 / \cos \theta_{1i}}{V_{s1}} + \frac{(D_2 - D_1) / \cos \theta_{2i}}{V_{s2}} + \dots + \frac{(D_i - D_{i-1}) / \cos \theta_{ii}}{V_{si}}$$

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

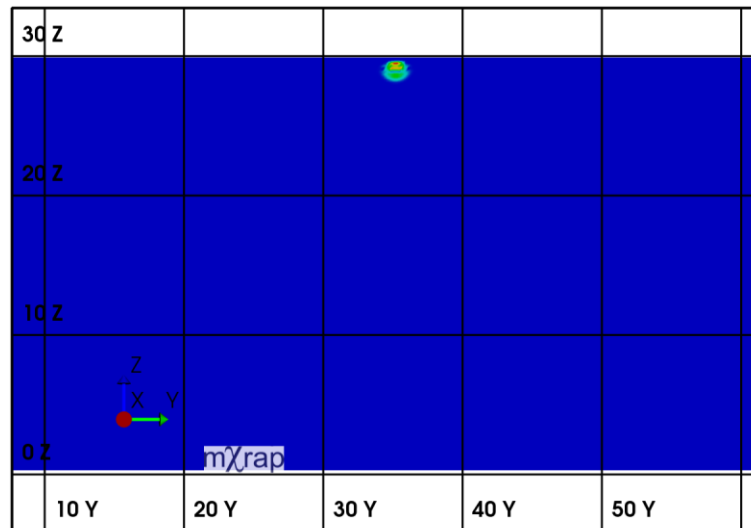
- Compare a vertical hammer blow source to an SH source
- Model with/out layering



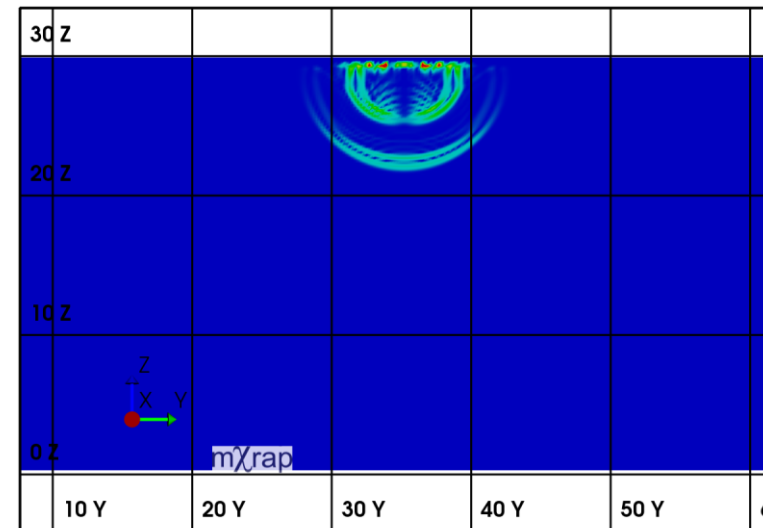
** property commands

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prop mat=2 d=1700 cp=281 cs=162
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prop mat=6 d=1700 cp=454 cs=262
prop mat=7 d=1700 cp=416 cs=240
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
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prop mat=17 d=1700 cp=386 cs=223
prop mat=18 d=1700 cp=412 cs=238
prop mat=19 d=1700 cp=430 cs=248
prop mat=20 d=1700 cp=527 cs=304
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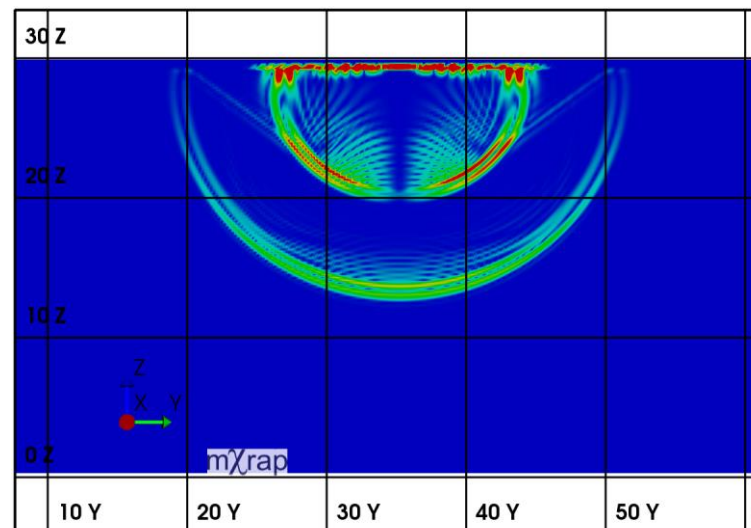

Vertical hammer blow (normal stress S22)



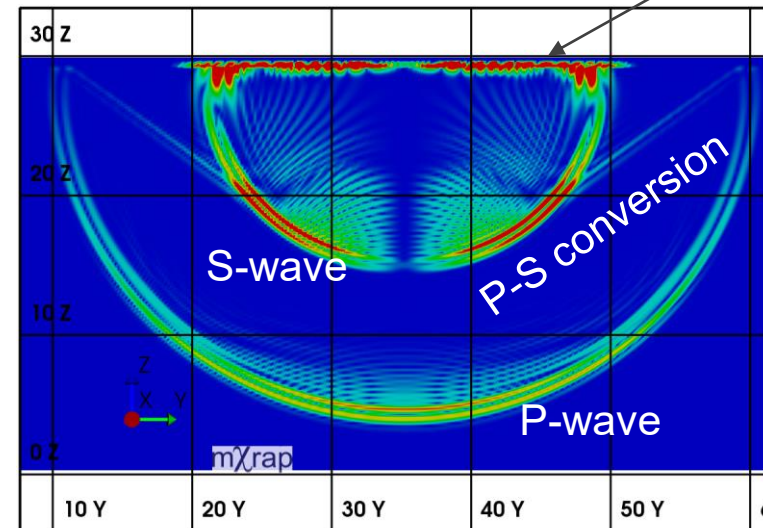
t=0.00441 s



t=0.01704 s



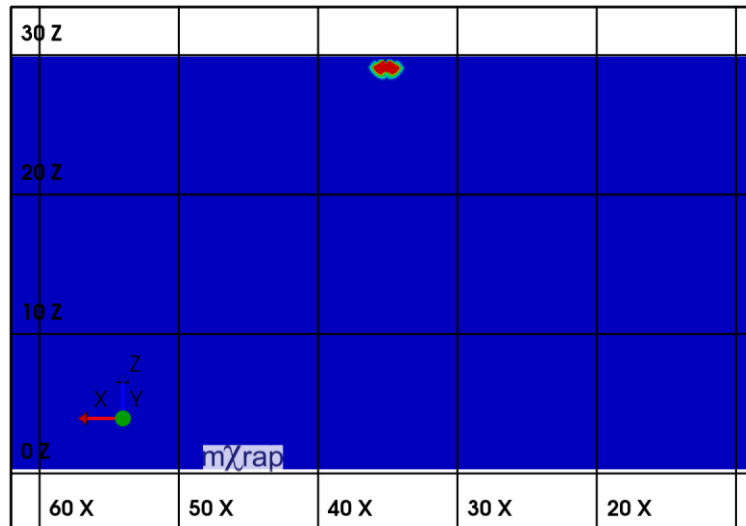
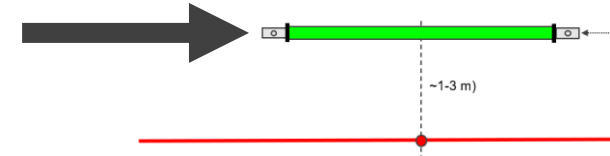
t=0.03507 s



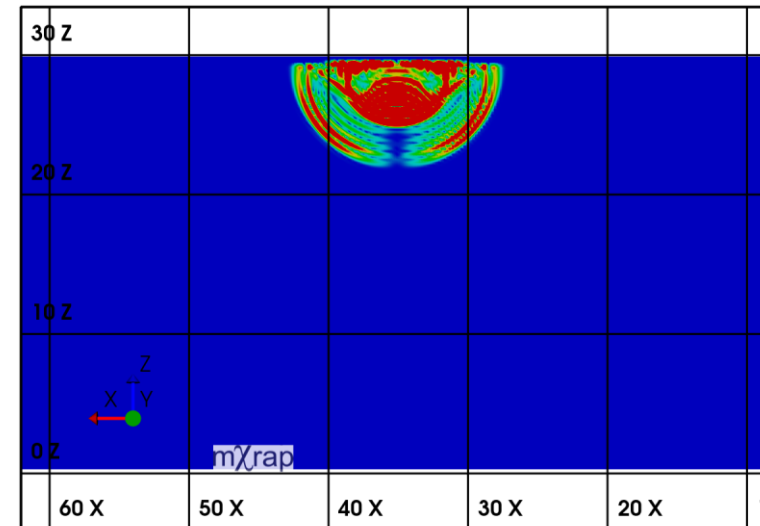
t=0.05311 s

SH hammer blow (shear stress S23)

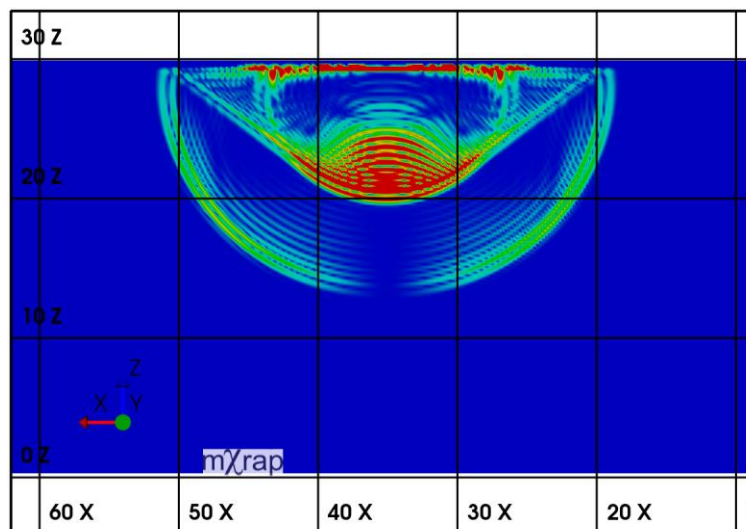
Axis parallel to long axis of source



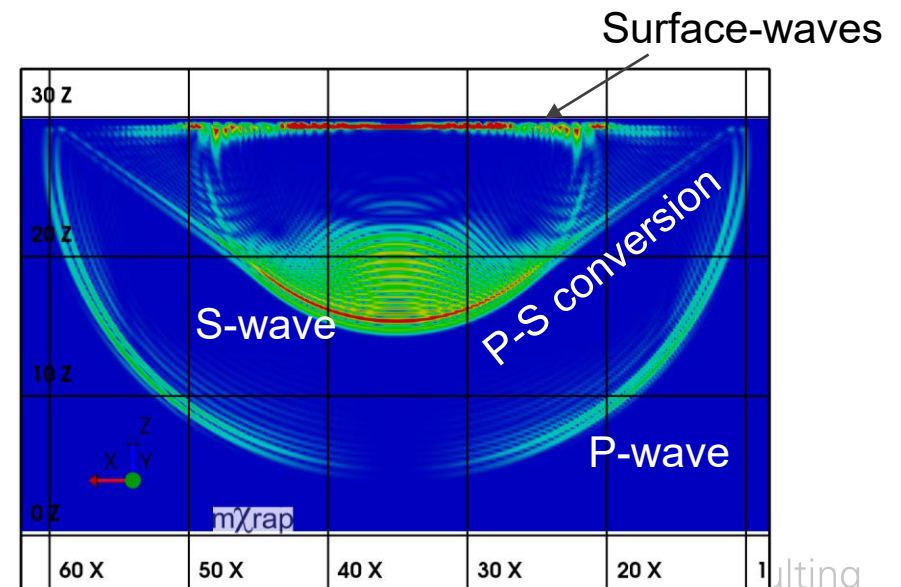
t=0.00441 s



t=0.01704 s



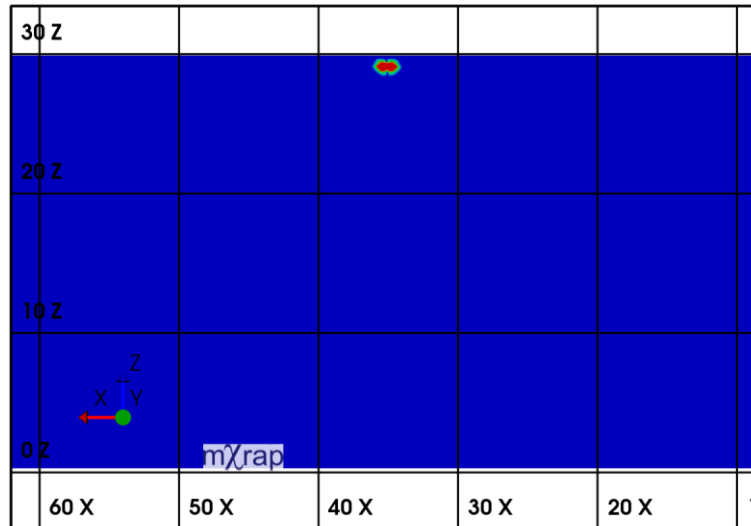
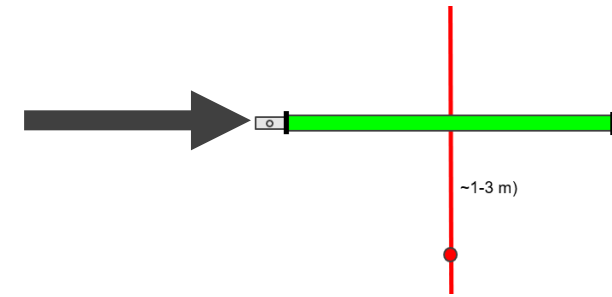
t=0.03507 s



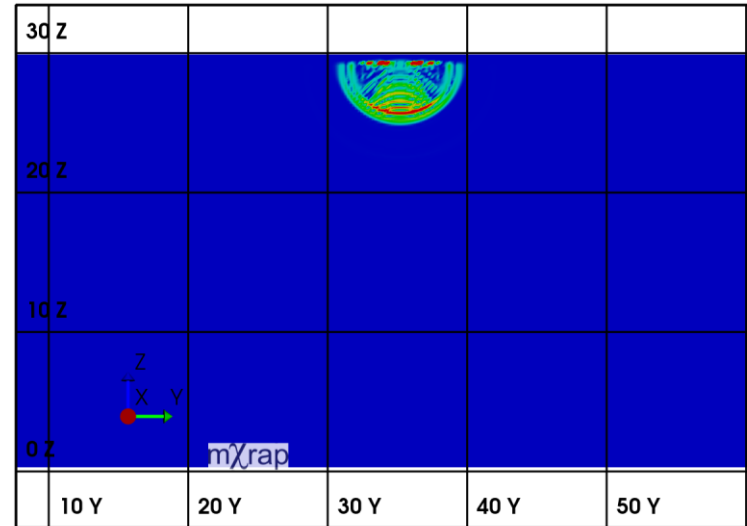
t=0.05311 s

SH hammer blow (shear stress S23)

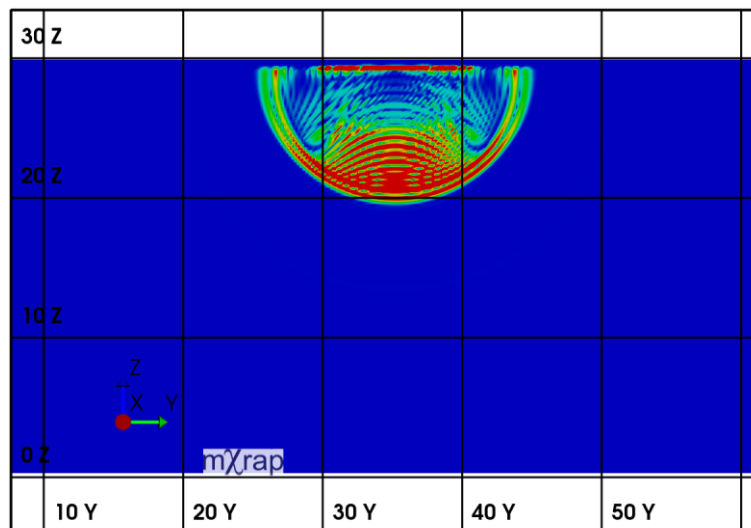
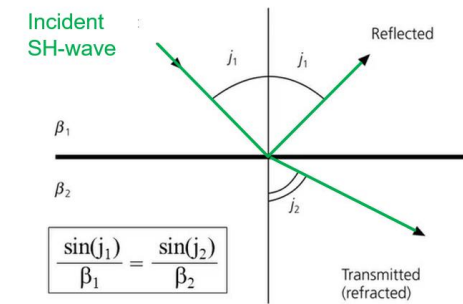
Axis orthogonal to long axis of source, no layering



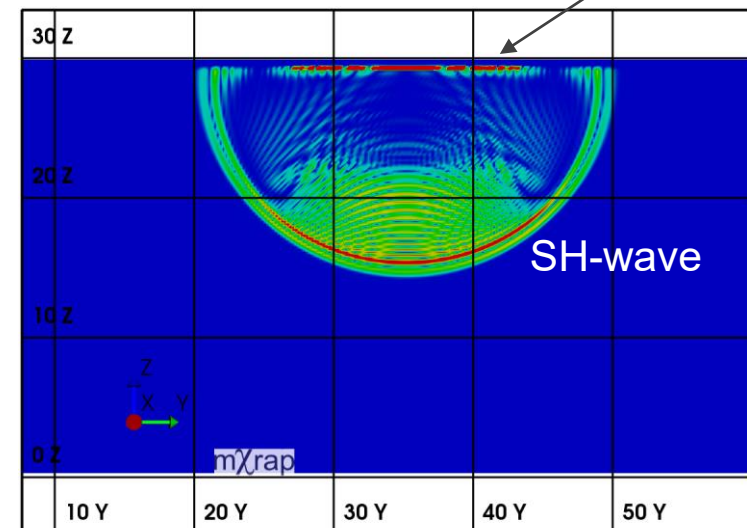
t=0.00392 s



t=0.01704 s



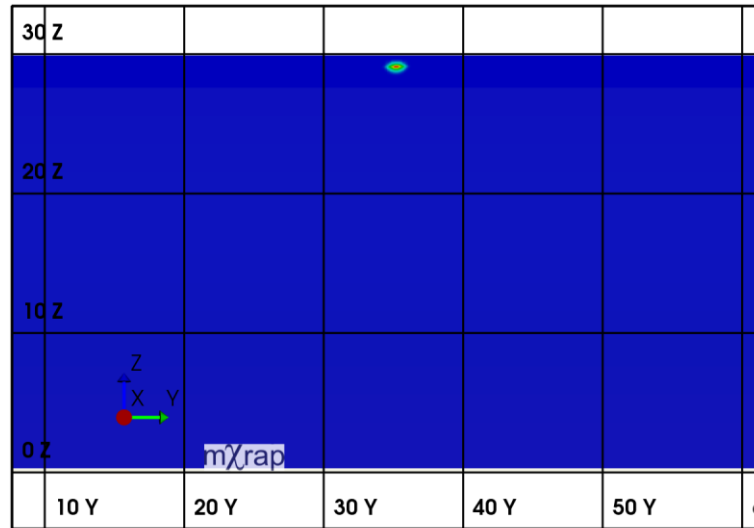
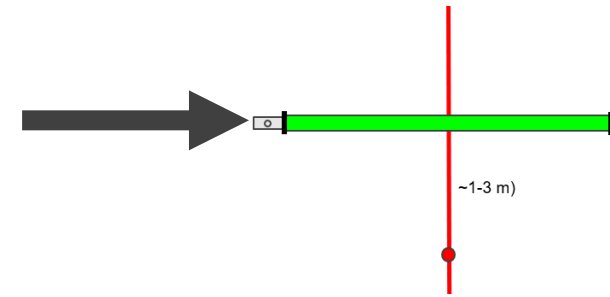
t=0.03507 s



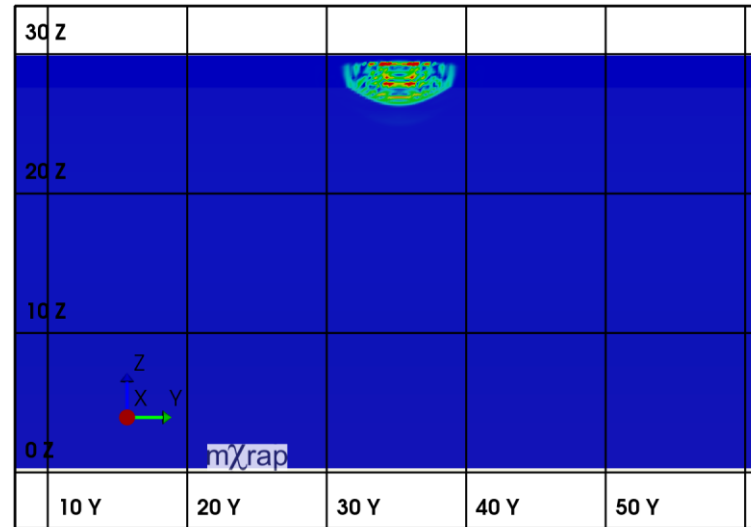
t=0.05311 s

SH hammer blow (shear stress S23)

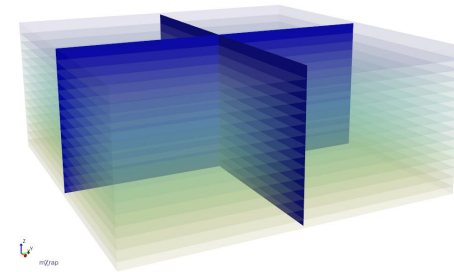
Axis orthogonal to long axis of source + layering



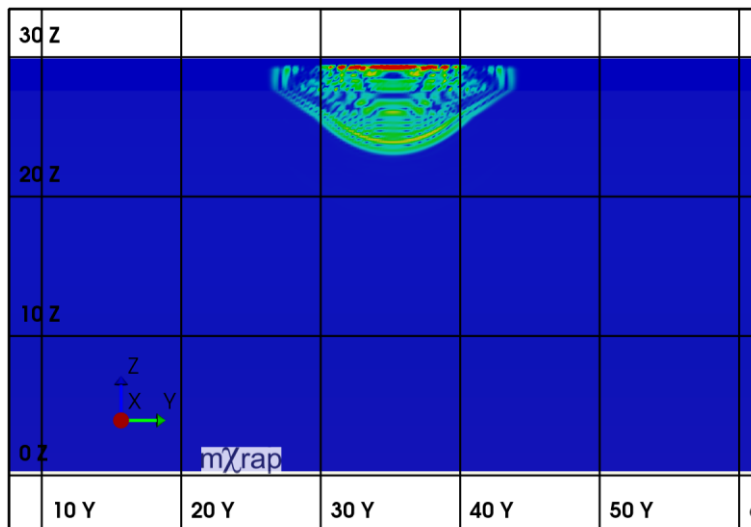
t=0.00392 s



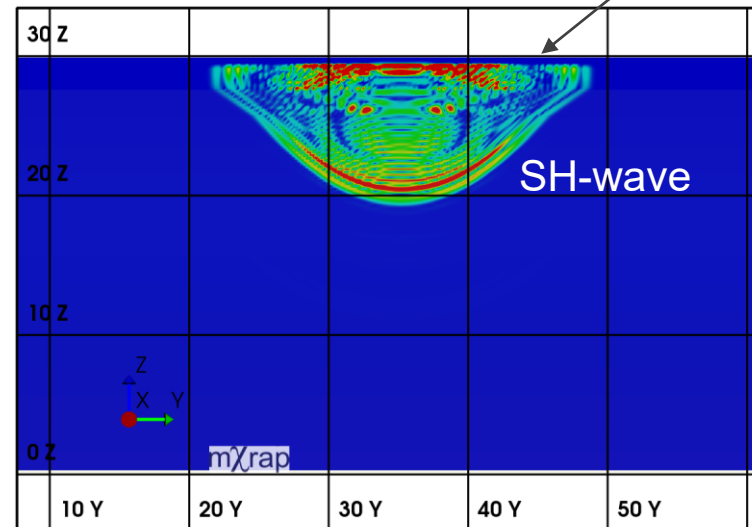
t=0.01539 s



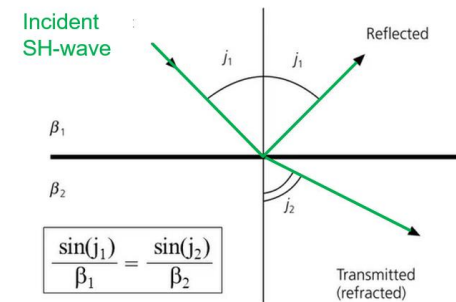
Surface-waves



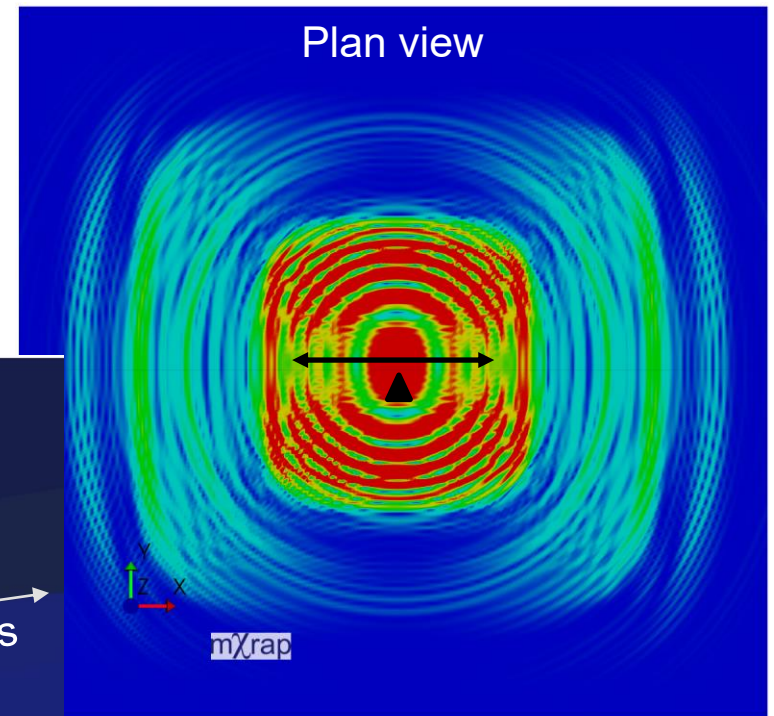
t=0.03179 s



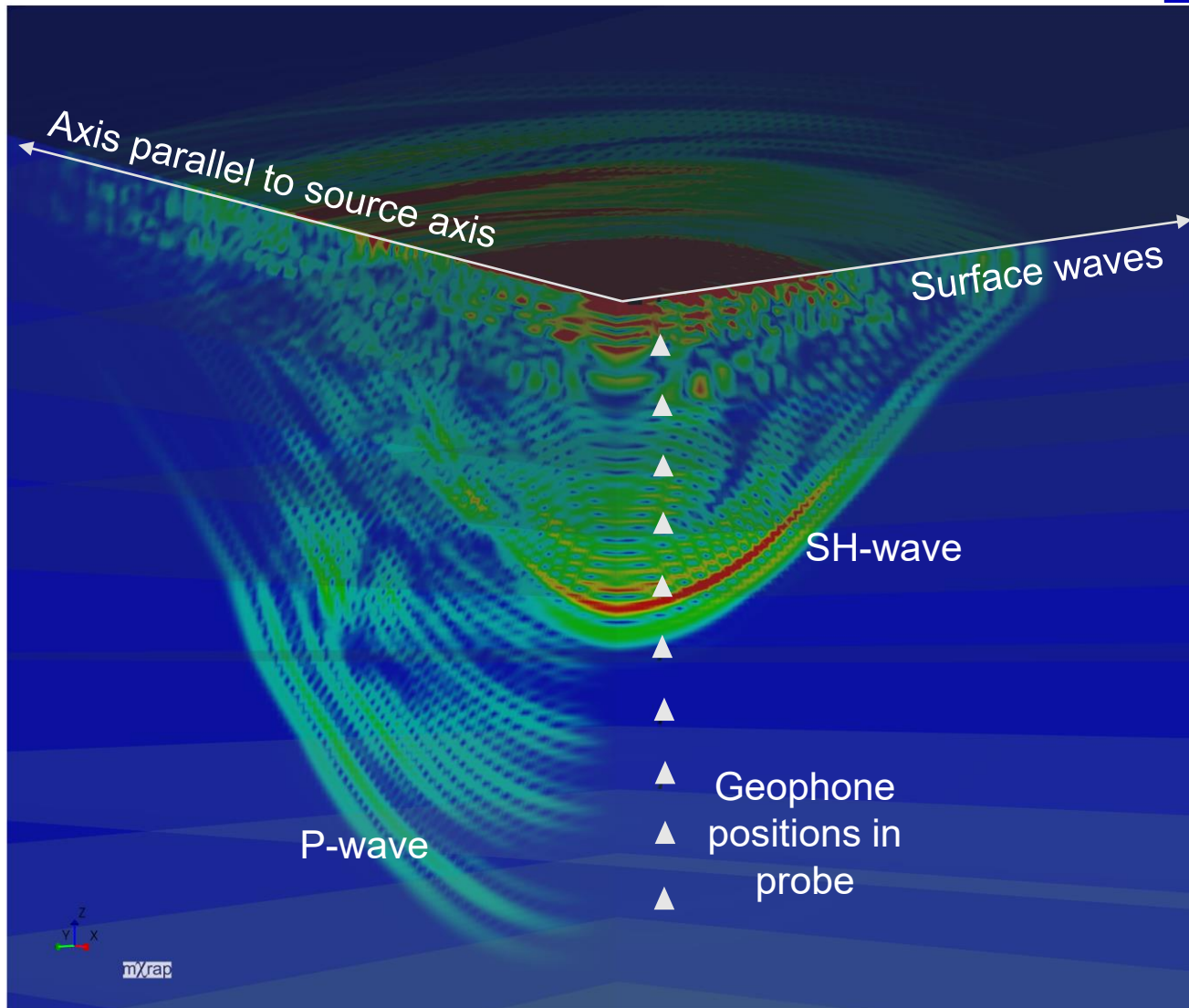
t=0.04818 s



SH hammer blow source + layering

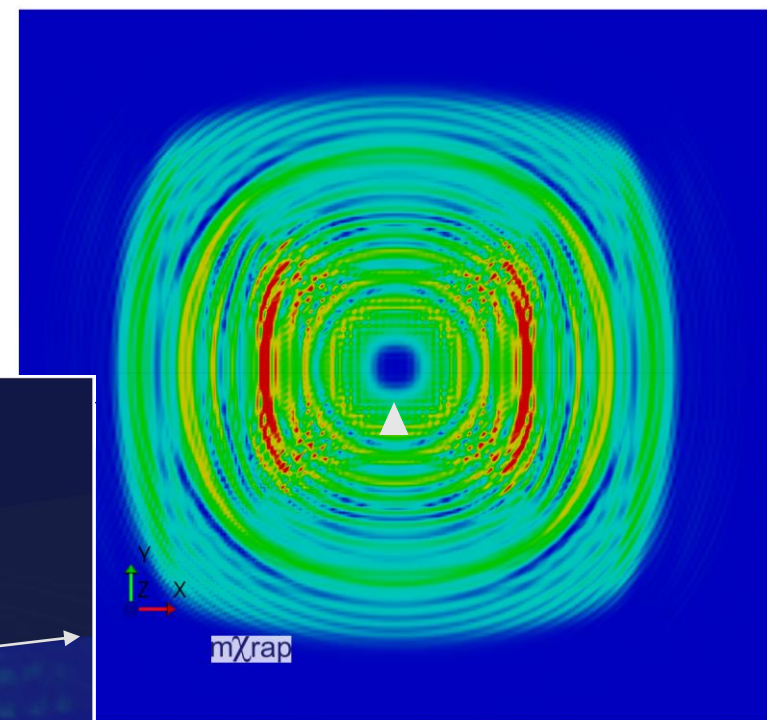
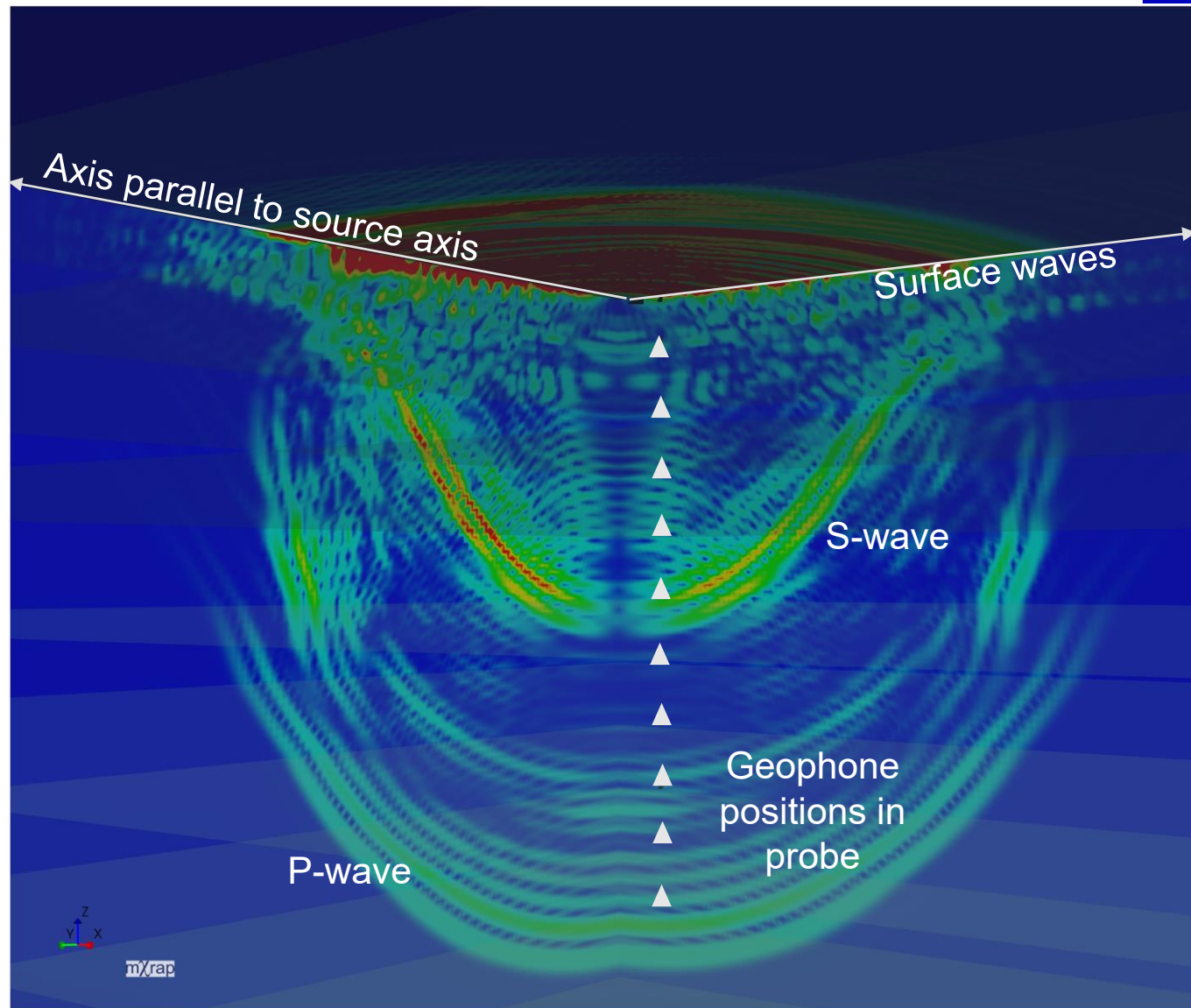


0.0531 s



t=0.0531 s

Vertical hammer blow + layering



31 s

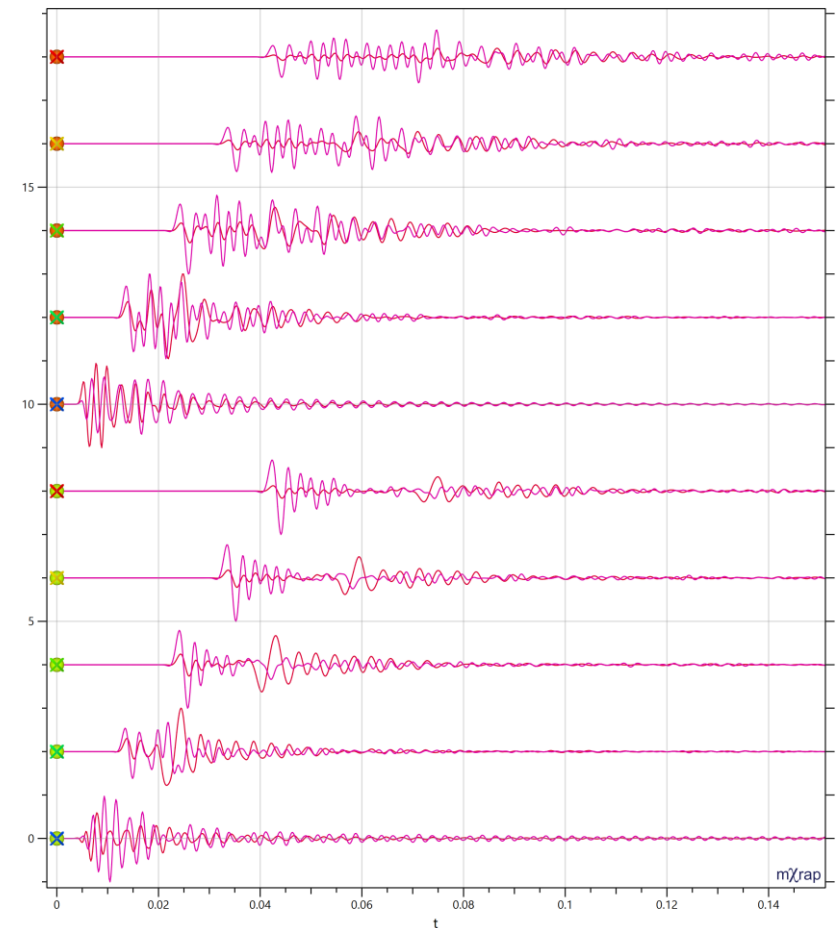
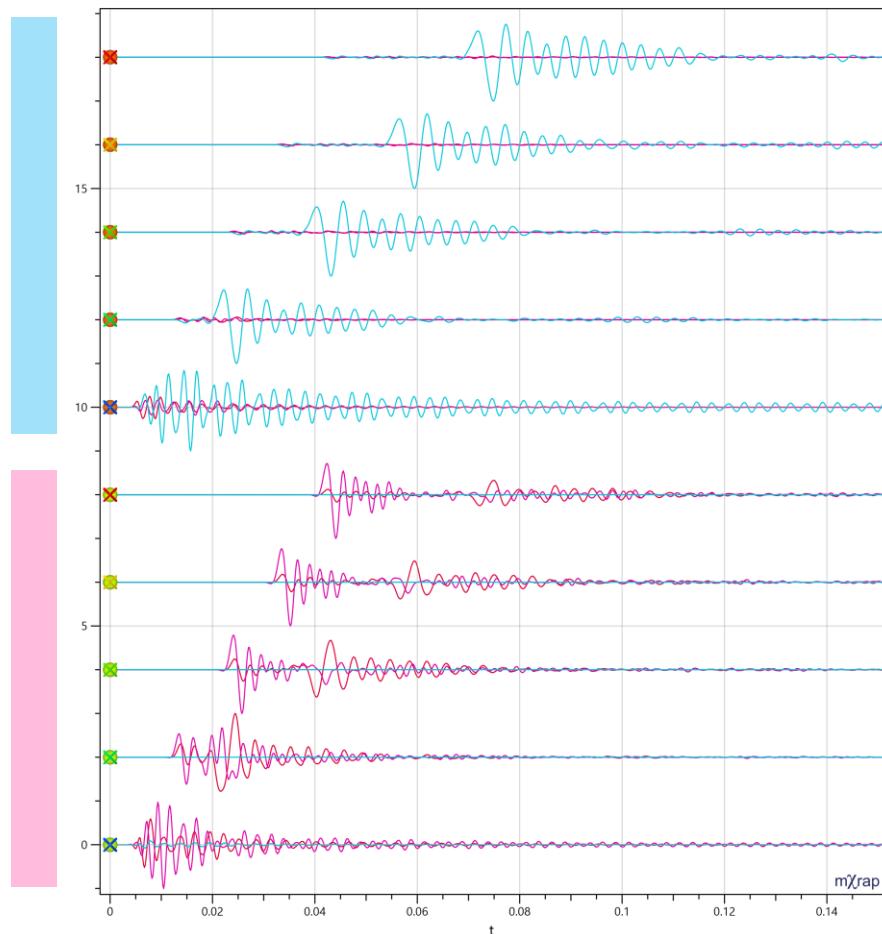
Seismograms for SH and vertical hammer blow

All components

Minus x-component

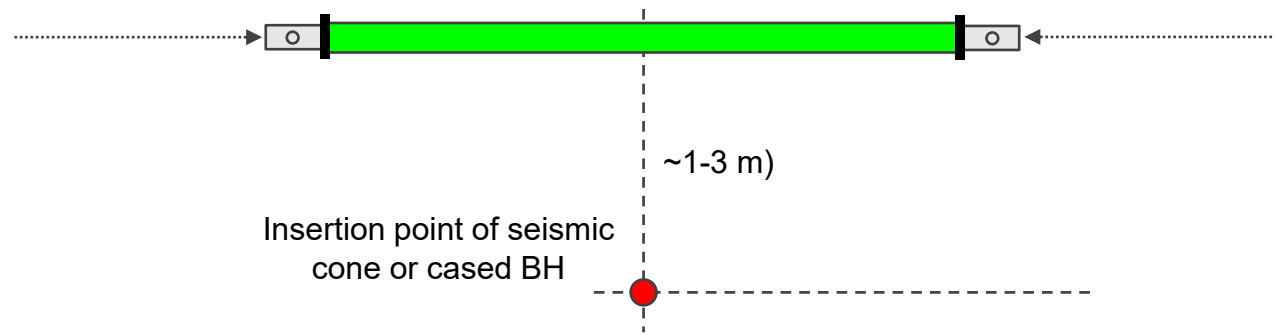
SH source

Vertical source



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

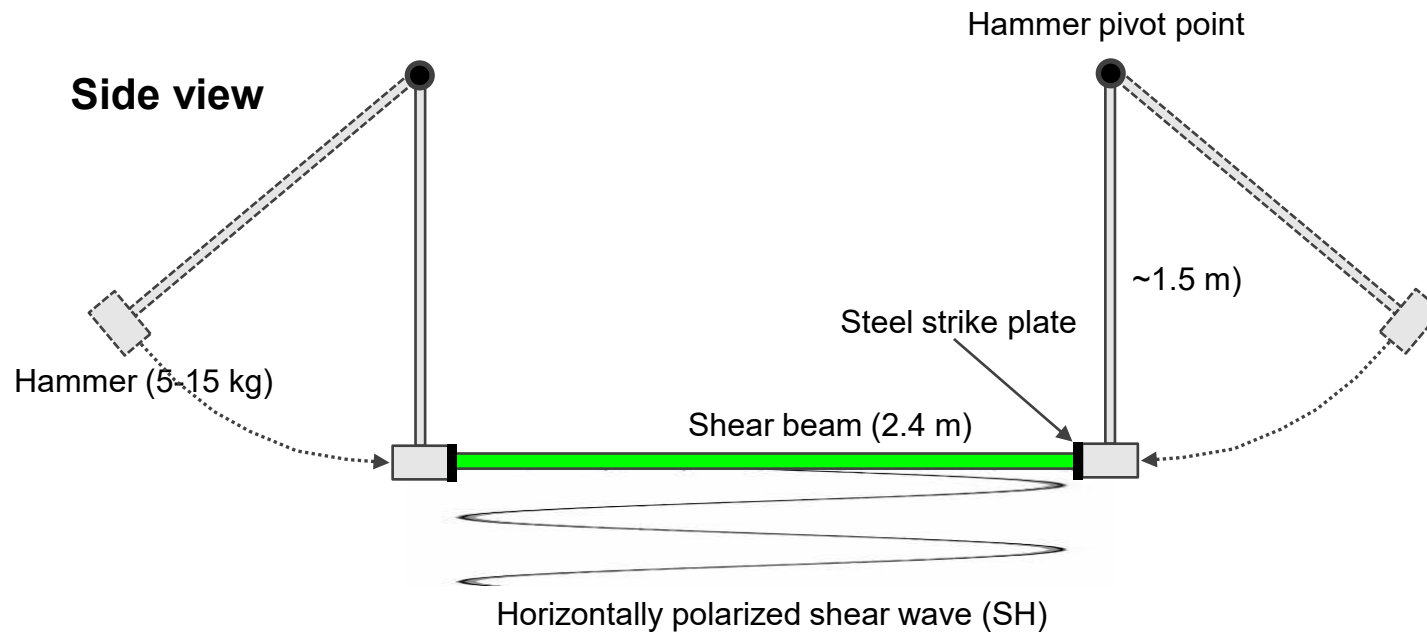
Summary



- 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



Plan view

