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Seismic monitoring network evaluation using an interferometry derived velocity model

Monitoring network performance including low velocity near-surface sediments in Holland using interferometry

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Introduction

Induced seismicity

- Known to be a problem in1970s(Raleigh et al, 1976 – Colorado Rangely experiment)
- Deep geothermal is limited by induced seismicity:
  - Basel, Switzerland, 2006 – Haring et al, 2008
  - Pohang, Korea, 2017 – Kim at al, 2018
- Deep geothermal is limited by induced seismicity
- Usual solution – traffic light systems

Hazard Mitigation – traffic light system

Seismik

Monitoring during injection

↓

Detection of seismic events

Magnitude < T1	T1 < Magnitude < T2	T2 < Magnitude
CONTINUE as planned	• REDUCE VOLUME OF INJECTION • If seismicity does not subside, reduce volume further	• STOP INJECTION • Bleed off the well • Monitor for several more (10) days

We must:

Monitor and in near-real-time and:

- Detect
- Locate
- Determine magnitude

Hazard Mitigation – traffic light system

- Usually done economically - sparse networks < 10 receivers

- Detection:
  - STA/LTA – usual threshold for surface stations ~ Mw 1.0, maybe lower

- Location:
  - Requires both P-wave and S-wave model to correctly locate the depth (horizontal position is generally more stable)
  - Only P-wave velocities are usually known or sonic logs from deeper parts

- Magnitude:
  - To determine Magnitude we need location and velocity model (S-wave)

Velocity model building

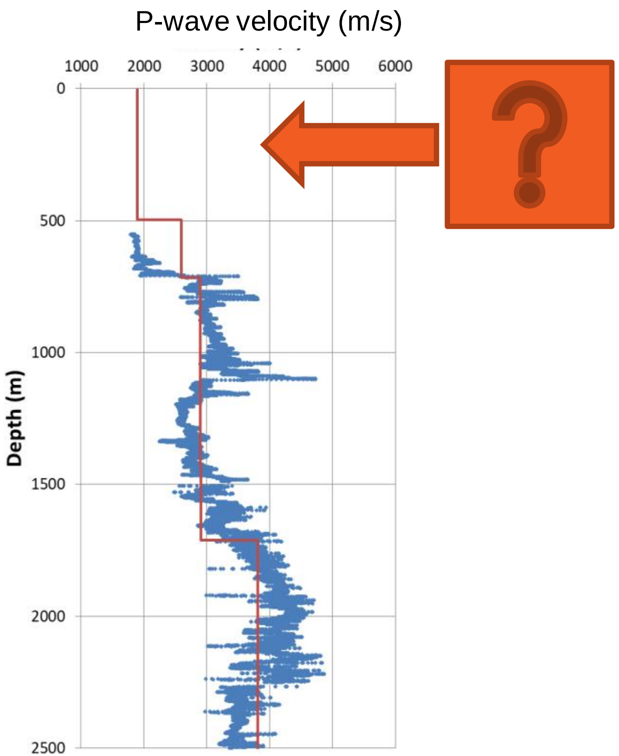
P-waves:

- Interval velocity from 3D seismic
  - Rolls-Royce – oil and gas, rare in geothermals
- VSP (3D), check shots
  - Can determine anisotropy Very good 10-100 Hz
- Sonic logs:
  - Not good – locking near surface info and frequencies 2-20 KHz

S-waves:

- Sonic logs:
  - Not good – lacking near surface info and info in 10-100 Hz

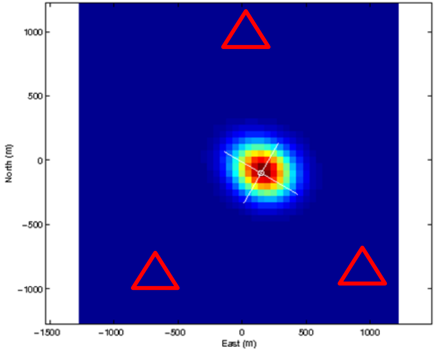
Example of sonic logs

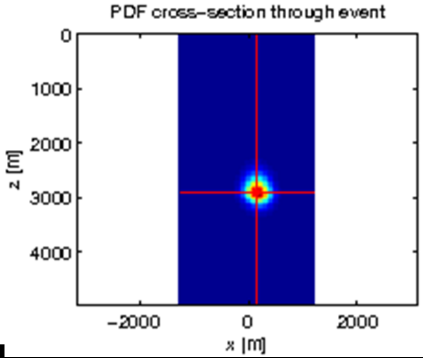


Effect of S-wave model on location

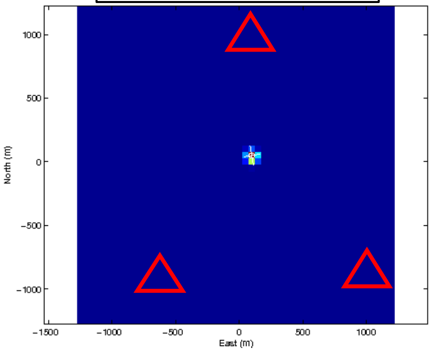
Event locations for different 1D-profiles of S-wave velocities in a sparse network

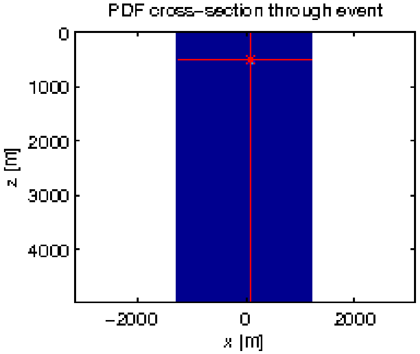
True VS model – red



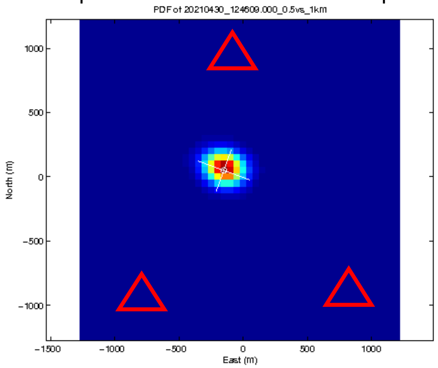


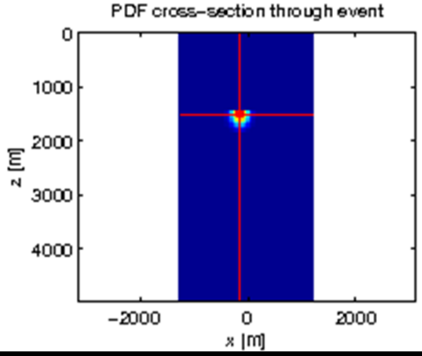
VS model – violet



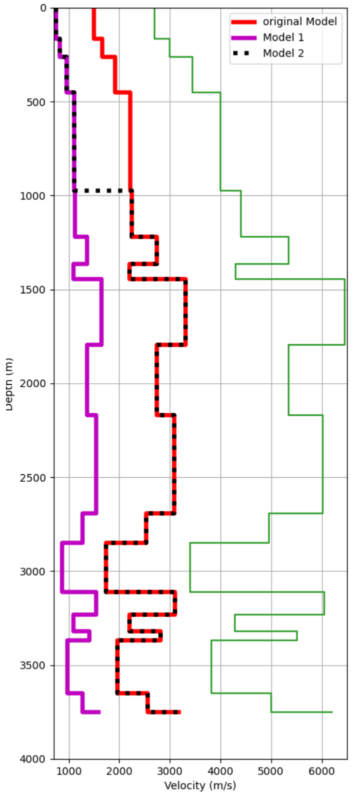


VS model – dashed

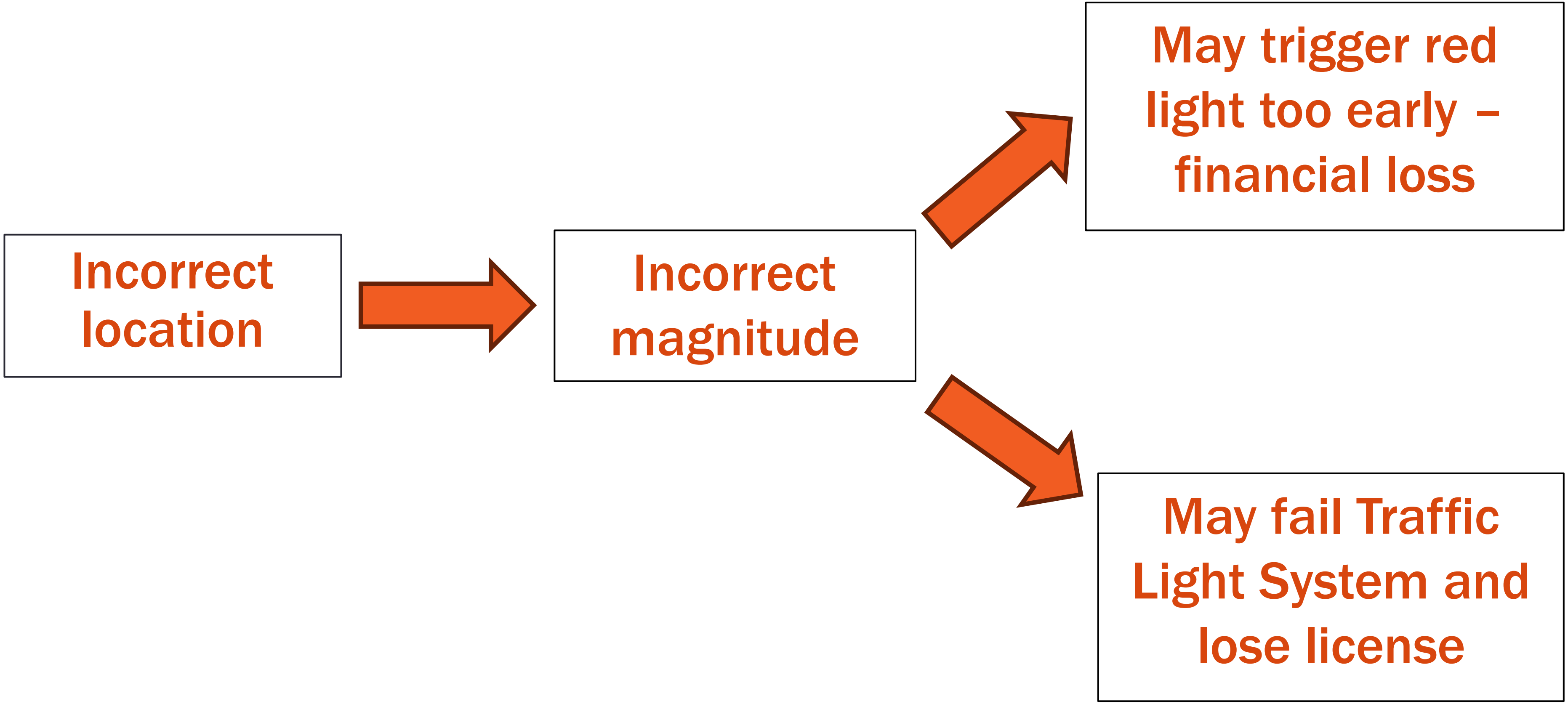




3 Vs velocity 1D, 1 Vp



Effect of S-wave model on location



Solution - methodology

- **Ambient surface noise interferometry**
  - Surface waves between sparse stations
  - Determination of the surface wave dispersion (group velocities)

- **Determine surface wave dispersion**
  - Invert dispersion to obtain 1D velocity profile of S-waves,
    - the inversion is non-unique
  - Geological constraints derived from P-wave profile or known geology

Interferometry – methodology

Phase 1:

Raw data → Remove instrument response, remove mean, remove trend, band-pass filter, and cut to length of 1-day → Apply time domain normalization → Apply spectral whitening

Phase 2:

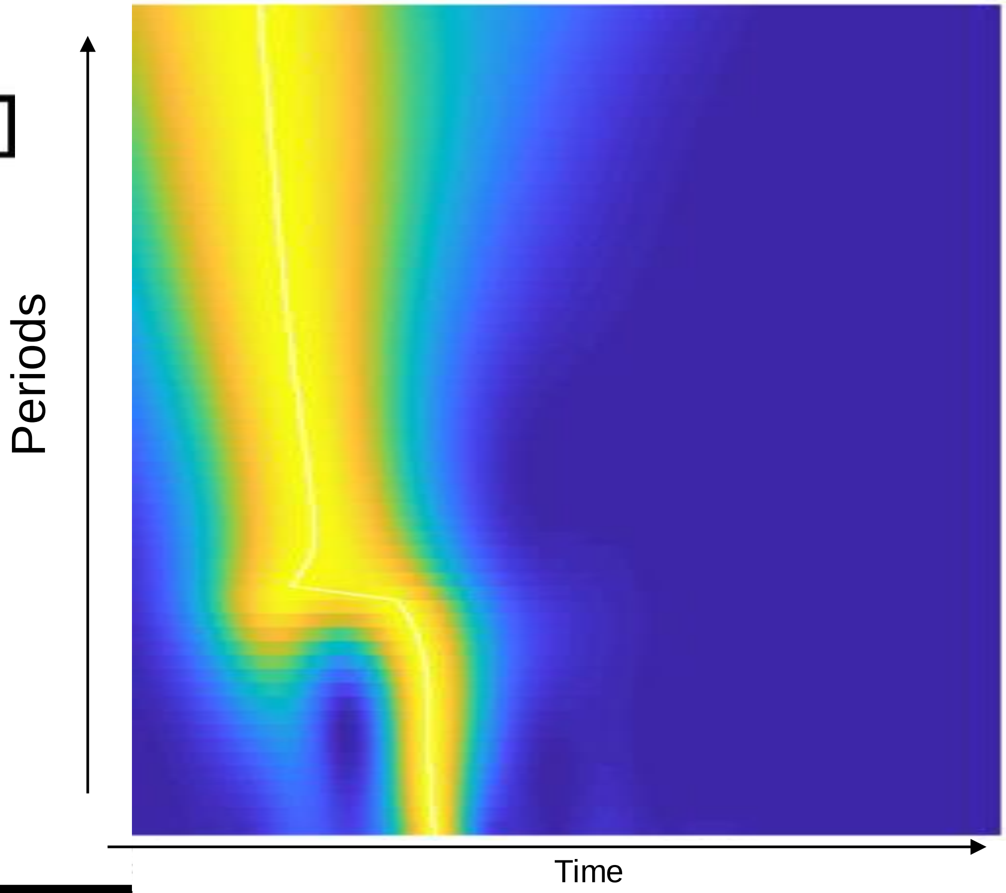
Compute cross-correlation → Stack day-correlations to desired number of days

Phase 3:

Measure group and/or phase velocity

Phase 4:

Error analysis → Selection of acceptable measurements



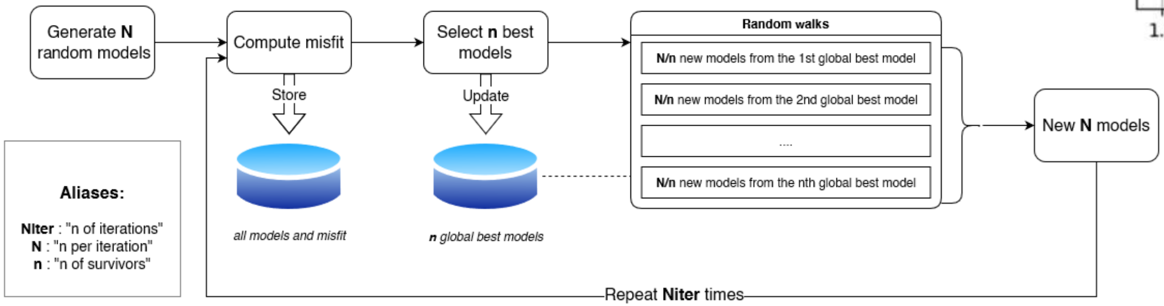
Surface wave inversion – methodology

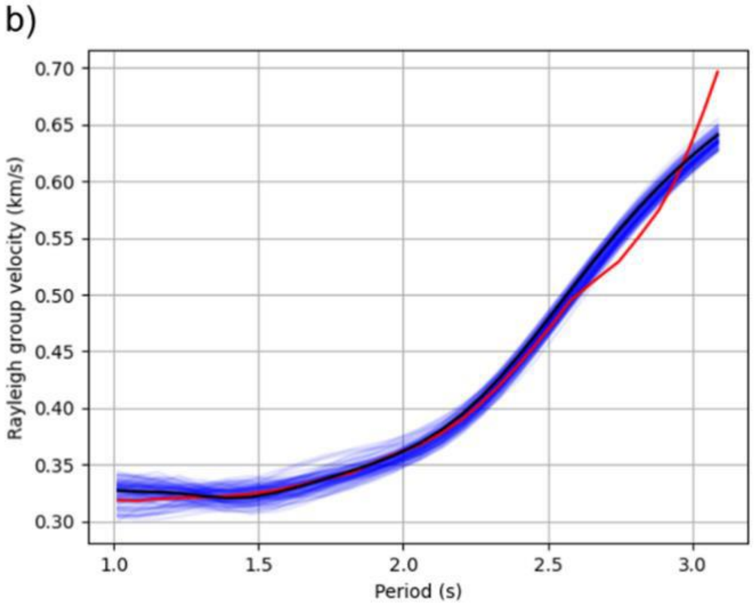
Seismik

Misfit:

Parameter characterizing the difference between modelled and measured dispersion curve

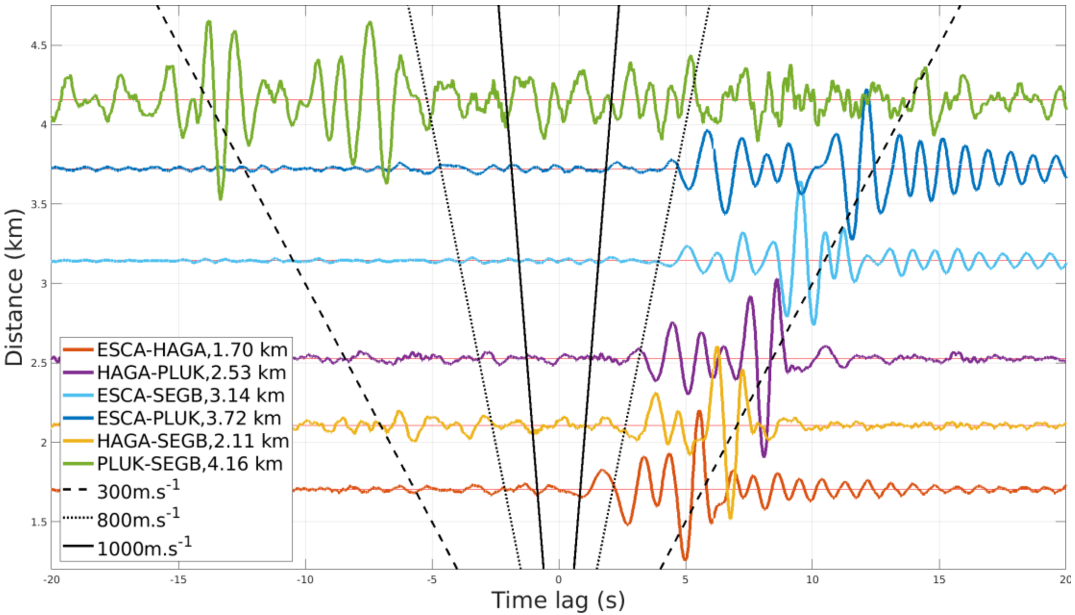
And velocity model search:





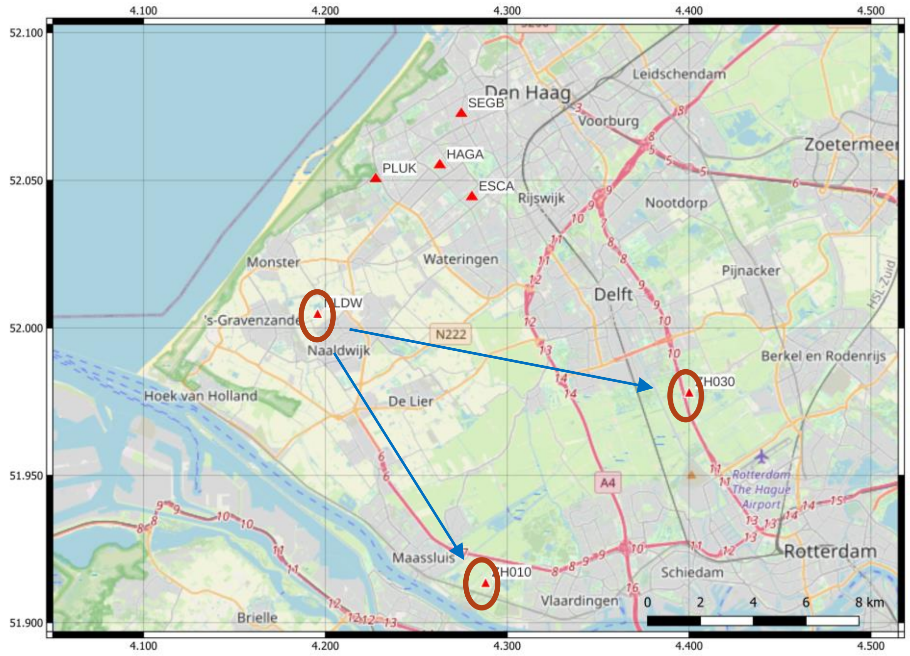
Sambridge, M, Geophysical inversion with a neighborhood algorithm—II. Appraising the ensemble, *GJI*, **138**, 3, 1999, pp 727–746, DOI 10.1046/j.1365-246x.1999.00900.x

Interferometry – the Hague case study

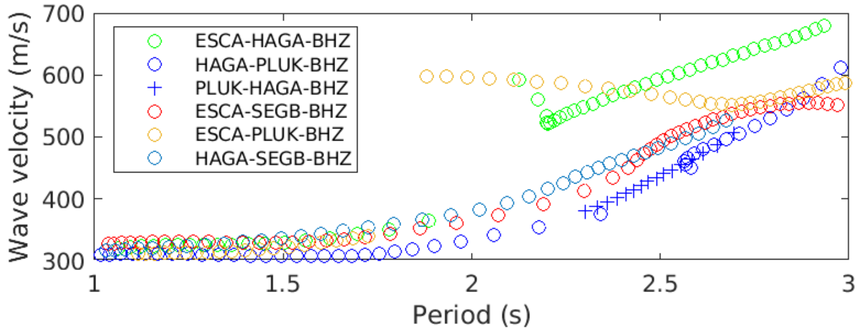


- Very low surface wave velocities – 340 m/s – is it a sound wave?
- Correlograms are asymmetric – mostly positive delay

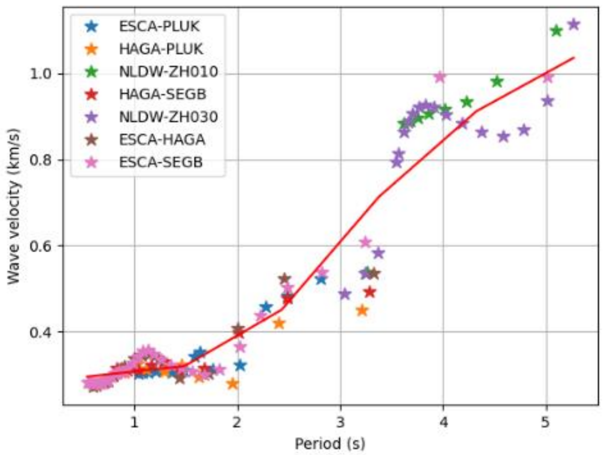
Overcoming local array limits - the Hague case study



Dispersion observed on the local array



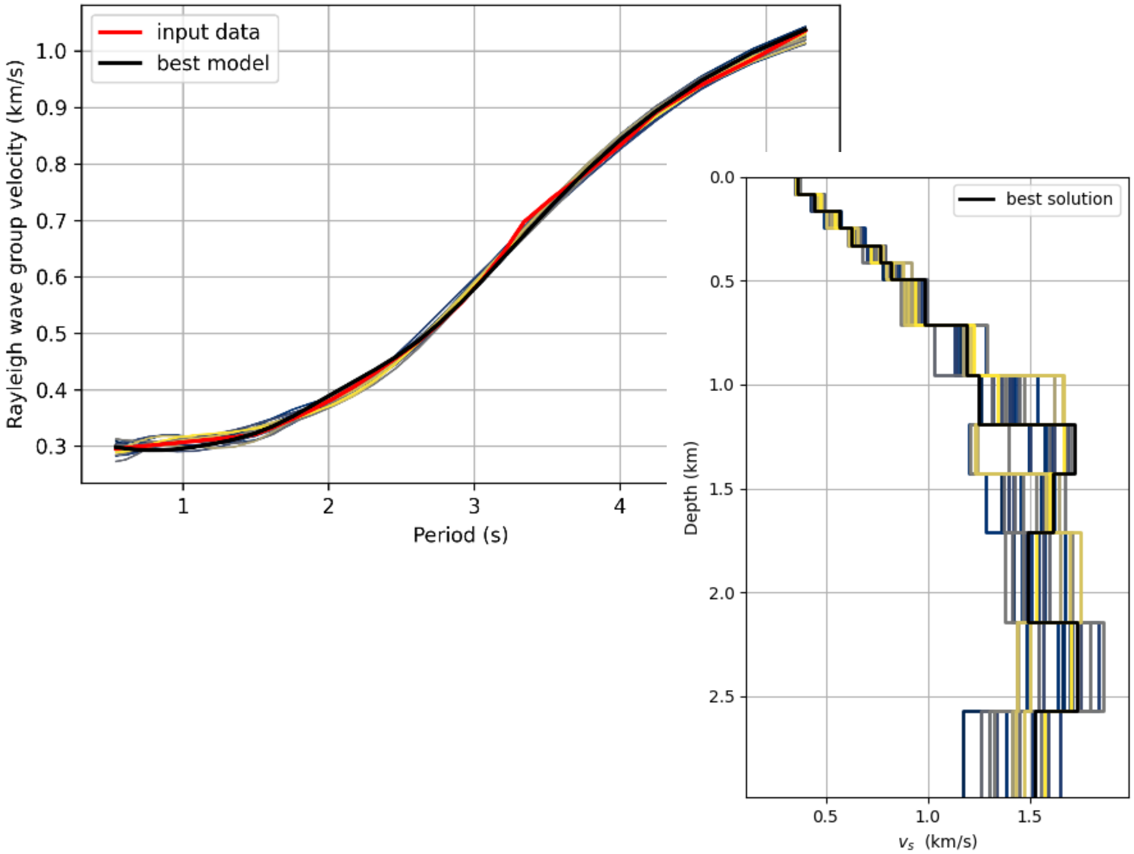
Dispersion including national network



Nat network and geology - the Hague case study

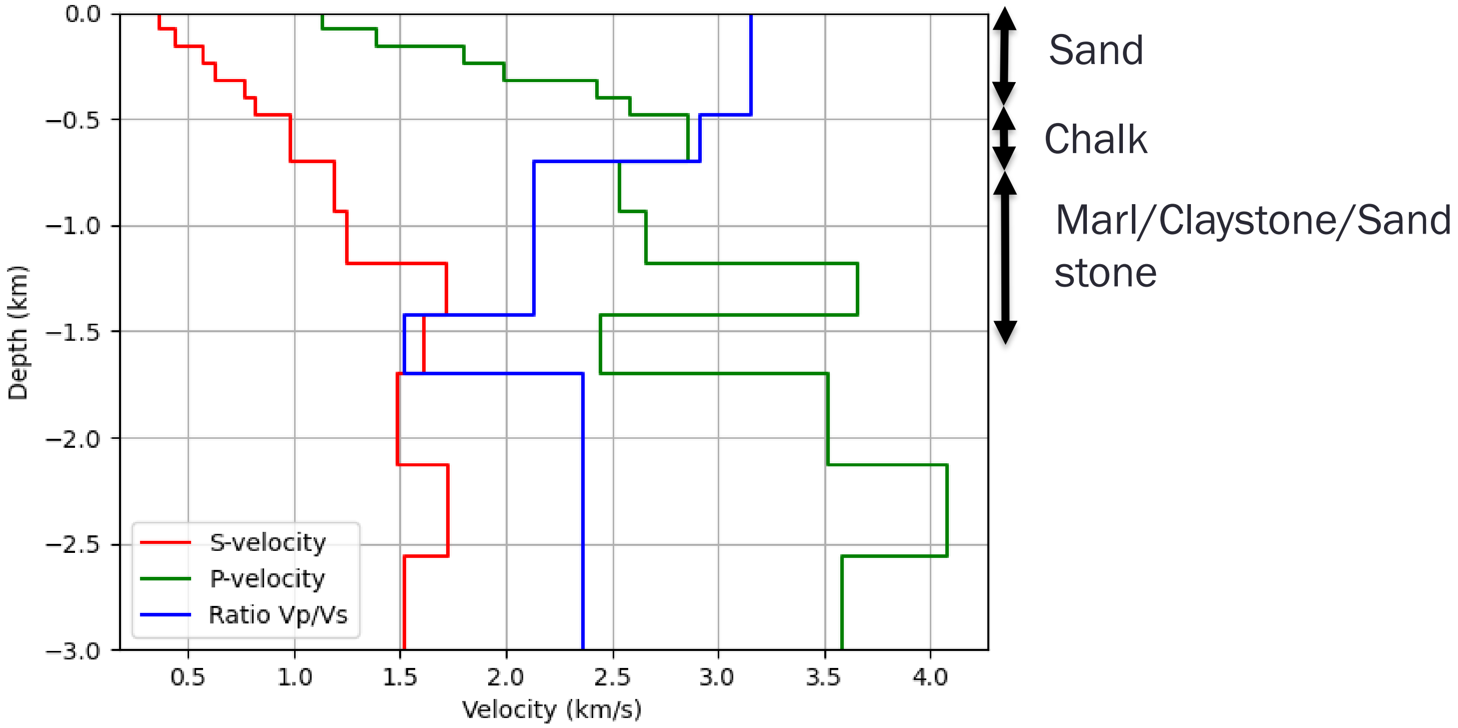
Seismik

- Split the big blocks to finer layers
- Removed constrains on S-wave velocity
- Assume a constant Vp/Vs ratio of 1.7, but the inversion is not sensitive to this
- the velocity seems to increase with gradient of 100 m/s per 100 m in the top 500 m, this is consitent with compaction of sediments



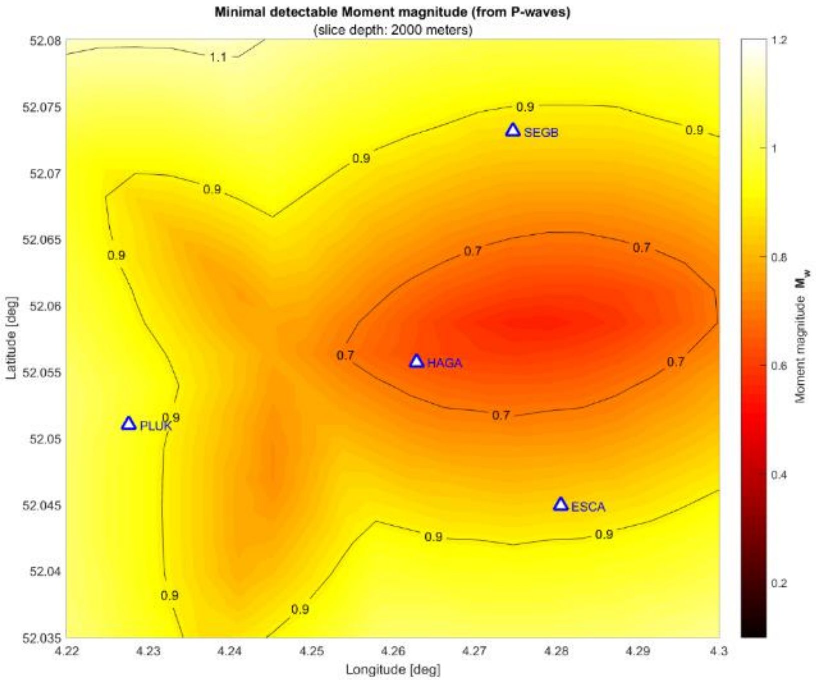
The final updated model

Use the constant VP/VS ratio per geological layer and change VP. This model change detectability of the network and probably reflects real model better

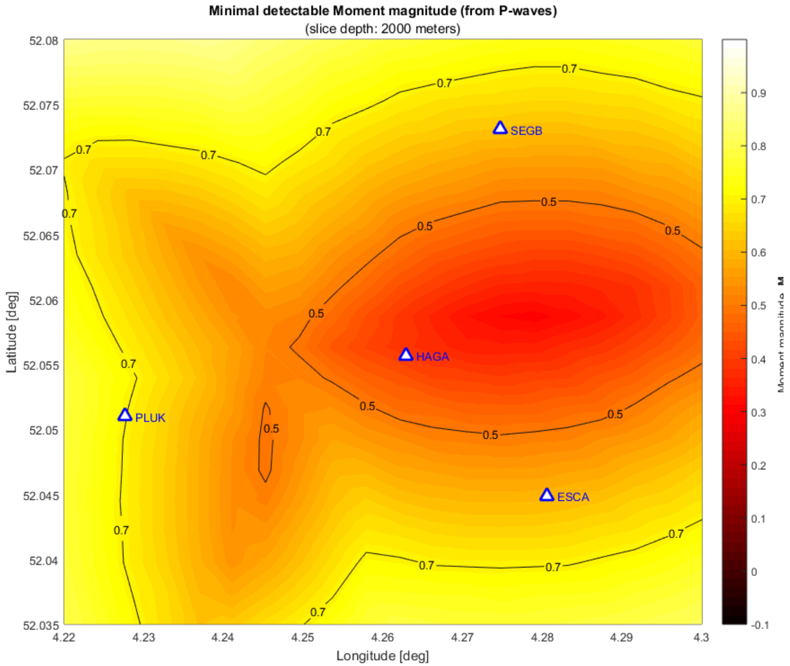


The sensitivity with and without the updated model

Original model



Updated model



Detection of events by 0.2 magnitude lower!

This is similar improvement as if all stations are installed in in 200 m deep boreholes.

Discussion

- Observed S-wave velocities at the near surface layers are very slow
  - ▶ Saturated unconsolidated sediments
  - ▶ High V_P/V_S
  - ▶ Consistent with earlier studies
  - ▶ Significant effect on the accuracy of depth of the located events
  - ▶ Low VS results in demand for longer periods to reach greater depths

- We do not try to constrain V_P – P-wave velocities account only for <5% of the misfit between observed and modeled velocity dispersion – need to use another constraint
  - VP/VS constrain in the inversion does not play significant role

- Better constrains:
  - ▶ National network - Broader frequency (accelerometers) and greater offsets
  - ▶ Fixing layer boundaries from geology

Conclusions

- Methodology allows to determine V_S profile under a sparse array
  - Free of charge (no active seismic, no additional stations)
  - Constrains near-surface layers where usually no information is available and right frequency range
  - Network detects 0.2 magnitude lower magnitudes

- Observe very low S-wave at near surface layer in west Holland are observed
  - Not sound waves
  - Consistent with Groningen and high V_P/V_S
  - Significant effect on the depth of the located induced events
  - Significant effect on network performance – high noise – high amplification

- S-wave inversion significantly benefits from broad period range of surface wave dispersion
  - Additional constrains: geology, V_P profile, other methods

Acknowledgement

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