Laboratory experiments on the non-invasive estimation of soil wave speeds

Ho-Chul Shin[1], Shahram Taherzadeh[1], Keith Attenborough[1], and Richard Whalley[2]

[1]The Open University, Milton Keynes, UK

[2]Rothamsted Research, Harpenden, UK

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Rationale

- Soil condition (strength and moisture content) is important for plant growth.
- Current monitoring requires laboratory measurements on extracted samples or time consuming field measurements using a penetrometer or an air permeability apparatus.

Introduction (1/2)

- When incident airborne sound interacts with a porous soil , the reflected sound depends mainly on the pore-related characteristics of the soil and is associated mainly with motion of air particles in and out of the surface.
- However soil particles are excited also, i.e., acoustic-to-seismic (A-S) coupling occurs.
- Experiments have been carried out in an anechoic chamber to investigate the correlation between the type and condition of the soil and A-S coupling.
- A Laser Doppler Vibrometer (LDV) has been used for non-invasive measurement of the surface particle velocities of the soil resulting from a point (loudspeaker) source of sound.
- Two vertically-separated near-surface microphones have been used to measure acoustic reflection from the surface.

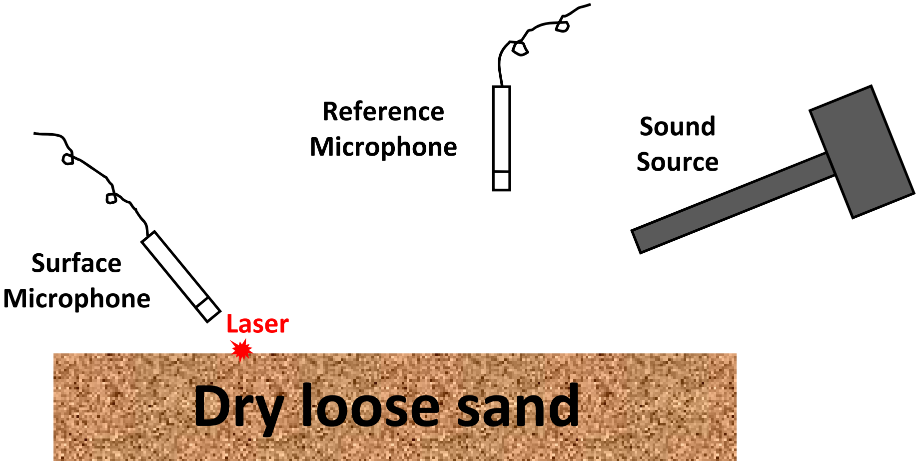
Introduction (2/2)

- Homogenous dry sand has been investigated.
- We use A-S coupling spectra and acoustic Level-Difference spectra in a parameter deduction algorithm.
- Initially, when we used continuous sine waves, we encountered a difficulty due to the nonlinear response of dry loose sand, which was resolved later by the use of maximum length sequence signal.
- We have also compared the responses of wet and dry sands.
- The feasibility of deducing physical (both acoustic and elastic) parameters of the soil from non-invasive measurements is demonstrated.

PFFLAGS

- A numerical code PFFLAGS been used to fit the measured A-S coupling spectra.
- **P**ulse **F**ast **F**ield **P**rogram for **L**ayered **A**ir **G**round **S**ystems
  - Biot theory of poroelasticity
  - FFP (Fast Field Program) with exact Bessel function evaluation rather than a large argument assumption
- Required parameters for each poroelastic layer
  - Airflow resistivity, Porosity
  - Pore and grain shape factor, tortuosity
  - Complex P-/S-wave speeds (or bulk and shear moduli)
  - Density
  - Layer thickness

A/S coupling measurements



Reference Microphone

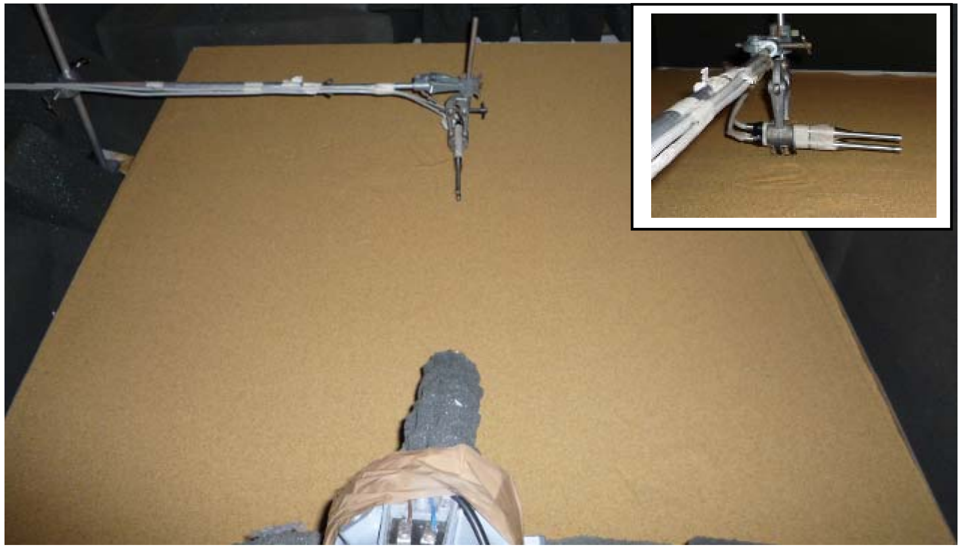
Sound Source

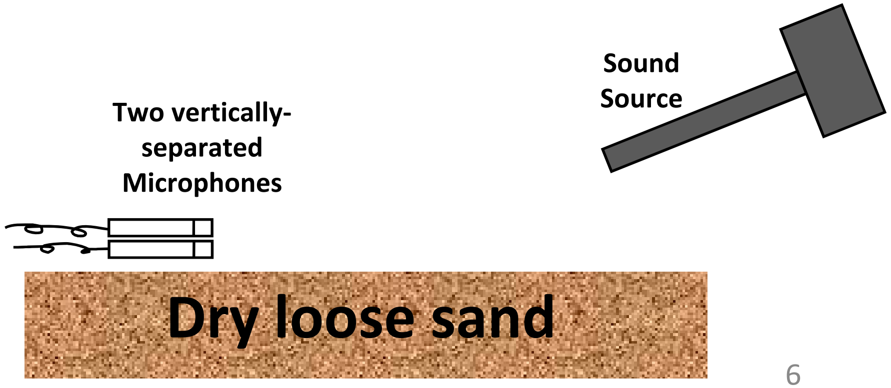
Surface Microphone

Laser

Dry loose sand

Acoustic Level Difference (LD) measurements





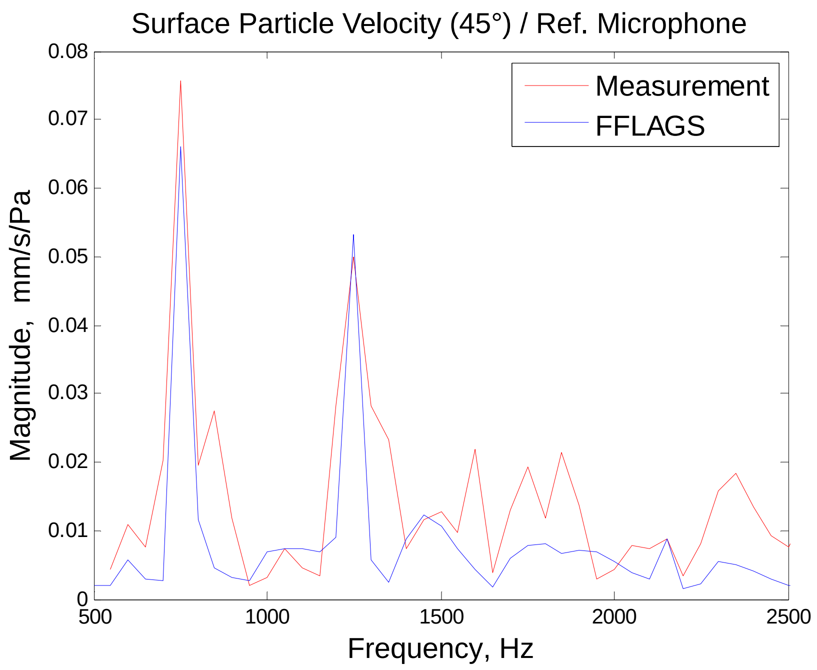
Sound Source

Two vertically-separated Microphones

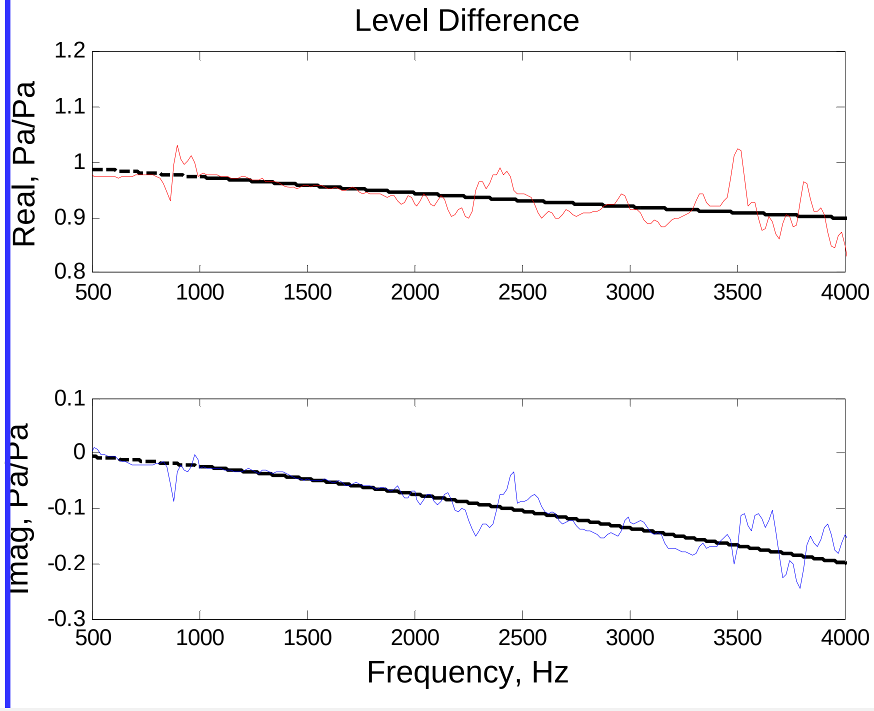
Dry loose sand

Initial Fitting Results (dry sand)

A-S spectrum



Level Diff.



Parameters (blue : deduced; black: assumed) via Slit-like Pore model

Flow resistivity = 116.9 kPa s/m^2;
Porosity = 0.43;
$V_{p\text{-wave}}$ = 114 m/s; $V_{s\text{-wave}}$ = 90 m/s;
Att. = 0.0003
Density = 1536 kg/m^3; Depth = 11.5 cm;

Flow resistivity = 119.4 kPa s/m^2;
Porosity = 0.38;
Depth = 11.5 cm;

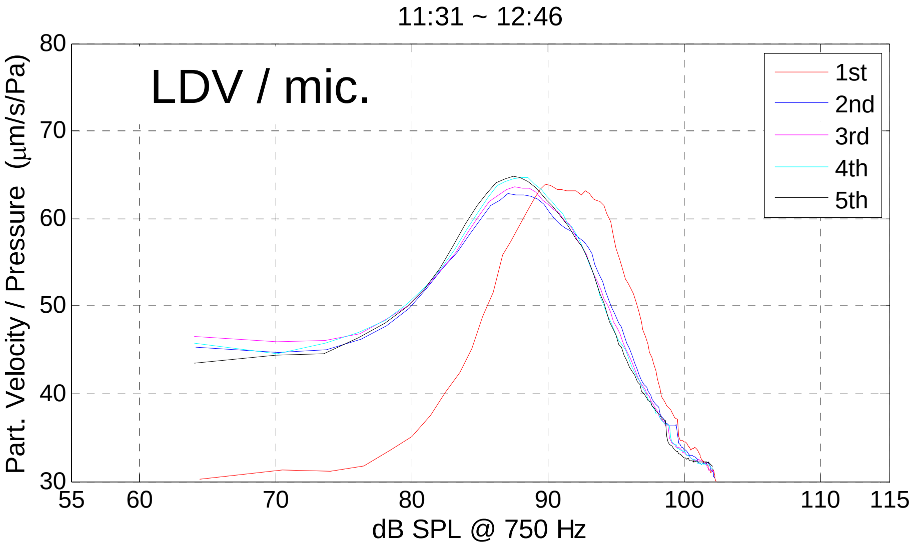
However,…

- The ratio of $V_{s\text{-wave}}$ to $V_{p\text{-wave}}$ does not conform to the assumption of a homogenous isotropic material. (the max. allowed value of V_s/V_p is 0.707, but the current estimate is 0.789, implying a negative Poisson’s ratio.)
- **Flow resistivity** and **porosity** affect the order of magnitude of the A-S spectrum.
- **V_p** and **Depth** affect the frequency of resonance peaks.
- **V_s** and **Attenuation** may be used to fine tune fit of the A-S spectrum.

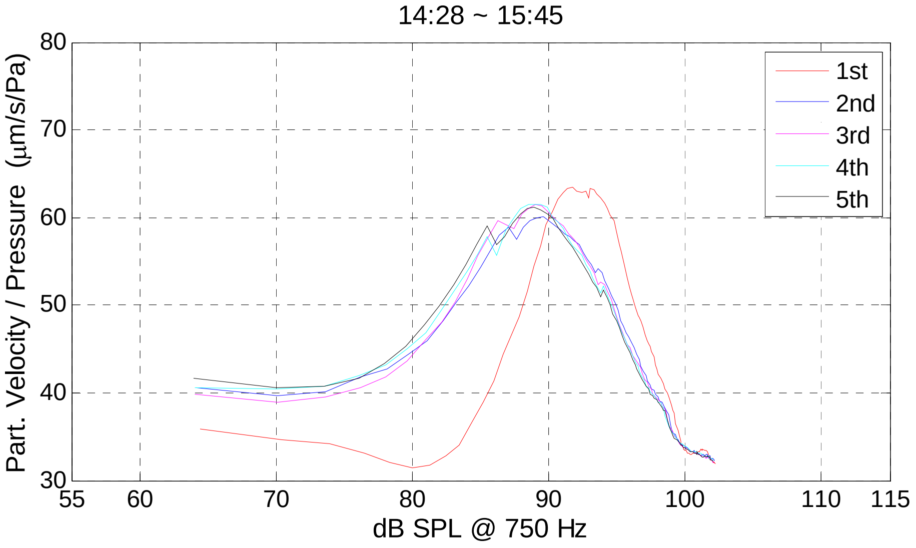
Subsequent considerations

- Response of dry loose sand is nonlinear.
- If the sand response is nonlinear at the sound levels used , then it cannot be accurately modelled by PFFLAGS (which assumes linear behaviour).
- Nonlinear behaviour may not affect the order of magnitude and the frequency of resonance peaks, but may affect the fine tuning of magnitude.
- Therefore, nonlinearity could have affected the deduction of V_s more than other parameters.

Evidence for Nonlinear behaviour (Sand)



Duration of measurements



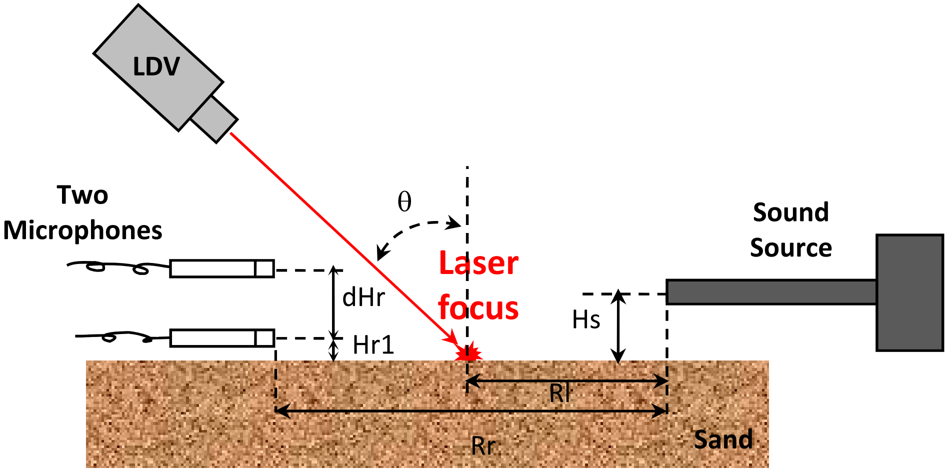
For lower SPL, a range of linear behaviour is observed.

For higher SPL, nonlinear A-S coupling is observed.

The 1st acquisition is always different from the rest. After breaks, the pattern was repeated. Perhaps, the 1st exposure to strong sounds may disturb the sand structure (esp. the surface) which may be restored during breaks.

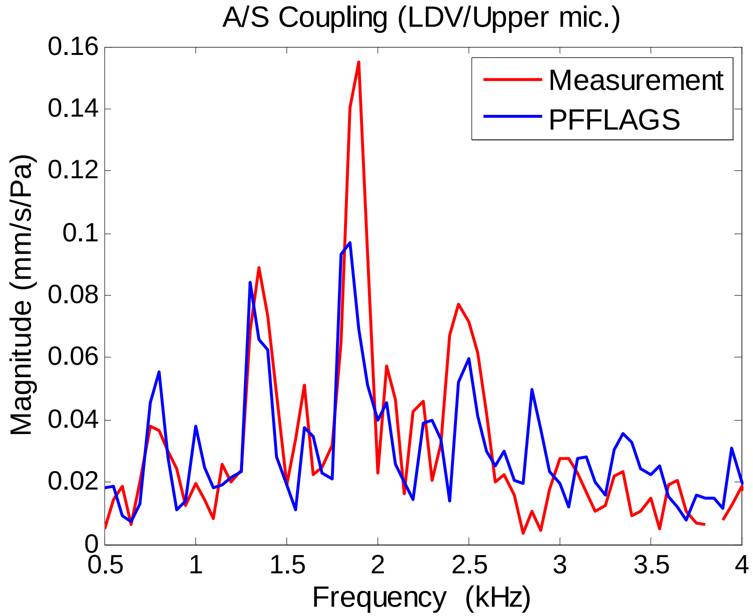
A/S + LD measurements

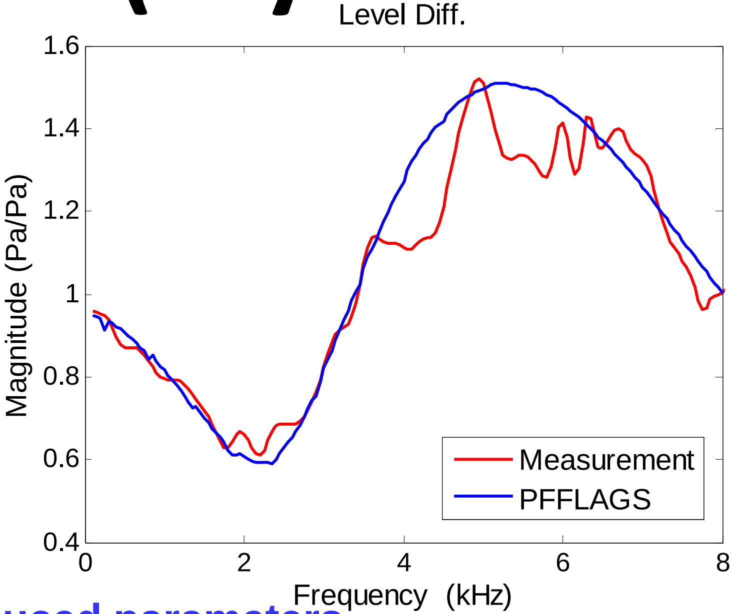
Now we have used lower source levels (using MLS) to avoid the nonlinearity problem.

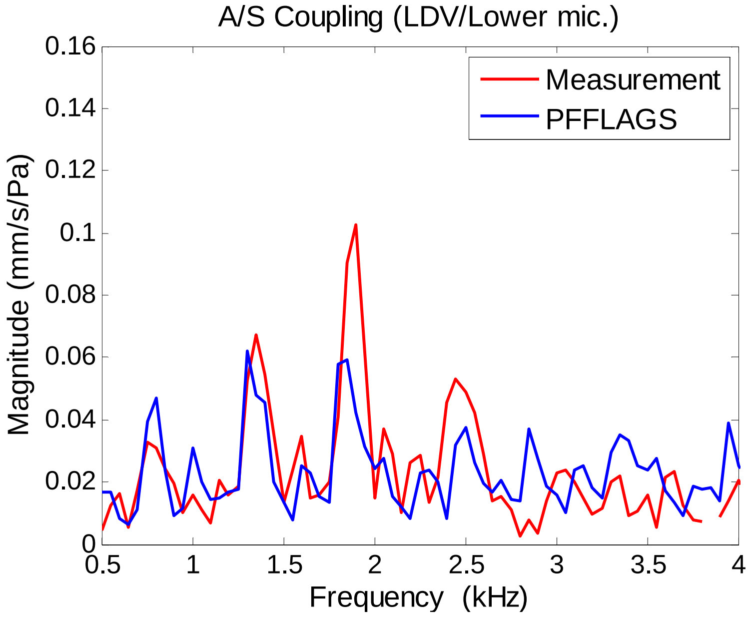


We have attempted to deduce both acoustic and elastic parameters of soils through one set of measurements.

Parameter deduction (dry loose sand)







Deduced parameters

Flow Resist. = 178 kPa s/m^2; Poro. = 0.44

V_p=113 m/s; Poisson = 0.39;

Density = 1498 kg/m^3 ; Loss = 0.003;

Assumed: Depth = 11 cm

Dependent parameters

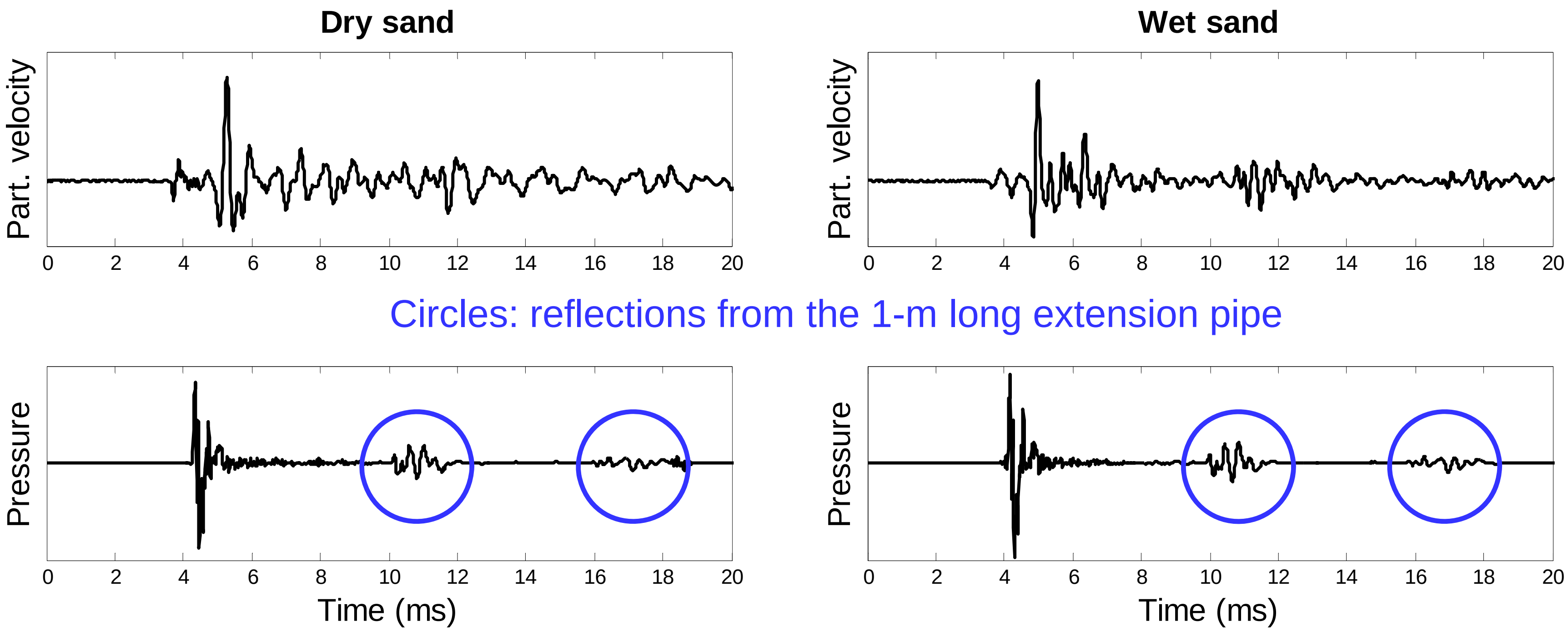
Bulk modulus = 14.7 MPa

Shear modulus = 3.3 MPa; V_s= 47 m/s.

Frequency range shown for LD is twice that used for A-S coupling .

Dry sand vs. Wet sand

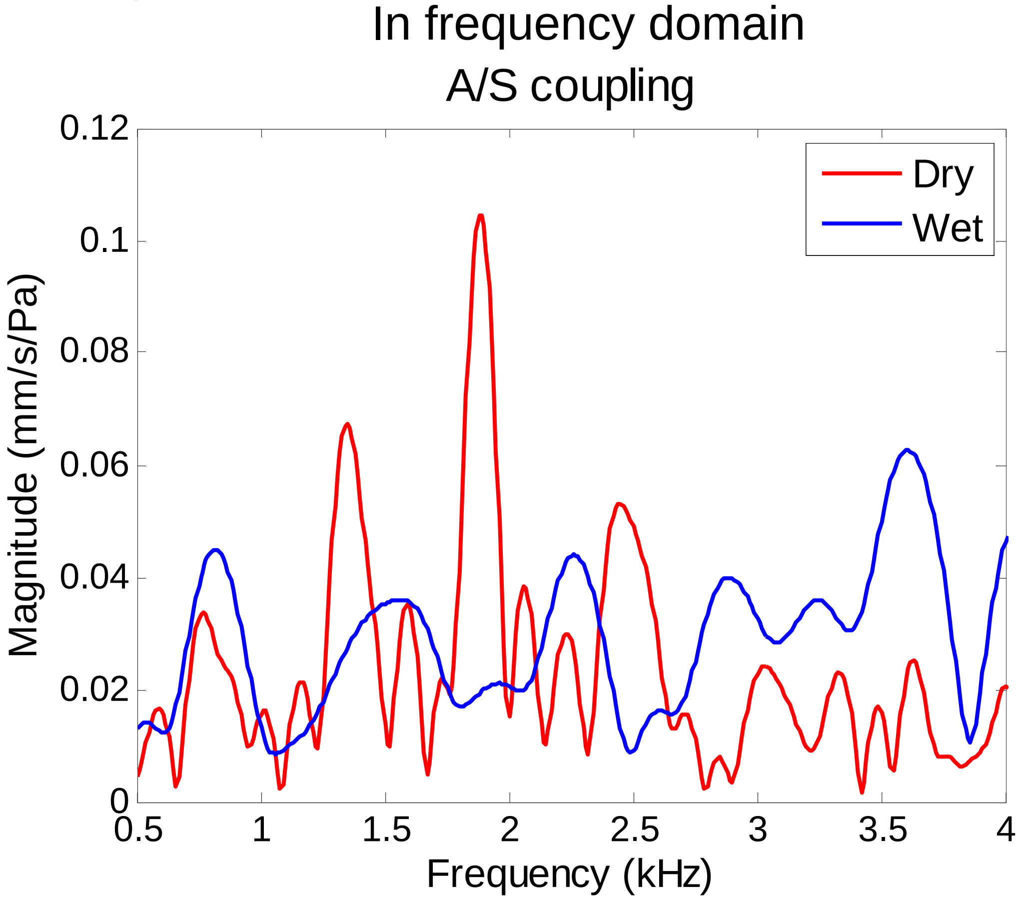
Temporal impulse response by maximum length sequence



Circles: reflections from the 1-m long extension pipe

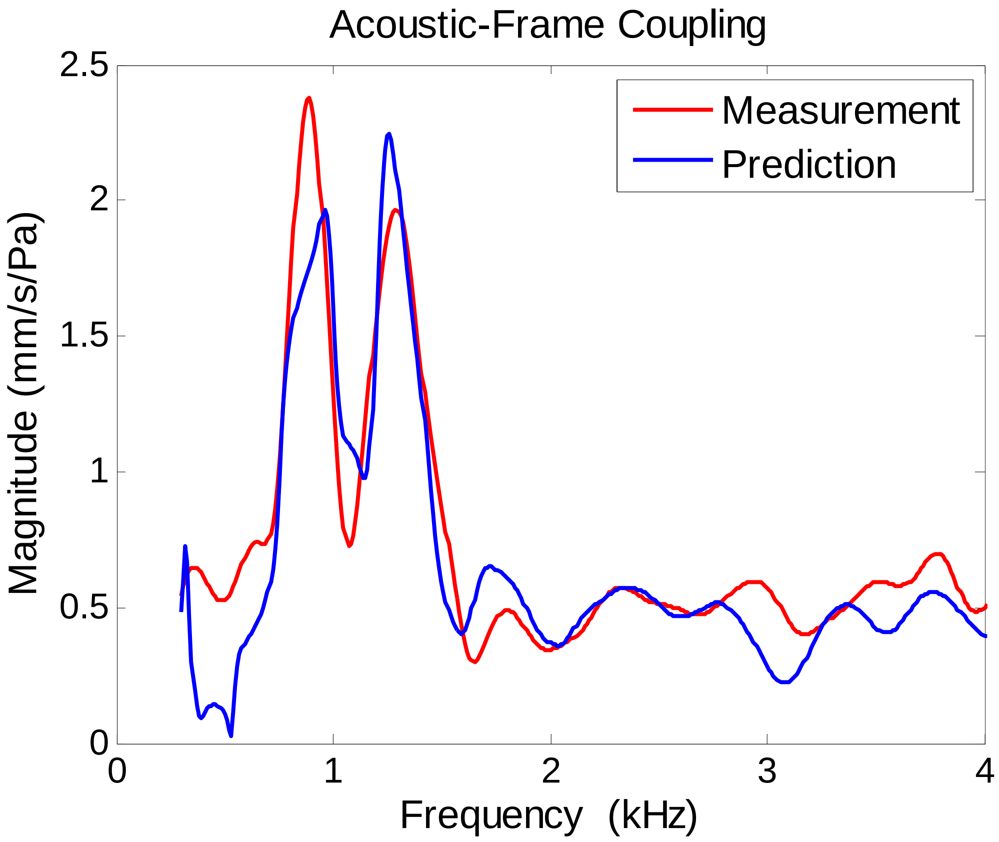
The volumetric moisture content of the wet sand is 12.9 ± 1.7 % (mean ± std).
For wet sand, the particle velocity dies out quickly.
For dry sand, the particle velocity does not die out quickly.

Dry sand vs. Wet sand



The geometries for both tests were slightly different. But, most differences were attributed to the moisture content. Therefore, it can be possible to deduce the moisture content (an important parameter in horticulture) based on A/S data, which we are working on.

How about plastic foams?



Flow resist. = 8760 Pa s/m^2; Poro. = 0.98; Bulk modulus = 690 kPa;
Shear modulus =11.5 kPa; Atten. = 0.045; Density = 23.9 kg/m^3; Tortuosity = 2.19;
thickness = 49mm. (Deduced parameters are in blue fonts)

Summary

- In principle, it seems feasible to deduce both acoustic and elastic parameters of soil properties non-invasively by matching the measured data and predictions of the Biot theory.
- Using two microphones and a LDV, we measure both A-S coupling and acoustic LD data simultaneously.
- Nonlinear behaviour poses a problem with unconsolidated sands. The issue has been resolved with lower source levels using MLS signal.
- The A/S coupling response of wet sand has been found different from that of dry sand. It raises the possibility of deducing the moisture contents of soils non-invasively.