



# MISS – Project

Minderung der Störwirkung von Windenergieanlagen auf  
seismologische Stationen

Gefördert durch:



EUROPÄISCHE UNION  
Investition in unsere Zukunft  
Europäischer Fonds  
für regionale Entwicklung

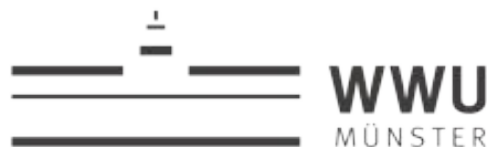
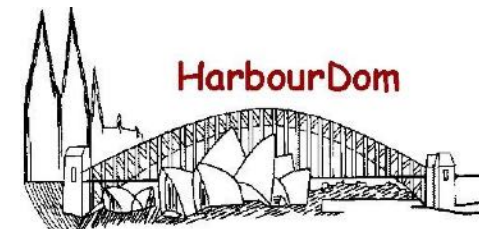
**Teilprojekt WWU:**

**Mitigation of effects on the travel path – a theoretical approach**

**Rafael Abreu, Christine Thomas**



BAUDYNAMIK  
HEILAND & MISTLER GmbH

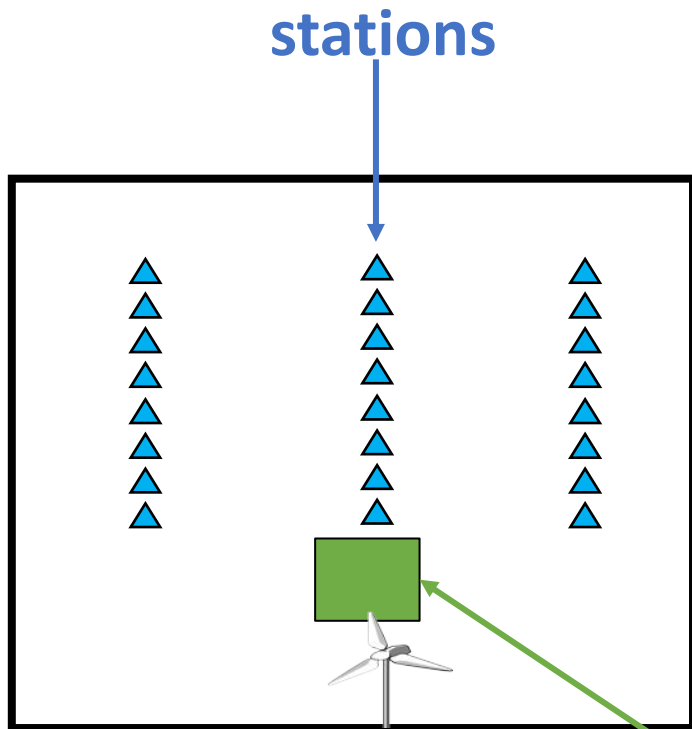


RUHR  
UNIVERSITÄT  
BOCHUM



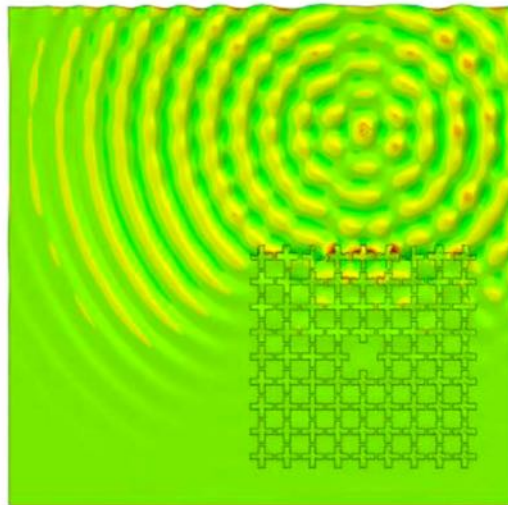
# Effects of arrangements?

We test two different scenarios in order to investigate the influence of the metamaterials' arrangement



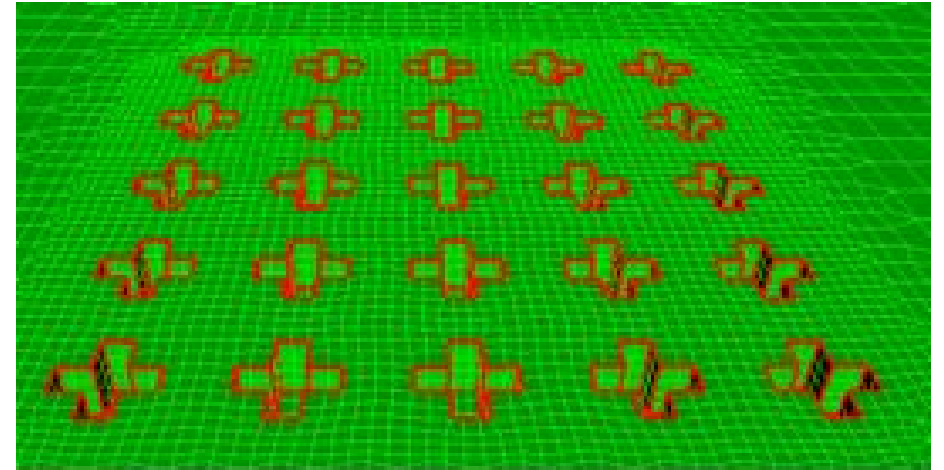
metamaterials

Previously done  
(Miniaci et al. 2016)

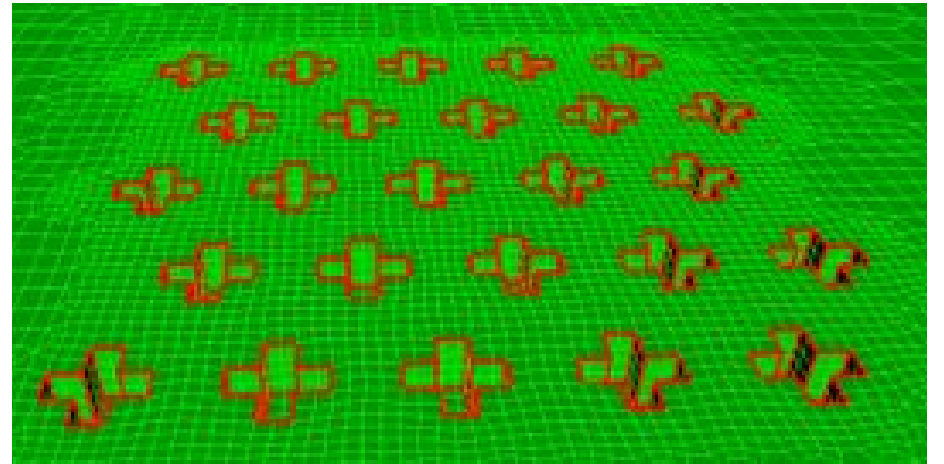


First case

65 m X 65 m

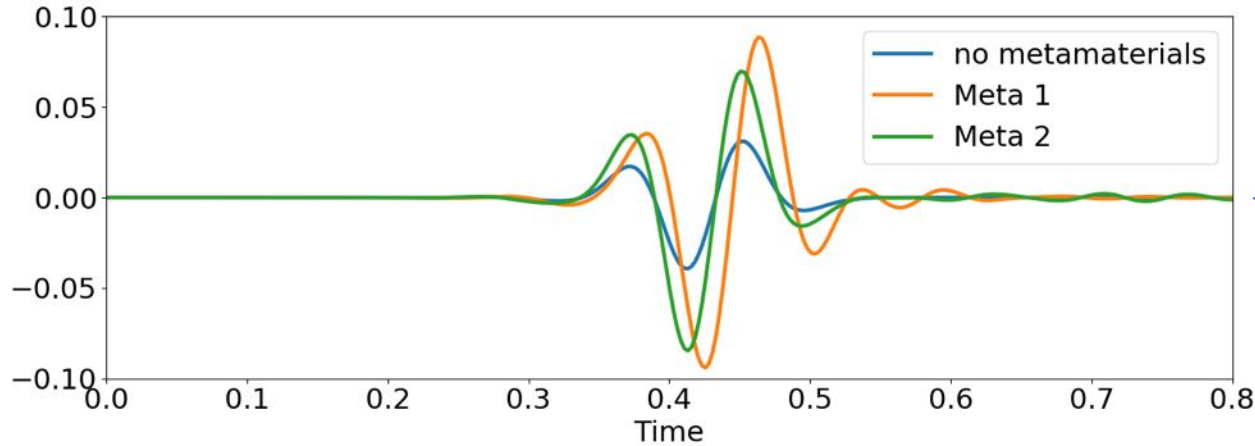


Second case

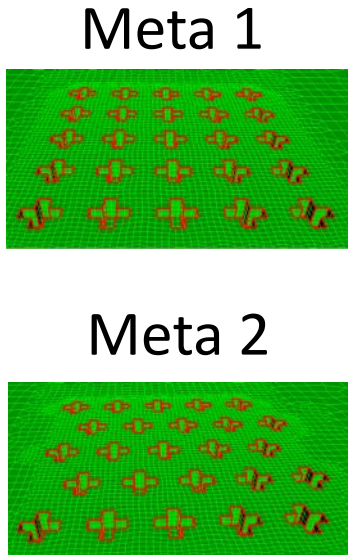
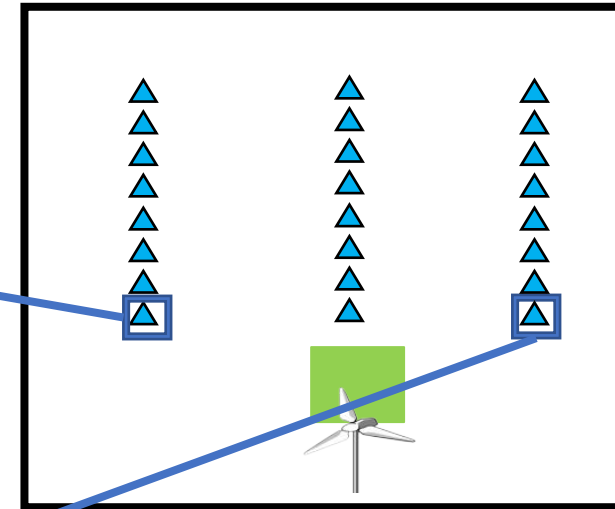
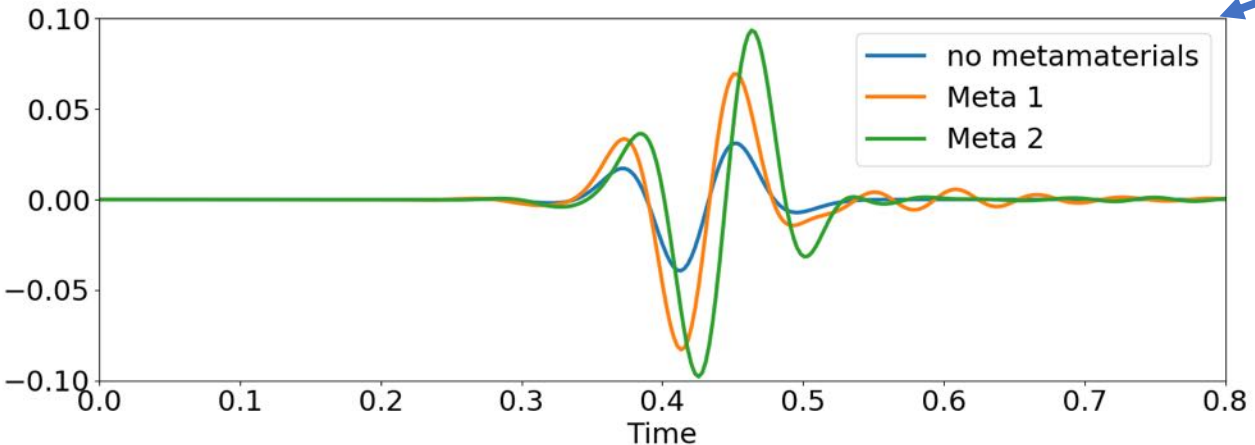


# Comparison of wave propagation 1

Velocity time series: station X0



Velocity time series: station X22



We can observe the presence of anisotropy in the wave propagation (meta 2)  
Models with metamaterials show larger amplitude. Why?  
Tests needed...

# The problem was...

The wave equation with a source time function --  $f(t)$

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} + f(t)$$

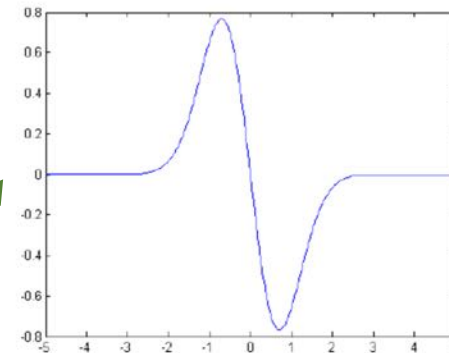
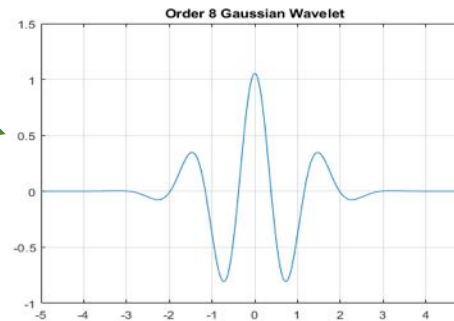
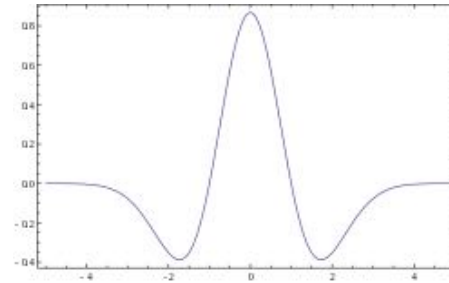
$c$  – wave speed  
 $u$  – displacement  
 $x$  – space variable  
 $t$  – time variable

# The problem was...

The wave equation with a source time function --  $f(t)$

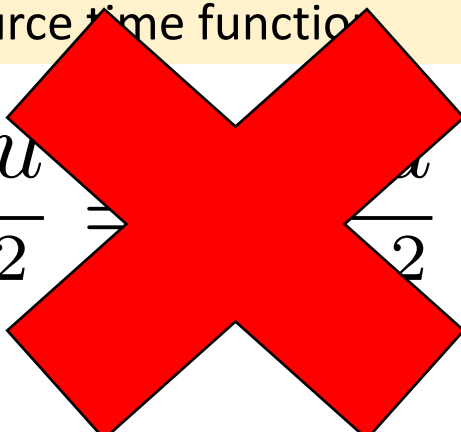
$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} + f(t)$$

$c$  – wave speed  
 $u$  – displacement  
 $x$  – space variable  
 $t$  – time variable



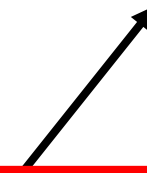
# The problem was...

The wave equation with a source time function

$$\frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 u}{\partial x^2} + f(t)$$


$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} + f(t) \delta(x - x_r)$$

Dirac delta function



# The solution is...

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} + f(t)\delta(x - x_r)$$

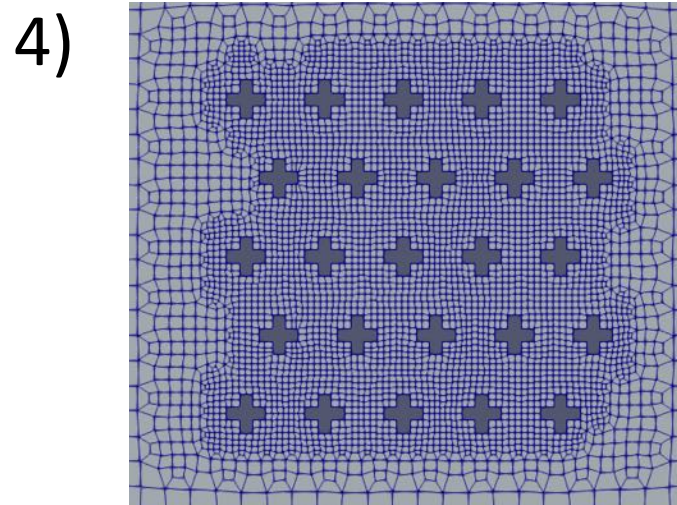
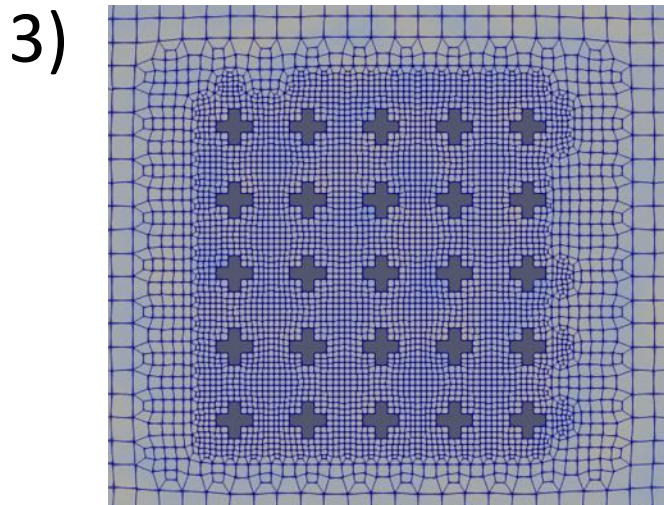
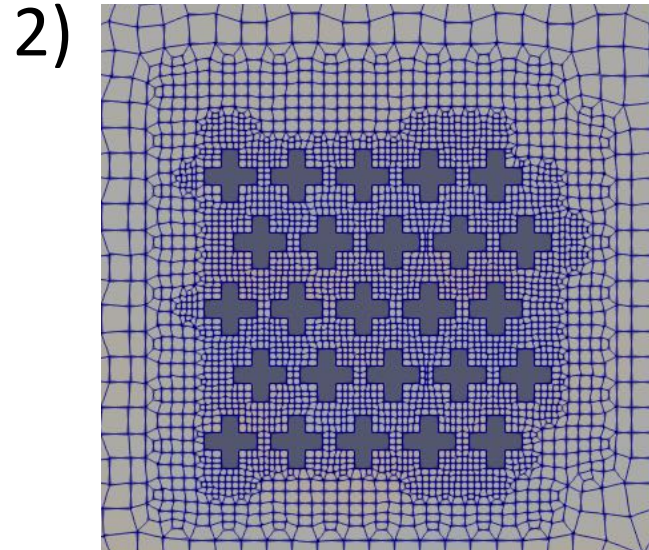
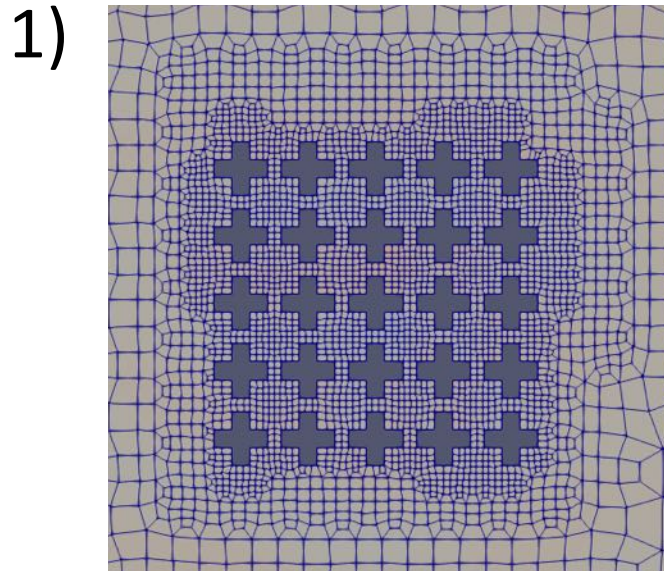
$\Delta x =$  grid discretization

$$\delta(x - x_r) \approx \frac{1}{\Delta x}$$

Numerical discretization +  $\frac{f(t)}{\Delta x}$

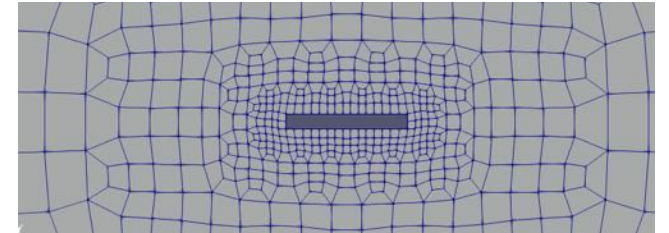
the grid spacing  $\Delta x$  controls the source amplitude for different meshes!

# The models and corrected simulations

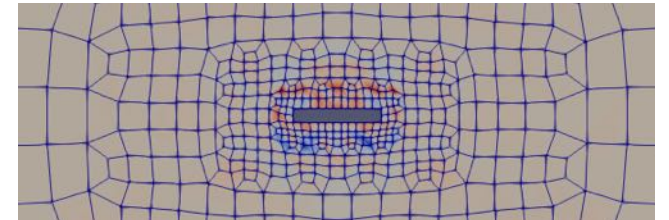


## holes

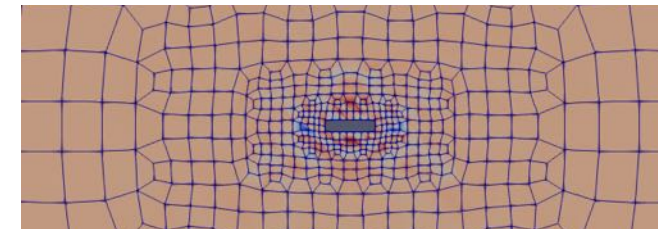
1) 40 m x 5 m x 20 m (deep)



2) 30 m x 5 m x 10 m (deep)

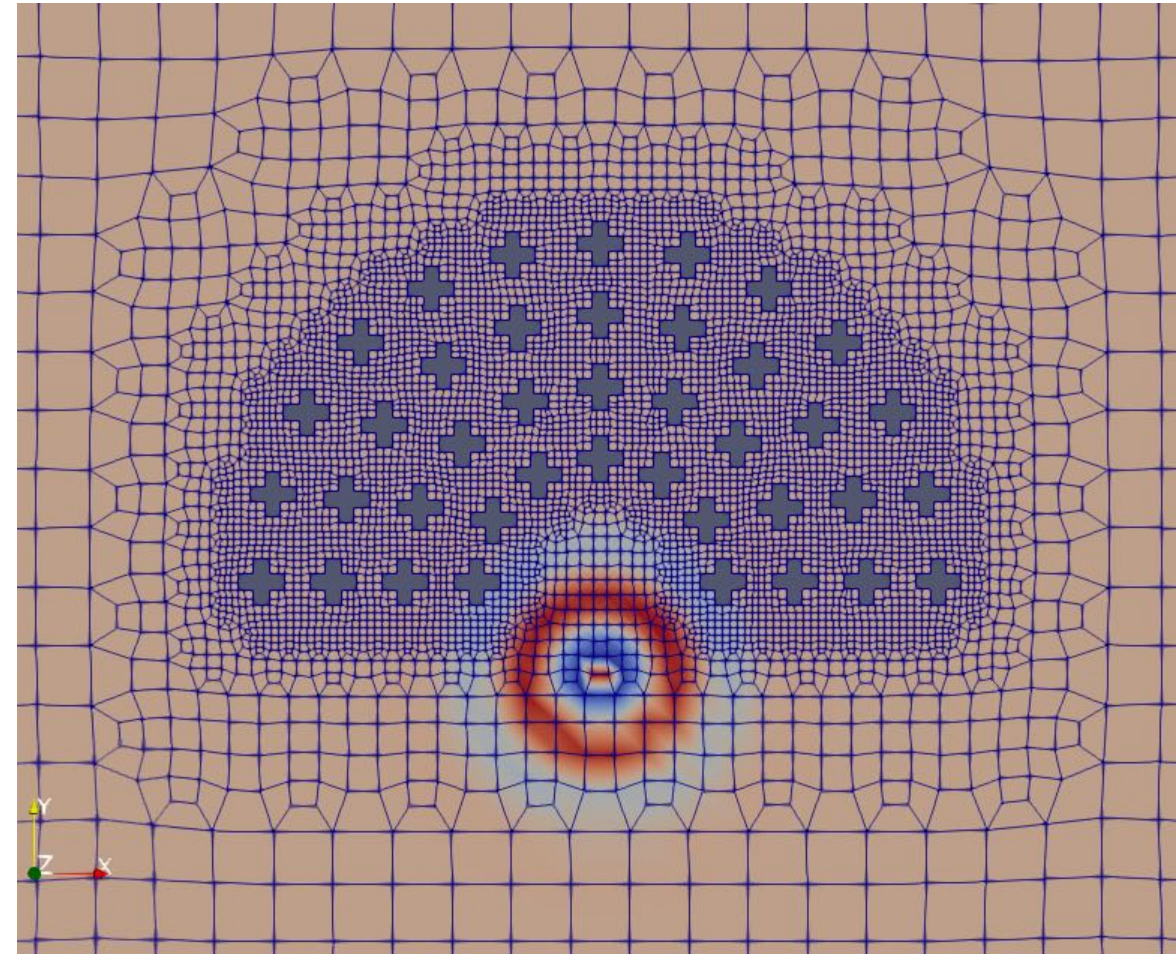
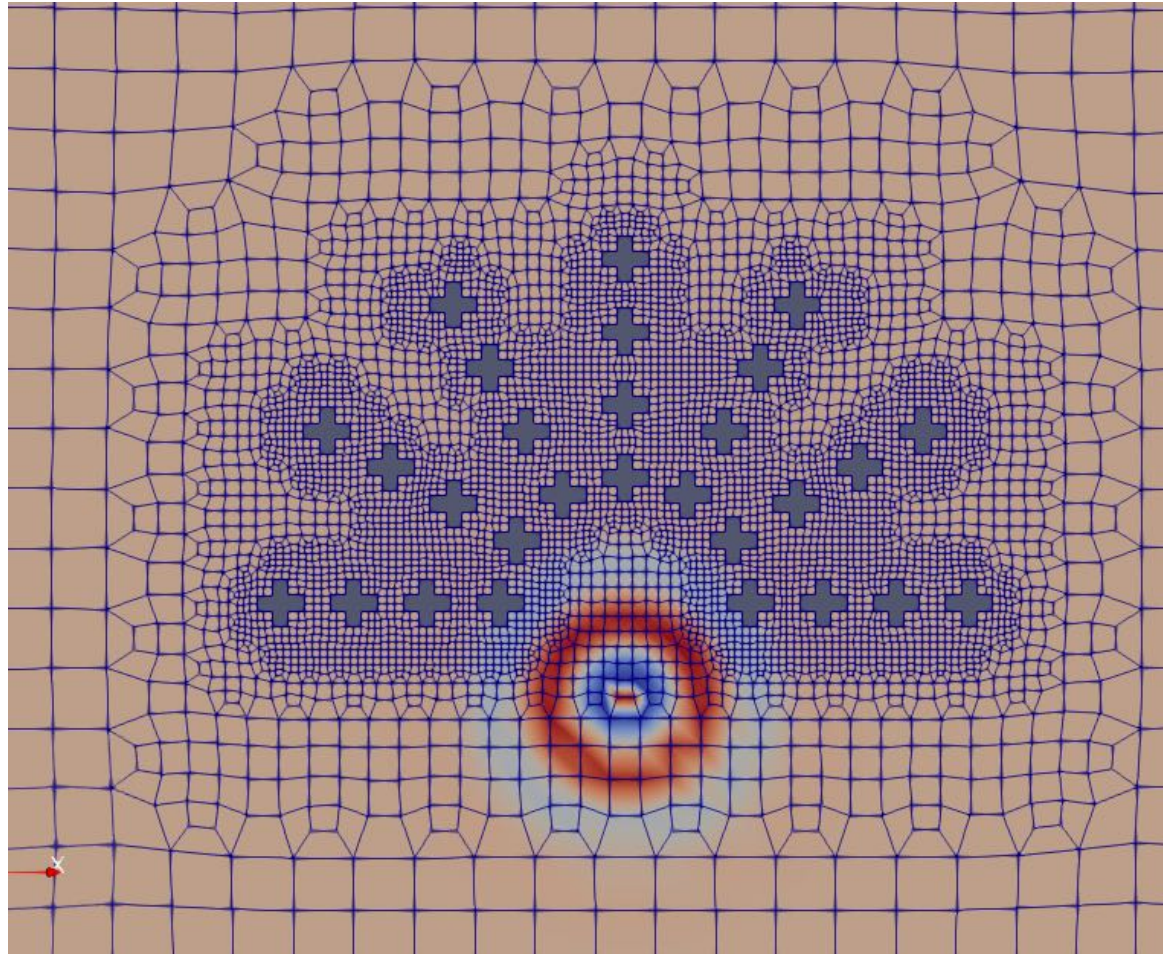


3) 20 m x 5 m x 10 m (deep)

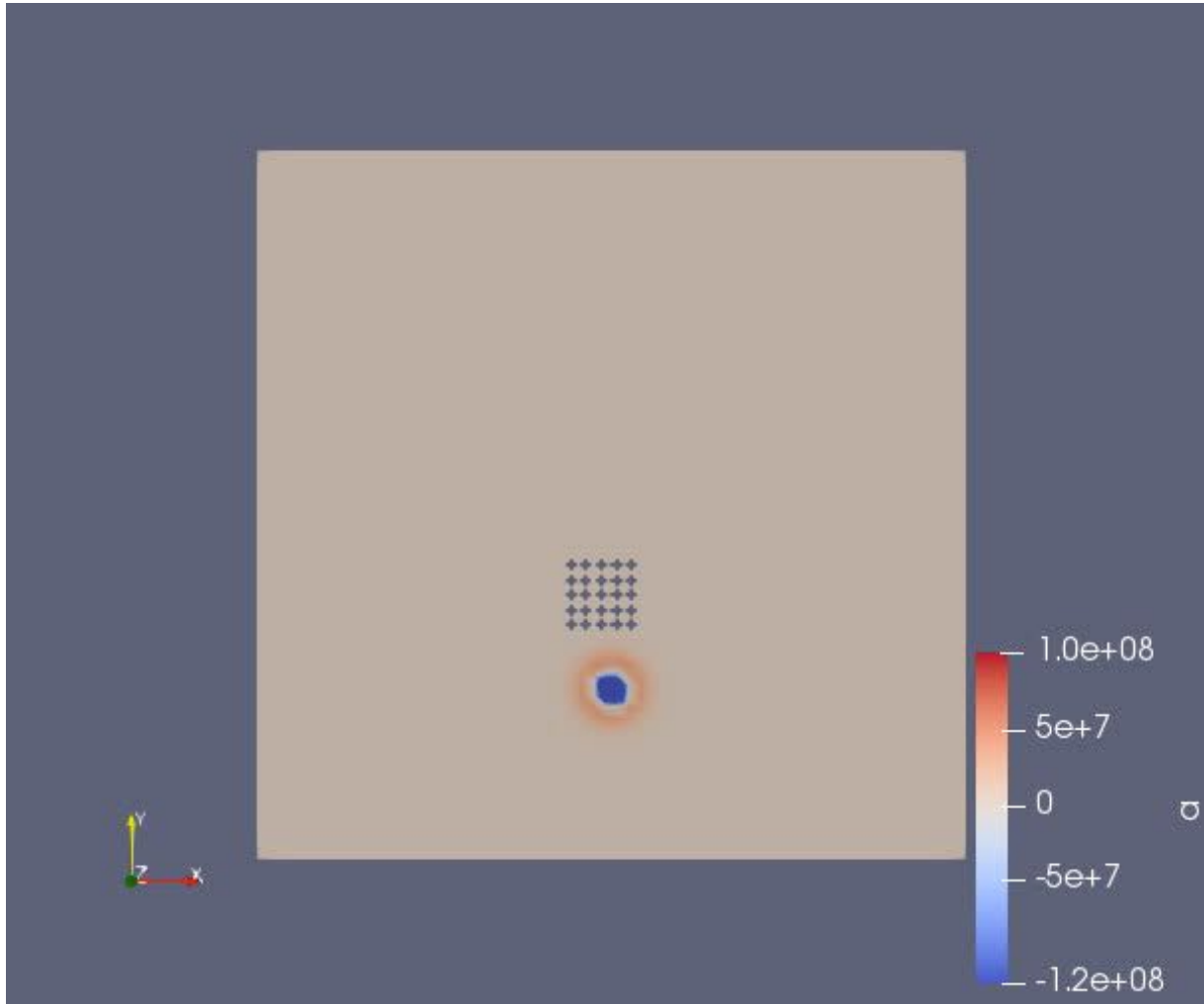




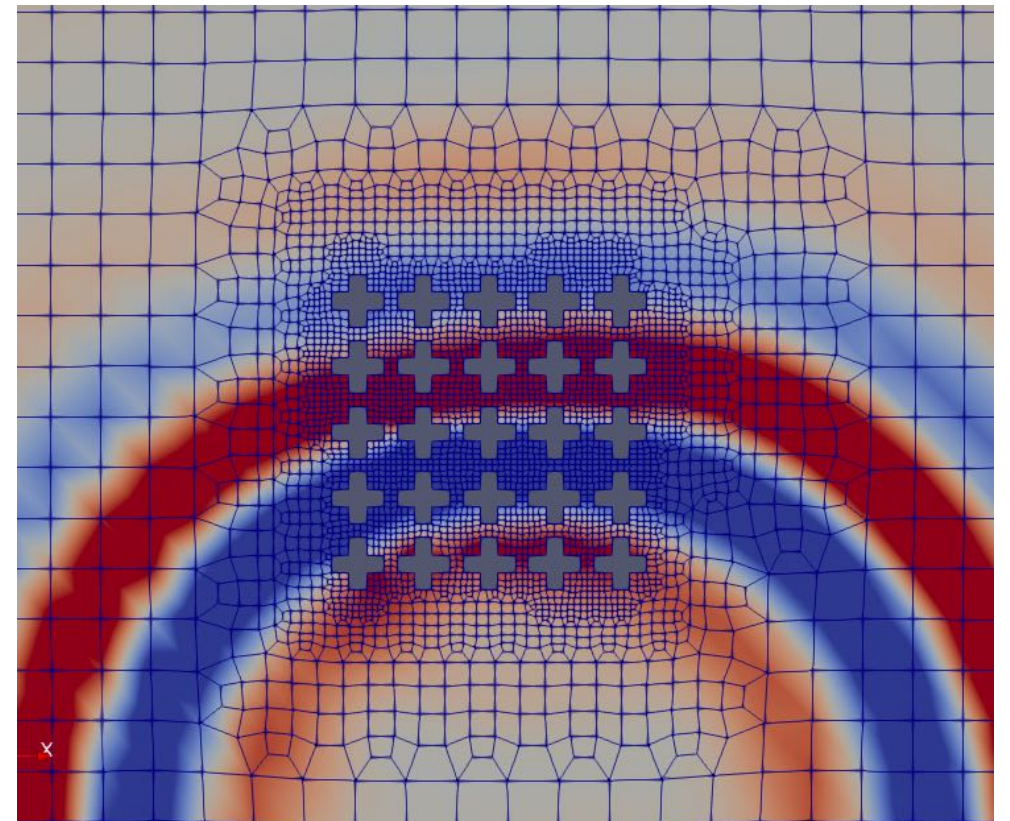
# Circular metamaterials



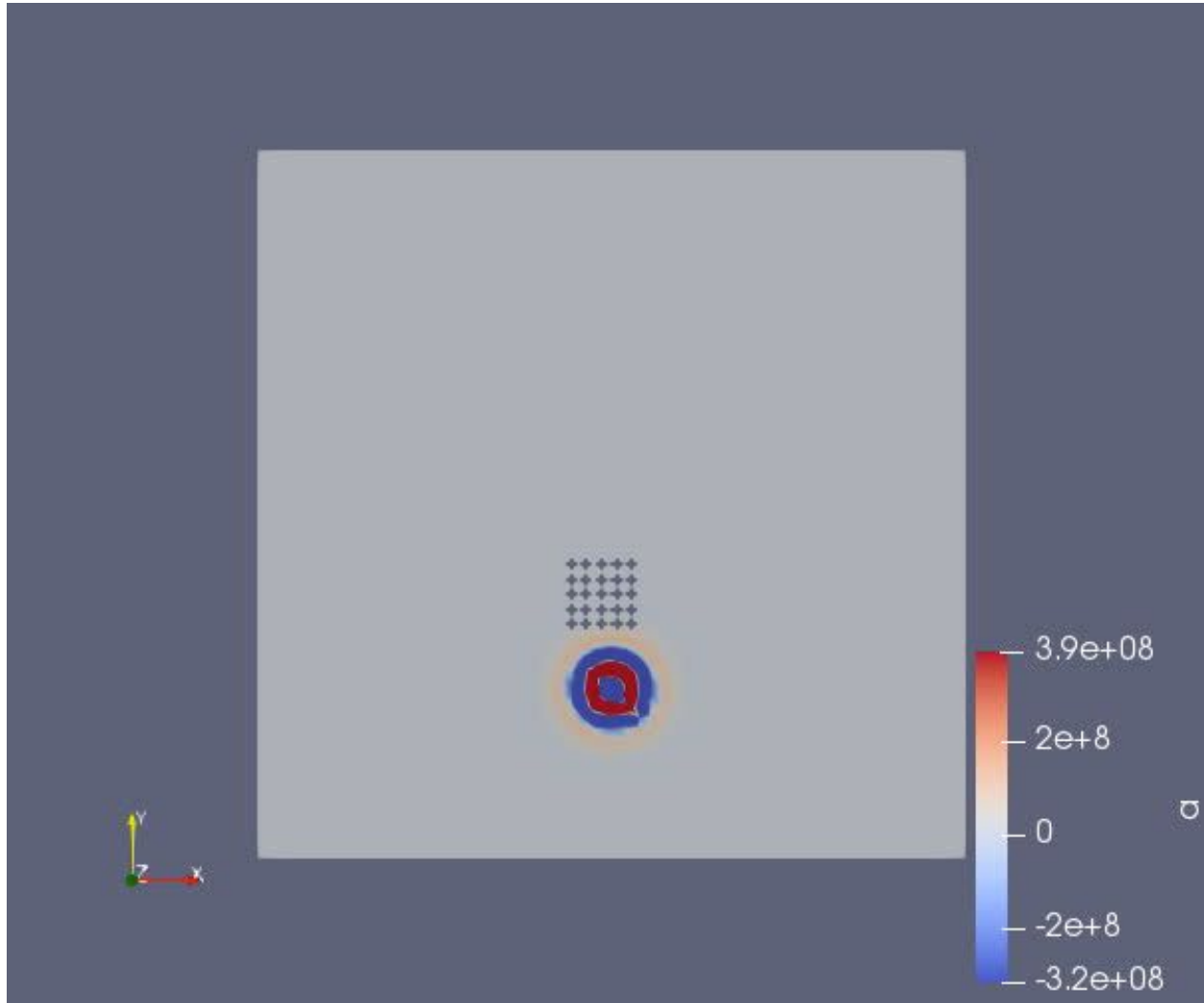
# Model 1



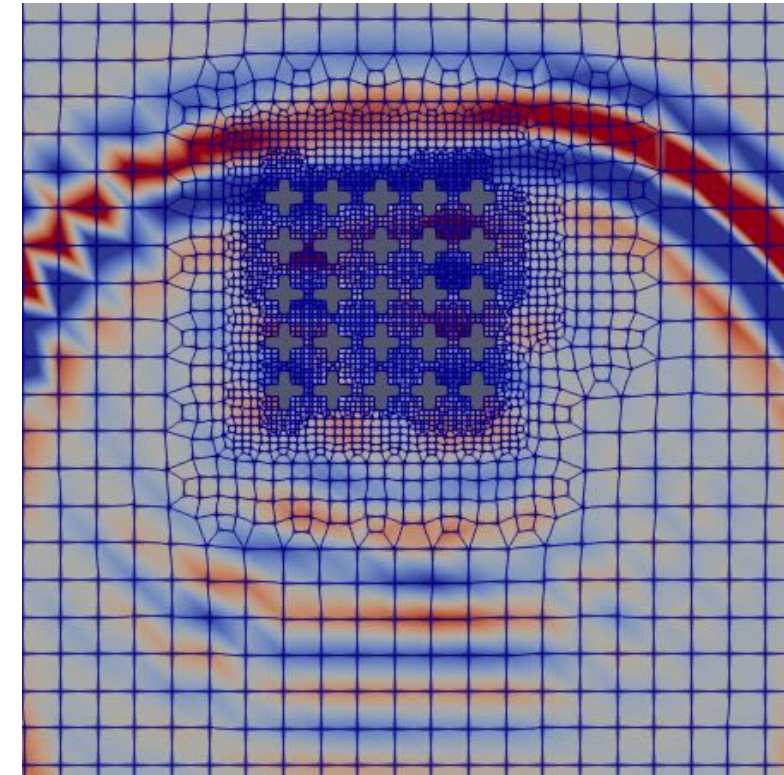
Dominant frequency = 8 Hz (approx 110-180 m)  
 $V_p = 1500$  m/s  
 $V_s = 900$  m/s



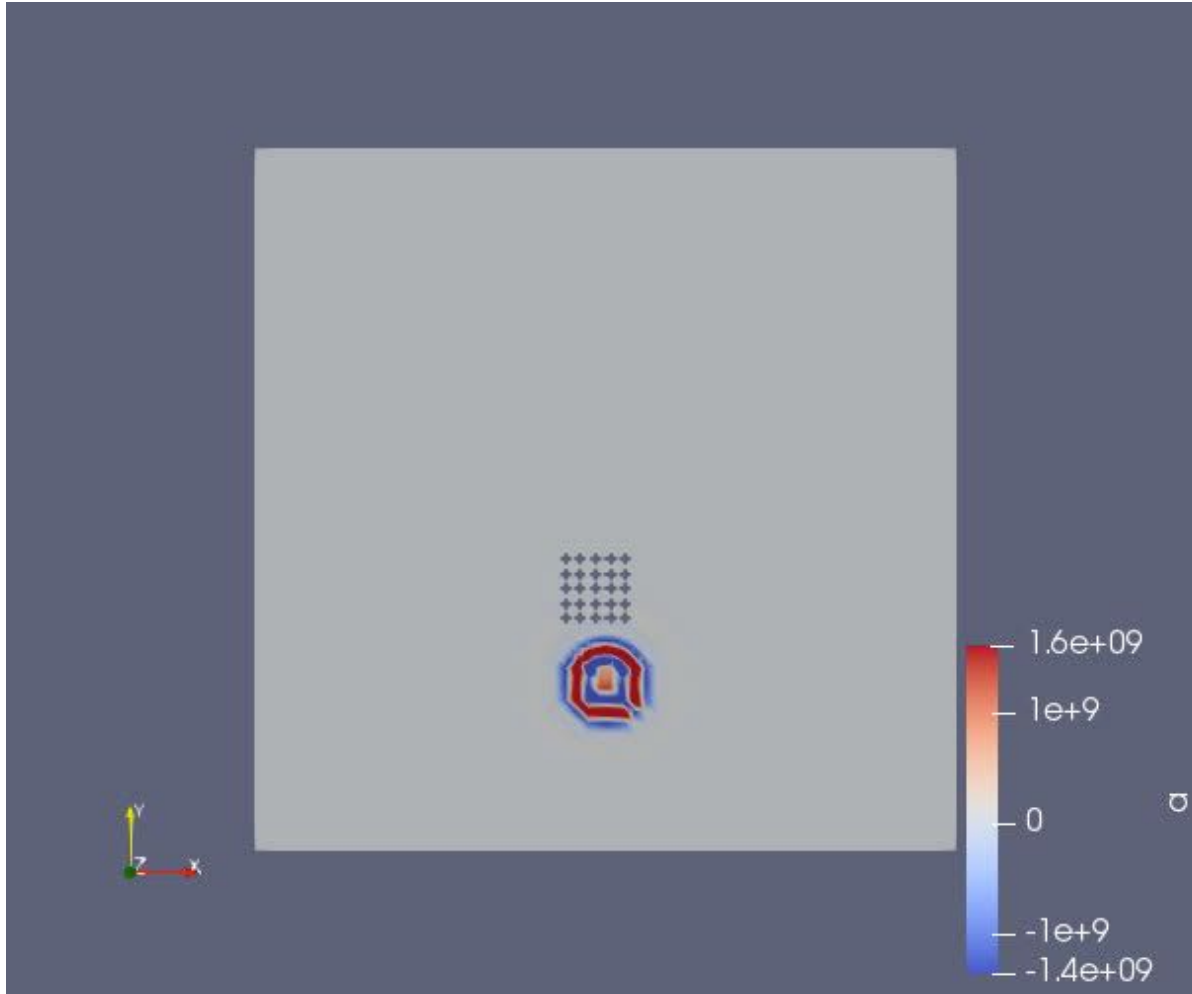
# Model 1



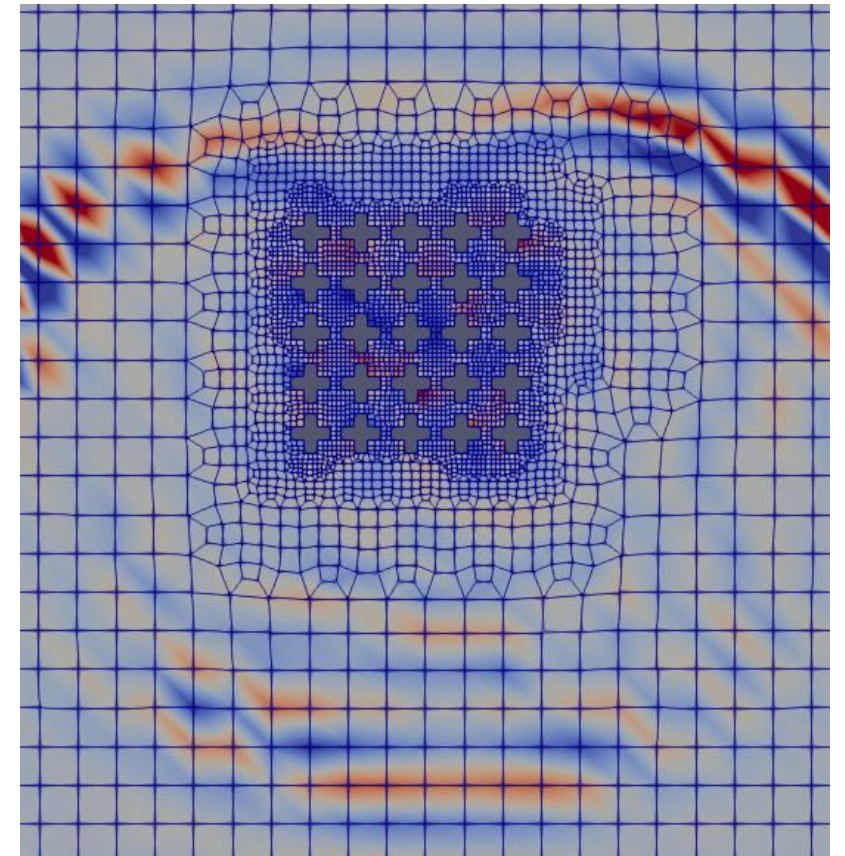
Dominant frequency = 15 Hz (approx 60-100 m)  
 $V_p = 1500$  m/s  
 $V_s = 900$  m/s



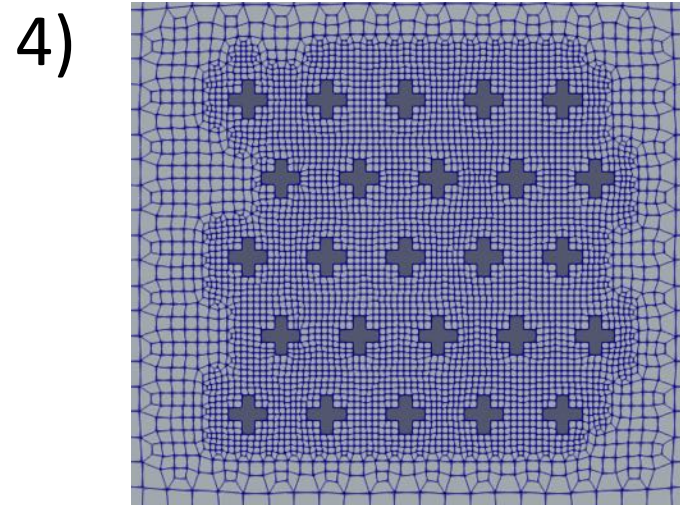
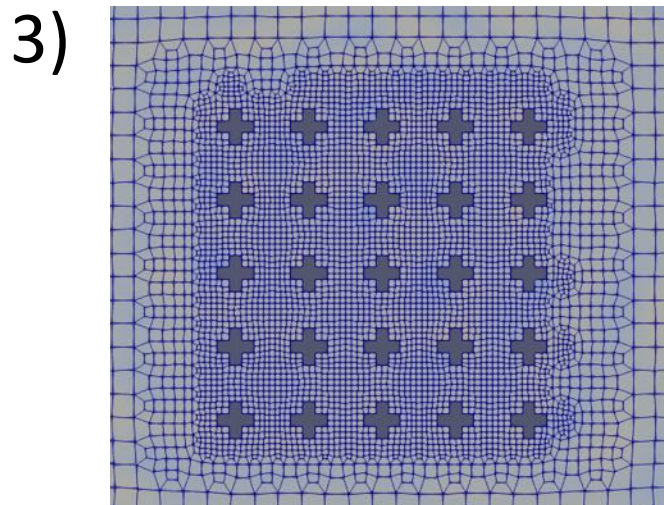
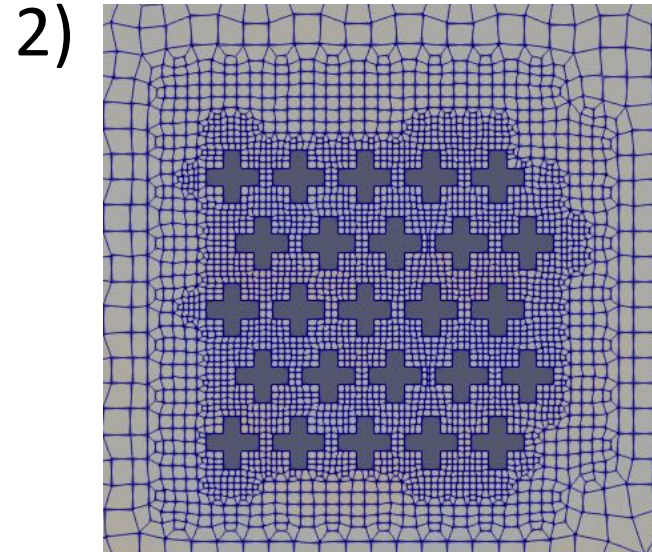
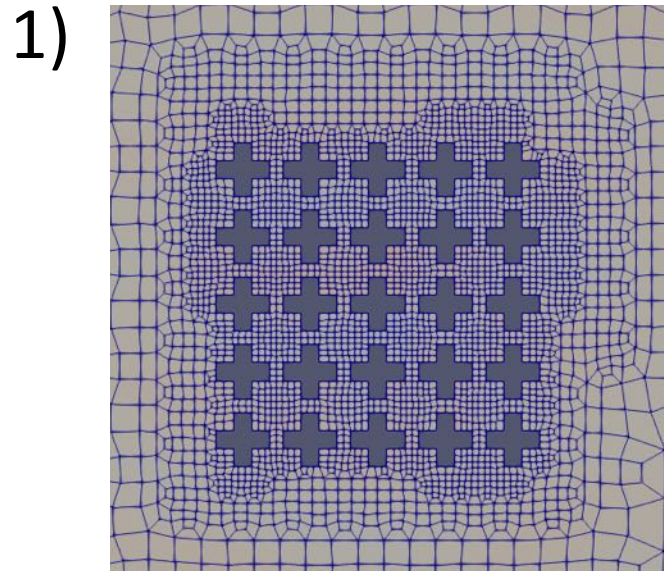
# Model 1



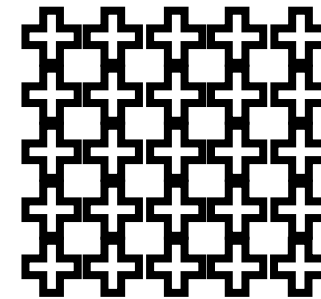
Dominant frequency = 20 Hz (approx 45-75 m)  
 $V_p = 1500$  m/s  
 $V_s = 900$  m/s



# The models



5x5 elements

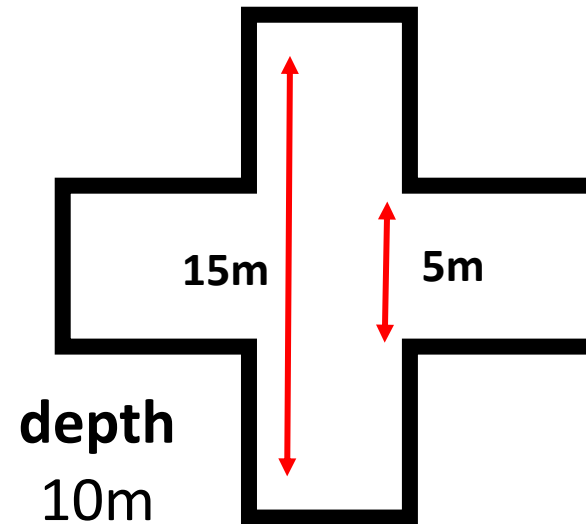


Metamaterials  
dimensions

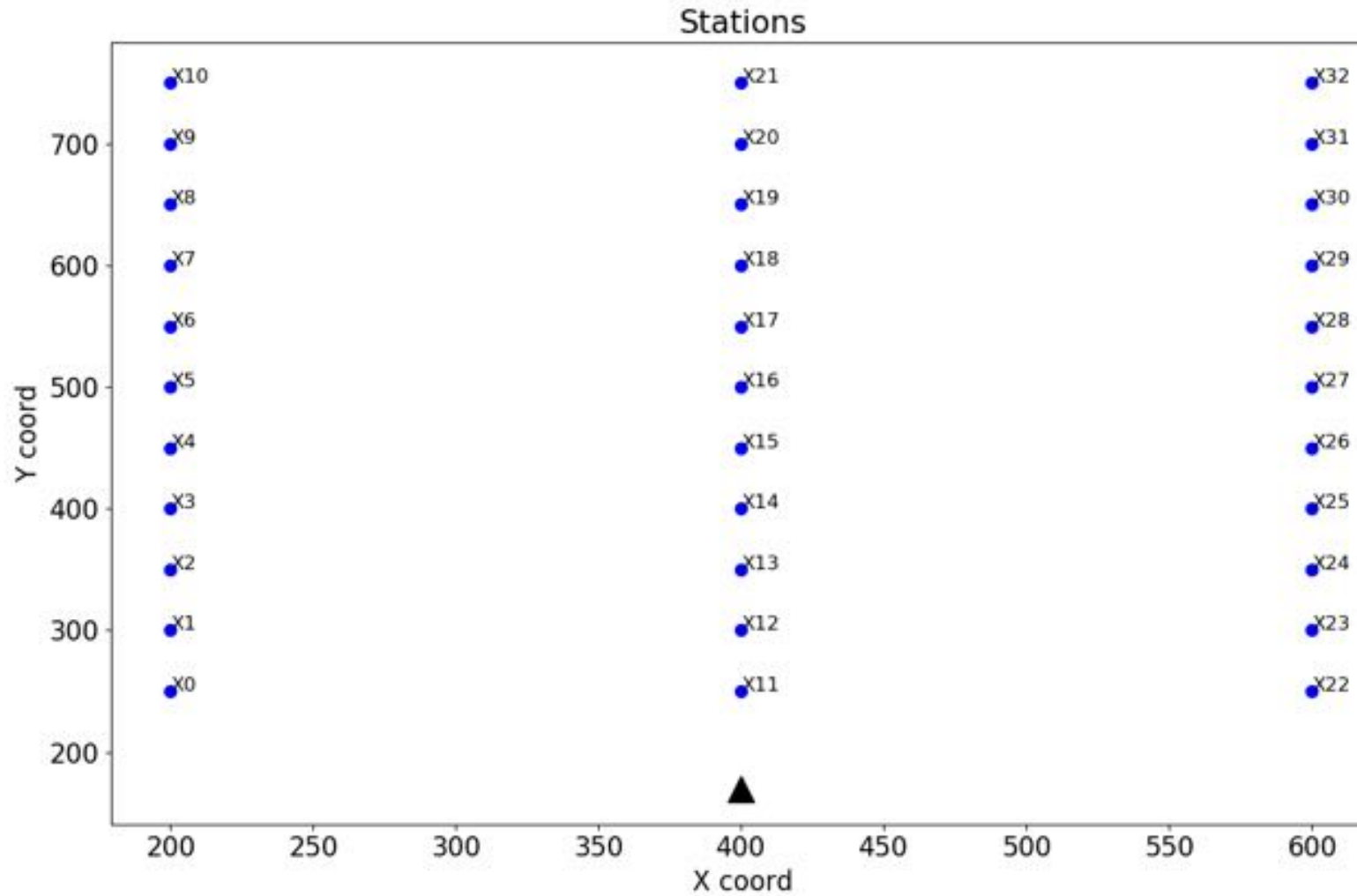
65 m X 65 m



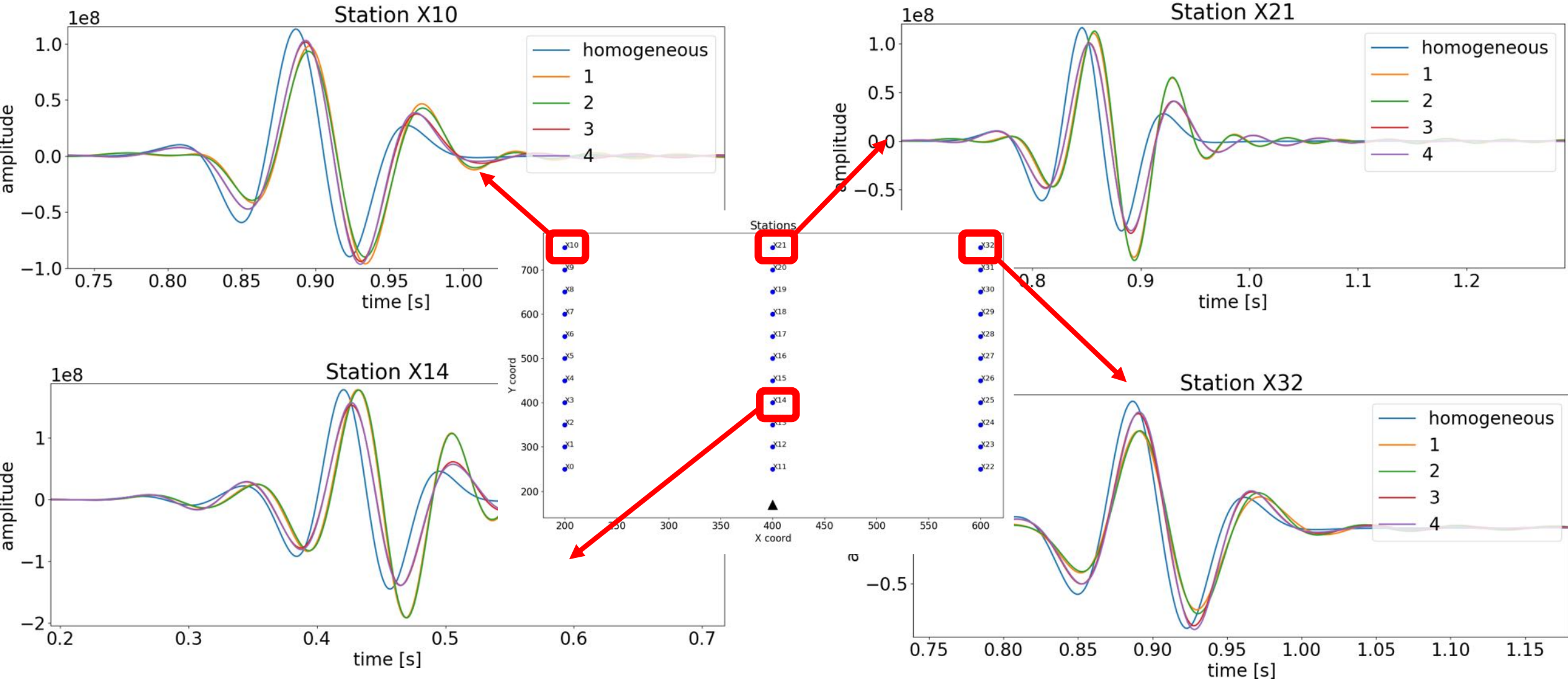
120 m X 120 m



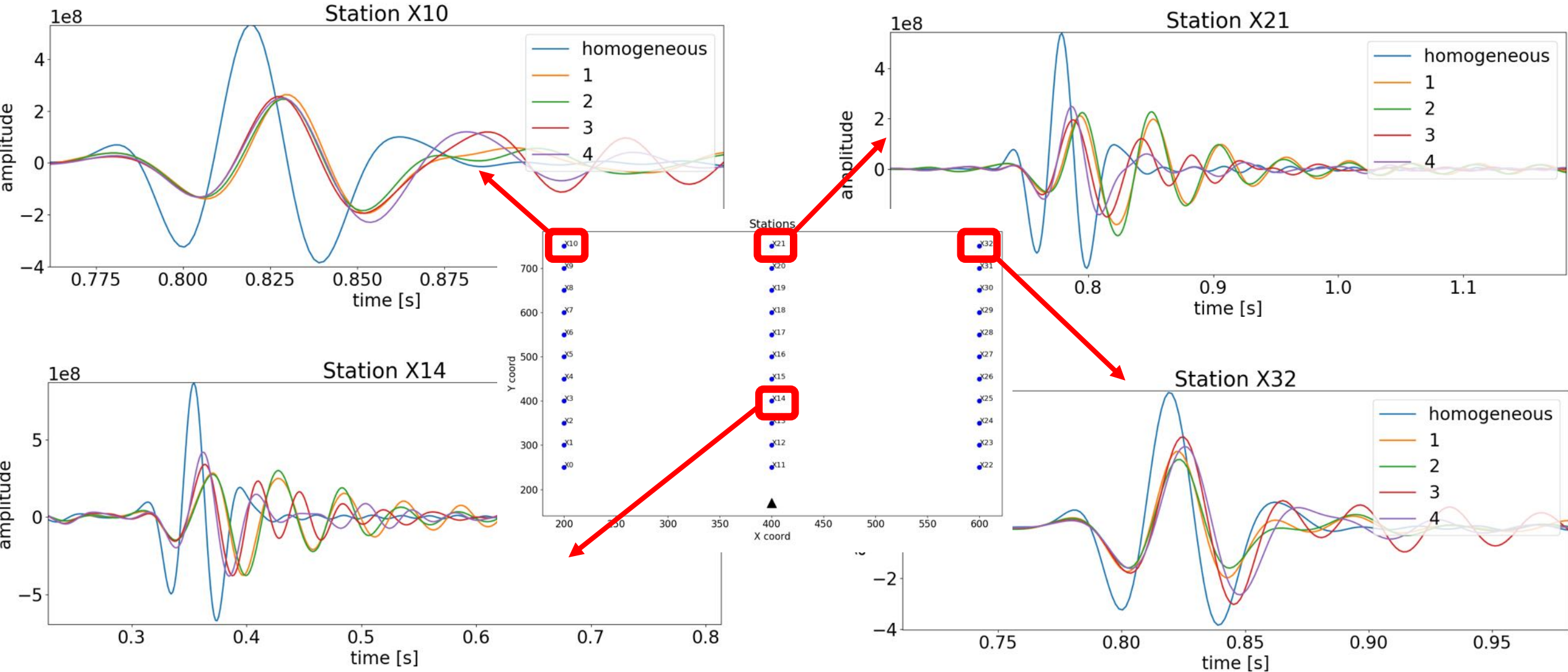
# Seismograms



# Seismograms at 8Hz – cross-shaped metamaterials



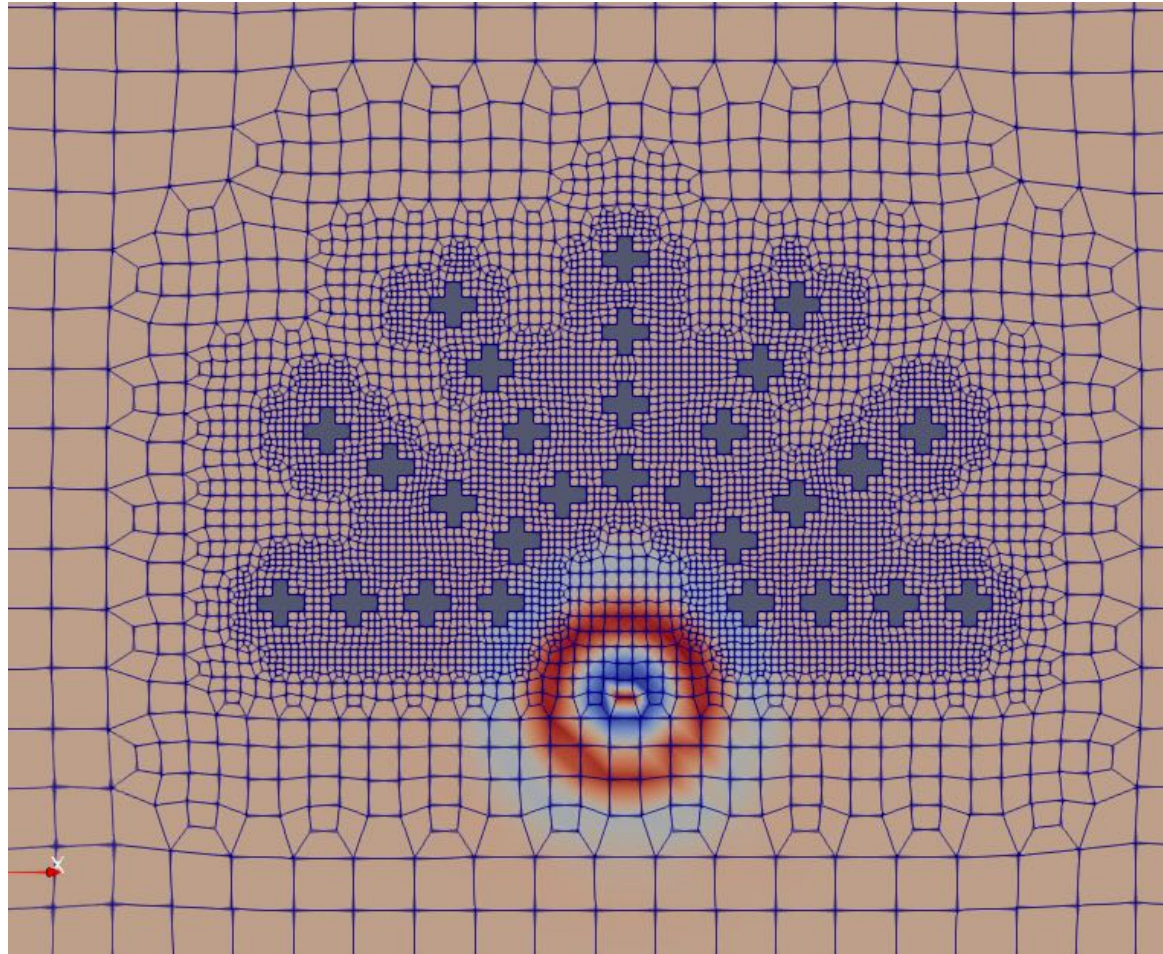
# Seismograms at 15Hz – cross-shaped metamaterials



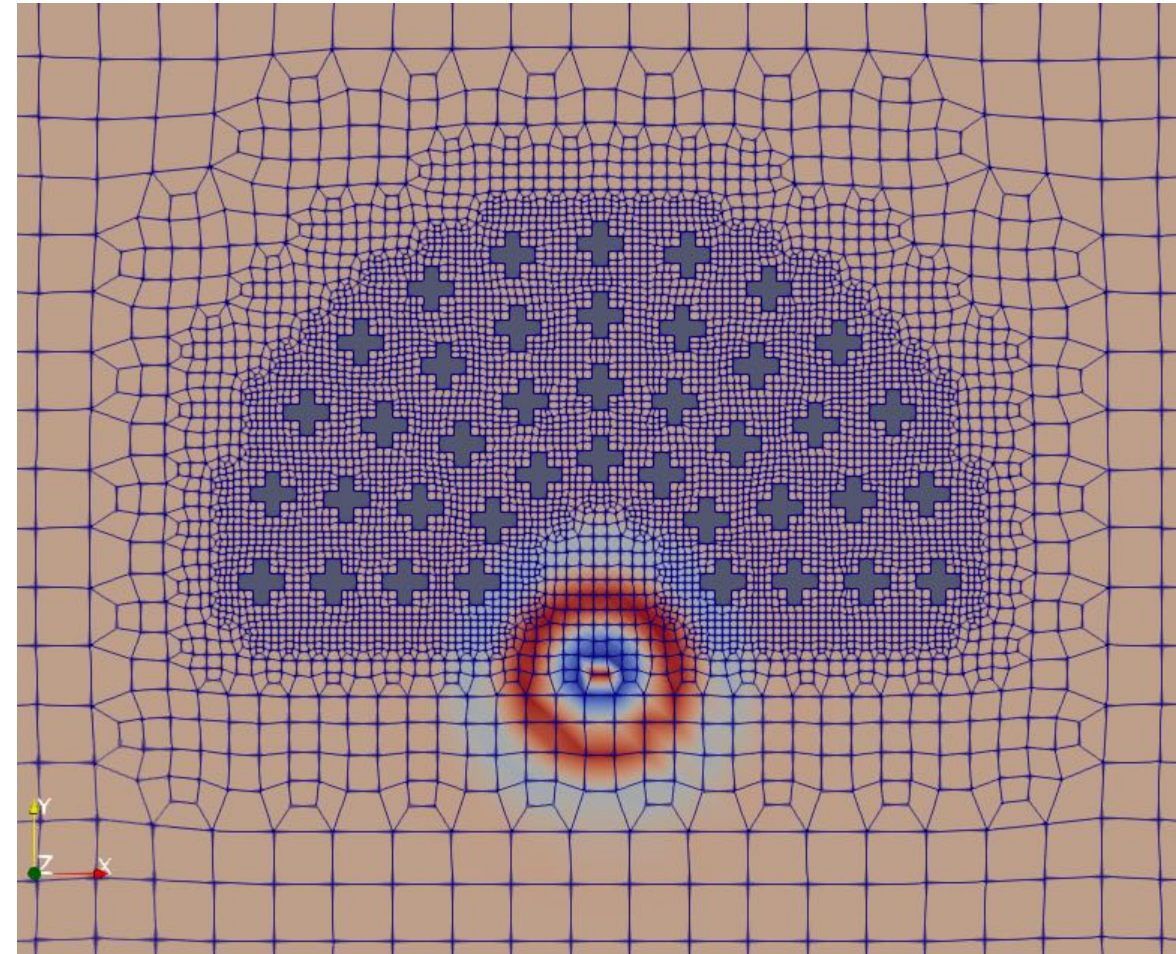


# The models: circular

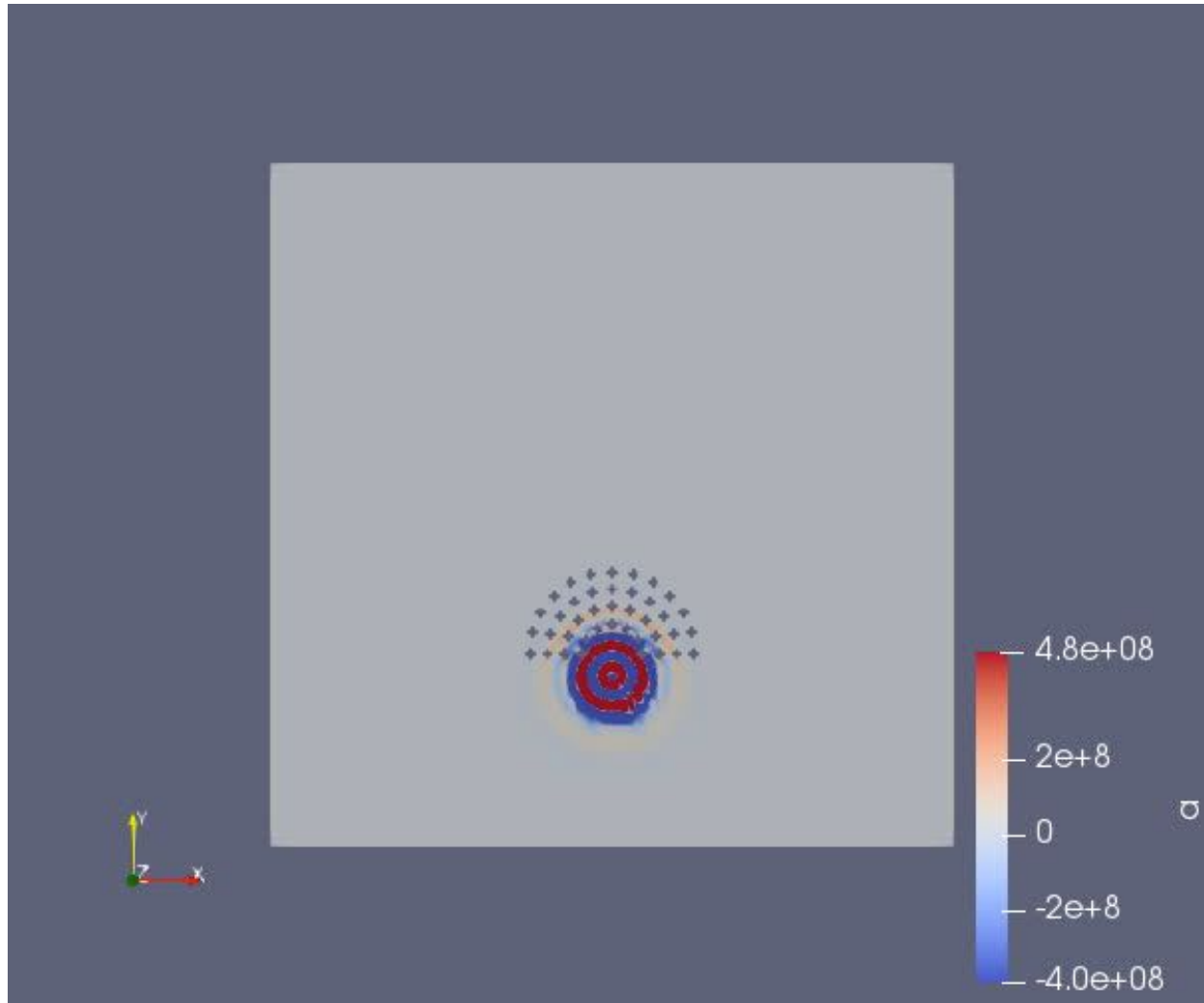
1)



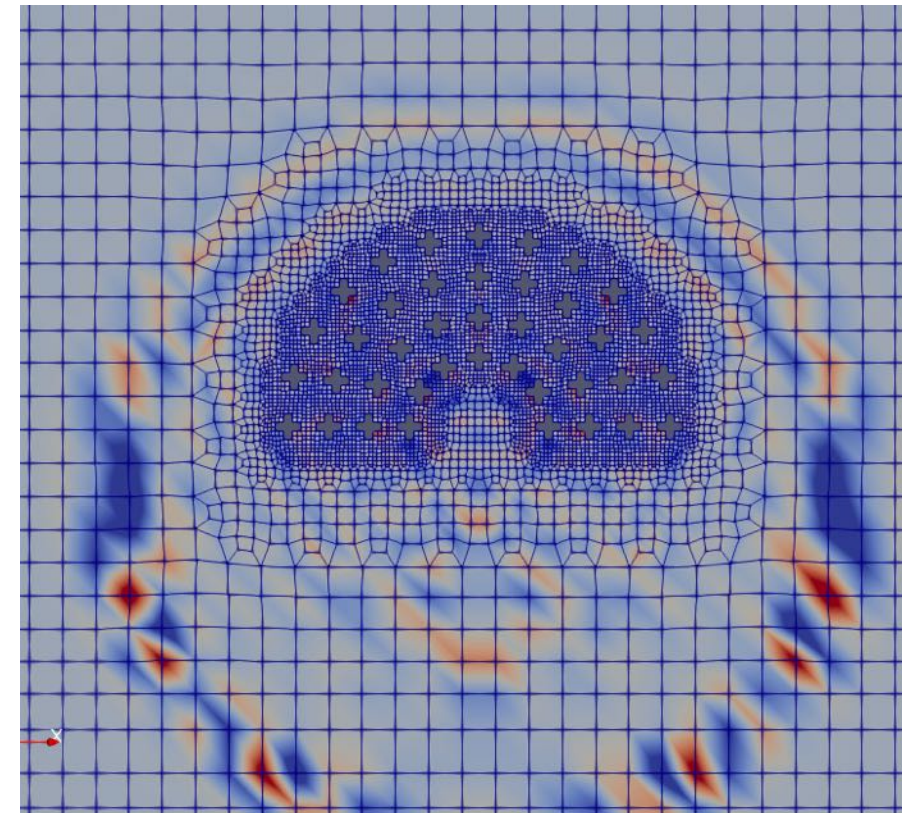
2)



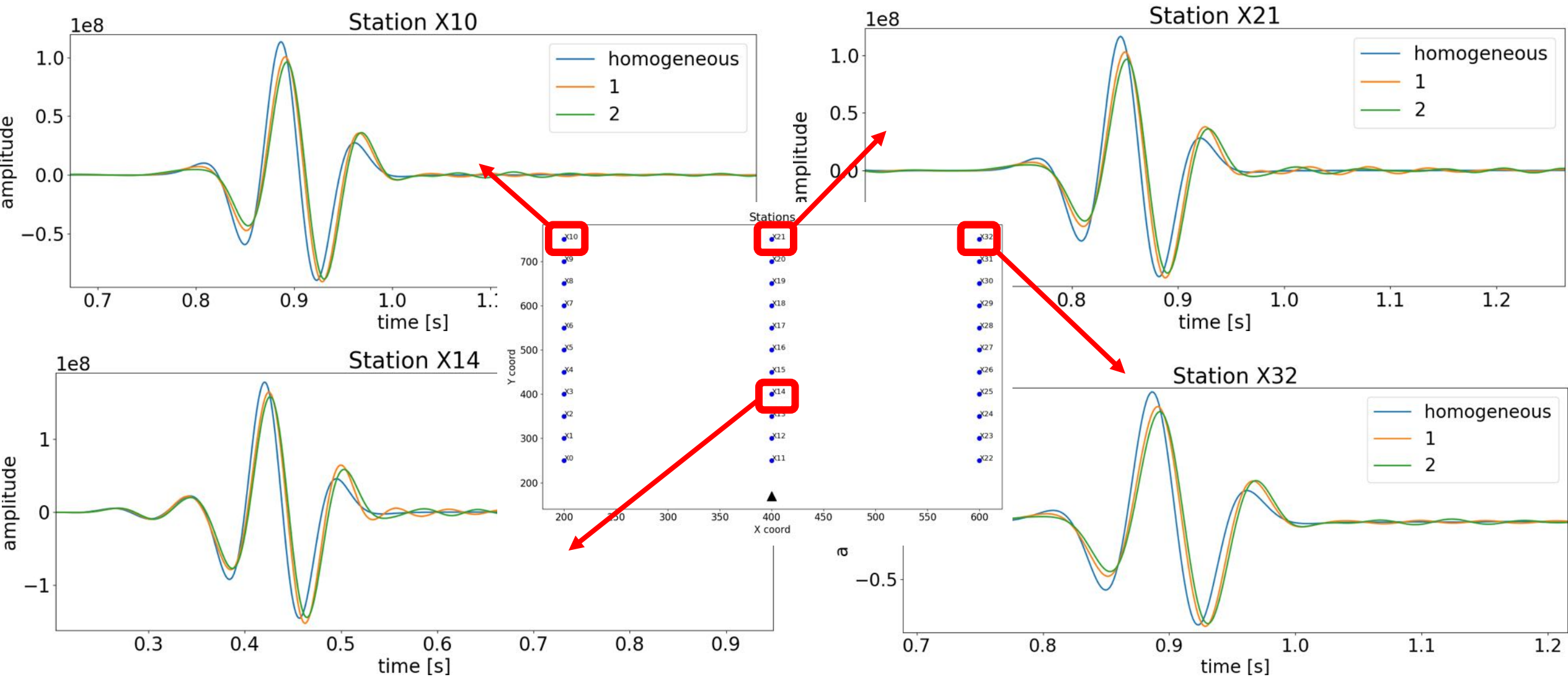
# Circular model 2



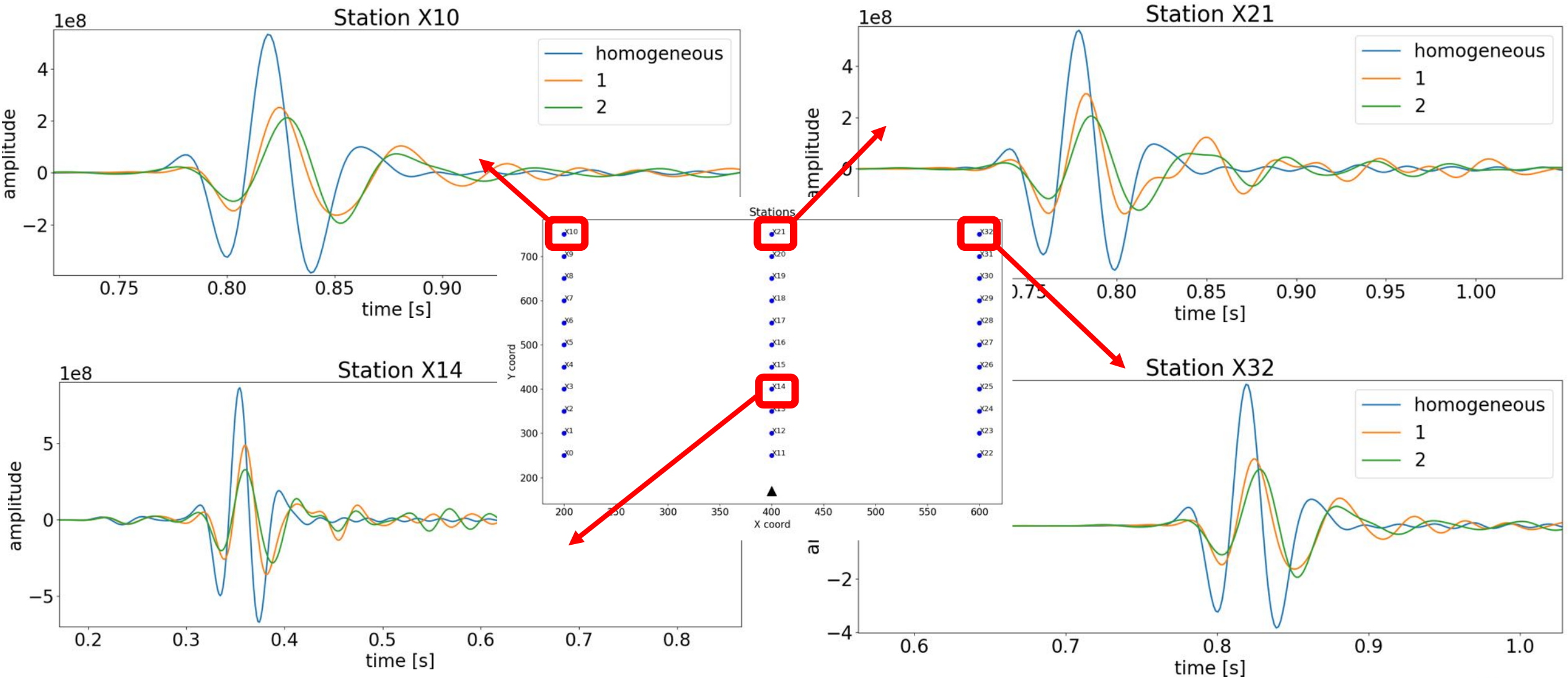
Dominant frequency = 20 Hz (approx 45-75 m)  
 $V_p = 1500$  m/s  
 $V_s = 900$  m/s



# Seismograms at 8Hz – Circular metamaterials

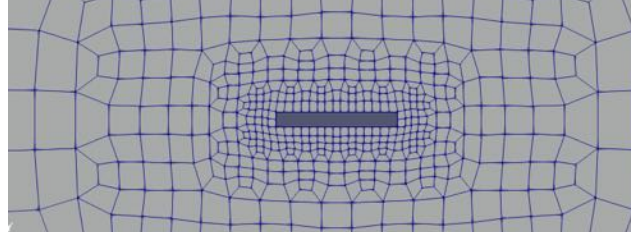


# Seismograms at 15Hz – Circular metamaterials

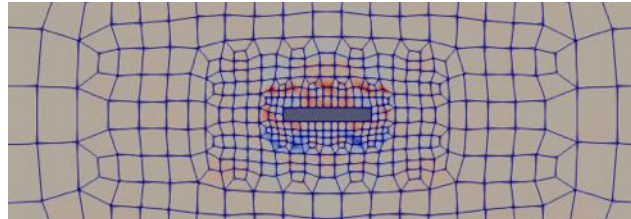


# The models: holes

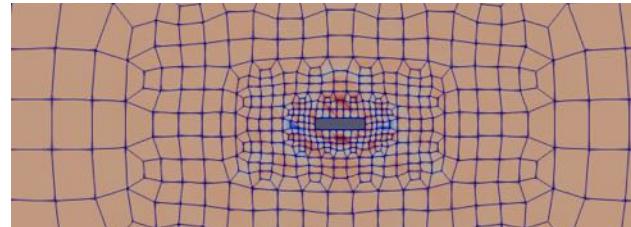
1) 40 m x 5 m x 20 m (deep)



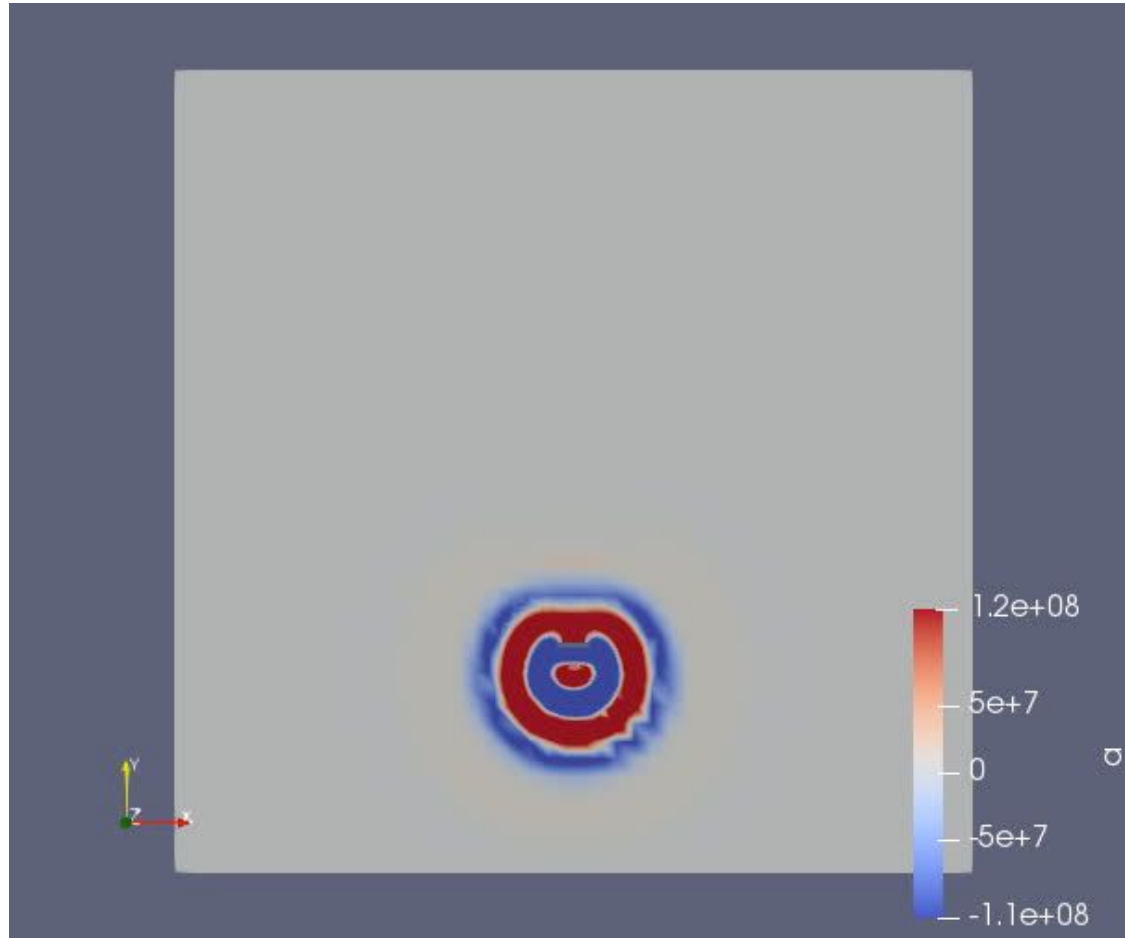
2) 30 m x 5 m x 10 m (deep)



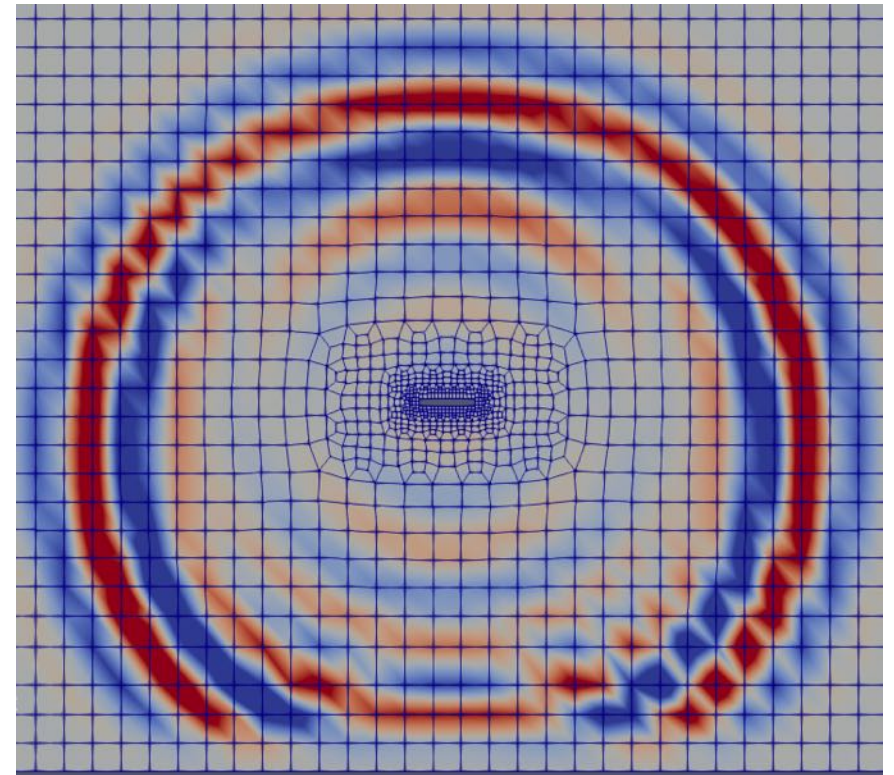
3) 20 m x 5 m x 10 m (deep)



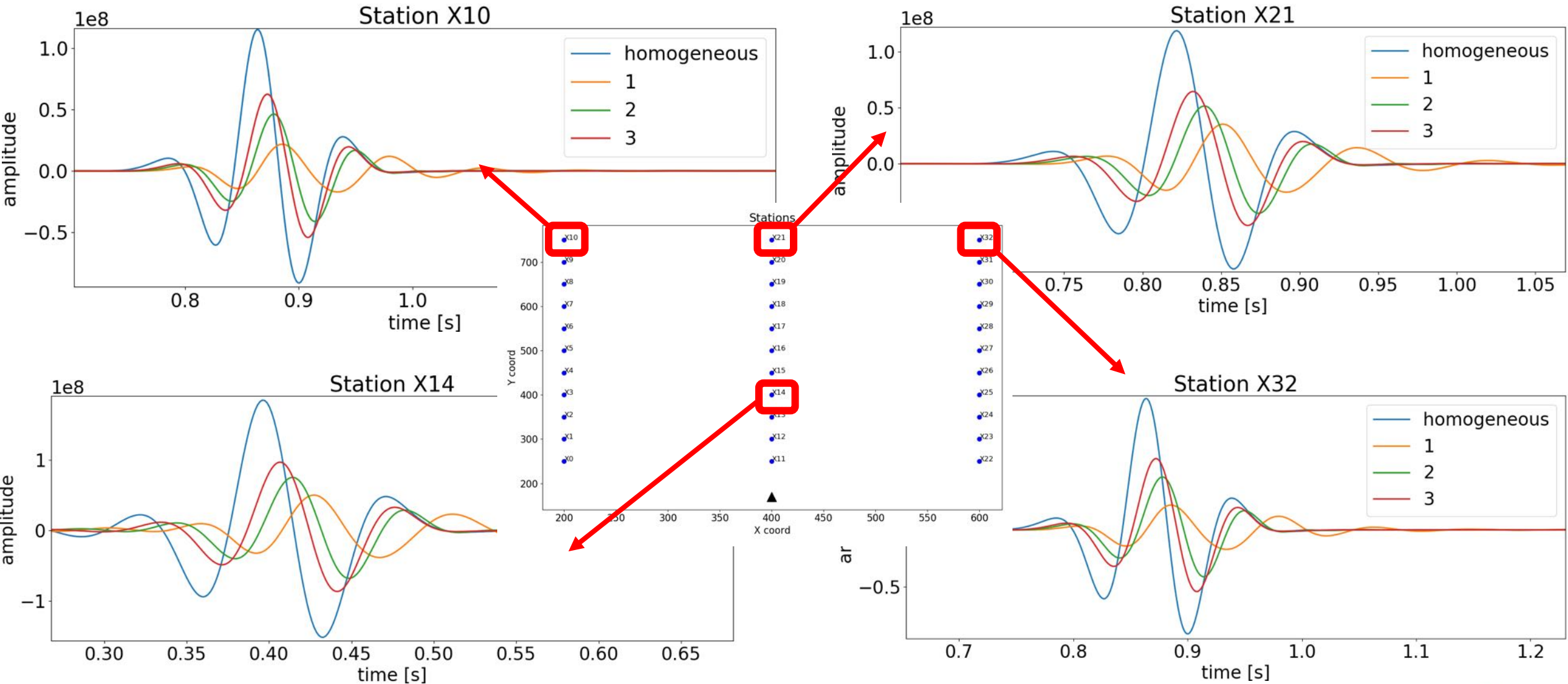
# Holes



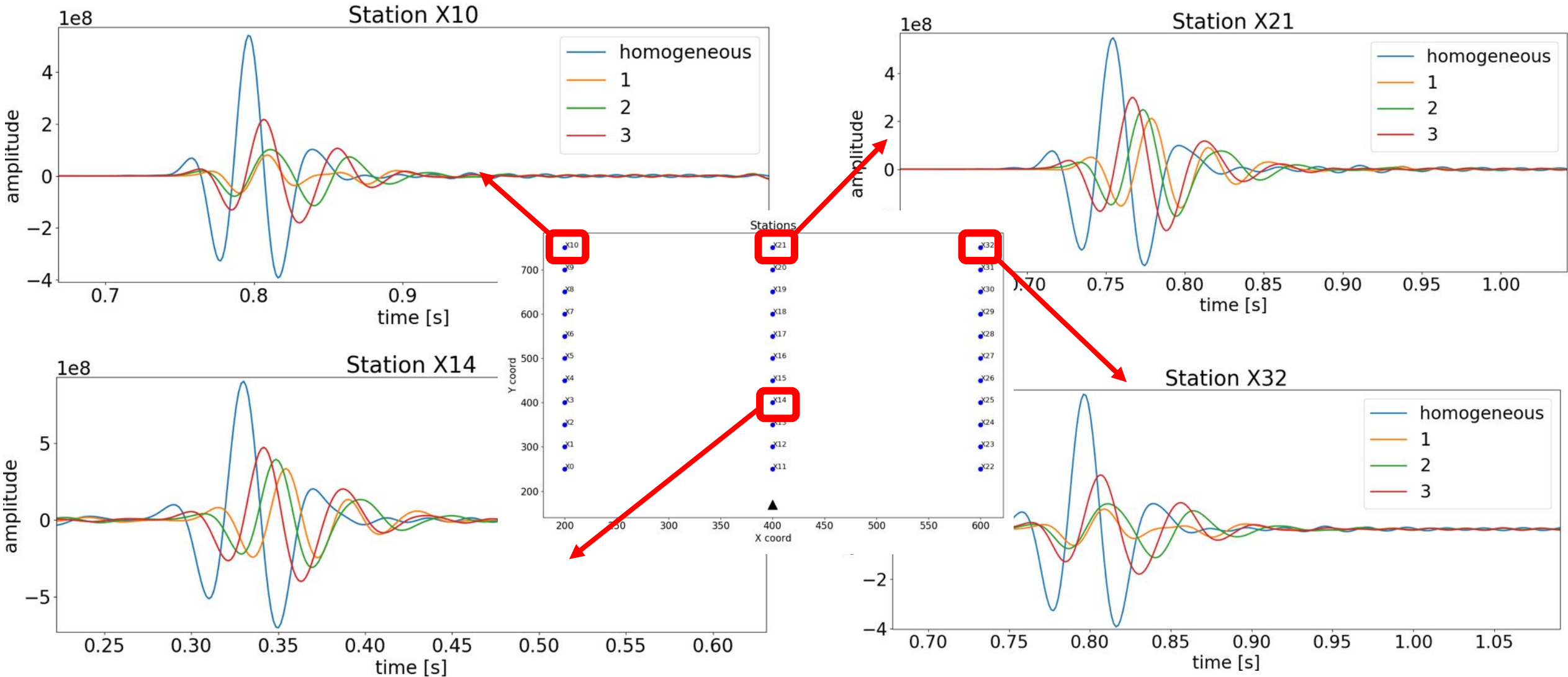
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# Seismograms at 8Hz -- Holes

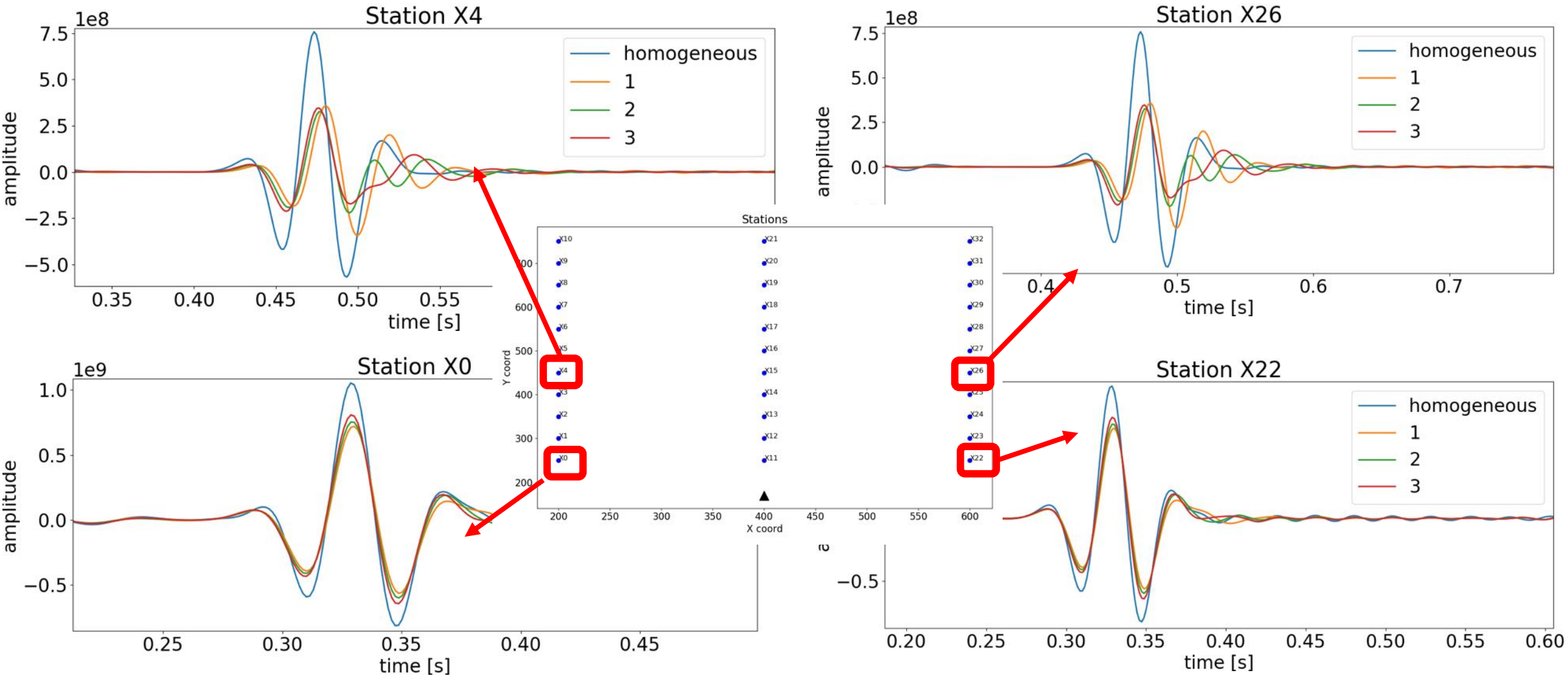


# Seismograms at 15Hz -- Holes

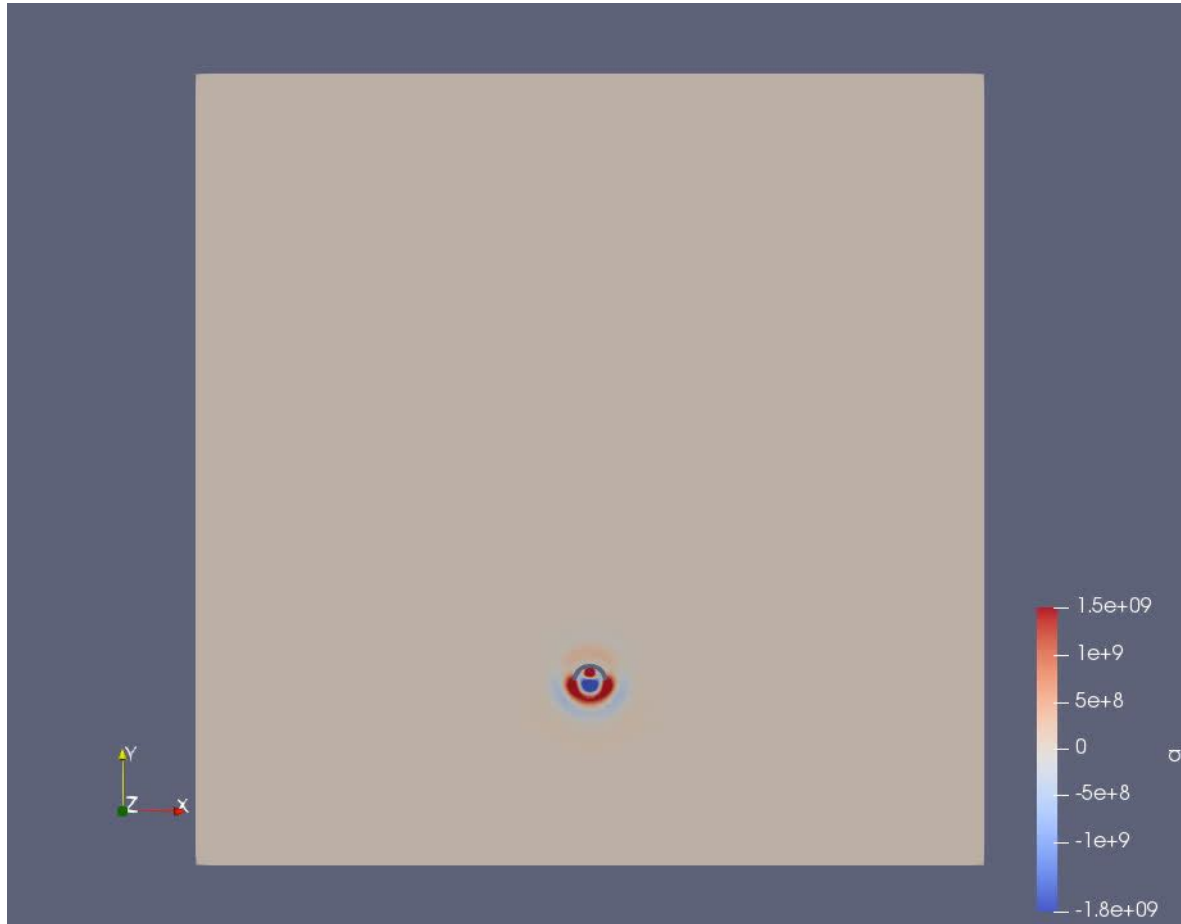




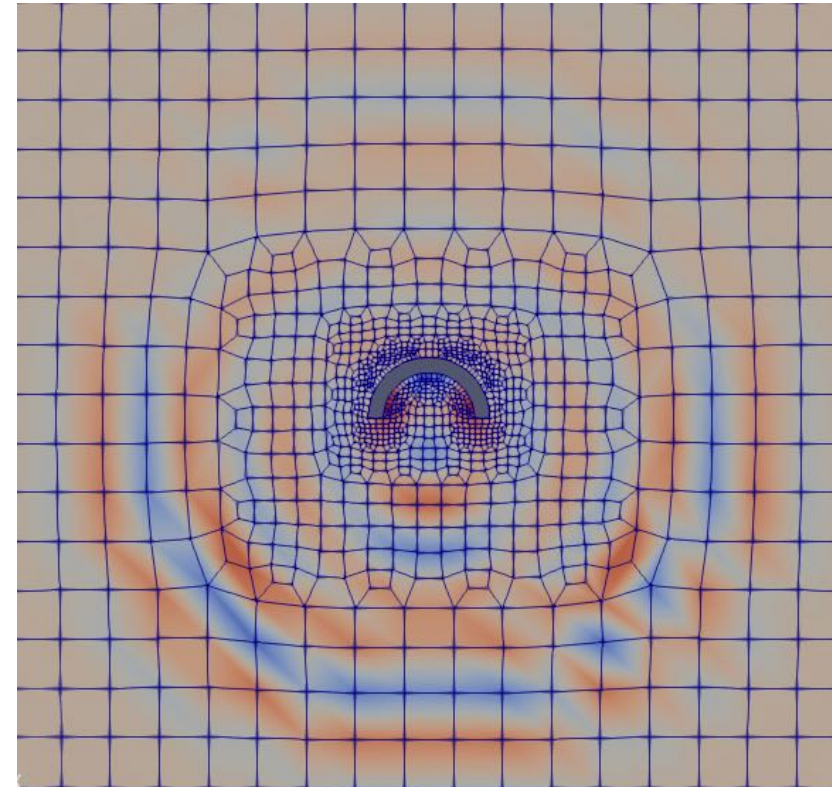
# Seismograms at 15Hz -- Holes



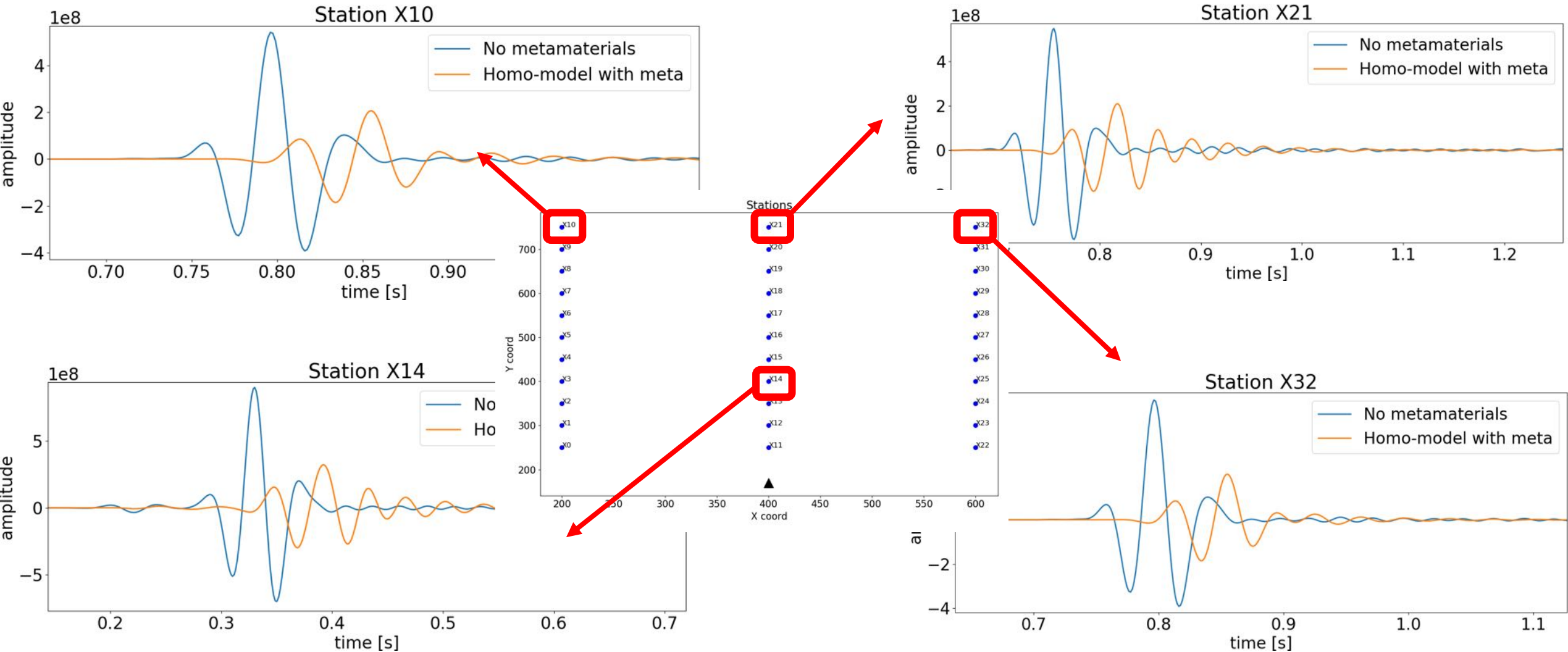
# Half-circular holes



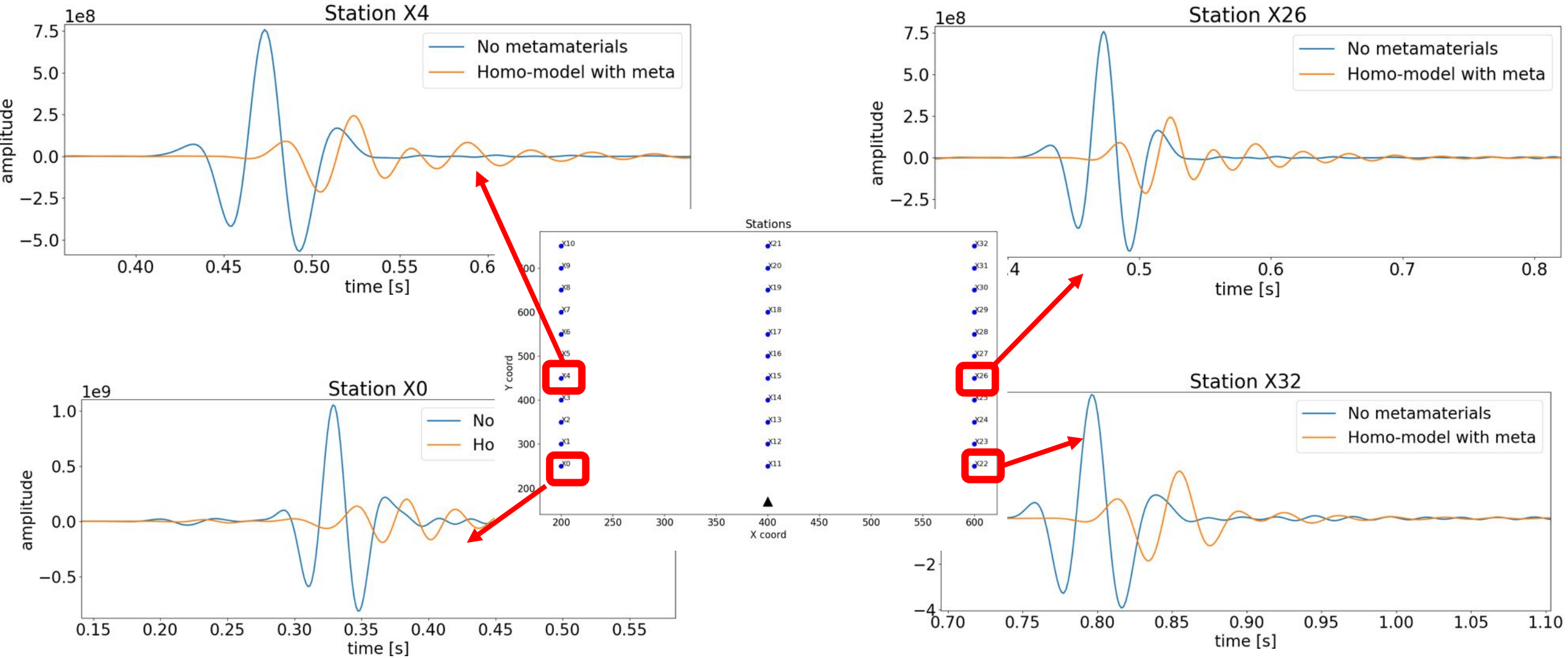
Dominant frequency = 15 Hz (approx 60-100 m)  
 $V_p = 1500$  m/s  
 $V_s = 900$  m/s



# Seismograms at 15Hz – half circular holes

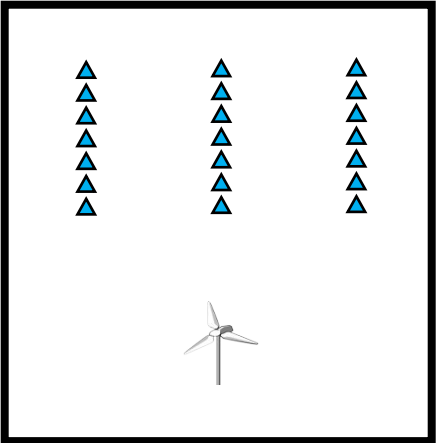


# Seismograms at 15Hz – half circular holes

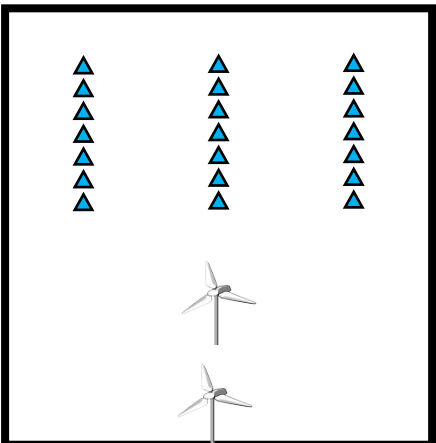


# Influence of wind-turbine locations

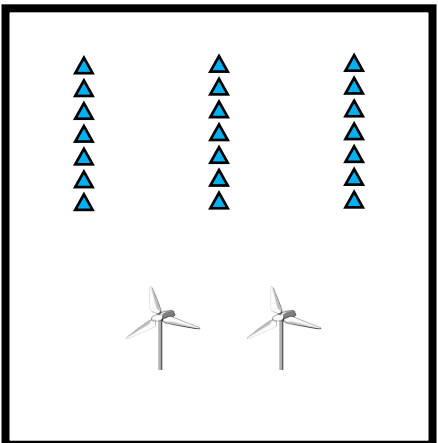
a) Single



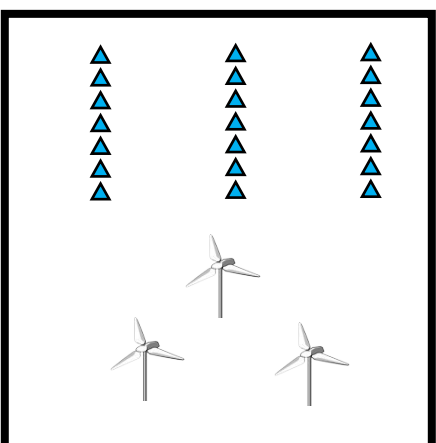
b) Two vertical



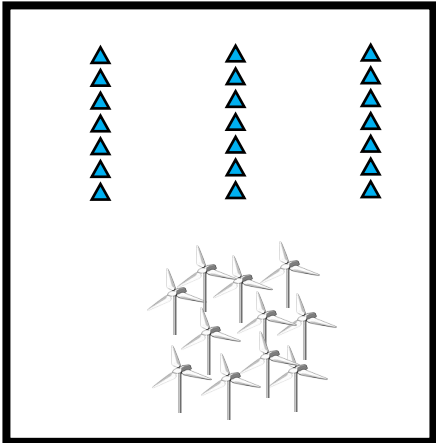
c) Two horizontal



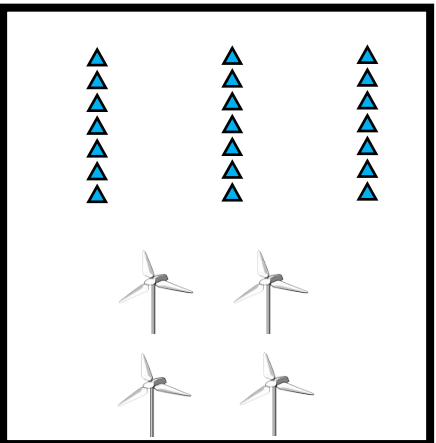
d) Triangle



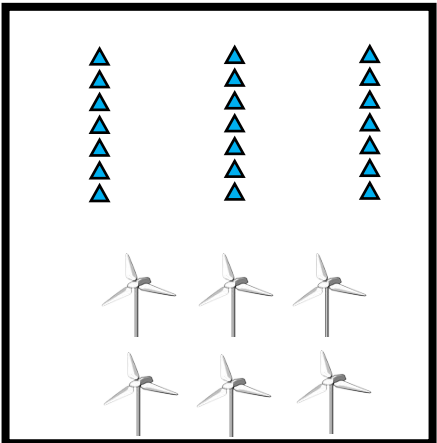
i) Random



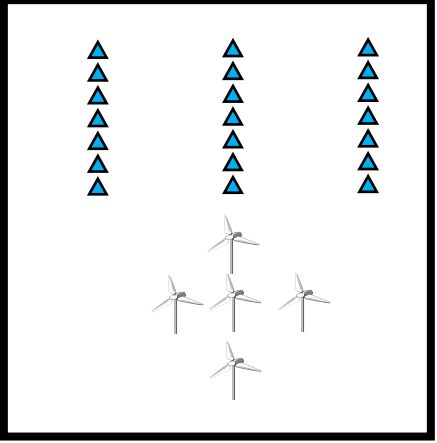
e) Square



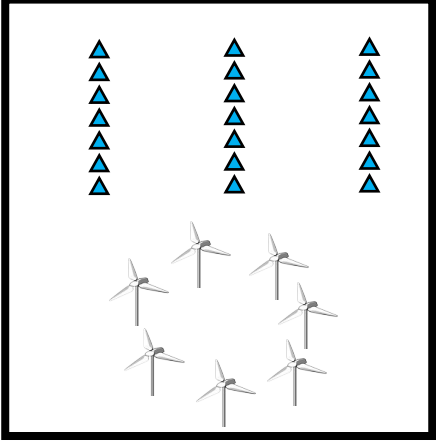
f) Rectangle



g) Crux

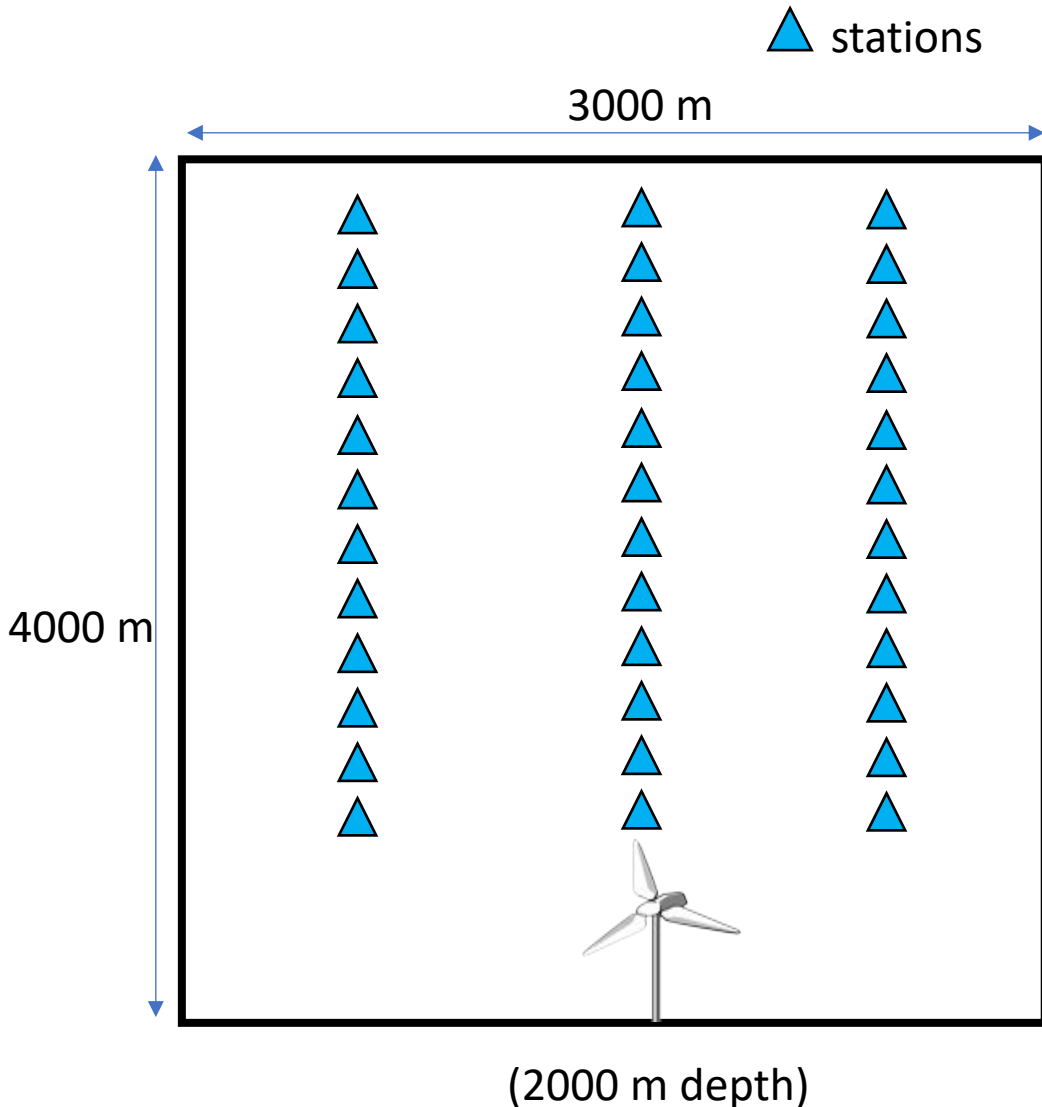


h) Circular



# Numerical experiments: setup

## Test models



Simulation of data using 3D models with one source and different model set-ups: homogeneous, velocity increase and 3 layers

$V_p = 1200 \text{ m/s}$   
 $V_s = 900 \text{ m/s}$

**homogeneous**

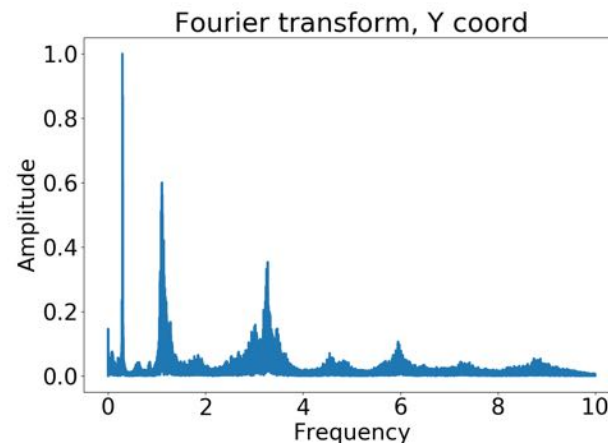
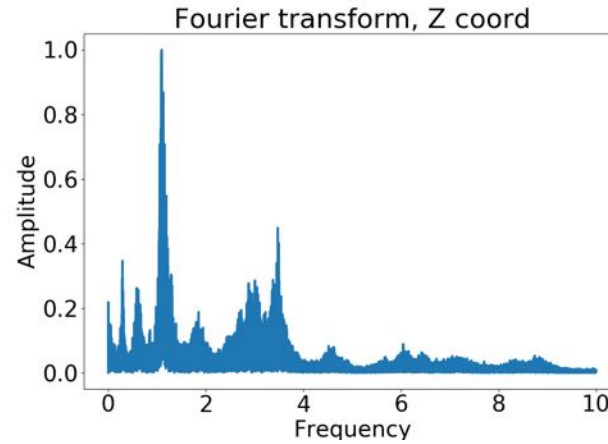
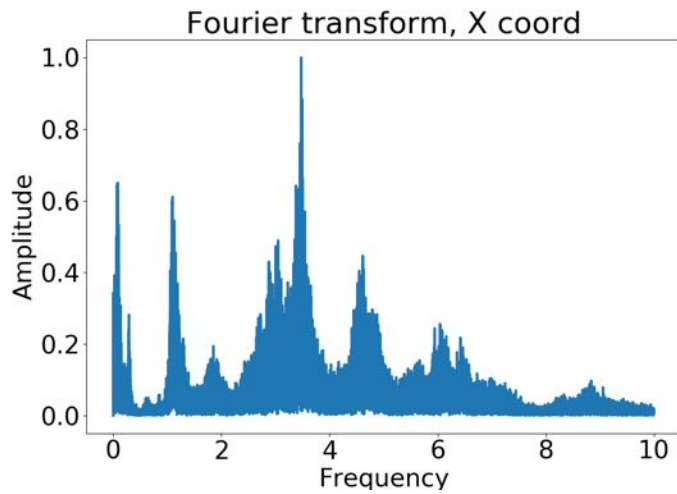
$V_p = 1200 \text{ m/s}$   
 $V_s = 900 \text{ m/s}$

**gradient**

$V_p = 2500 \text{ m/s}$   
 $V_s = 1400 \text{ m/s}$

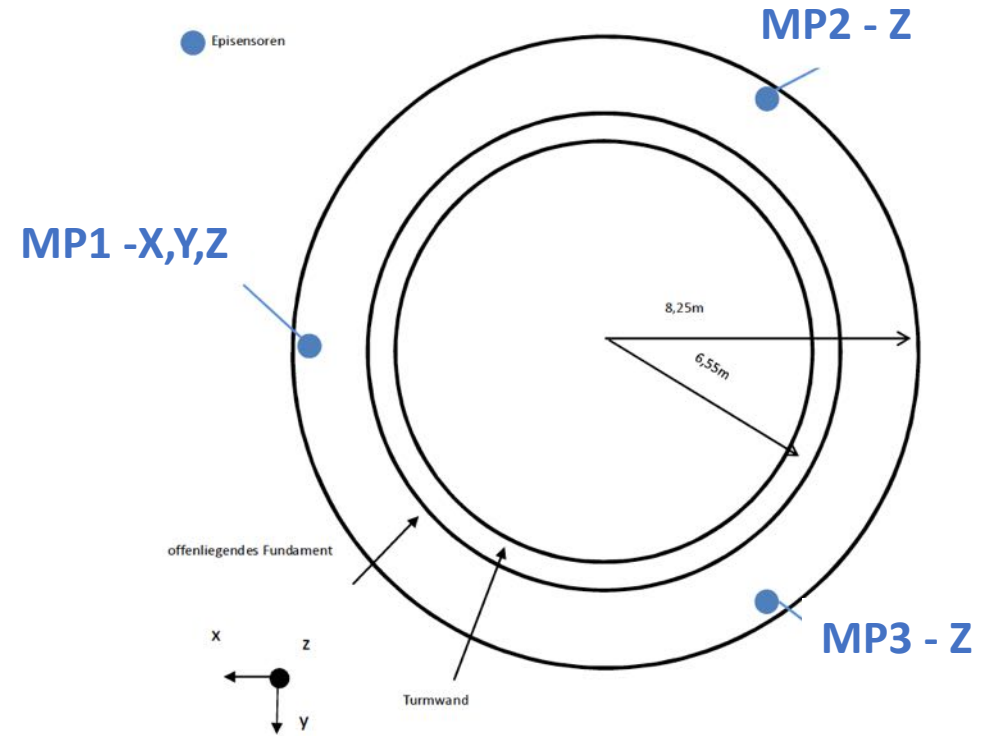
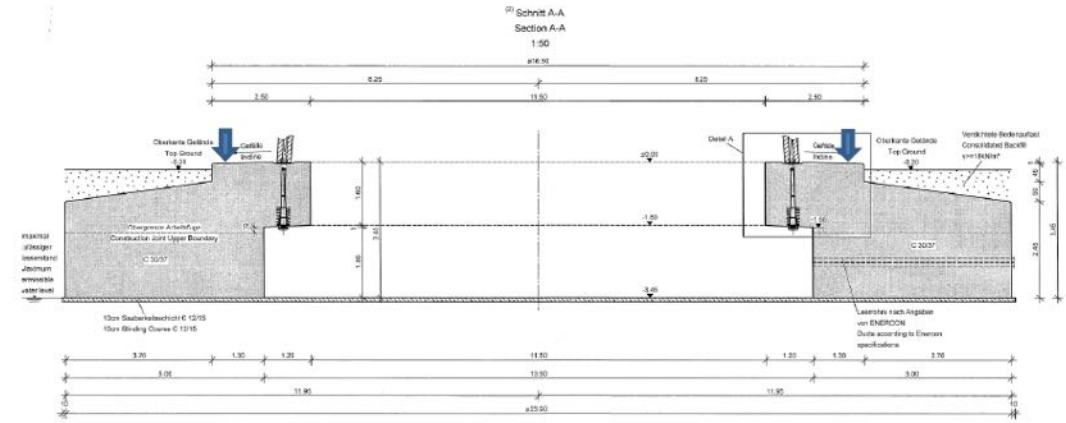
# BHM collected data

## STATION MP1



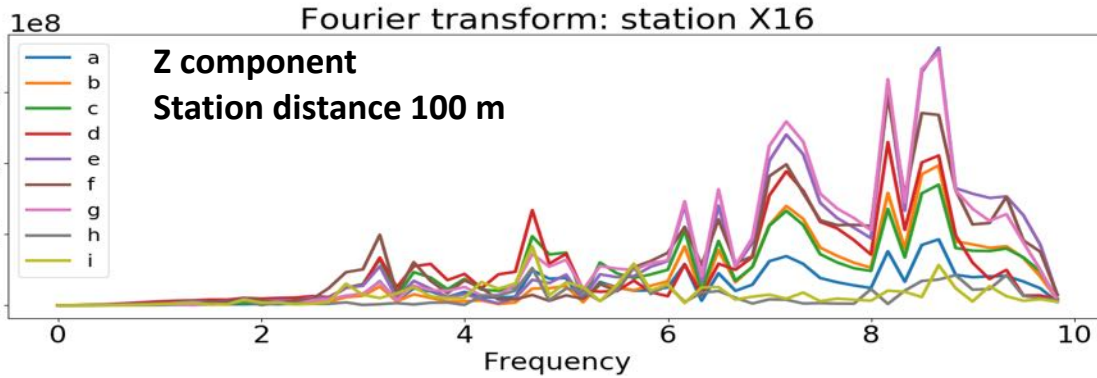
Velocity spectra  
entire trace

Layout of measuring points:

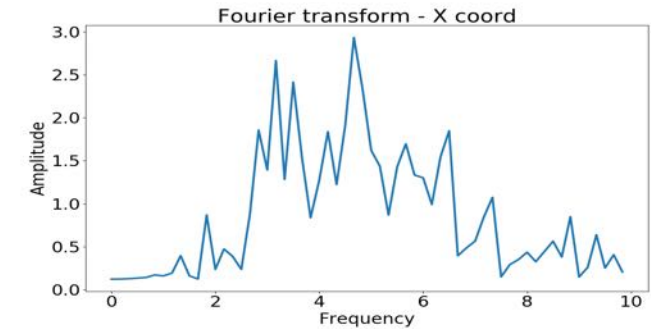


# BHM data and simulations: spectra comparison

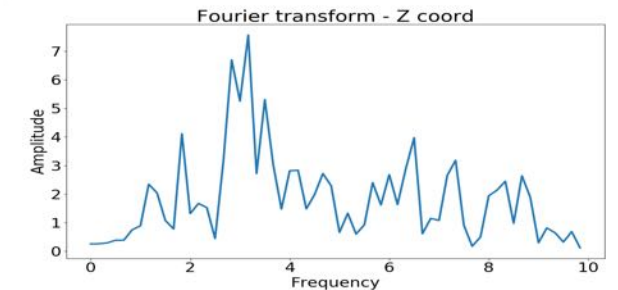
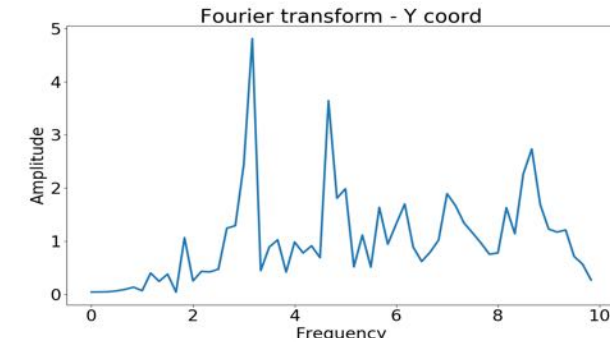
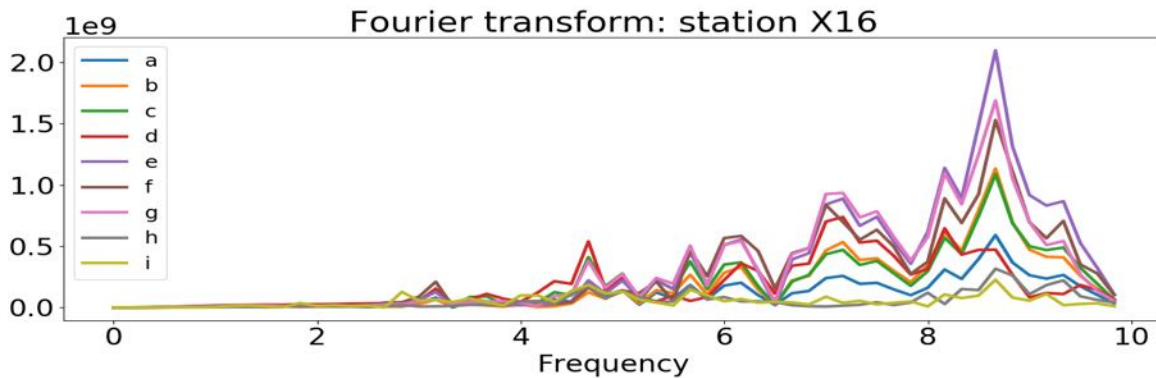
Homogeneous model



Combined source time functions in 3 directions, measured at MP1



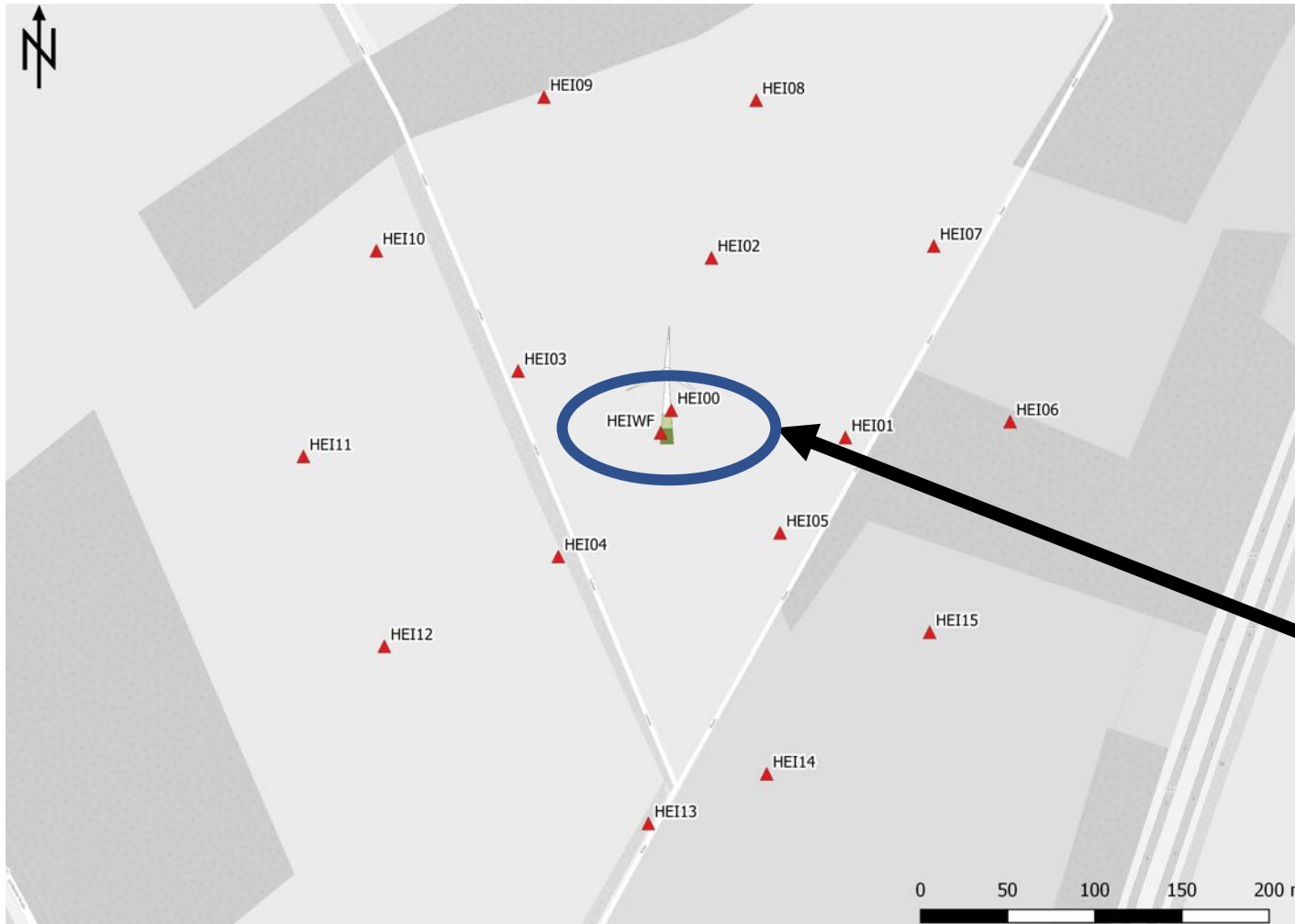
Layered model



Spectra show peaks, they are different from z-comp measured spectra due to combination of 3 spectra for source. Peaks seem to have large amplitudes at different frequencies for different models



# Data from DMT



BHM have only stations at foundation of WEA. To compare path effects, we use measured data from DMT.

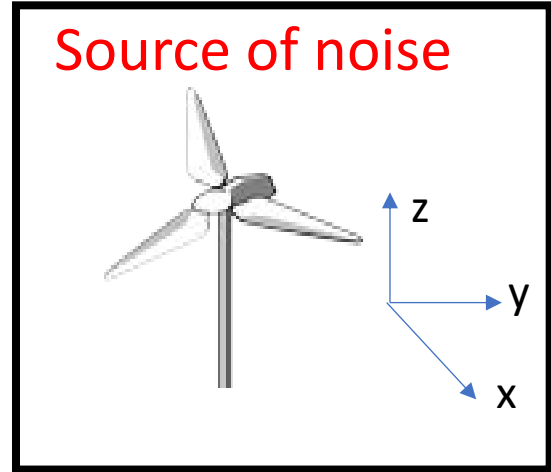
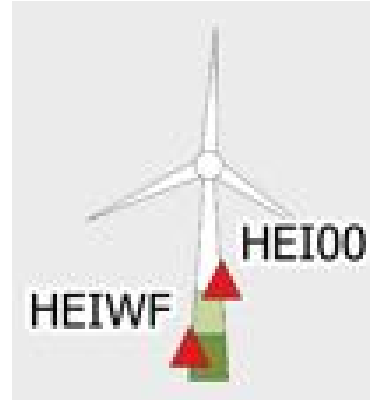
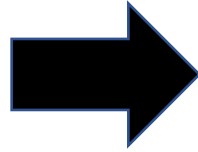
Stations at the Wind-turbine:

- HEI00
- HEIWF

*Low and high wind speeds velocity measurements*

# Different types of noise sources from DMT

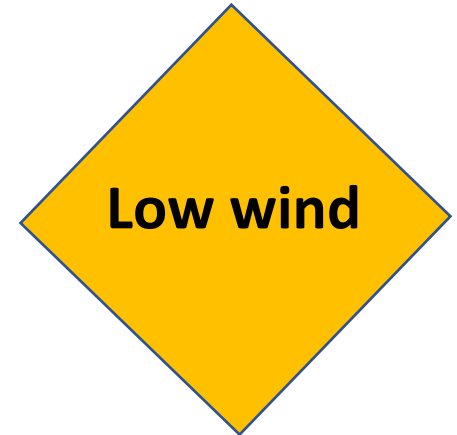
Seismic stations at the wind turbine



+

3 components measurements (X,Y,Z)

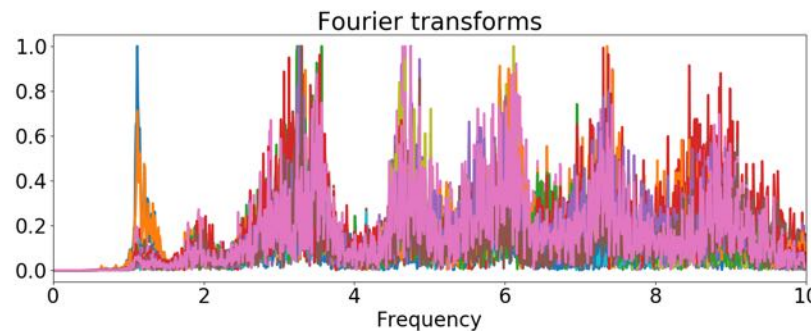
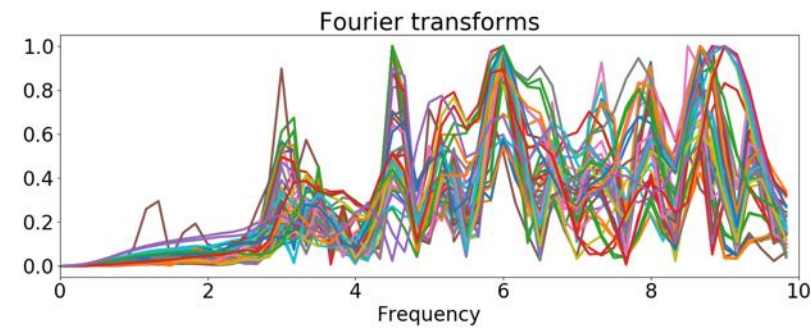
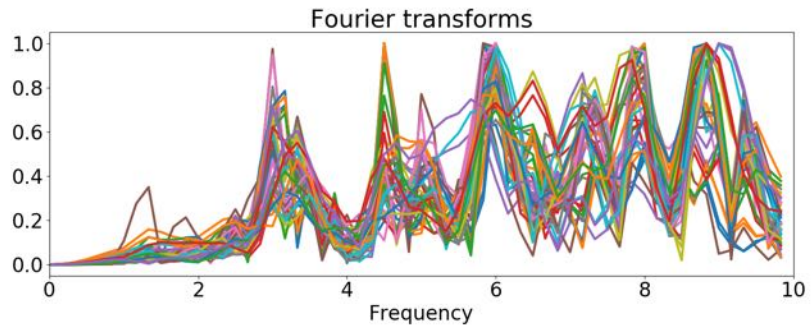
+



**TOTAL of measurements:** 3 (comp) x 1 (sta) x 2 (scenarios) = 6 source time functions

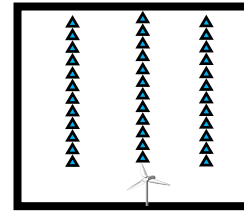
# Comparison with distance- stack of all simulated spectra

high wind speed



SIMULATIONS

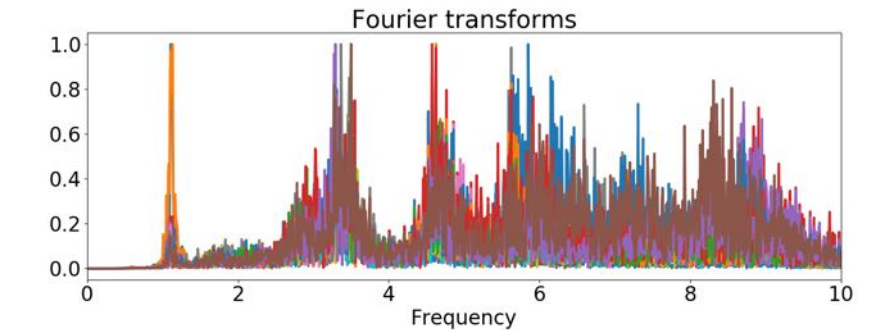
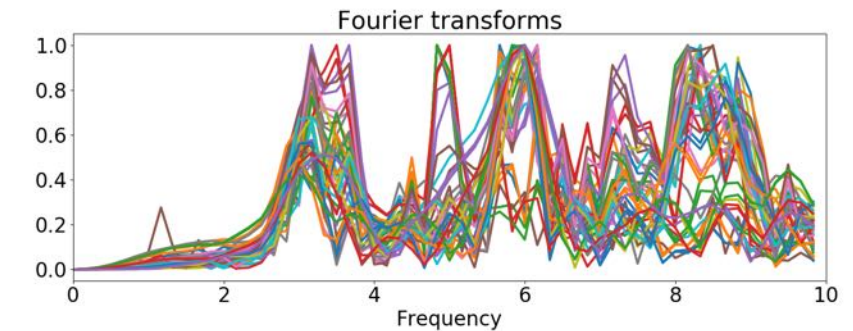
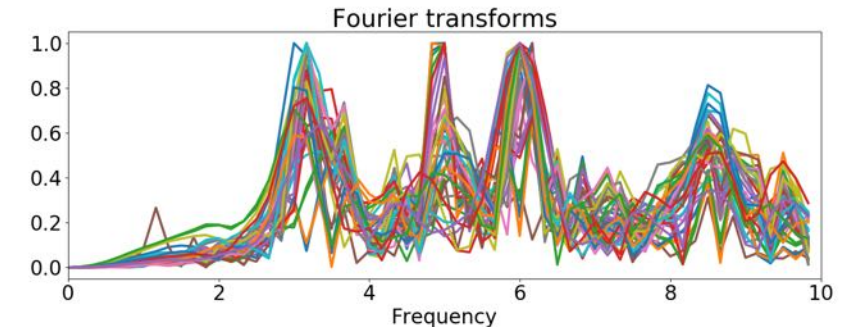
Homogeneous model



Layered model

data

low wind speed

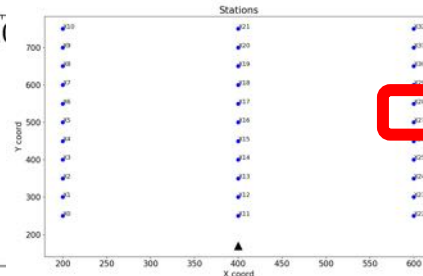
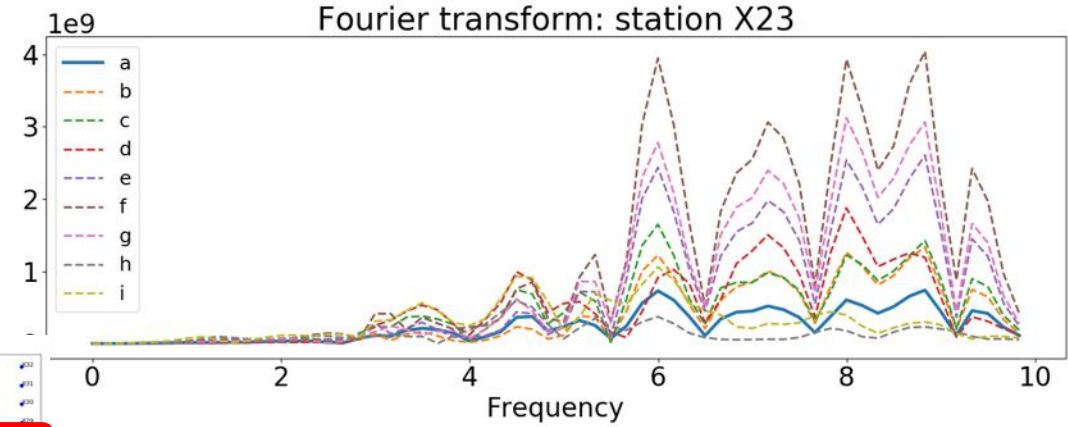
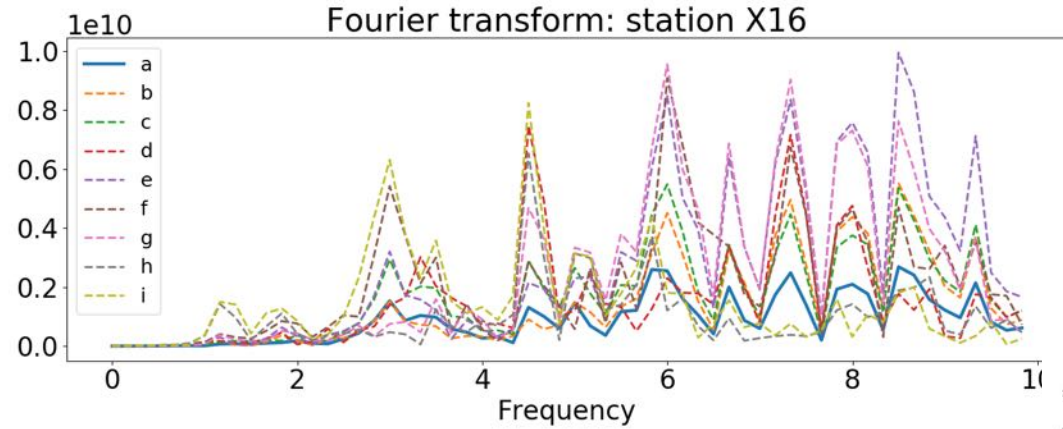


# Influence of wind-turbine locations

high wind speed

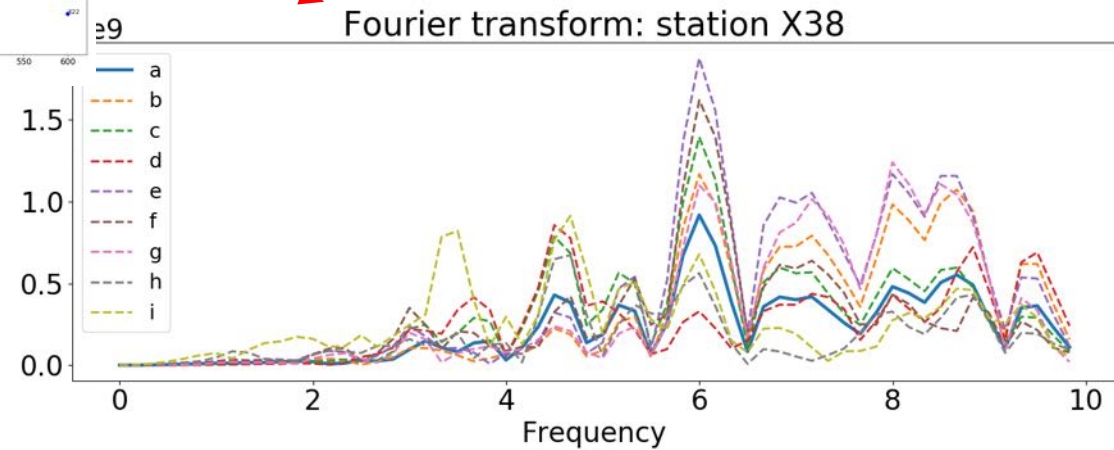
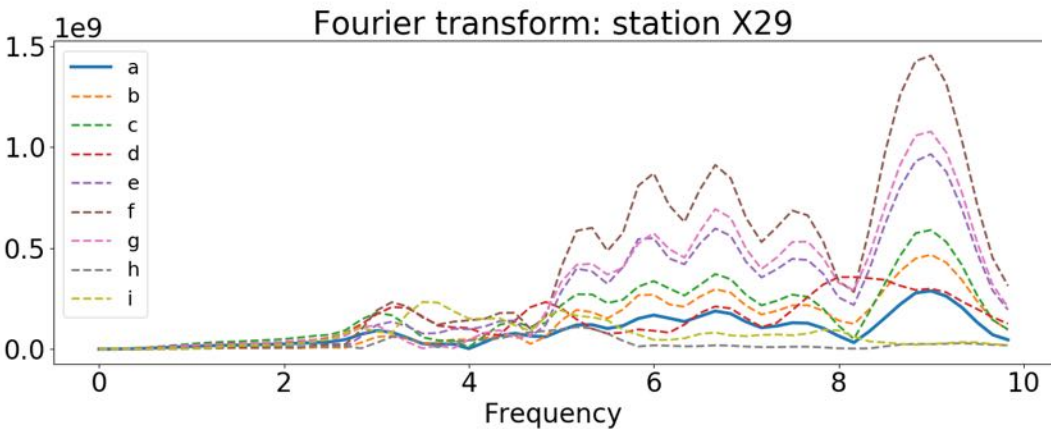
distance 100 m

distance 2300 m



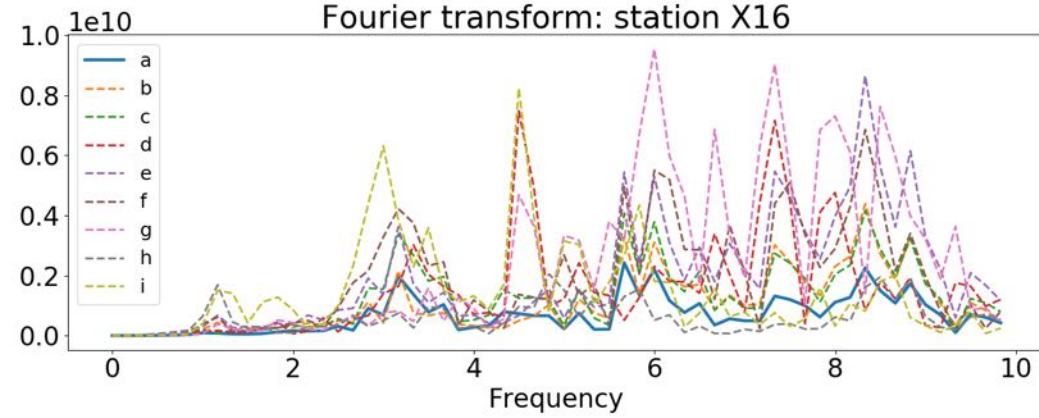
distance 2500 m

distance 3500 m



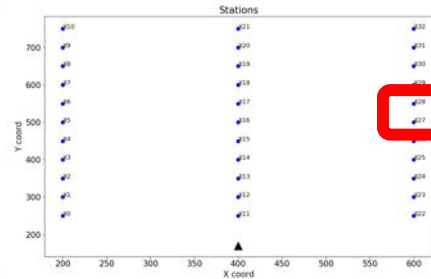
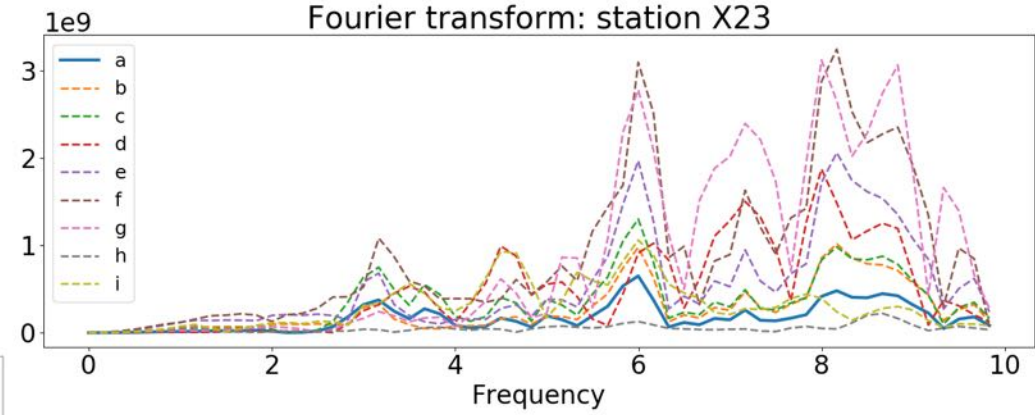
# Influence of wind-turbine locations

distance 100 m



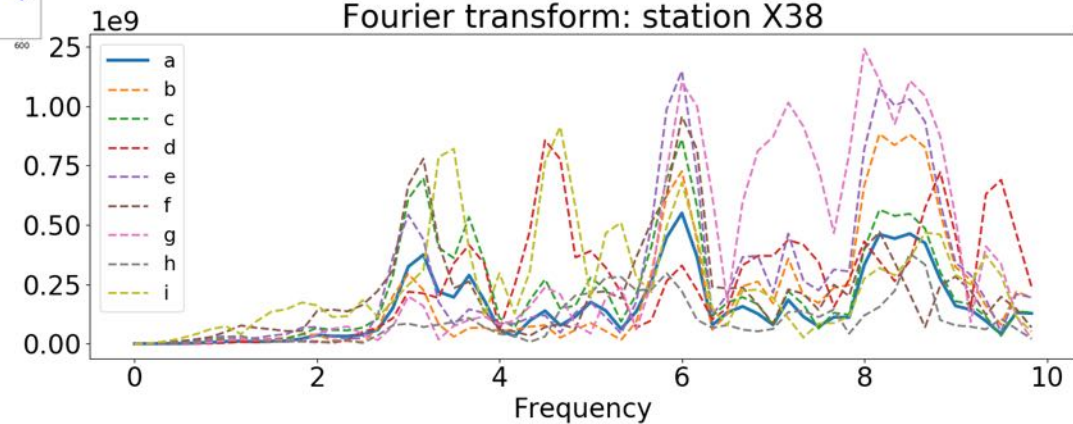
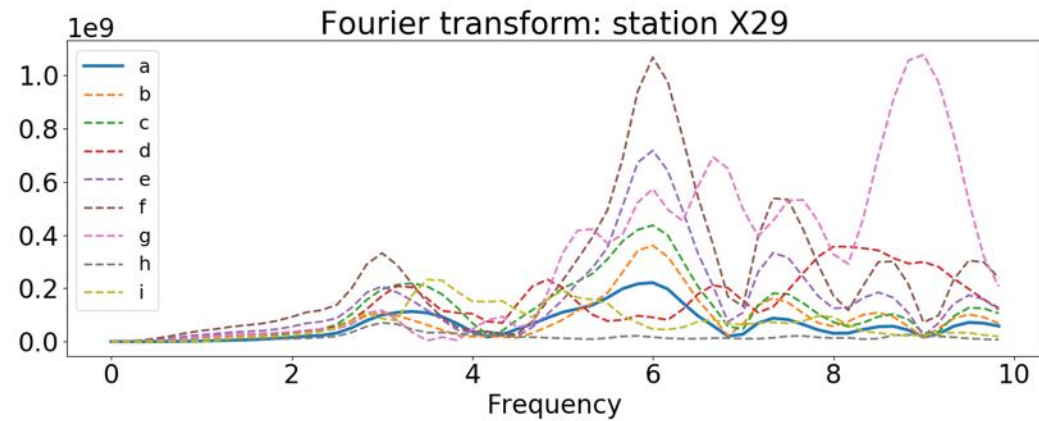
low wind speed

distance 2300 m



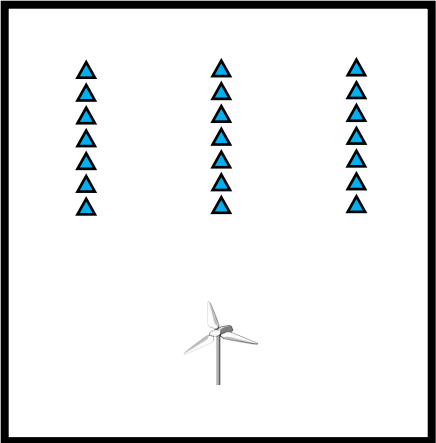
distance 2500 m

distance 3500 m

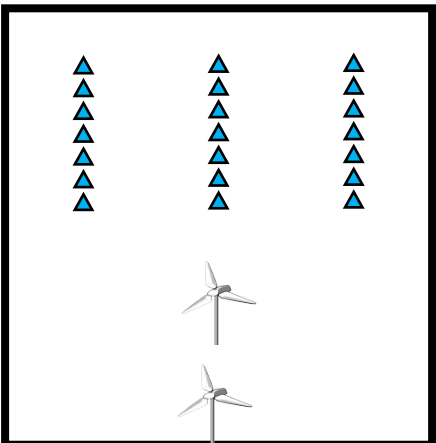


# Influence of wind-turbine locations

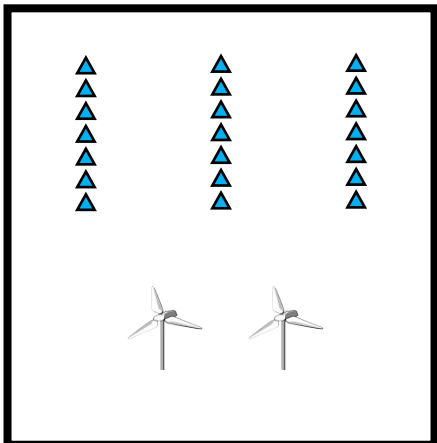
a) Single



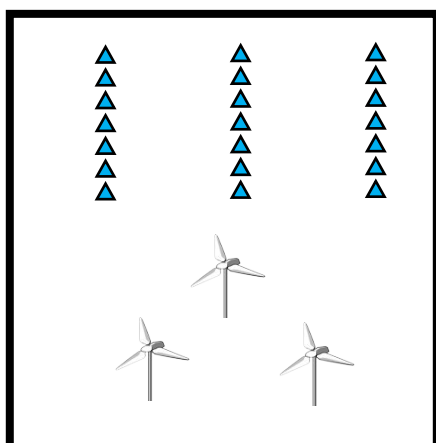
b) Two vertical



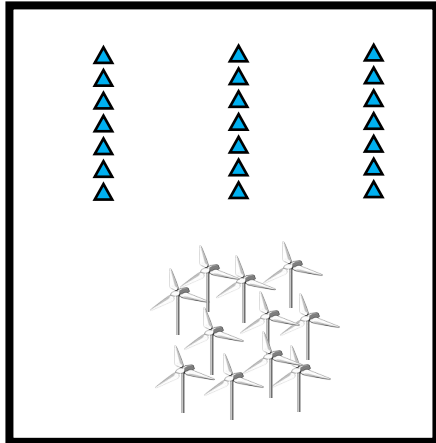
c) Two horizontal



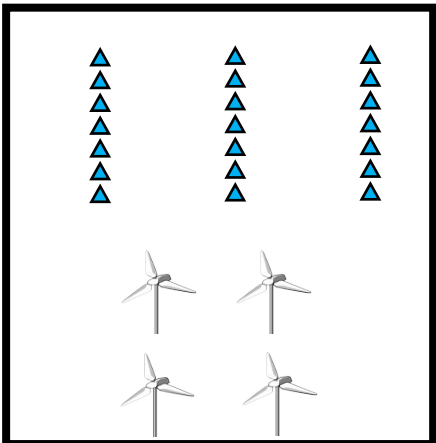
d) Triangle



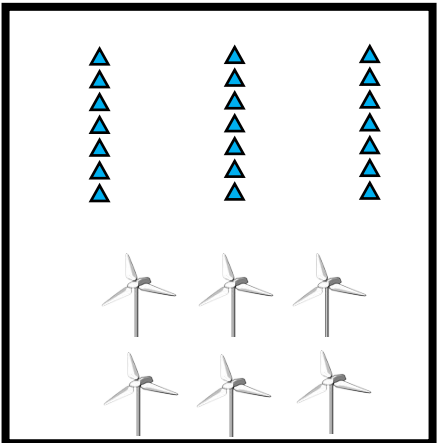
i) Random



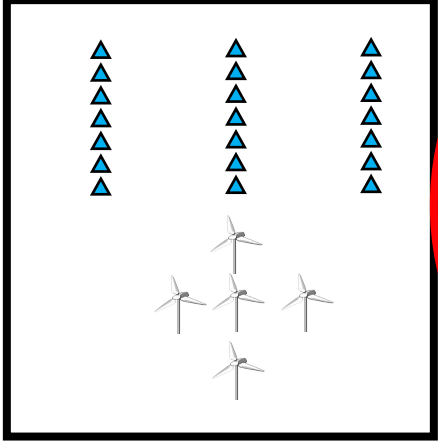
e) Square



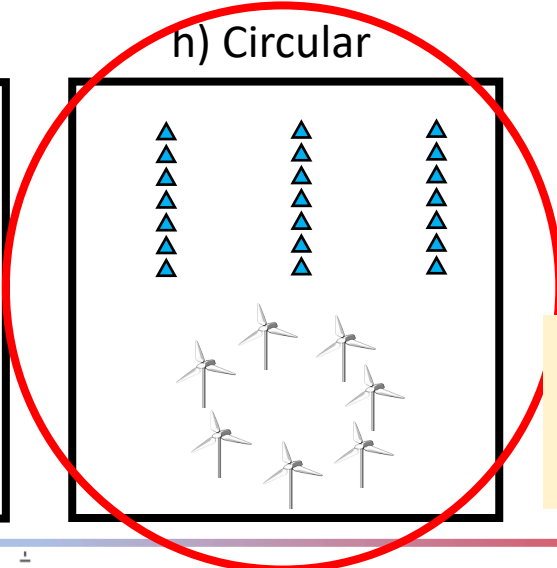
f) Rectangle



g) Crux

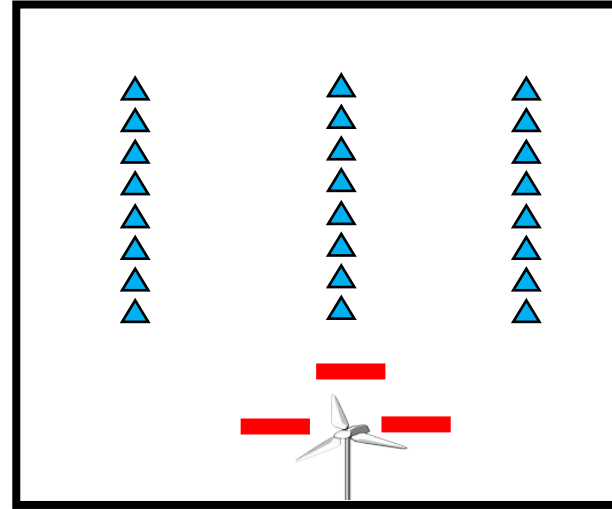
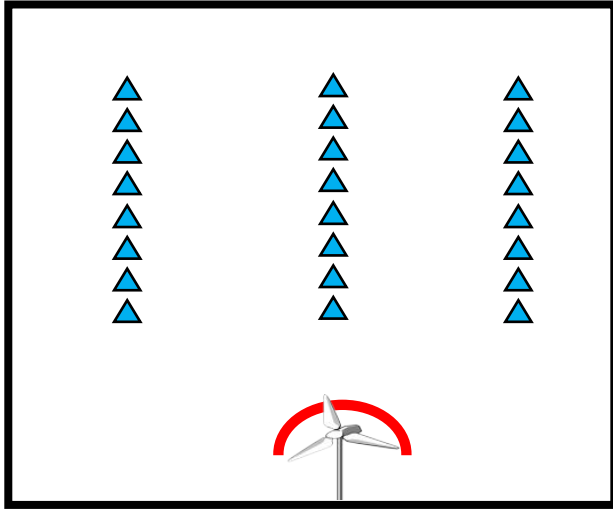


h) Circular



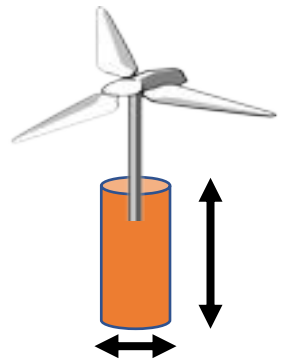
Circular array of WTs seems to attenuate the seismic noise

# Ongoing work



varying width and depth

- ✓ Mesh done!
- ✓ Adding attenuation in the model!



- Answer the question: how much depth and width matter?

Fill models with:

- Pumice, tuff (light) materials
- Any other possible cheap candidate