Effect of shallow heterogeneities on wavefield gradients measurements

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How sensitive are the wavefield gradients to shallow localized velocity changes?

In this study we **investigate the sensitivity of the wavefield and the wavefield gradient measurements** to shallow localized velocity changes.

Seismic simulation software	Spectral element simulation software (SEM46[1]) modified: rotations and strains as a direct output

Experiments performed

Seismic array placed above a velocity anomaly

Weak anomaly (10% velocity drop)

Strong anomaly (70% velocity drop)

[1] Brossier et al. 2019, “Efficient time-domain 3D elastic and viscoelastic full-waveform inversion using a spectral-element method on flexible Cartesian-based mesh”

We performed each simulation two times, the first time considering a fully homogeneous medium, the second time including the seismic anomaly.

How a seismic anomaly interacts with the wavefield and its observables?

Phase shift

The seismic phases acquire a delay or advance with respect to the homogeneous case.

↓

Very precise methods to measure it by frequency-time decomposition, adapted to slight velocity variation, the continuous wavelet transform[2]

Amplitude variations

The normalized waveform changes its amplitude when the anomaly is placed in the medium

↓

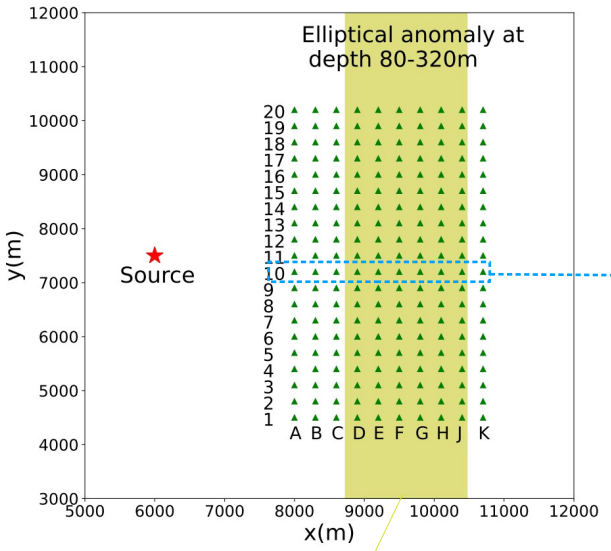
Comparison of the amplitude in the time domain

[2]Mao et al 2019, "On the measurement of seismic traveltime changes in the time-frequency domain with wavelet cross-spectrum analysis"

Weak anomaly simulation

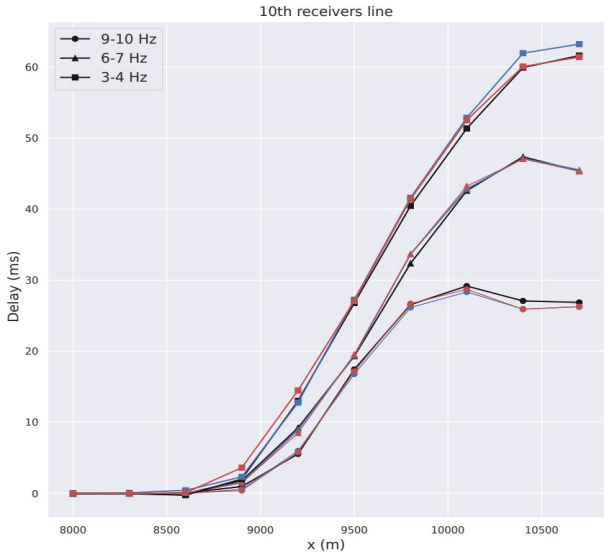
Delay measured at the 10th line of receivers in three frequency bands, 3-4Hz, 7-8Hz, 9-10Hz

Experiment configuration



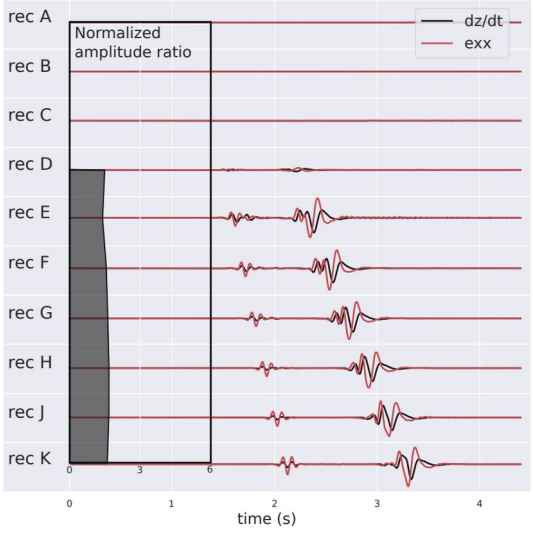
10% velocity drop

Delay



Comparison of observed delays in displacement x, black, in ε_{xx} red ω_y blue. Squares: 3-4Hz, triangles: 6-7Hz, circles, 9-10Hz.

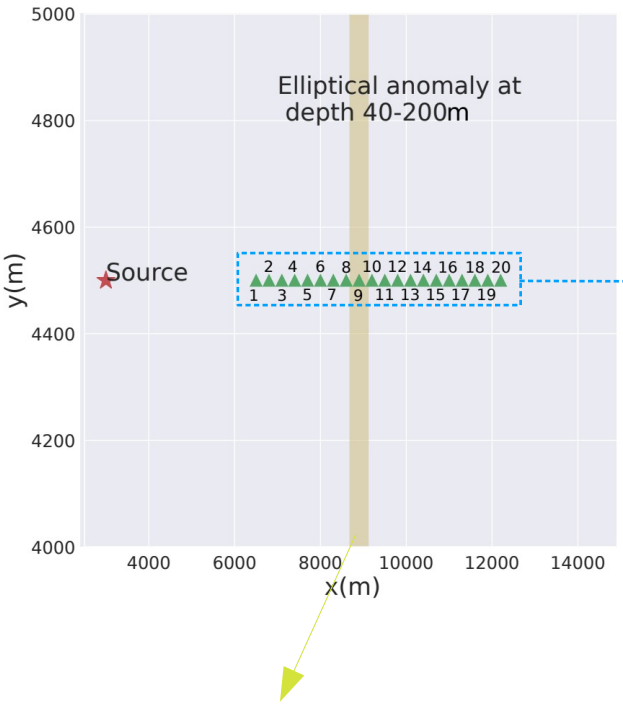
Amplitude change



Scattered field, vertical velocity and ε_{xx}.

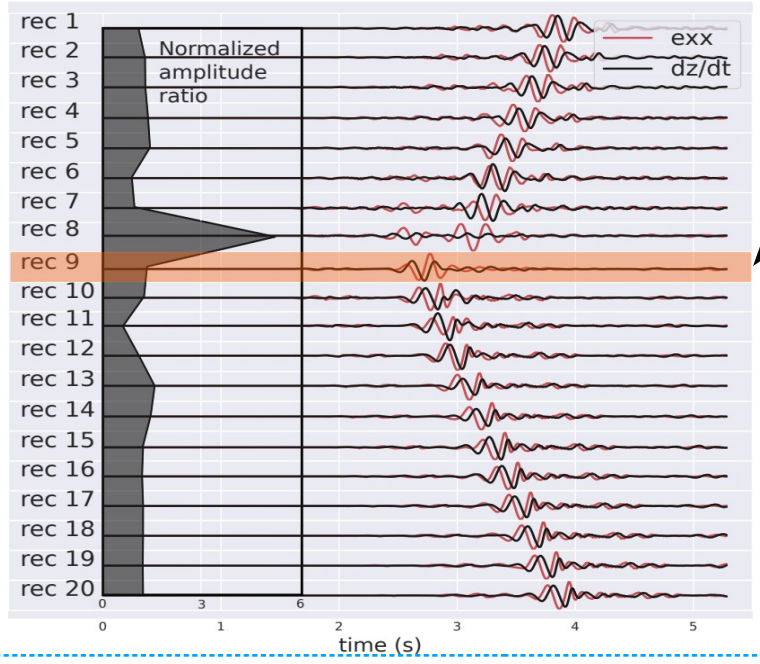
Strong anomaly simulation

Experiment configuration



70% velocity drop

Amplitude change



Receiver above the anomaly

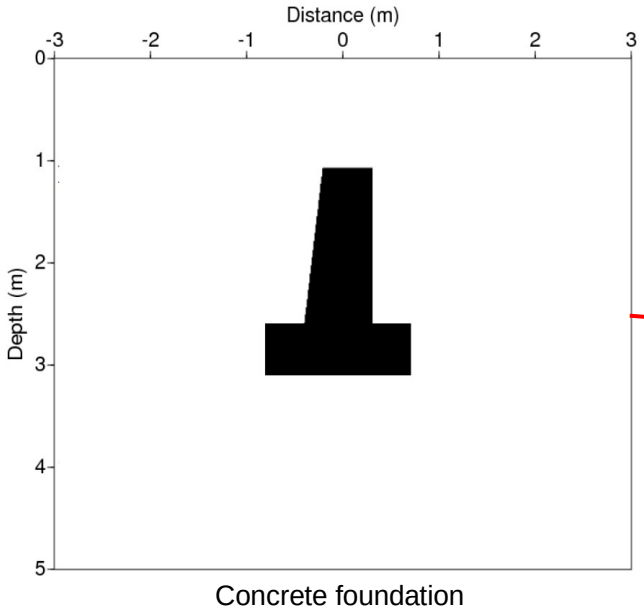
Scattered field, vertical velocity and ε_{xx}.

Localized large amplitude of the gradients!

The experiment focused on analyzing the amplitude variation due to the presence of a strong velocity change

Experiment at Grenoble Campus

A concrete foundation is placed in the ground



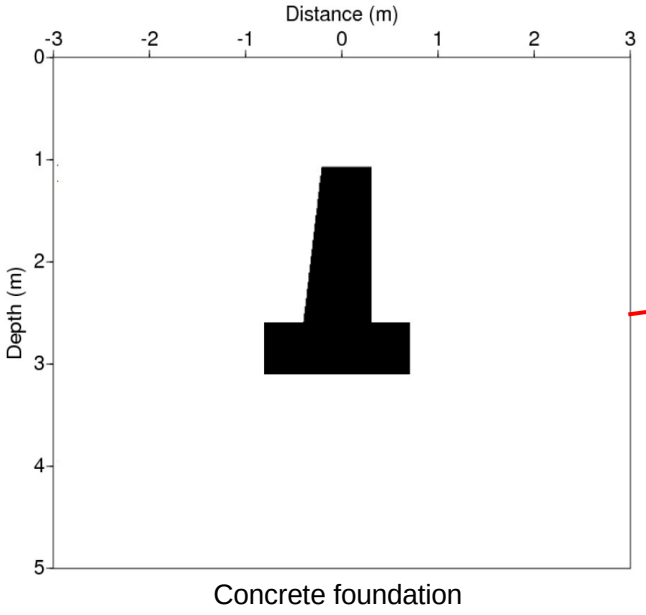
Concrete foundation

Experiment site

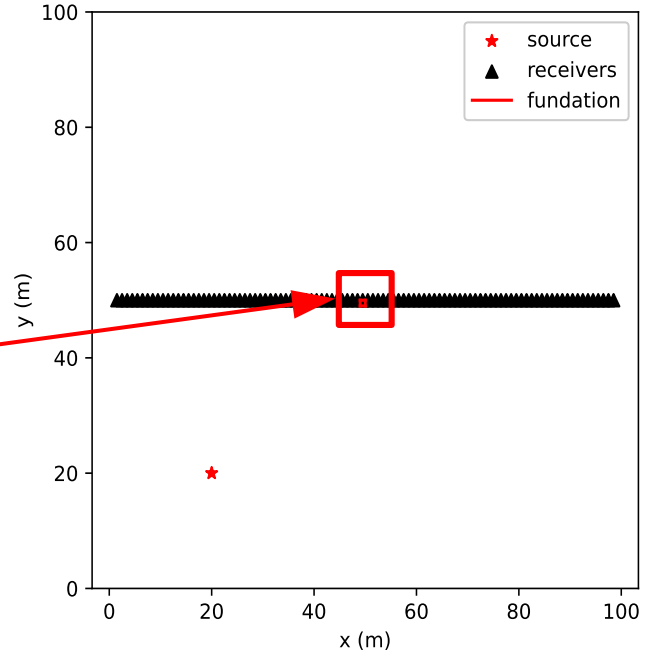
[1] ISTerre, Université Grenoble Alpes

The experiment focused on analyzing the amplitude variation due to the presence of a strong velocity change

Simulation



Concrete foundation



Simulation setting

Simulation setting

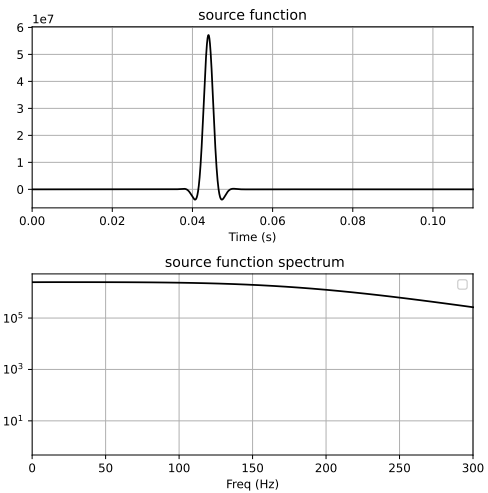
Grid size = 100x100x100 m
Element size = 1x1x1m
Source function = Gaussian, corner frequency 250Hz
Source moment tensor $M_{xx}=M_{yy}= 0$, $M_{zz} = 1$
Heterogeneity standard deviation = 10%

Background

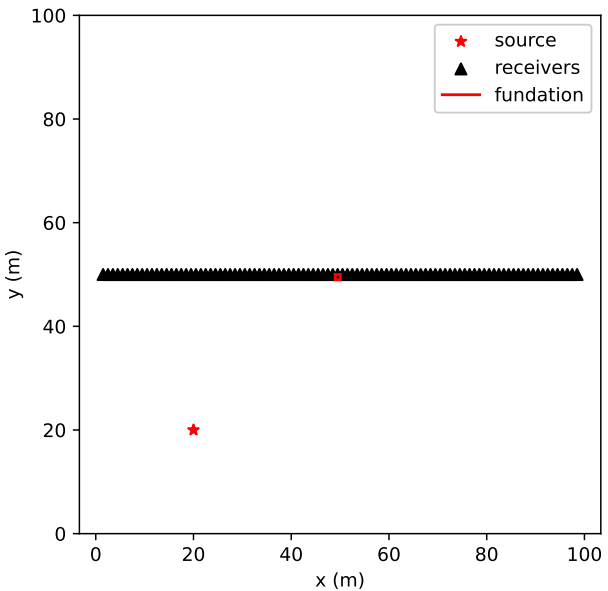
Vp = 1000m/s
Vs = 300m/s
Rho = 1500kg/m^3

Fundation

Vp = 4400m/s
Vs = 2200m/s
Rho = 1500kg/m^3

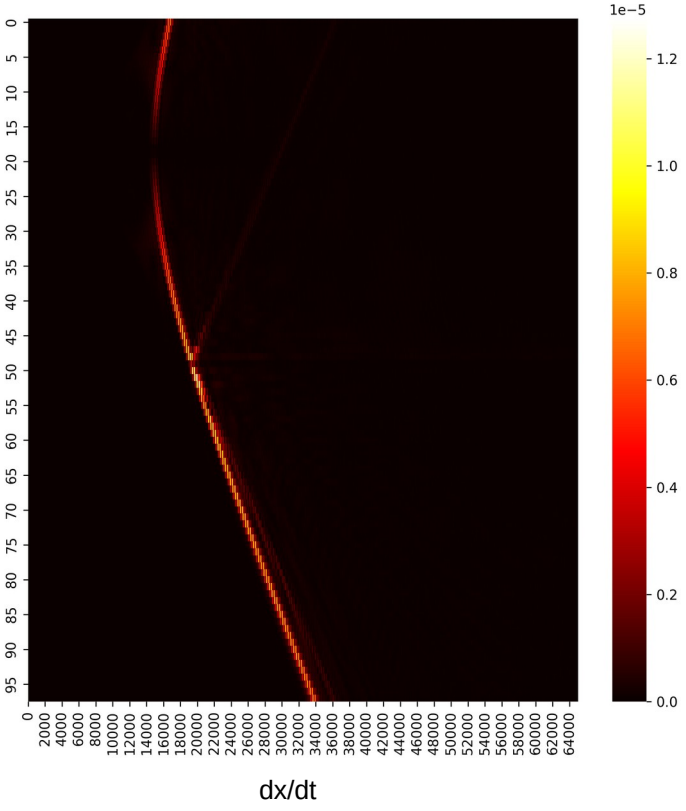


Source function

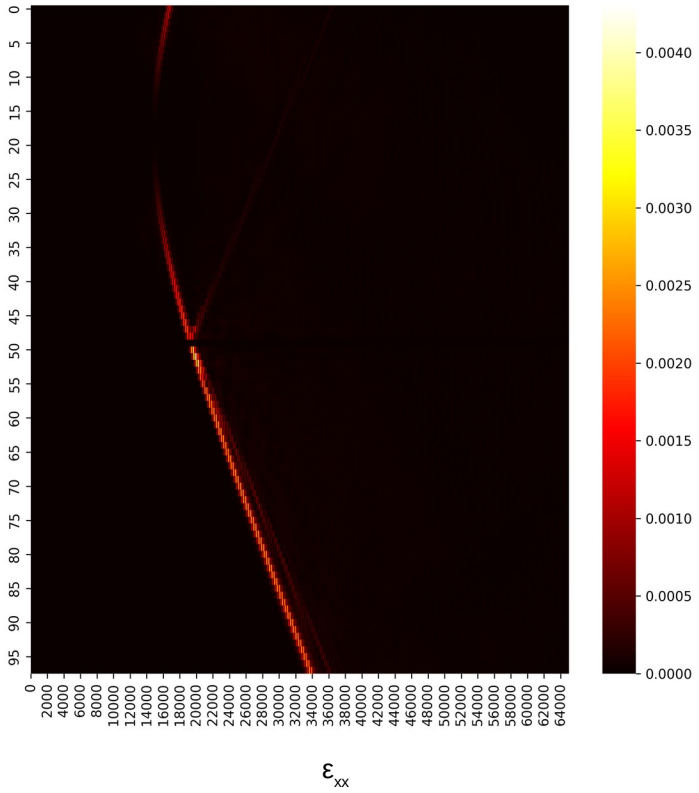


Source- receivers configuration

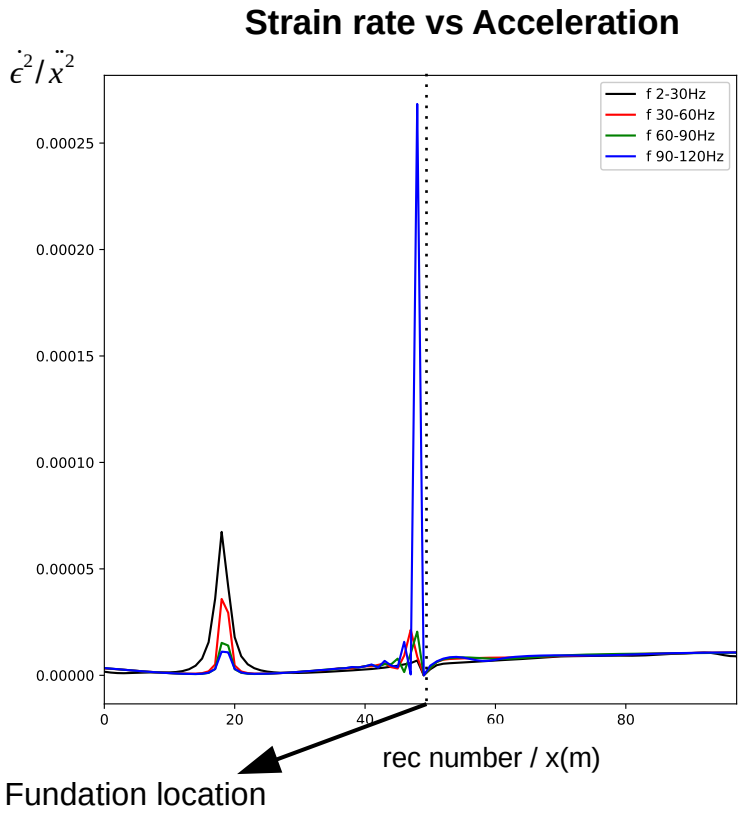
Amplitude of the field

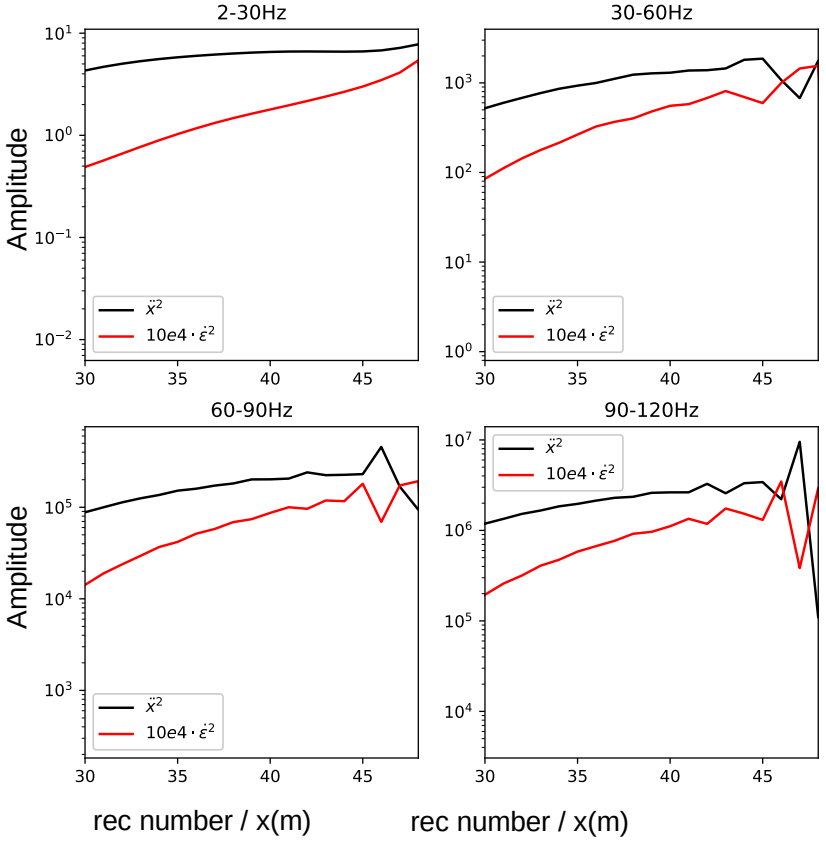


dx/dt



ε_{xx}


Strain rate vs Acceleration
$\dot{\epsilon}^2 / \ddot{x}^2$
f 2-30Hz
f 30-60Hz
f 60-90Hz
f 90-120Hz
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
0
20
40
60
80
rec number / x(m)
Fundation location


2-30Hz
30-60Hz
60-90Hz
90-120Hz
Amplitude
Amplitude
$\ddot{x}^2$
$10e4 \cdot \dot{\epsilon}^2$
30
35
40
45
rec number / x(m)
rec number / x(m)

Observations

Born approximation

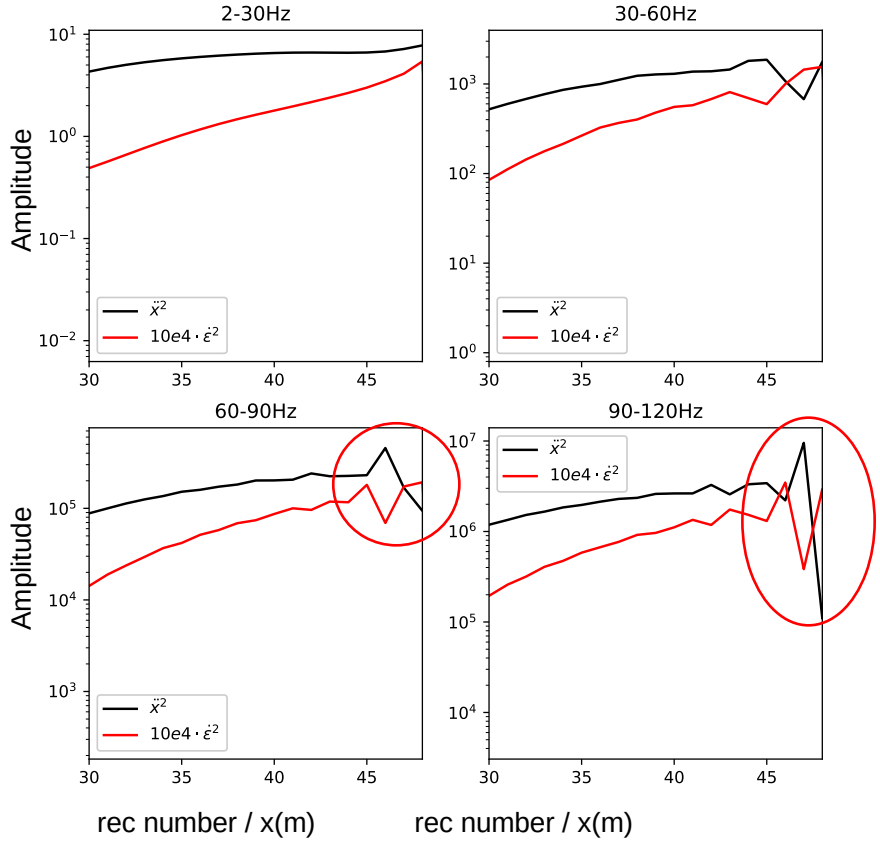
Close to the anomaly a **medium field term** need to be taken into account in the gradients

The wavefield and its gradient behave in a different way at distances smaller than λ/2π

Reflection conditions at the interface

The incident wave and the reflected wave **interfere destructively or constructively** depending on whether the change in velocity is positive or negative.

If the wavefield increases, the gradient decreases (and vice versa). This effect is visible up to λ/2



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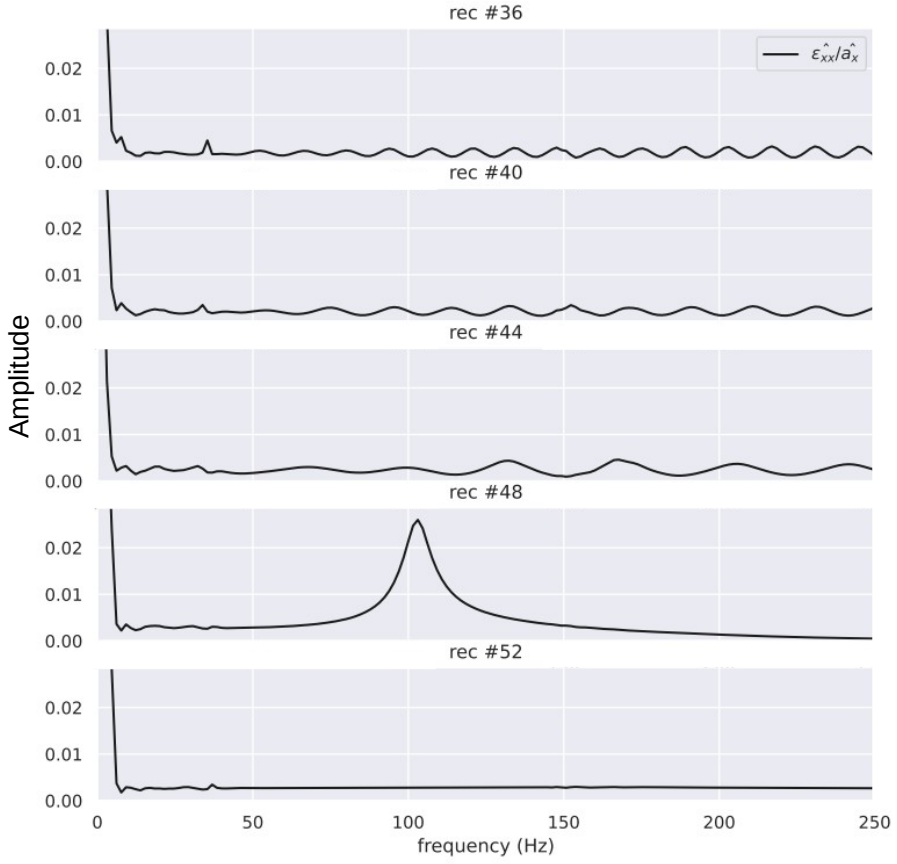
Interference between direct and scattered wave

Ratio of the spectrum



Conclusions

Weak anomaly

In mediums where the velocity exhibits changes up to 10%, the wavefield gradients do not show any significative difference in therms of phase shift or amplitude change if compared to the wavefield itself.

Strong anomaly

- In presence of an interface with strong impedance contrast, the wavefield gradients amplitude changes in proximity of the anomaly.
- The comparison between the amplitude of the wavefield gradients and the wavefield itself could provide information about strong heterogeneity in the subsurface, such as **faults, buried objects** and **empty cavities**.