Seismology and Computational Rock Physics Group

Dept of Geology

University College Dublin

(National University of Ireland, Dublin)

IRELAND

<u>People directly involved</u>:

Chris Bean, Gareth O' Brien, Martin Moellhoff,

Ivan Lokmer

Differential equations (continuum mechanics)

Solve 'by hand'

↓

Analytical Solution

Differential equations (continuum mechanics)

Solve directly on computer

↓

Numerical Solution

Discrete Micromechanical Rules

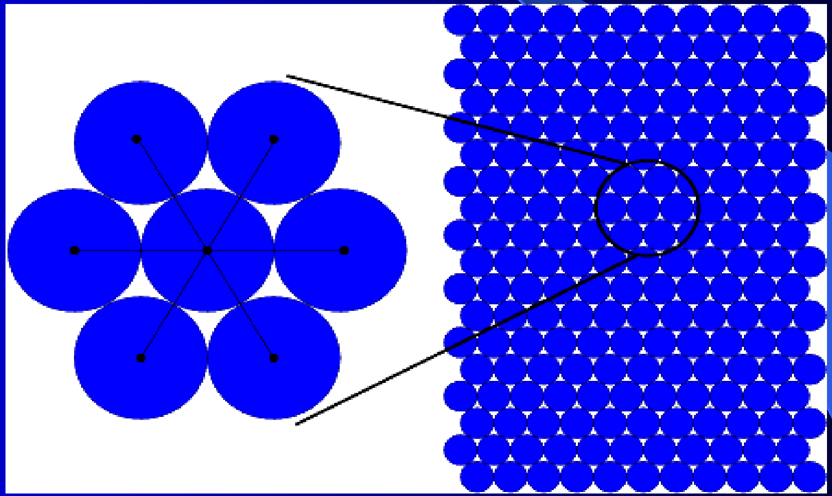
Impliment rules directly on computer

↓

Non-continuum Numerial Solution

Numerical Model - Discrete Particle Scheme (DPS)

- Particles represent atoms / grains of sand / blocks of crustal rock
- Implementation shown: 2D, hexagonal geometry (results in a fixed Poisson's ratio of 0.25)



- Neighbouring particles interact through Hooke's law (normal forces only):

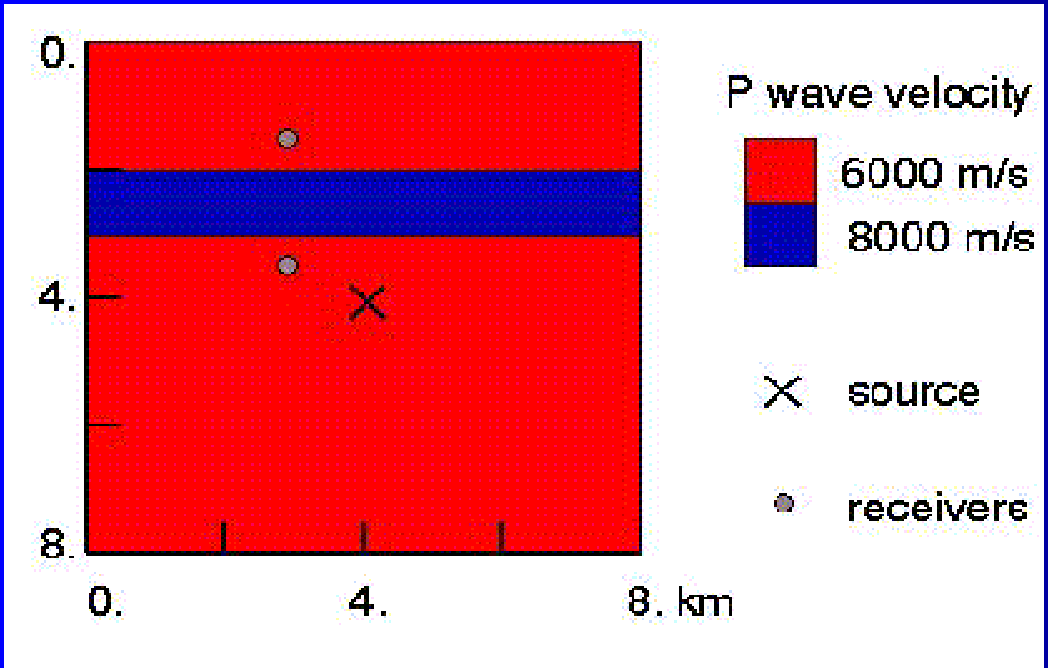
$$F = K(r - r_0)$$

- F=force between particles → gives acceleration, integrate twice to update particle positions
- K=bond stiffness
- r_0=particle spacing

K and r_0 → control the elastic properties of the model

Simulating Wave Propagation

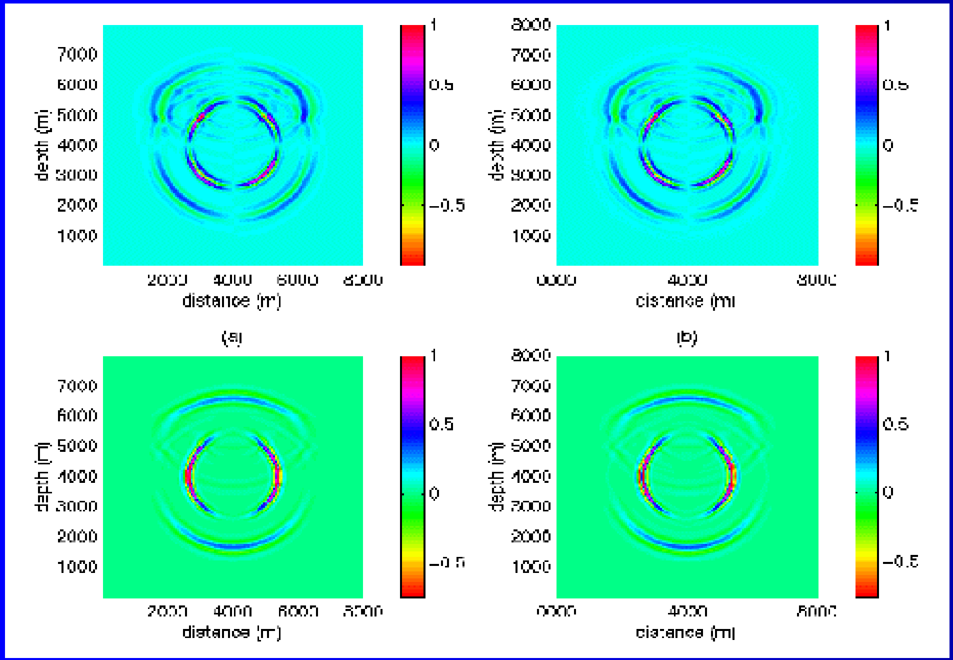
- Wave propagation initiated by applying a displacement or force to one particle (point source) or to a row of particles (plane wave source)
- Force-displacement particle interaction implicitly includes all boundary conditions between zones with different material properties



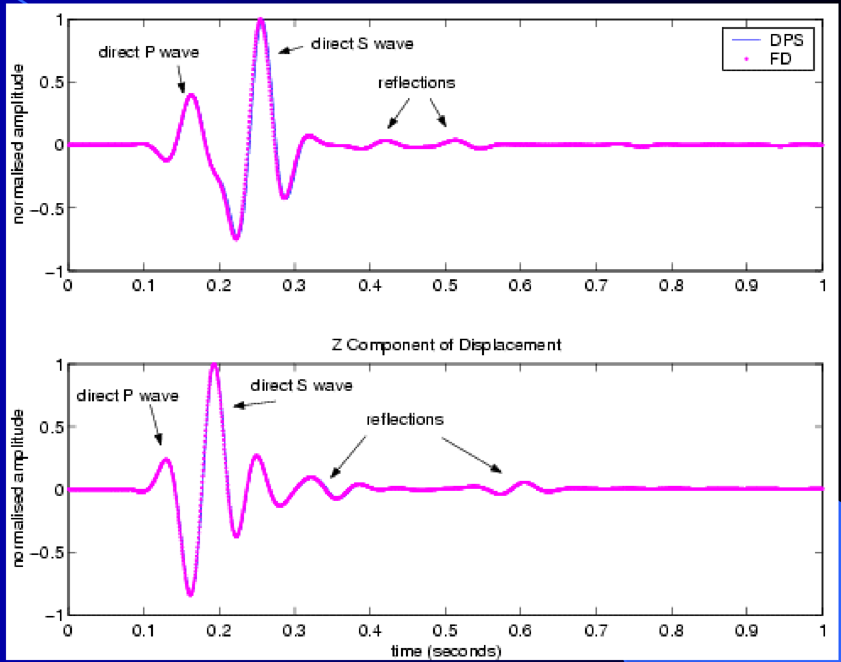
Layered Model

- 8000x8000 m^2
- ν=0.25, density=2000 kg/m^2
- V_s background=3464. m/s; V_s in layer=4619. m/s
- Particle diameter= 10. m; timestep: 5 ms
- Source=15 Hz ricker wavelet

Results compared to those of a high order finite difference scheme



Snapshots of displacement



Reflected wave ~ 1300 m from source

- Accuracy and computation time found to be of the same order as for a high order finite difference solution to the wave equation

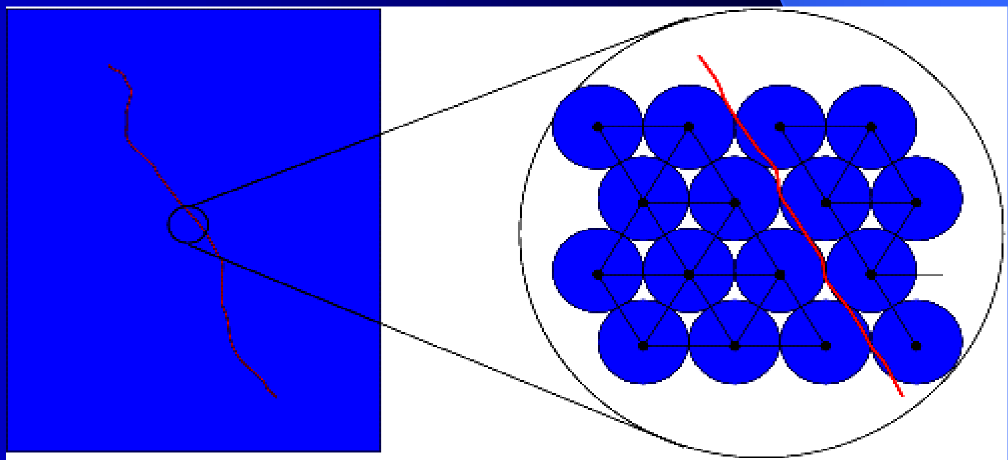
Toomey and Bean GJI 2000

Fracture Representation

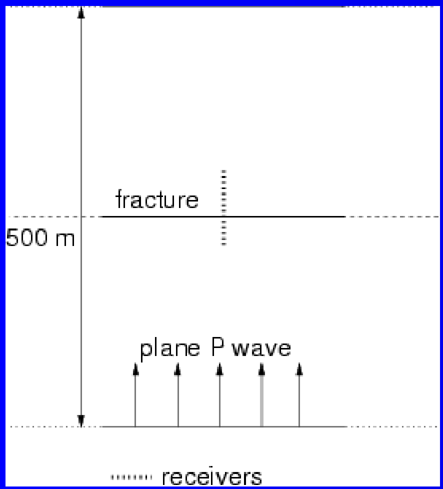
- Fractures are represented in the DPS as discontinuities which are more compliant than the intact material
- Fractured inter-particle bonds obey a modified version of Hooke's law:

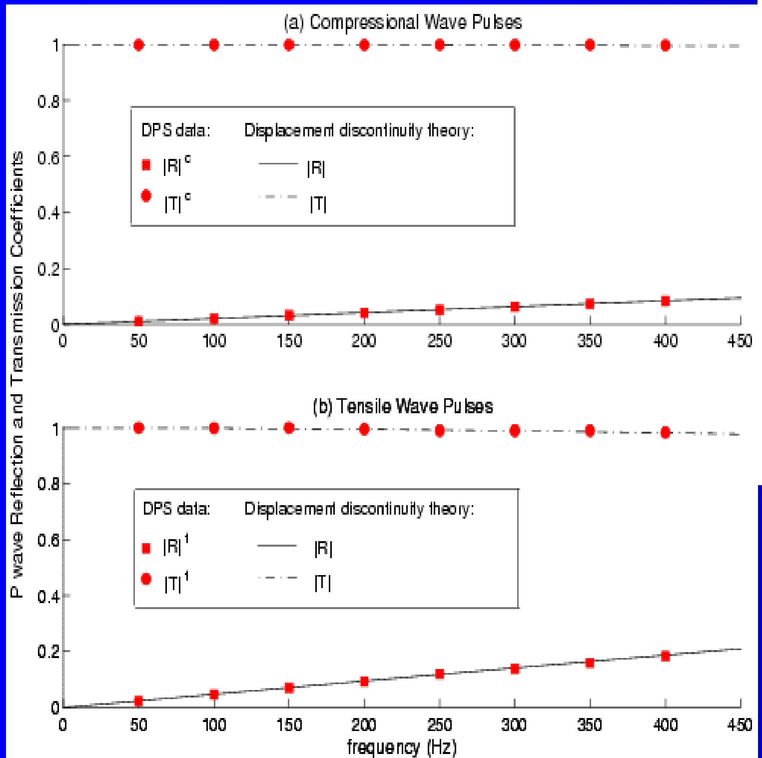
$$F = \begin{cases} K^{c}(r - r_0) \ldots r < r_0 & \text{(compression)} \\ K^{t}(r - r_0) \ldots r > r_0 & \text{(tension)} \end{cases}$$

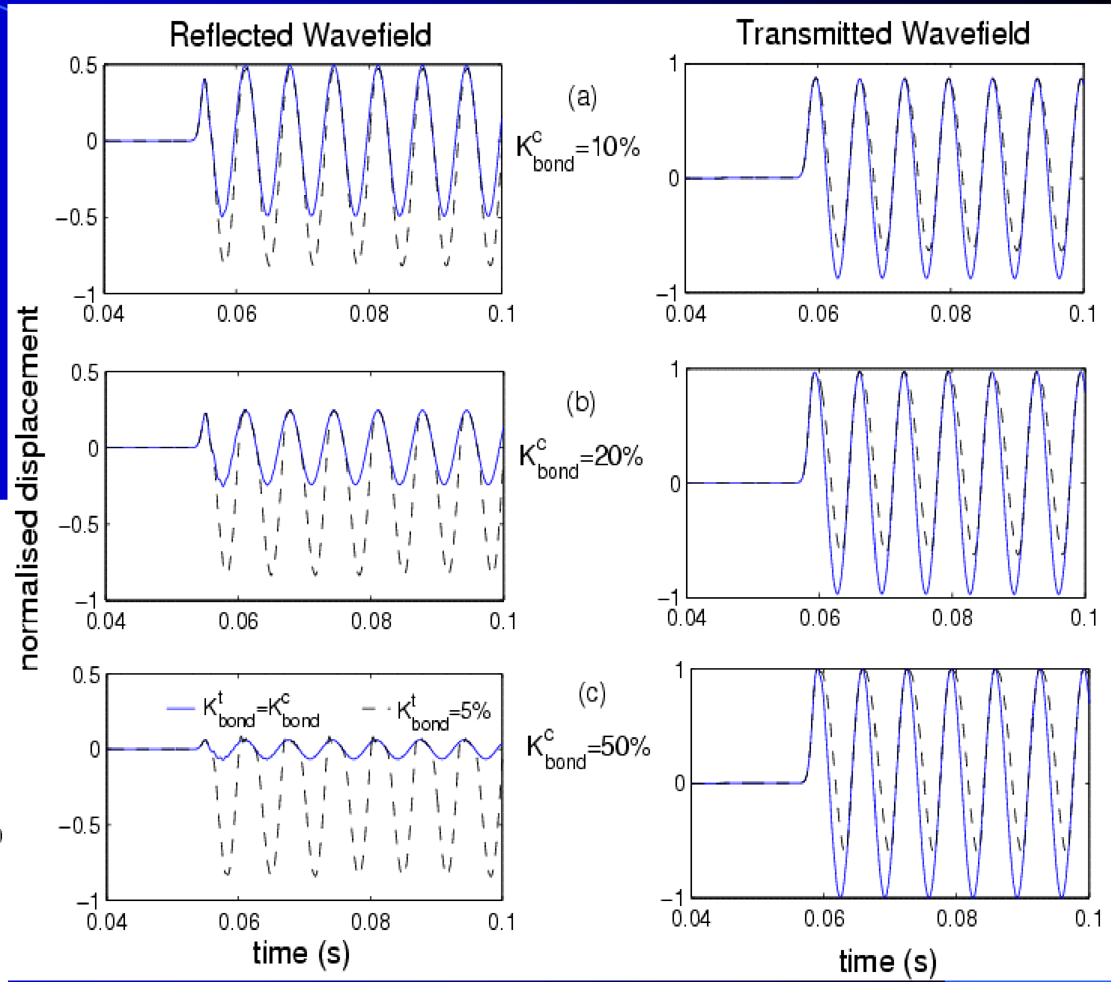
- The fracture's response to stress is controlled by two bond stiffnesses:
  - K^{c}_{bond} = compressional stiffness
  - K^{t}_{bond} = tensile stiffness (cohesion)



Wave propagation across a bi-compliant crack, using discrete mechanics

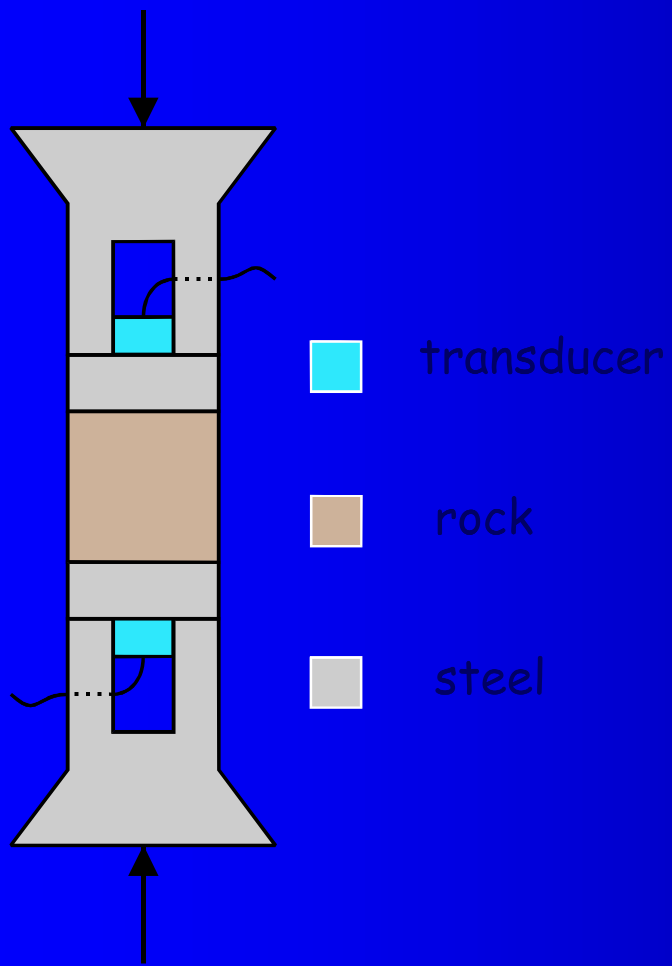




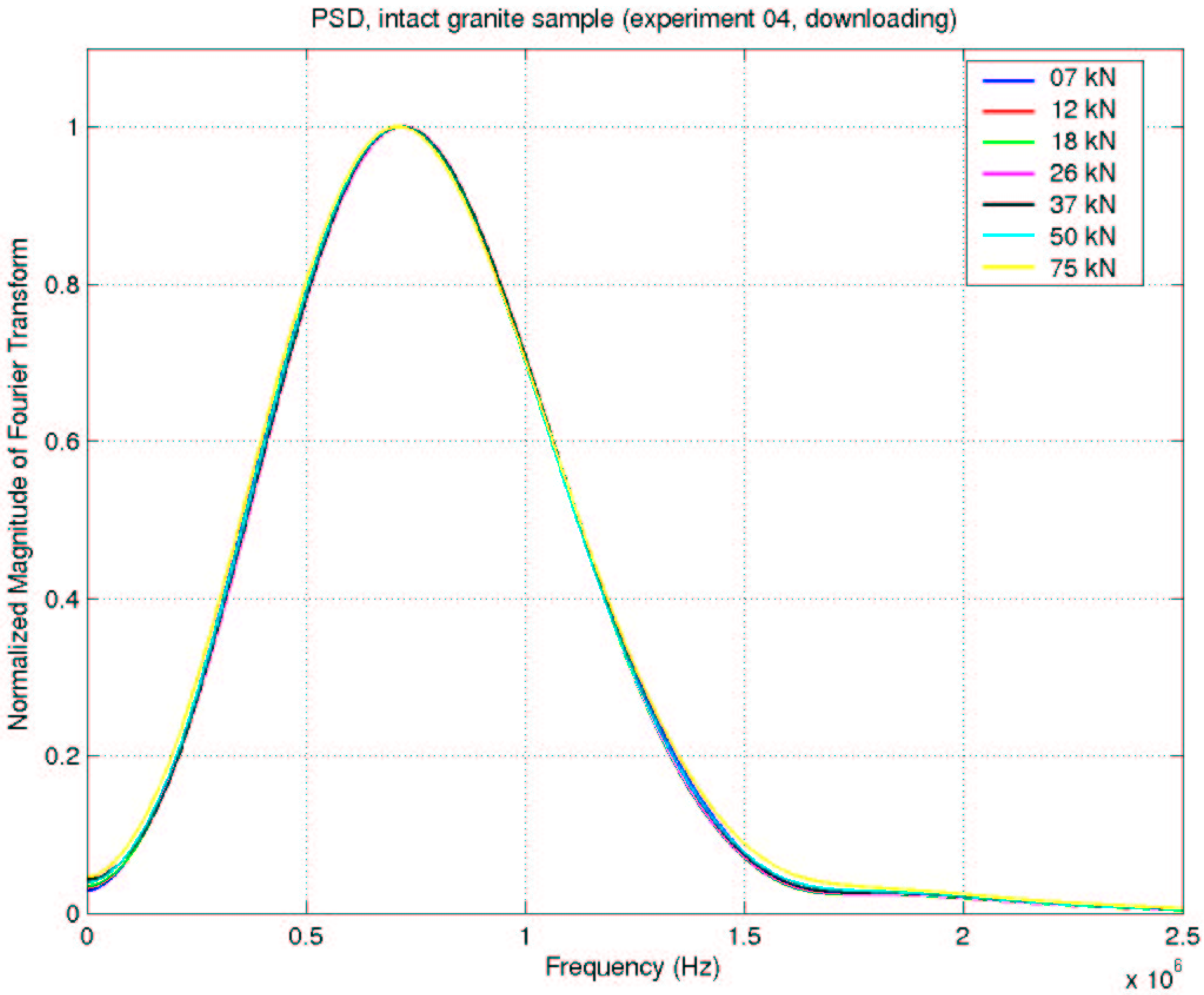


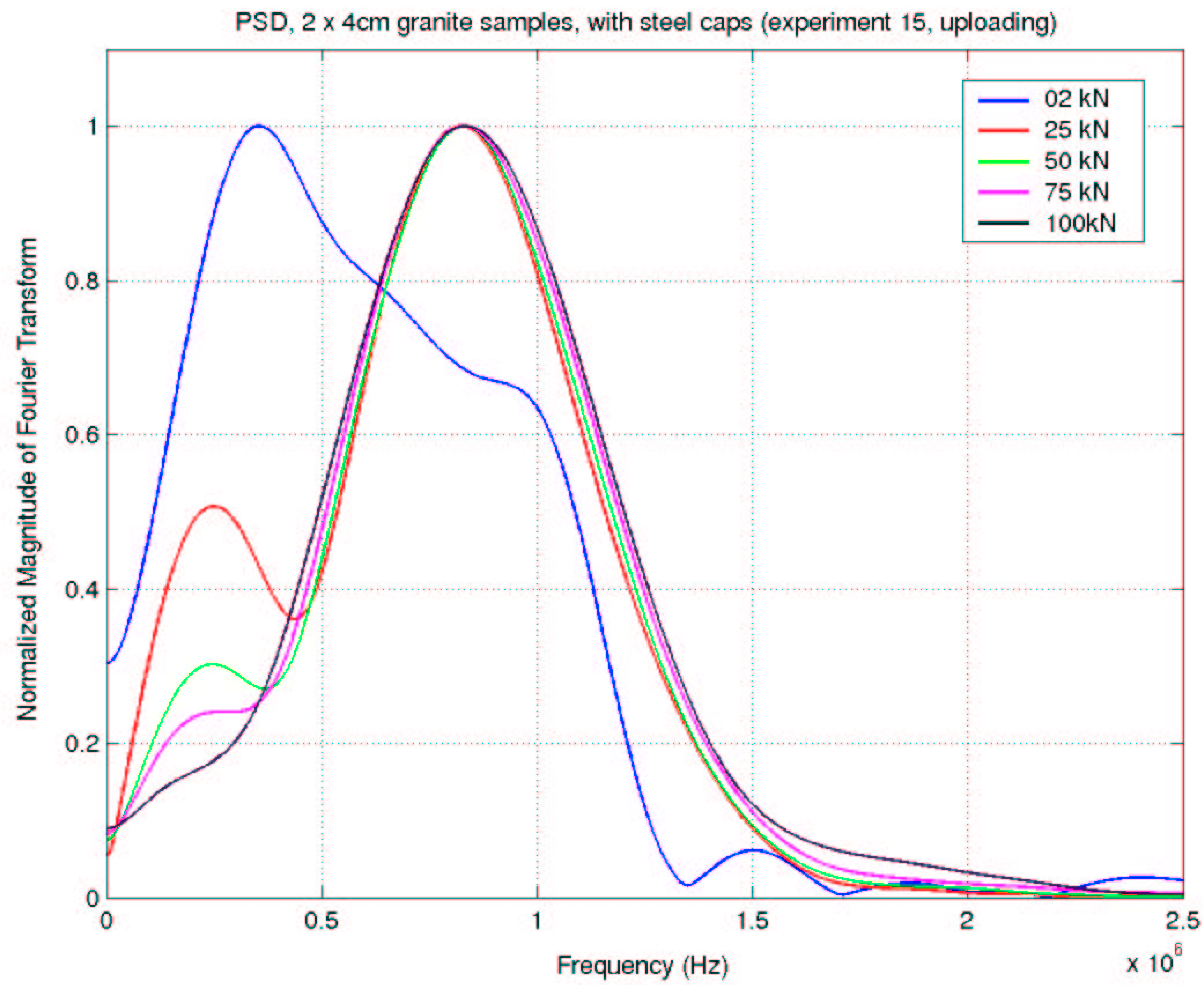
Toomey, Bean and Scotti 2002, GRL

Laboratory Experiment

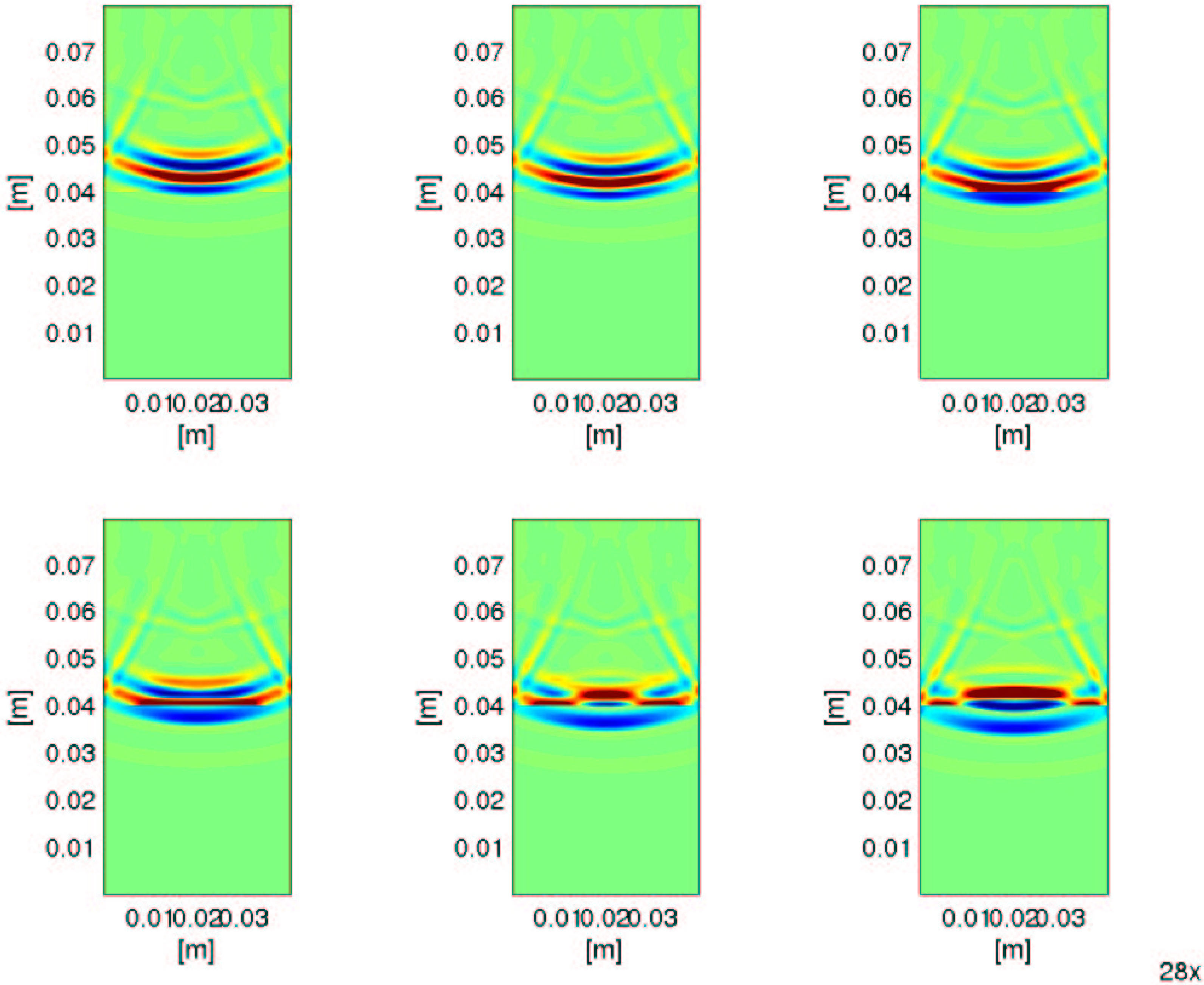


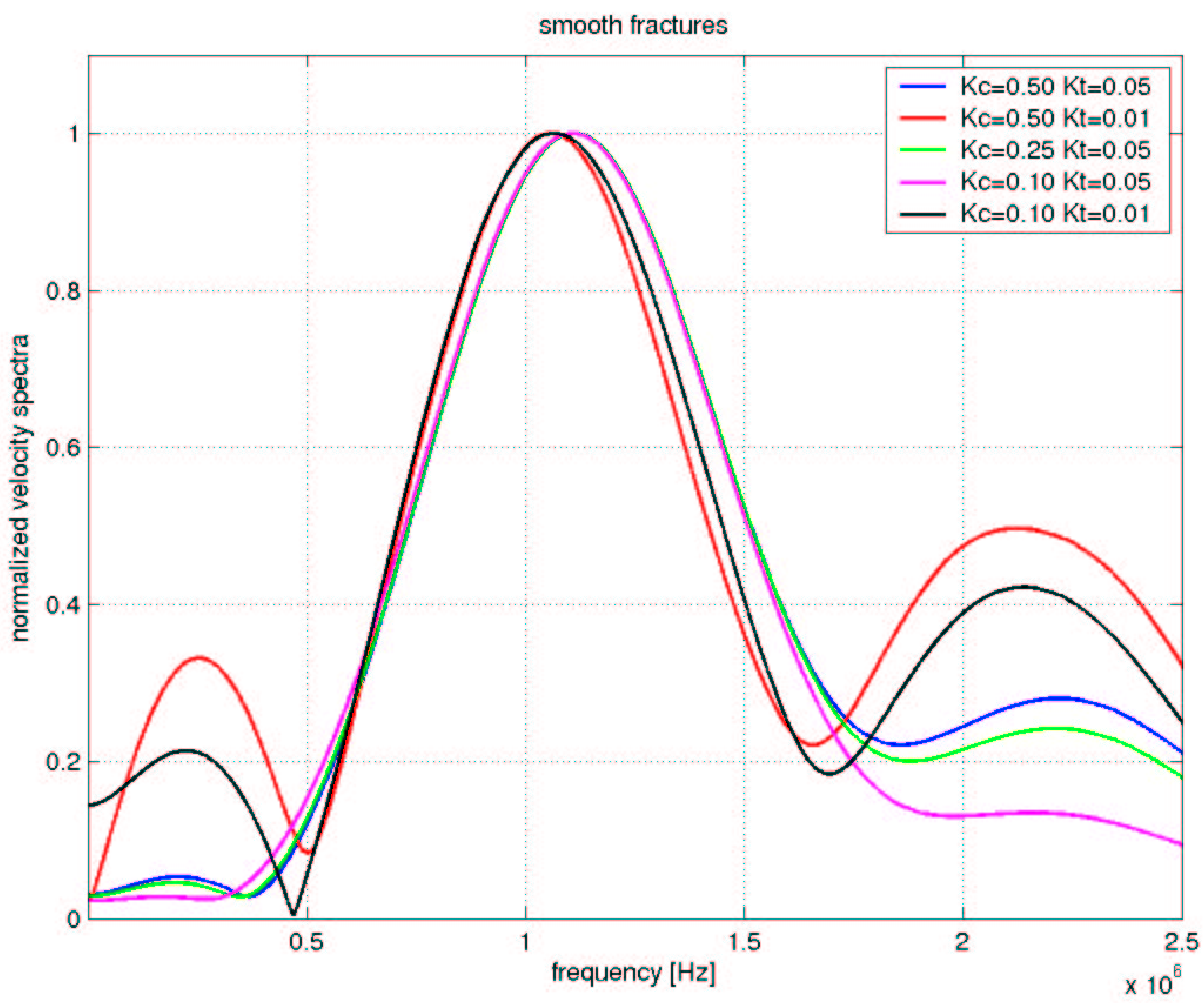
20 tonne servo-hydraulic uniaxial loading frame

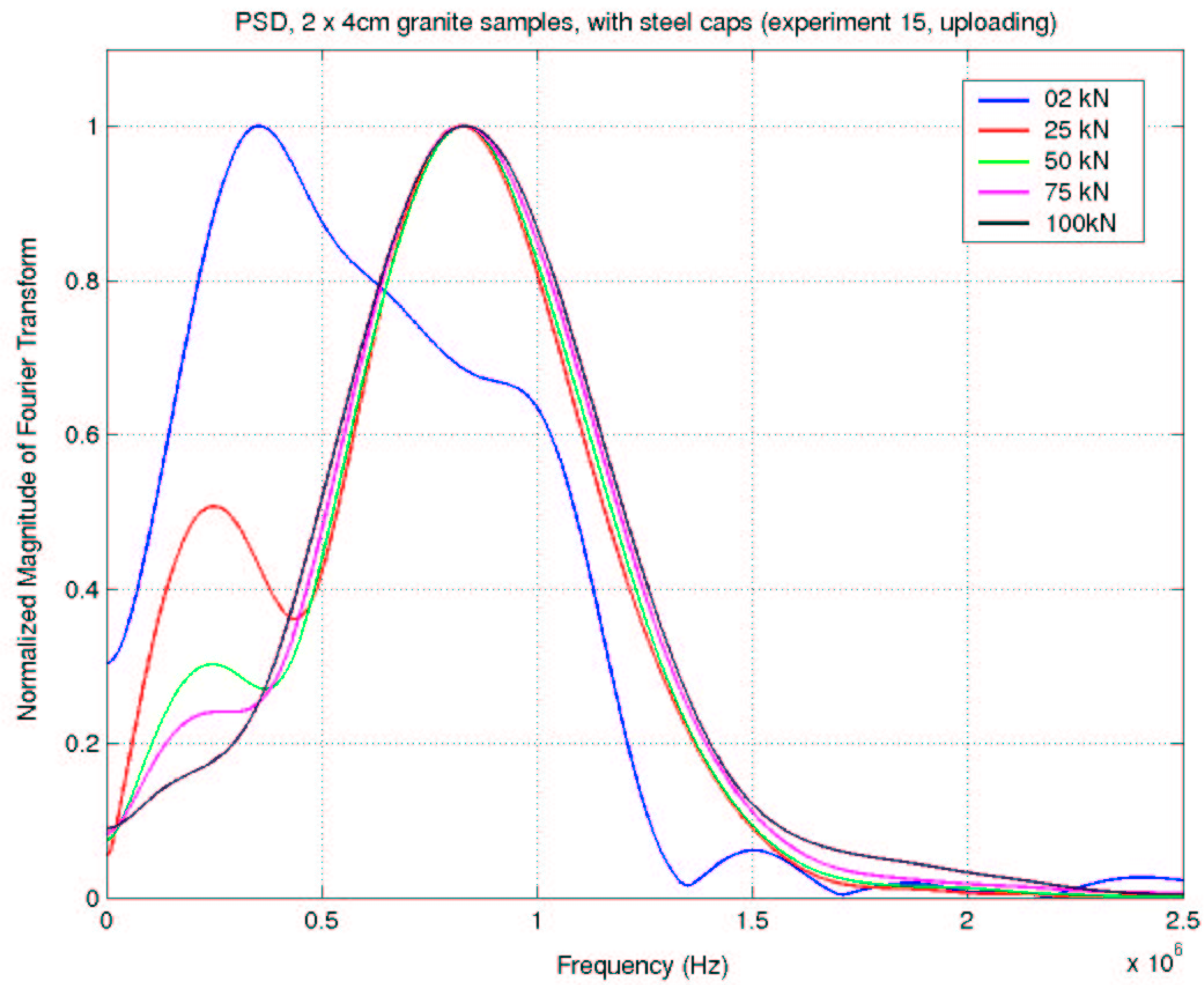

PSD, intact granite sample (experiment 04, downloading)
Normalized Magnitude of Fourier Transform
Frequency (Hz)
x 10^6
07 kN
12 kN
18 kN
26 kN
37 kN
50 kN
75 kN
0
0.2
0.4
0.6
0.8
1
0.5
1.5
2
2.5


PSD, 2 x 4cm granite samples, with steel caps (experiment 15, uploading)
02 kN
25 kN
50 kN
75 kN
100kN
Normalized Magnitude of Fourier Transform
Frequency (Hz)
x 10^6
0
0.2
0.4
0.6
0.8
1
0.5
1.5
2
2.5

vertical source, vertical displacement snapshots

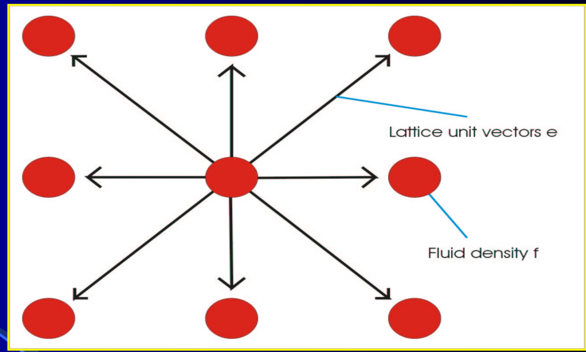



smooth fractures
Kc=0.50 Kt=0.05
Kc=0.50 Kt=0.01
Kc=0.25 Kt=0.05
Kc=0.10 Kt=0.05
Kc=0.10 Kt=0.01
normalized velocity spectra
0
0.2
0.4
0.6
0.8
1
0.5
1
1.5
2
2.5
frequency [Hz]
x 10^6



PSD, 2 x 4cm granite samples, with steel caps (experiment 15, uploading)
02 kN
25 kN
50 kN
75 kN
100kN
Normalized Magnitude of Fourier Transform
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
2.5
Frequency (Hz)
x 10^6

Fluid Modelling



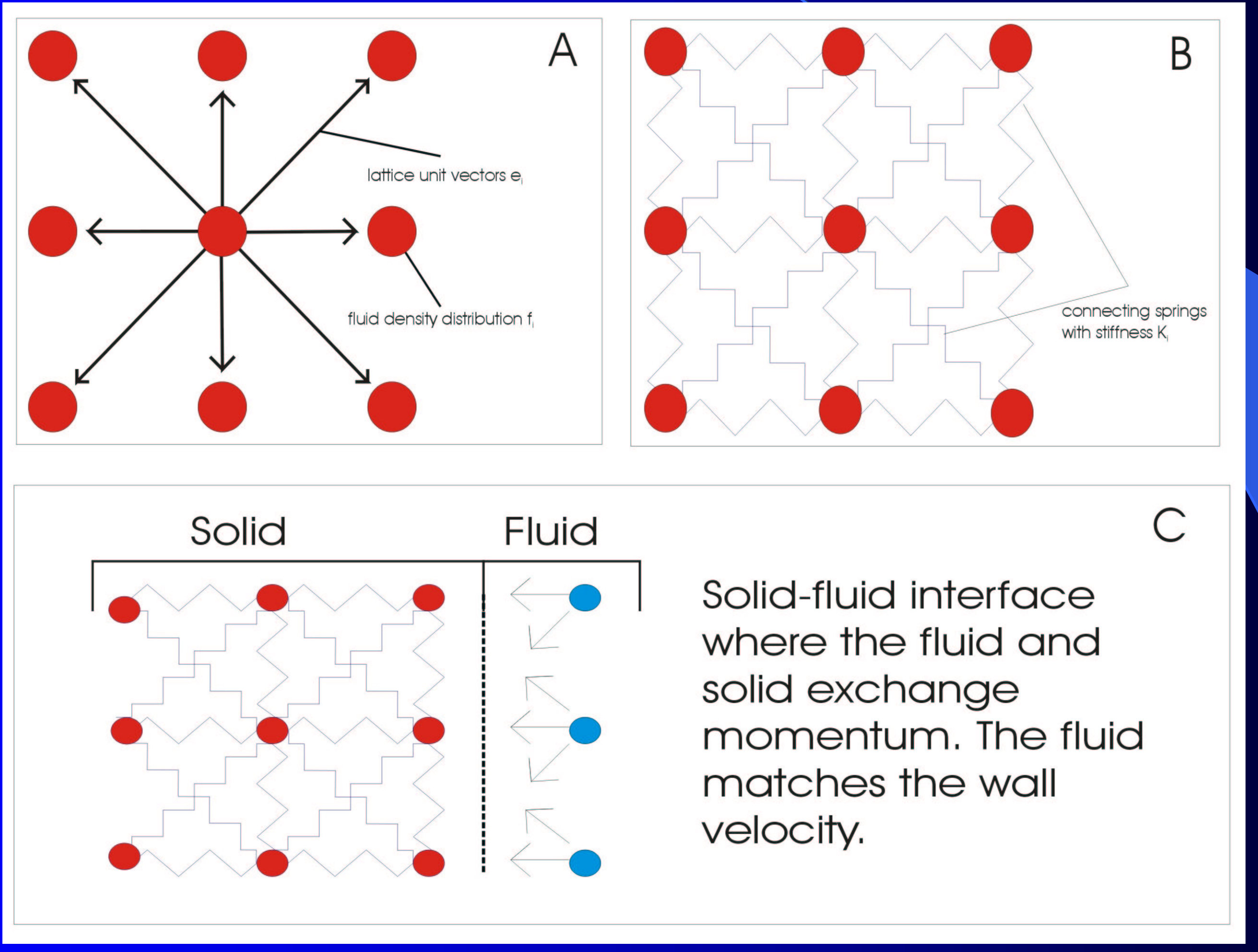
Use the 2D-9 particle lattice Boltzmann method (Qian et al. 1993). Scheme has been tested for simulating sound waves (including non-linear waves) in a viscous fluid, (Buick et al. 1998).

Discrete scheme with two steps

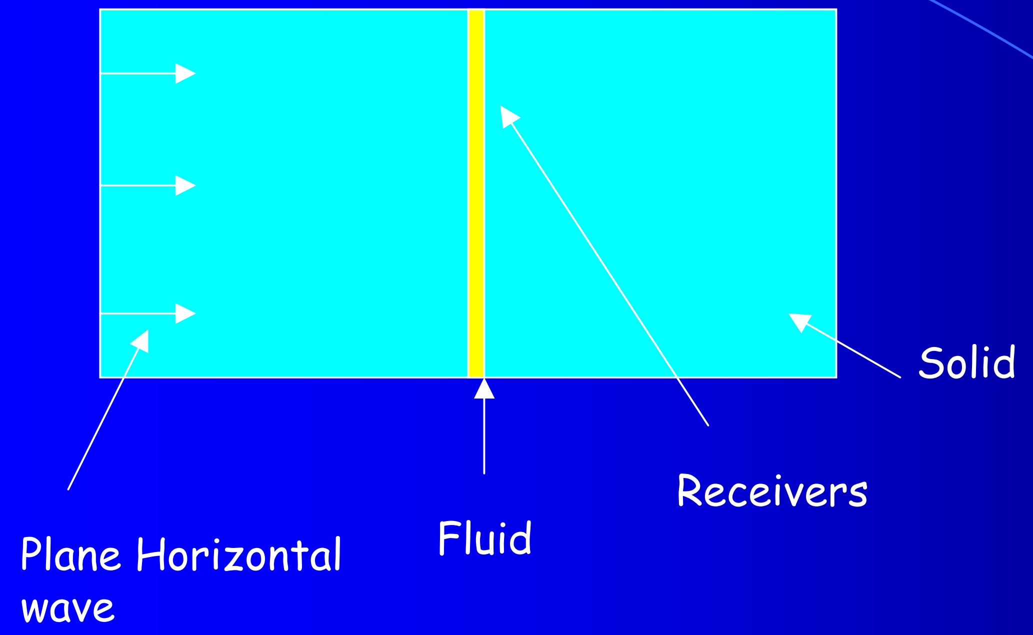
i) propagating fluid density particles across a square lattice

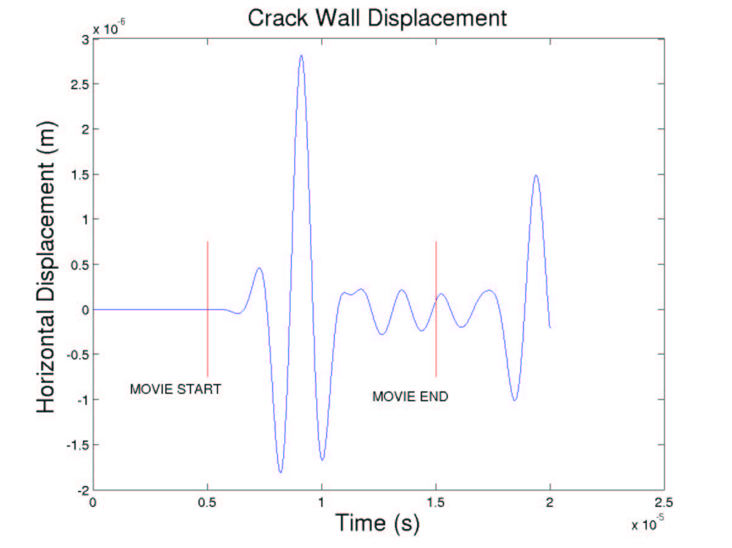
ii) exchanges momentum through collisions of the particles by relaxing the scheme to an equilibrium distribution.

Coupling discrete schemes to including Fluid-solid interactions

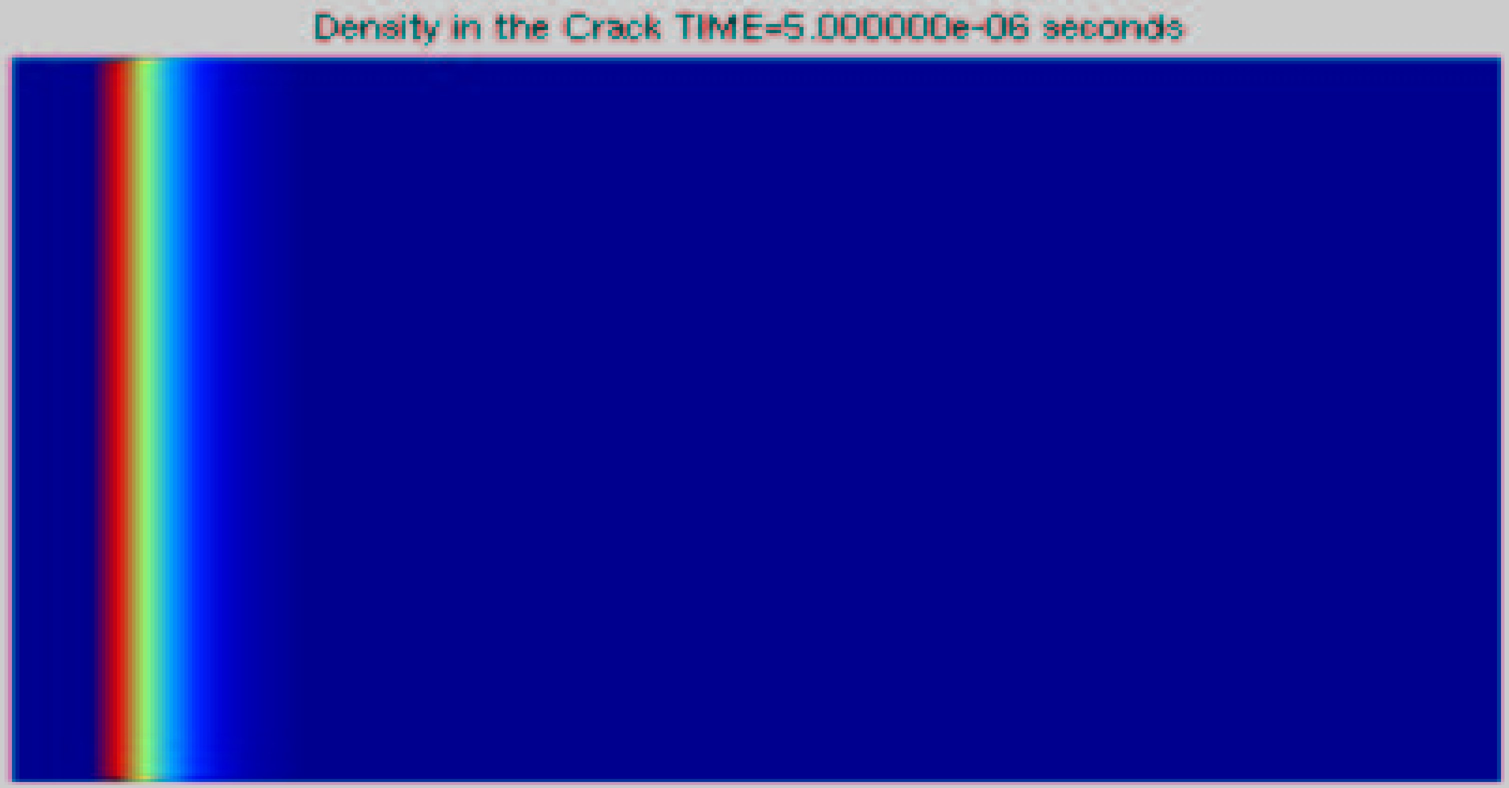


Wave propagation across a fluid-filled crack

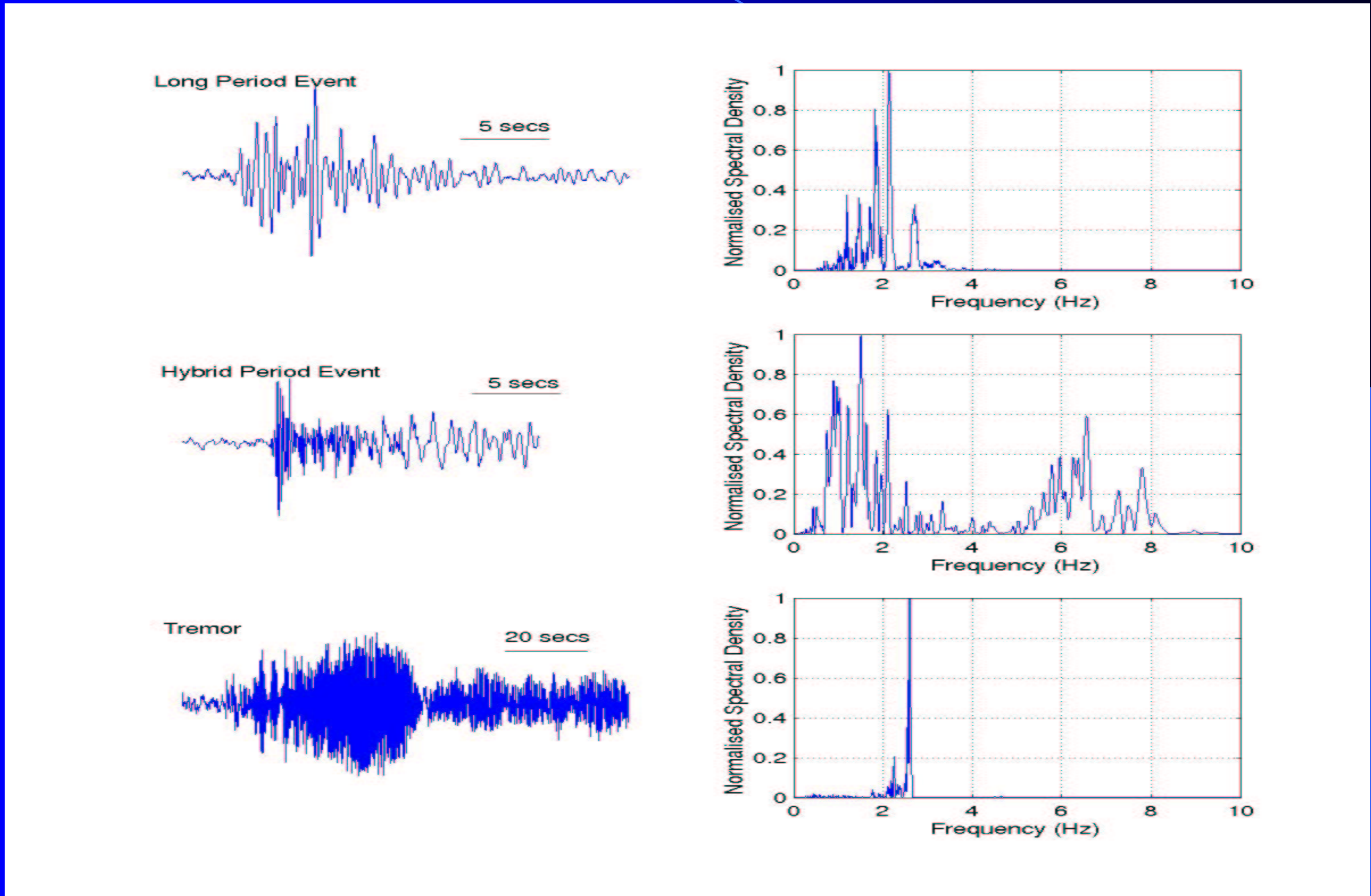




Wave-induced changes in fluid density.

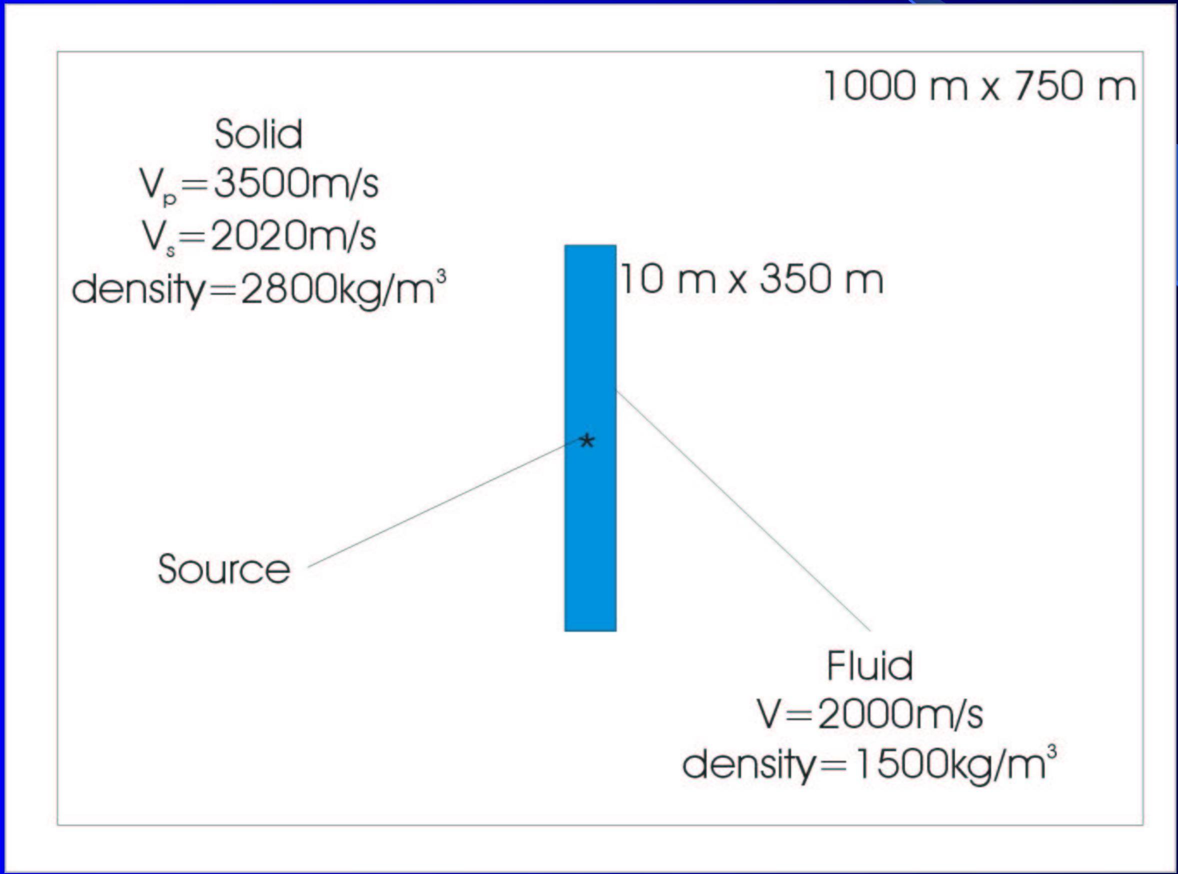


Applications to volcanic-seismicity

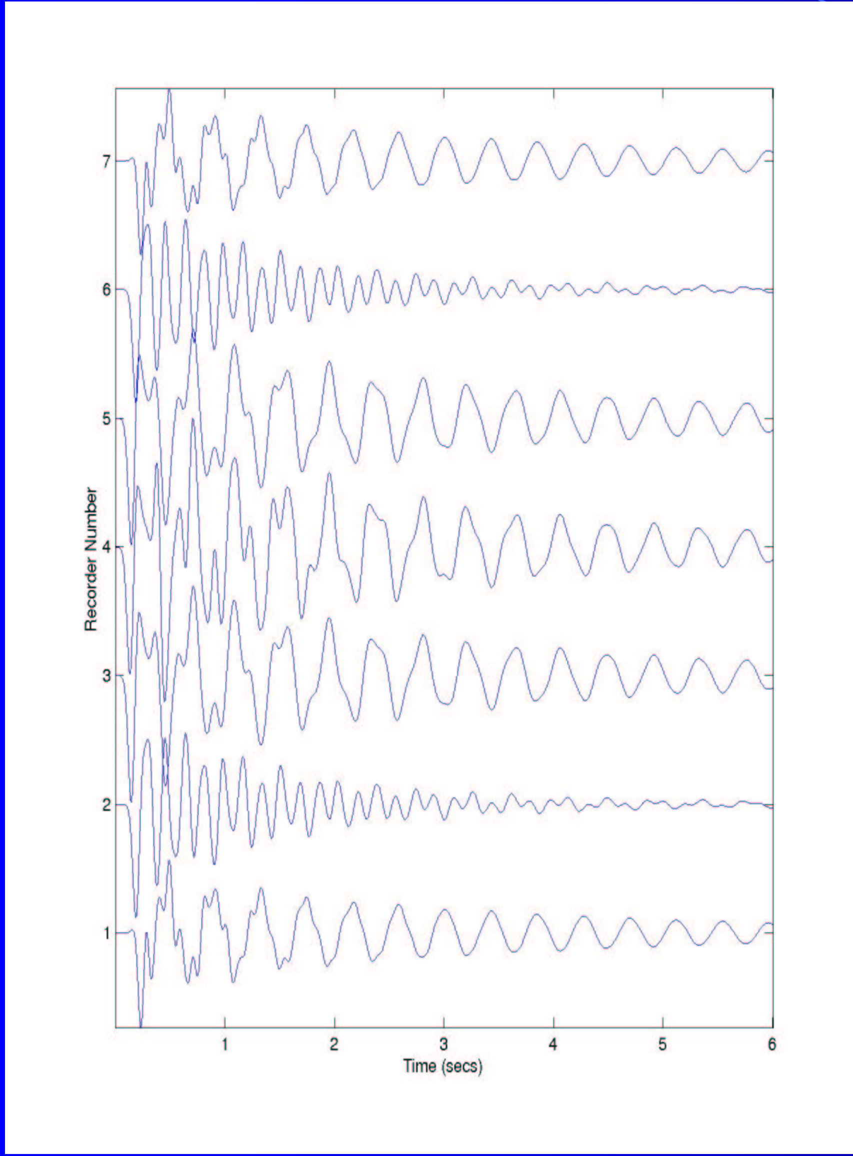


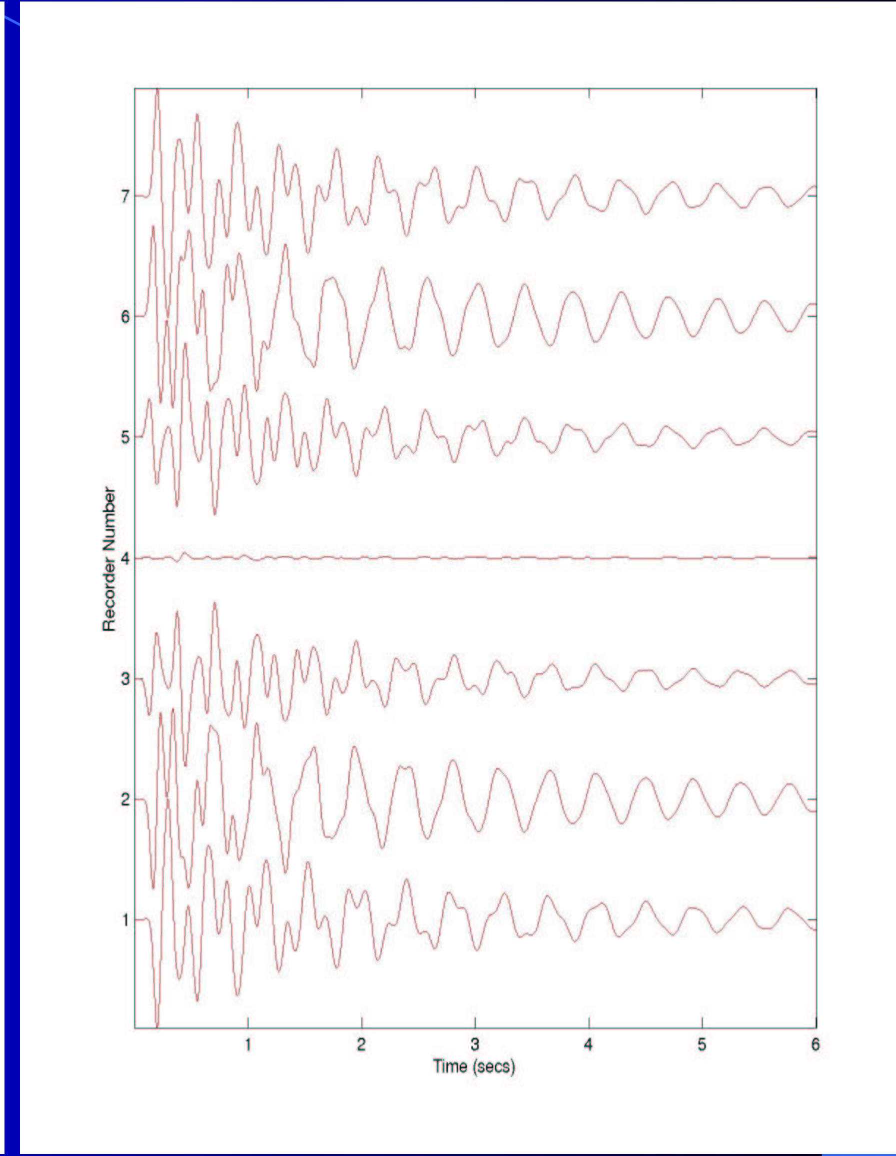
Signals recorded at Deception Island, Antarctica

Fluid Conduit inside an elastic homogeneous medium

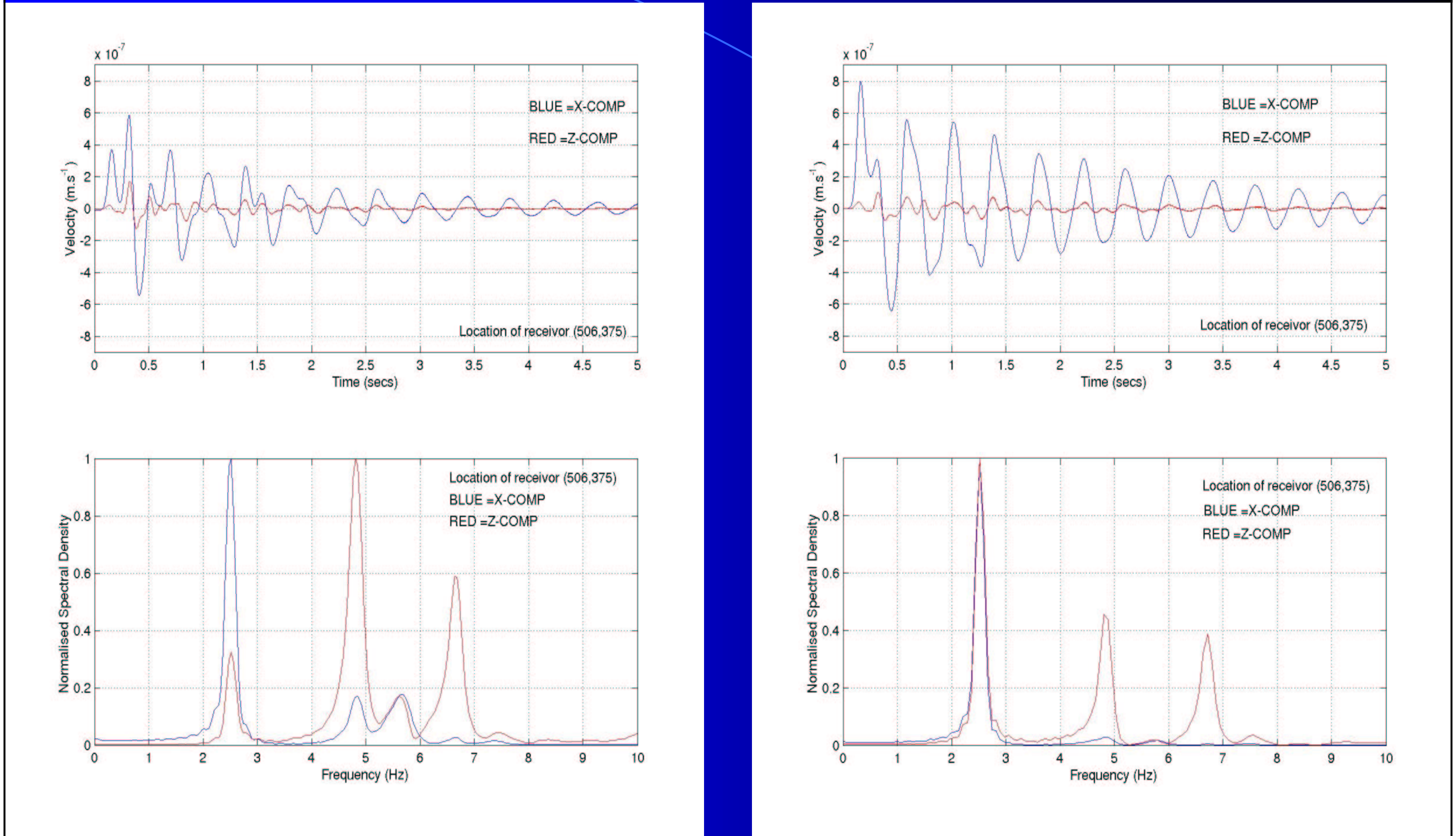


X and Z velocities on the conduit wall

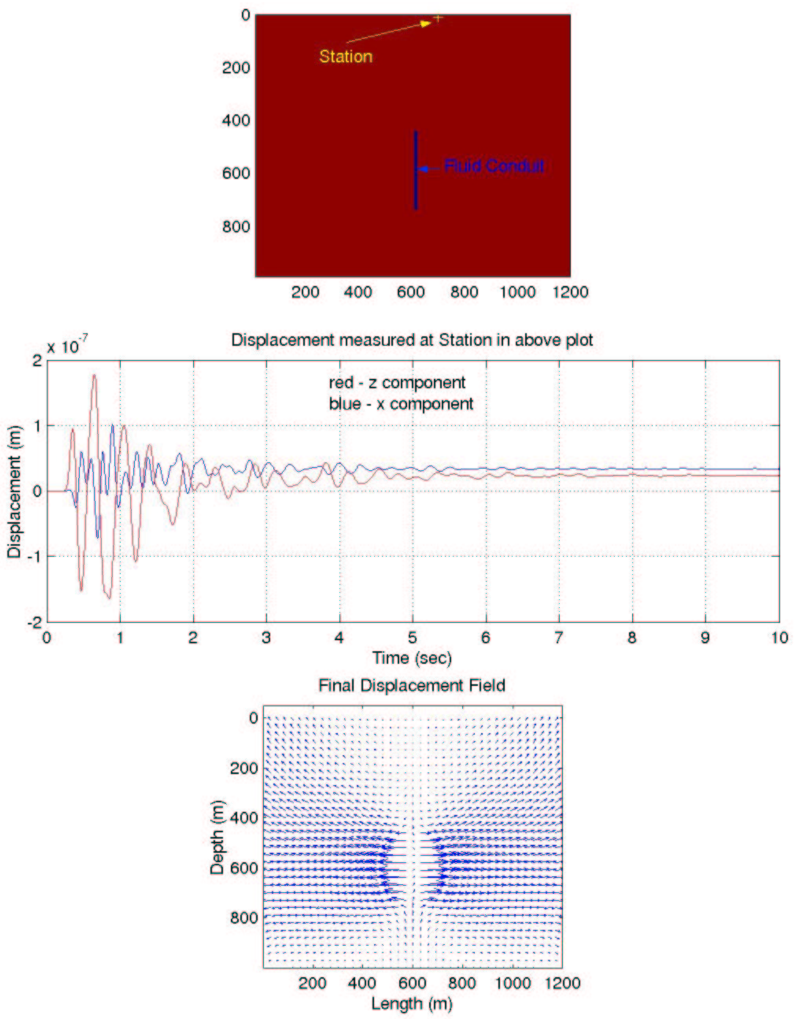


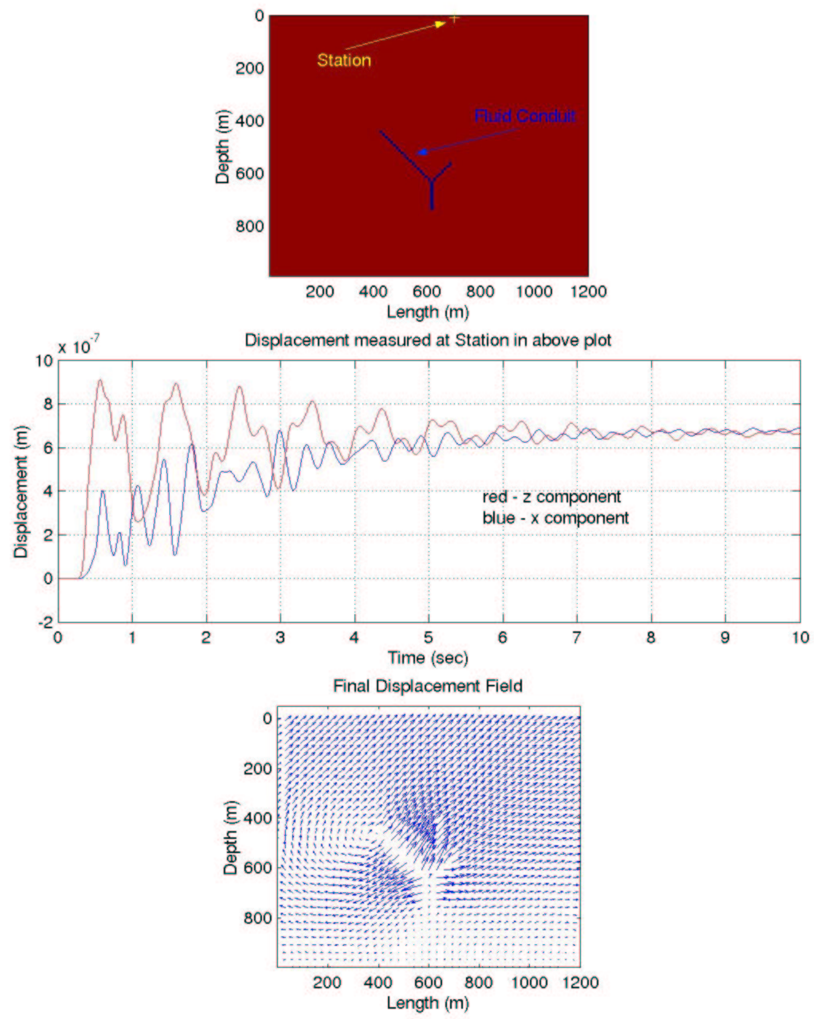


Velocity on the conduit walls for different viscosity fluids

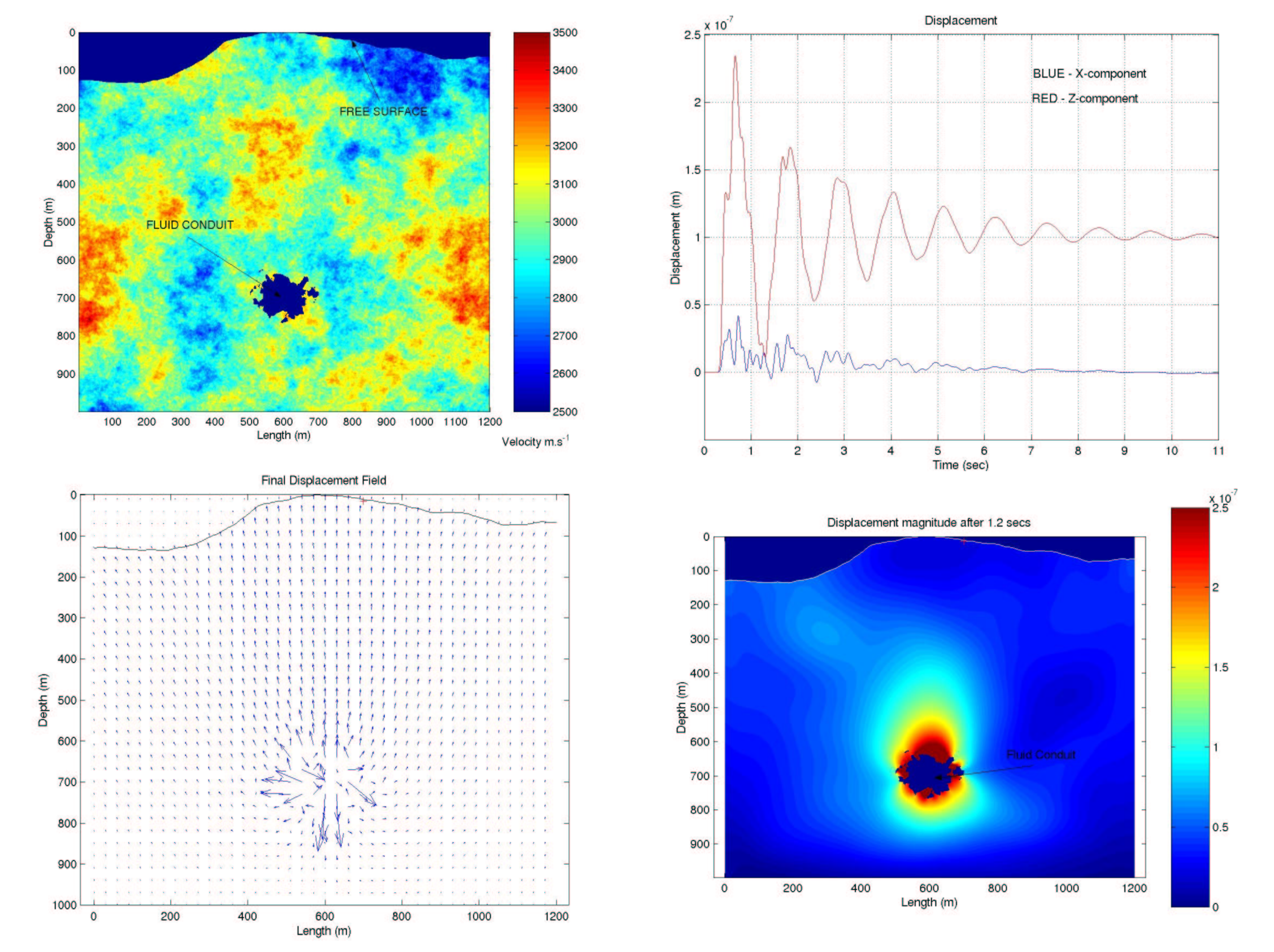


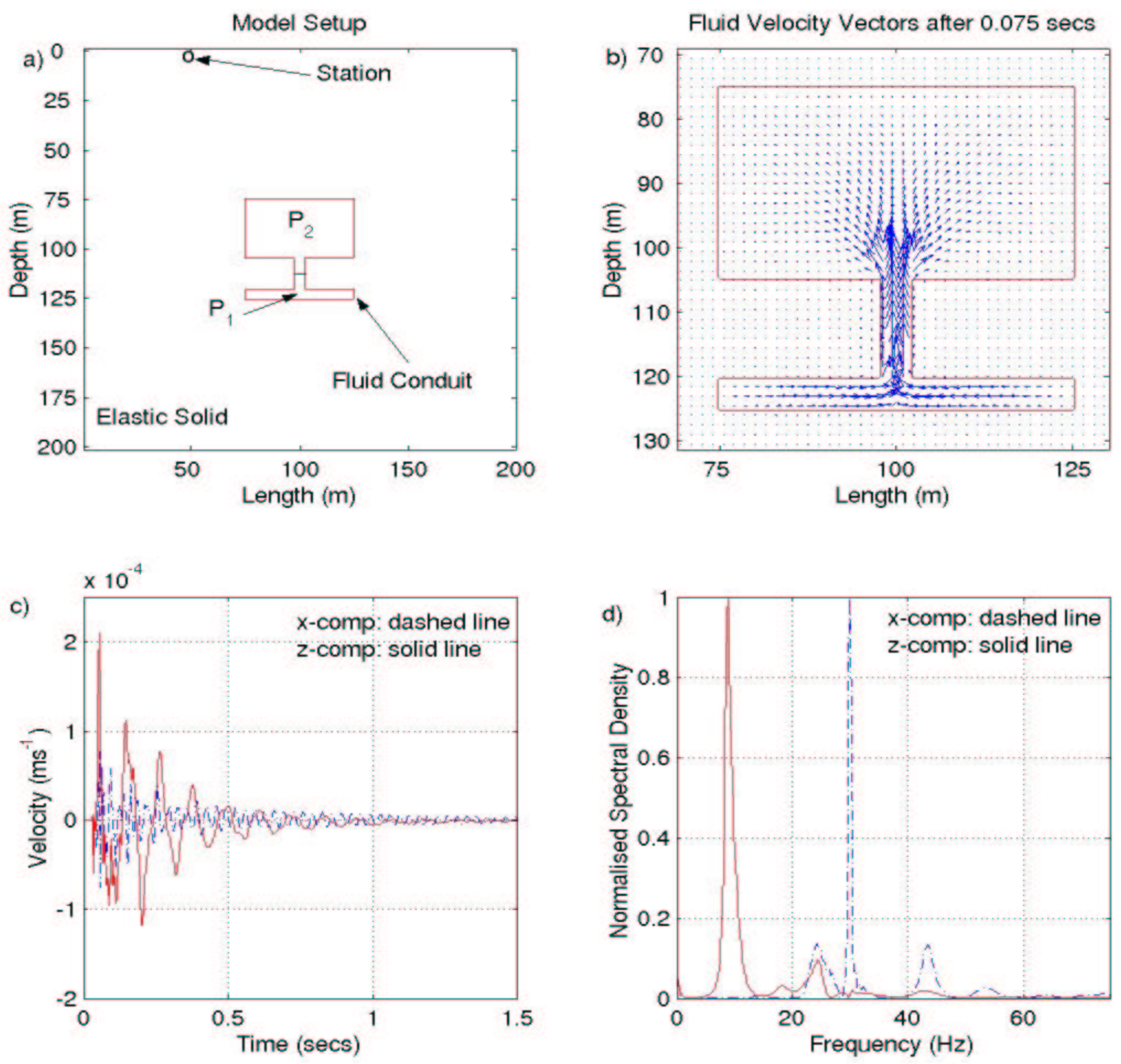
Low viscosity High viscosity (order of mag. Higher

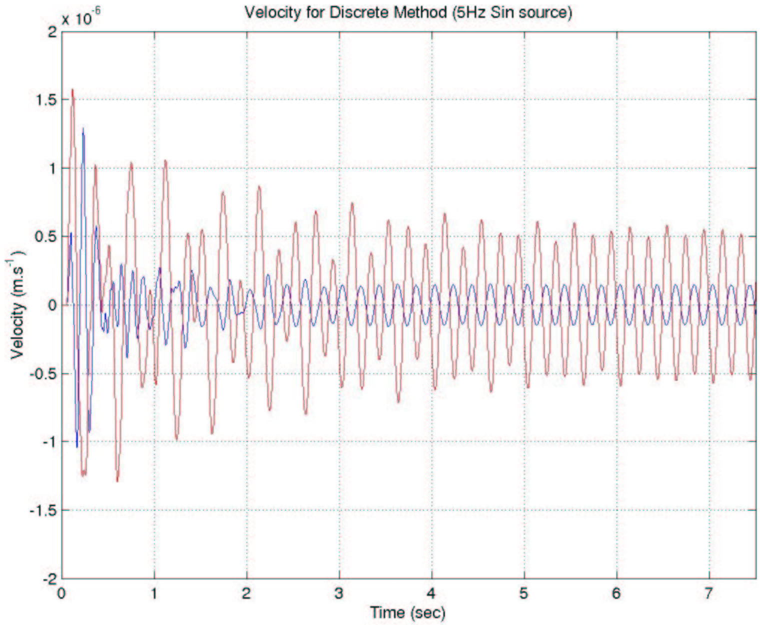


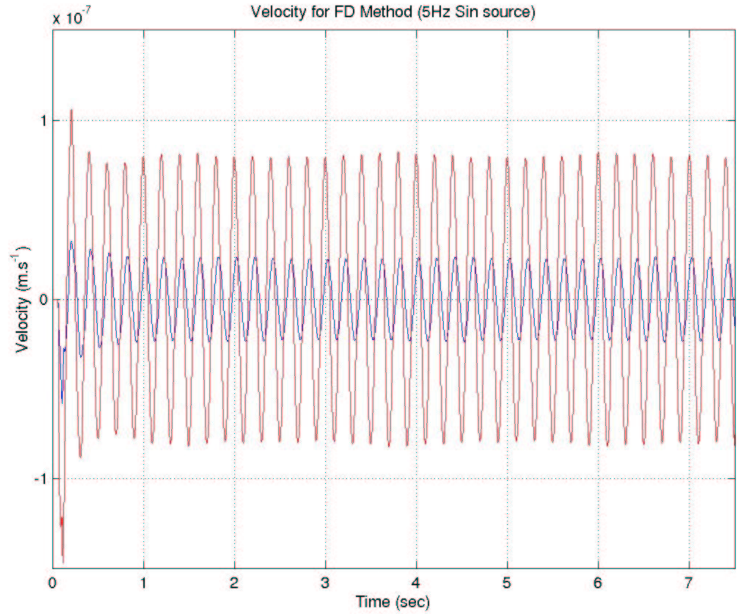


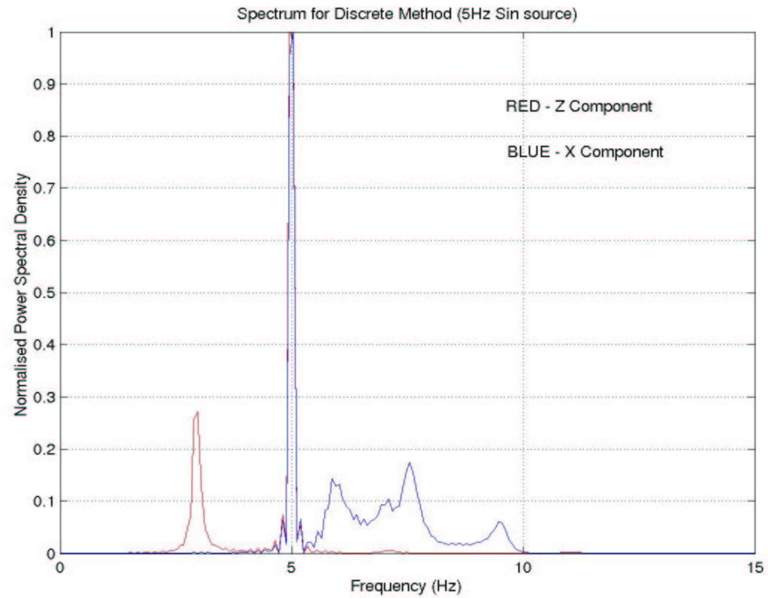
Input source is a positive Gaussian pulse, at centre of conduit

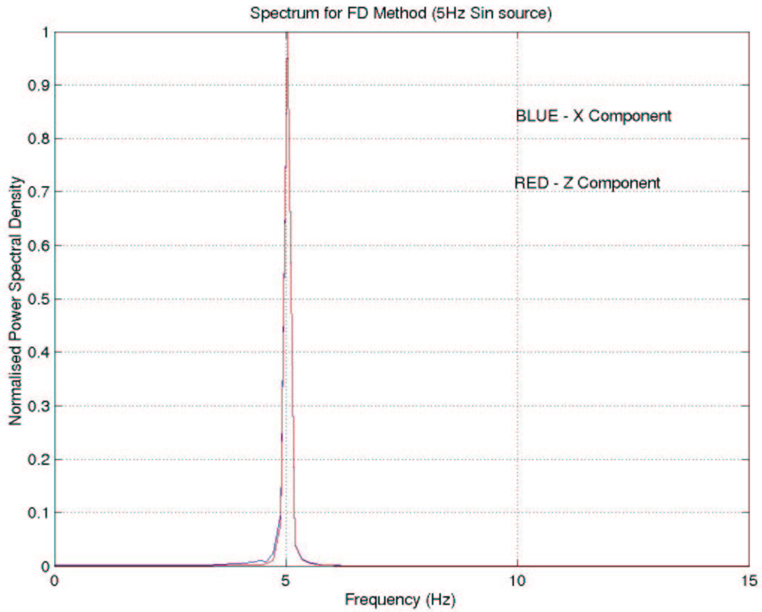

FREE SURFACE
FLUID CONDUIT
Depth (m)
Length (m)
Velocity m.s^{-1}
Displacement
BLUE - X-component
RED - Z-component
Displacement (m)
Time (sec)
x 10^{-7}
Final Displacement Field
Displacement magnitude after 1.2 secs
Fluid Conduit


Model Setup
a)
Station
P2
P1
Fluid Conduit
Elastic Solid
Depth (m)
Length (m)
Fluid Velocity Vectors after 0.075 secs
b)
Depth (m)
Length (m)
c)
x 10^-4
x-comp: dashed line
z-comp: solid line
Velocity (ms^-1)
Time (secs)
d)
x-comp: dashed line
z-comp: solid line
Normalised Spectral Density
Frequency (Hz)









Model is vertical conduit. Input source in the fluid is a continuous 5Hz sine wave
Recorded frequency a combination of driving and ‘natural’ frequency

Equipment:

• 20 cpu beowulf cluster in the lab
• 100 cpu (50Gb) cluster at Cork
• Building 200 cpu (100Gb) machine at University College Dublin in Summer 2004 under COSMOGRID project (site #1 of Irish Gov. Funded GRID computing initiative for computational physics)
• Codes: in-house, Promax

Other projects:
• COSMOGRID
• e-ruption

Teaching materials:

• We will develop an introductory course on the methods outlined here (not yet available)

Dublin-SPICE projects:

• PhD … further develop and use these tools to help understand volcano sources. Vesuvius Observatory is involved in this project.

• PostDoc … Numerical modelling of effects of micro-mechanical damage on time lapse seismic images of petroleum reservoirs. TOTAL's Geoscience Research Centre in London is involved.

• Other interests in Spice:
Adopt other methods through SPICE consortium
See if these methods are applicable to other SPICE problems, e.g. dynamic rupture.