Path effects on surface-wave amplification in sedimentary basins

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Abstract

Sedimentary basins strongly affect earthquake ground motions of both body and surface waves that propagate through them. Yet to characterize seismic hazards at a specific site, it is common practice to consider only the effects of near-surface geology on vertically propagating body waves despite surface waves often causing strong damage. Recently, Bowden & Tsai (2017) proposed an semi-analytical method to predict surface-wave basin amplification and noticed that certain large regional earthquake ground motions are under-predicted if surface waves are not properly accounted for. Since the theory is based on a 1-D approximation of the near-surface geologic structure and does not account for path effects, it is of interest to know how significantly such additional complexity affects the 1-D predictions. When considering deep basins, several other basin parameters play a role in the amplification of surface waves: transmission and conversion at the basin edge, basin shape, lateral resonance and focusing effects. As surface waves propagate back and forth in a highly dispersive medium, the amplification also varies strongly from the edge to the center of the basin. These effects are not always accounted for because of the cost of geophysical surveys that would accurately constrain the structure, the lack of earthquake data for empirical predictions, the poor understanding of what main factors are responsible for basin amplification, and the absence of quantitative estimates of their contribution to the overall amplification. The current study aims to provide quantitative estimates of the importance of these various path effects on surface waves amplification and also extend the current 1-D theory to more complex multi-dimensional basin structures.

PATH EFFECTS ON SURFACE-WAVE AMPLIFICATION IN SEDIMENTARY BASINS (S23C-0546)

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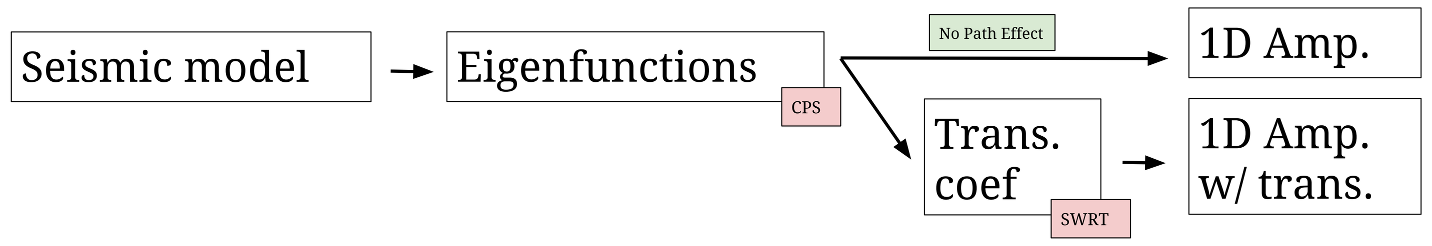
MOTIVATIONS

- Surface waves propagating in sedimentary basins strongly affect earthquake ground motions and cause strong damage *(Kawase, 1996)*
- *Bowden & Tsai (2017)* proposed a 1-D semi-analytical method to predict surface-wave basin amplification between two sites
- 1-D approximation of the near-surface geologic structure does not account for path effects (reflections, conversions)

⇒ The current study aims to provide quantitative estimates of the importance of these various path effects on surface-wave amplification and also extend the current 1-D theory to more complex multi-dimensional basin structures.

1 - SEMI-ANALYTIC MODELS



Pure 1D theory

- Conservation of energy flux
  ⇒ relative amplitude between two sites:

$$\frac{A_n}{A_n^R} = \frac{u_n(0)}{u_n^R(0)}\left(\frac{UI_0}{U^R I_0^R}\right)^{-1/2},$$

where A_n wave amplitude at the surface,
$u_n(0)$ surface-wave eigenfunction amp. at the surface,
U group velocity, $I_0 = \int_0^\infty \rho(z)(u_1(z)^2 + u_2(z)^2)dz$

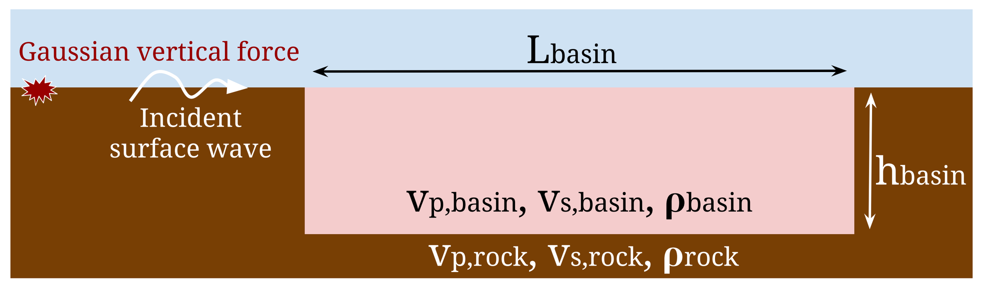
- Neglect path effects (reflections and mode conversions)

1D Theory w/ transmission coef. (SWRT)

- *Levshin (1989)* At a vertical boundary
  ⇒ wavefield = incident, reflected and transmitted waves
- Approximation of reflection/transmission coef. by Green's function method of *Its and Yanovskaya (1985)*
- Numerical code for transmission coef. by *Datta (2018)* named Surface Wave Reflec. Trans. (SWRT)
- Neglect body-wave diffraction at the basin edge

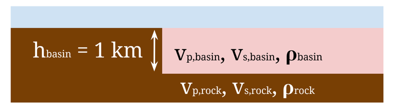
Eigenfunctions: computed using Computer Program in Seismology *(Herrmann, R. B., 2013)*.
Reference solutions: high-order numerical axisymmetric solutions from SPECFEM package *(Komatitsch & Vilotte 1998)*.

2 - SIMULATION SETUP



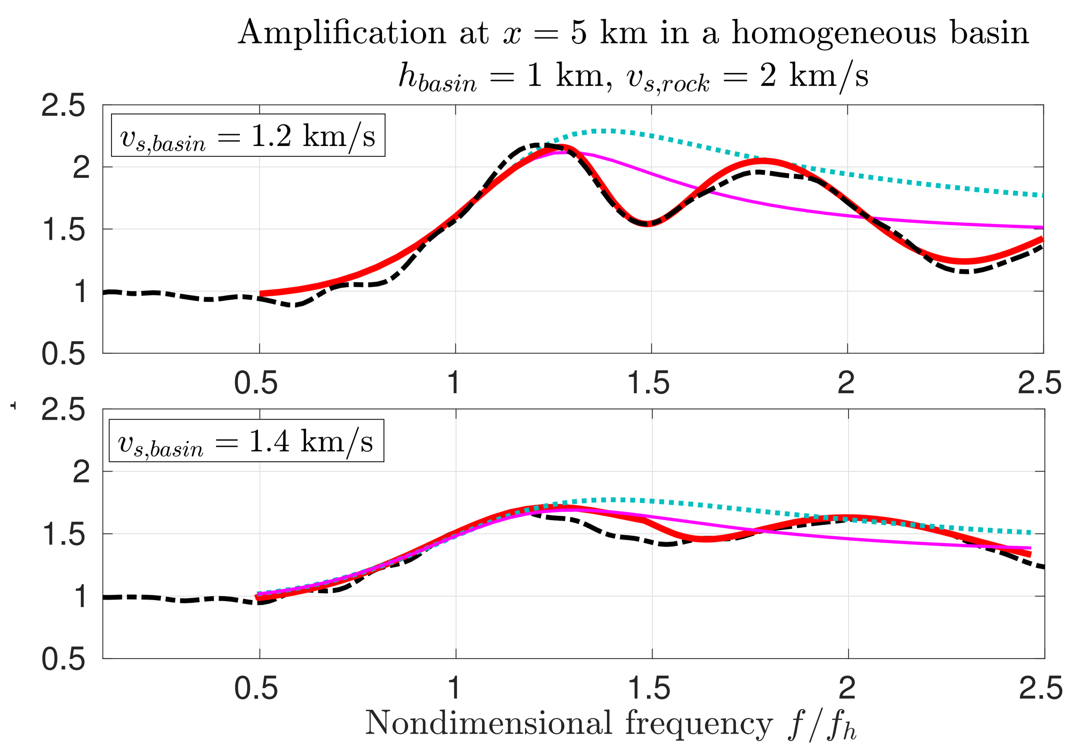
- Axisym. basin with length L_{basin}, depth h_{basin} and shear veloc. $v_{s,basin}$
- Relationships between v_p, v_s and ρ are extracted from *(Brocher, 2005)*
- We use a nondimensional freq. $f_h \approx \frac{f}{v_{s,basin}/3h_{basin}}$ *(Colombero, 2018)*

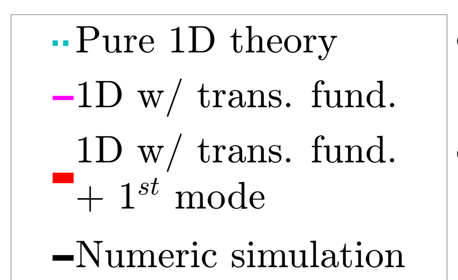
3 - TRANSMISSION AND CONVERSION IN SEMI-INFINITE BASINS ($L_{basin} \to \infty$)



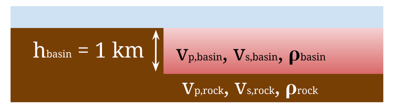
Homogeneous semi-inf. basin w/ various shear velocities

Amplification at $x = 5$ km in a homogeneous basin
$h_{basin} = 1$ km, $v_{s,rock} = 2$ km/s



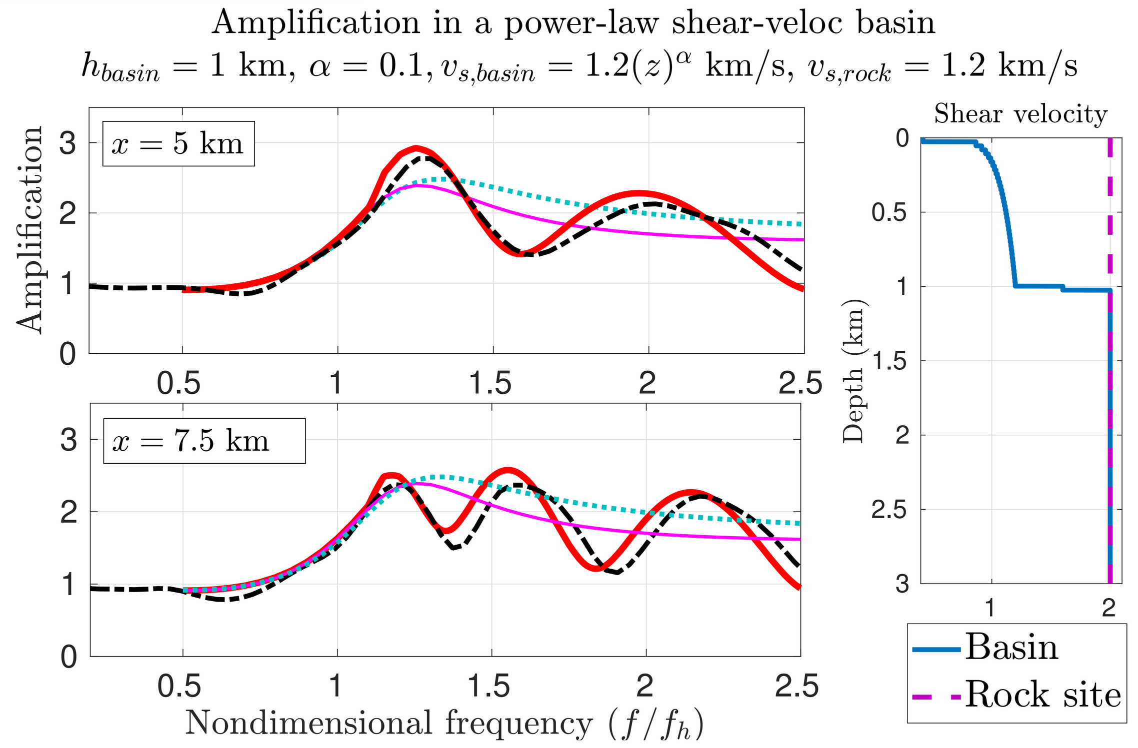


- Fund.-mode transmission coefficient captures well the average amplification spectrum
- Higher modes introduce strong oscillations in the spectrum that can be reproduced by considering fund.-to-higher modes conversions



Heterogeneous semi-inf. basin at various distances

Amplification in a power-law shear-veloc basin
$h_{basin} = 1$ km, $\alpha = 0.1$, $v_{s,basin} = 1.2(z)^\alpha$ km/s, $v_{s,rock} = 1.2$ km/s



- Amplification spectra for vertically heterogeneous basin velocity structures can be well approximated by transmission coefficients
- Main amplification peak amplitude can be increased by higher modes

4 - 1D FUND.-MODE AMPLIFICATION

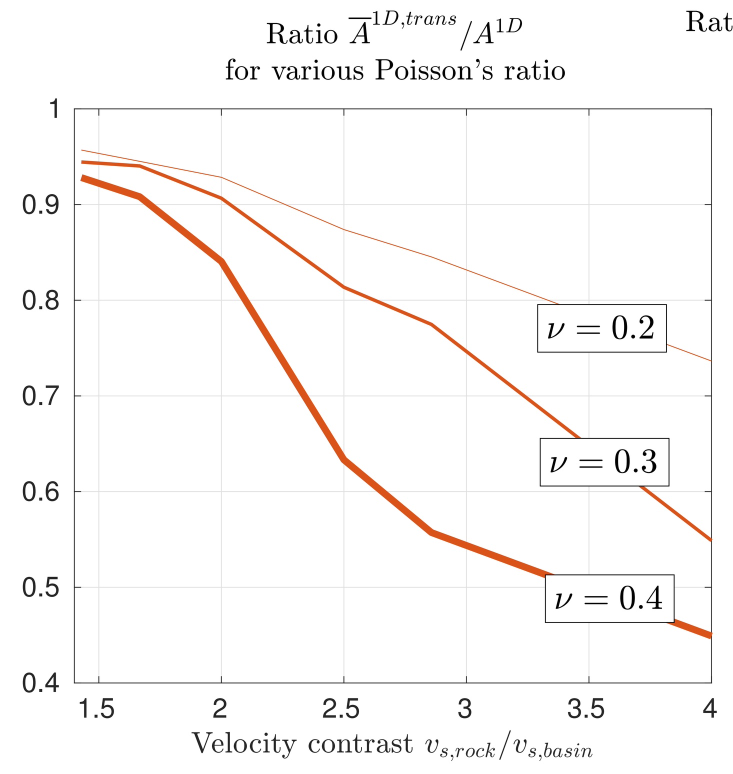


Figure: Ratio of max. amplification from the 1D theory A^{1D} and the mean transmission coefficients over the 10 first km from basin edge $\overline{A}^{1D,trans}$ against velocity contrasts for various Poisson's ratio

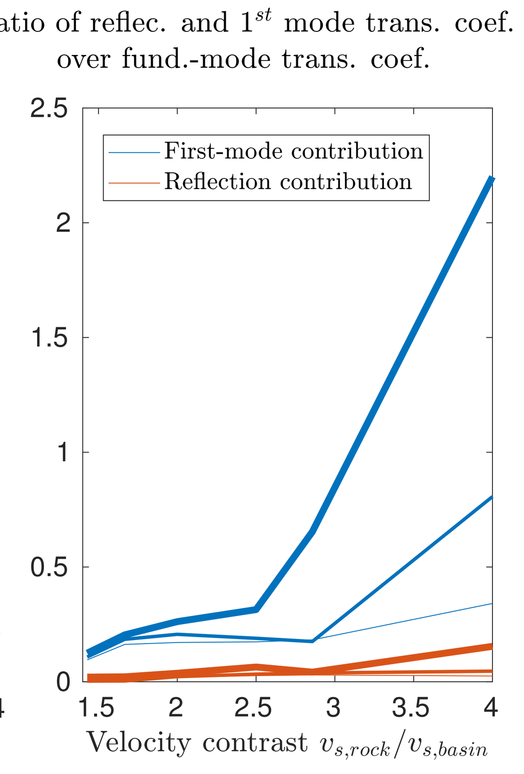


Figure: Ratio of reflection and 1^{st} mode trans. coef. over $A^{1D,trans}$

- Discrepancies between pure 1D theory and trans. coef. come from mode conversions and reflection at the basin boundary
- Using a nondimensional freq. f_h we can assess the accuracy of the 1D theory to predict the surface-wave amplification

5 - LATERAL RESONANCE

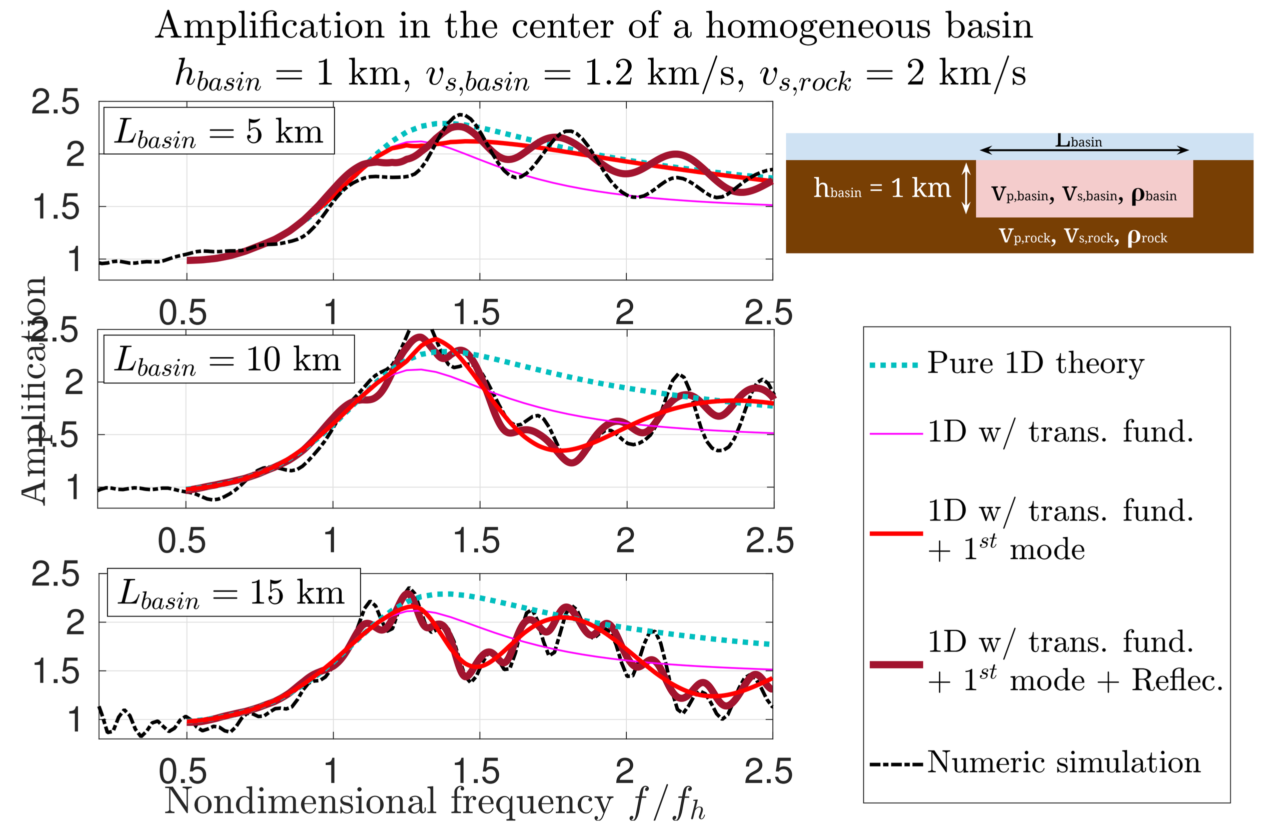
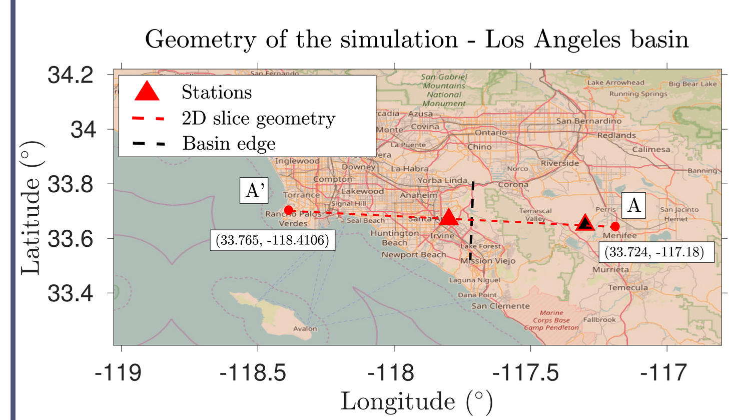


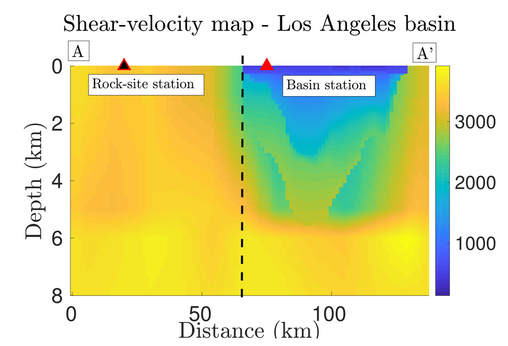
Figure: Top to bottom, Spectral amplification against nondimensional frequency f_h for basin length $L_{basin} = 5, 10, 15$ km and basin depth $h_{basin} = 1$ km.

- Lateral boundaries introduce extra oscillations in the amplification spectrum due to back and forth reflections within the basin
- Close to the basin edges and/or as the surface-wave wavelength range tends to the basin length, the maximum amplitude can be significantly altered

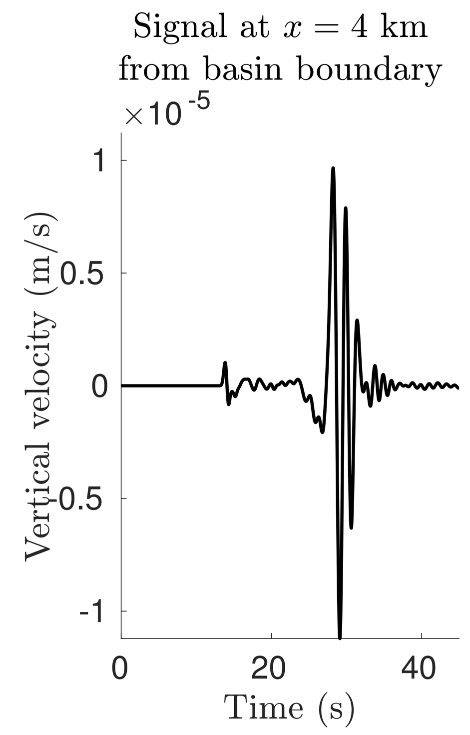
6 - LOS ANGELES BASIN AMPLIFICATION

- 2D velocity profile in the LA basin extracted from SCEC Community Velocity Model (CVM-S4.26, *Lee (2014)*) w/ sharp velocity jump
- Basin edge location is chosen at the largest horizontal shear-velocity jump ($d \approx 66$ km)
- Transmission coefficients are computed from the 1D profiles beneath the stations





- Simple 1D seismic models provide a good estimate of the amplification main frequency peaks
- The fundamental-mode low-frequency amplification is well captured by the pure 1D theory
- The conversion between fundamental to 1^{st} overtone has a significant impact on amplification and we can capture the higher-mode amplification frequency range and amplitude



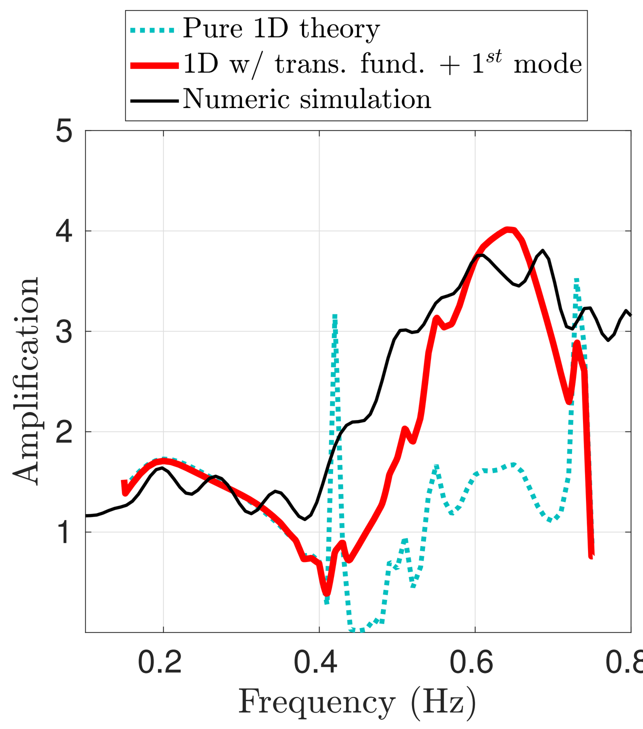


Figure: Left, Vertical velocity against time at the basin station. Right, amplification spectrum against frequency at the basin station

CONCLUSIONS AND FUTURE WORK

Conclusions

- 1D Theory
  ⇒ **good estimate of the amplification** (over-predict. < 30% of max. amp.) **for low velocity contrast** $\frac{v_{s,rock}}{v_{basin}} < 2.5$
- Approximate trans./reflec. coefficients:
  ⇒ can very well reproduce amplitude and variations of the amp. in axisym. basins
  ⇒ **good estimate of amplification in laterally heterogeneous axisym. sedimentary basins** w/ sharp vertical boundaries

Future work will include

- More complex axisym. basin geometries
- Love-wave amplification and Rayleigh-to-Love conversions
- Full 3D basins structures and subsequent path effects