Use of site-specific response analysis at Heathcote Valley to examine extreme ground motion amplitudes

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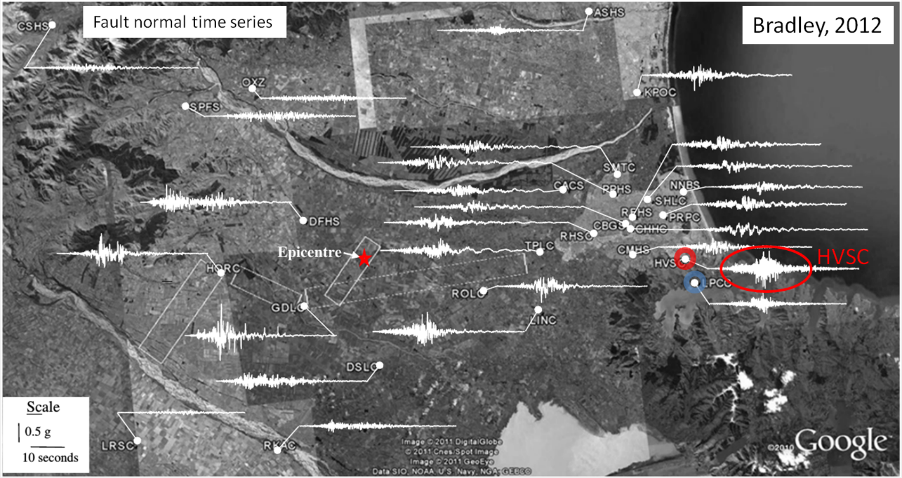
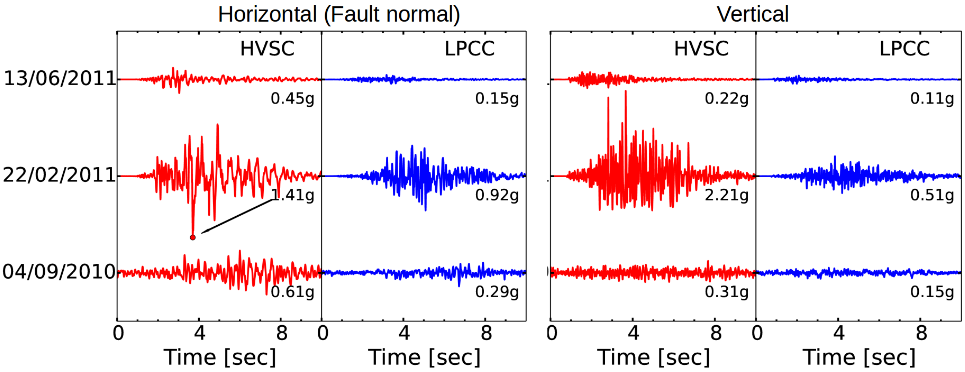
Observed site amplification: 4 Sept 2010



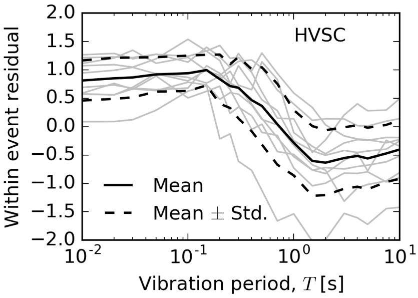
- Acceleration amplitude at HVSC significantly higher than nearby stations (similar source-site distances and azimuths)

Observed site amplification: HVSC VS. LPCC

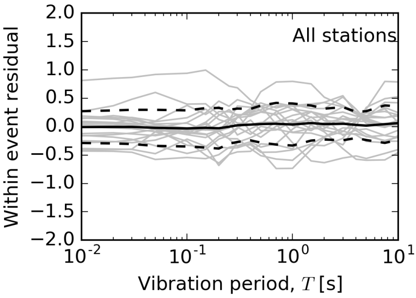


- Consistently higher amplitude at HVSC throughout the sequence of events
- Intense vertical acceleration

Empirical predictions [Bradley 2015]



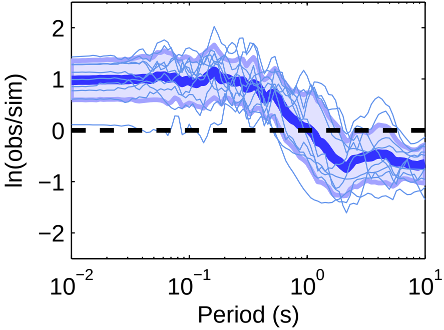
(a) HVSC



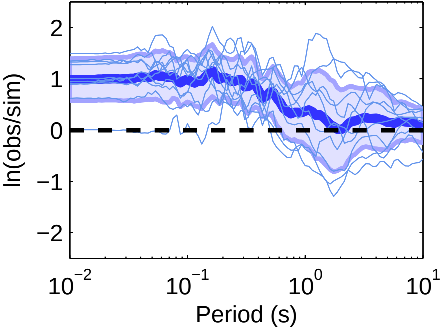
(b) All stations

- Non-ergodic empirical analysis of ground motions suggests strong systematic site amplification in periods $T < 0.5s$

Broadband ground motions simulations



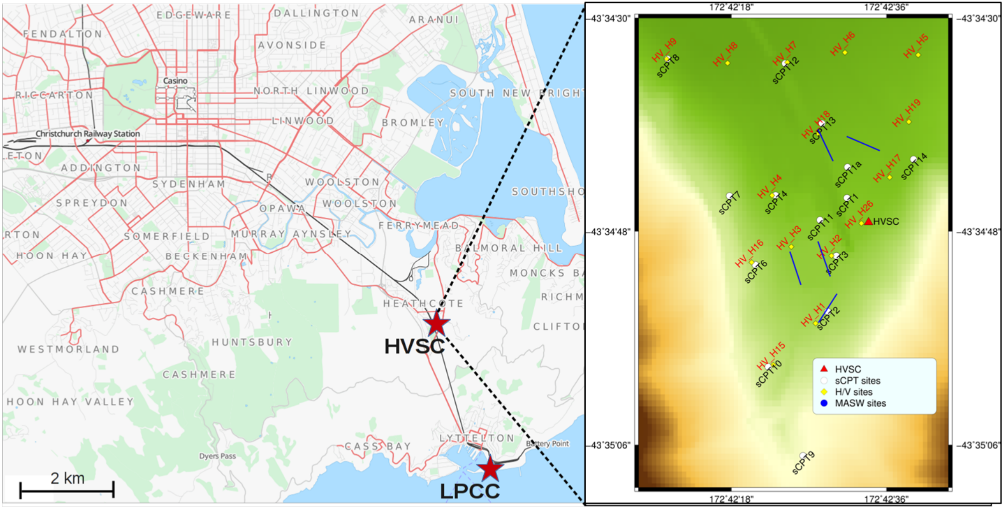
(a) 1D velocity model



(b) 3D velocity model

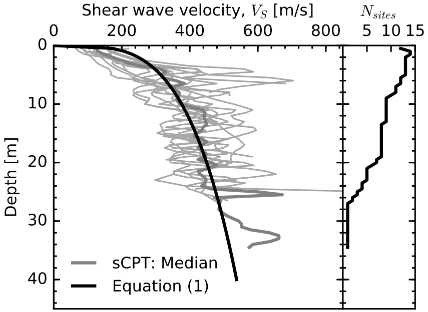
- Hybrid ground motion simulations using the Graves and Pitarka method, with a recently developed 1D and 3D velocity models of the Canterbury region
- V_{S30} based empirical correction factor to account for the site amplification
- 3D velocity model significantly improves prediction of long period ($T > 2s$) ground motions, but the prediction is still poor in short periods

Site investigation

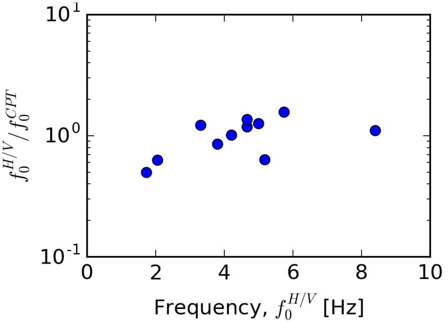


- 15 seismic CPT, 15 ambient noise H/V, 5 surface wave tests
- Lidar-based DEM to account for topography

Site investigation



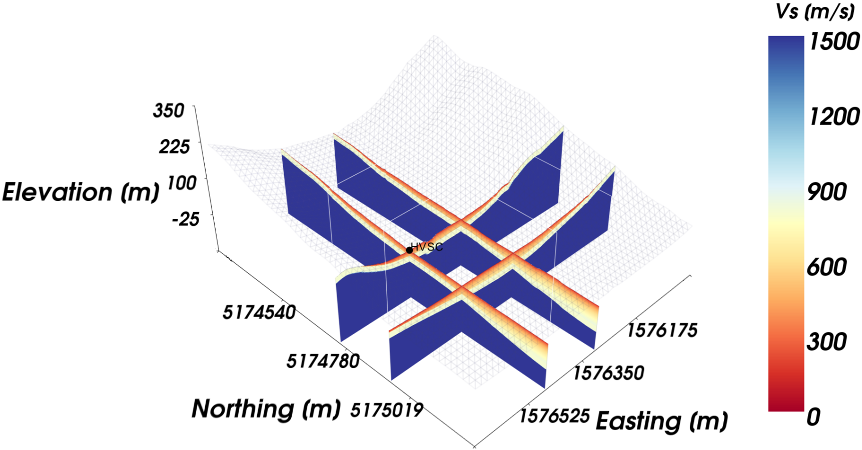
(a) V_S from sCPT



(b) Comparison of f_0 from H/V and sCPT

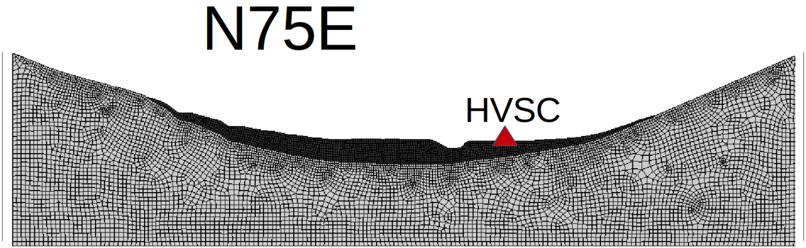
- Measured soil velocities are modelled with a power law equation: $V_S = 207z^{0.25} m/s$
- Site periods measured by H/V and sCPT are broadly consistent

3D geological model of Heathcote Valley



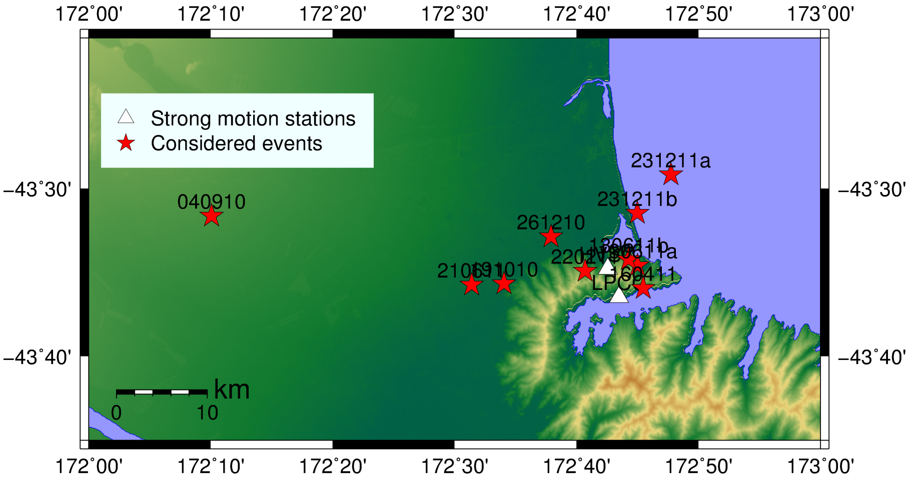
- $V_S = 207z^{0.25}$ m/s for soils; $V_S = 1500$ m/s for the volcanic bedrock
- Soil thickness profile from CPT refusal depths and the estimated depths from H/V spectral ratios

2D finite element model



- 2D finite element simulations using OpenSees
- Non-reflective boundaries; equivalent force input at the base of the model
- PDMY model (UCSD) for soils and the linear elastic model for rocks:
    - Soil: $\rho = 1.8 Mg/m^3$, $V_S = 207z^{0.25} m/s$, $\phi = 36°$, $\nu = 0.25$
    - Weathered rock: $\rho = 2.4 Mg/m^3$, $V_S = 800 m/s$, $\nu = 0.25$
    - Basement rock: $\rho = 2.4 Mg/m^3$, $V_S = 1500 m/s$, $\nu = 0.25$

Earthquake events for simulations



- Deconvolved and amplitude-corrected (based on the empirical model by Bradley 2010) LPCC rock motions as input motions

Earthquake events for simulations

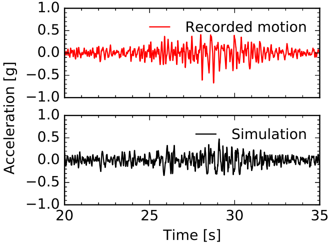
Table: Earthquake events used in the analyses, in chronological order.

		HVSC			LPCC		
Event date	M_W	R_{rup}[1] (km)	PGA[2] (g)	PGV (cm/s)	R_{rup} (km)	PGA (g)	PGV (cm/s)
04/09/2010	7.1	20.8	0.61	29	22.4	0.29	19
19/10/2010	4.8	12.8	0.09	3.2	13.1	0.02	0.71
26/12/2010	4.7	4.7	0.11	2.9	7.7	0.02	0.65
22/02/2011	6.2	3.9	1.41	81	7.0	0.92	46
16/04/2011	5.0	7.3	0.68	32	5.2	0.29	8.5
13/06/2011(a)	5.3	4.7	0.45	14	5.3	0.15	5.4
13/06/2011(b)	6.0	3.6	0.91	55	5.8	0.64	33
21/06/2011	5.2	14.9	0.26	8.0	15.6	0.07	2.1
23/12/2011(a)	5.8	9.9	0.31	12.7	11.4	0.24	7.6
23/12/2011(b)	5.9	9.7	0.26	42	12.4	0.44	23

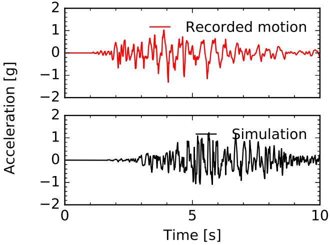
[1] The shortest source-to-site distance based on the models by Beavan et al. (2012)

[2] Horizontal fault-normal component

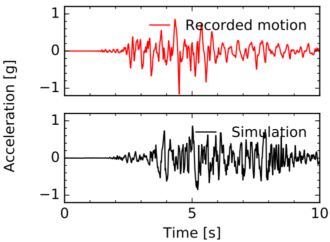
Simulations VS. Records: Time Series



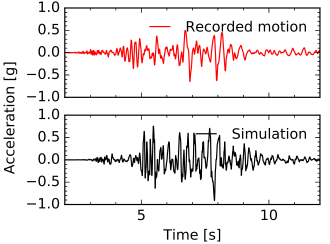
(a) 04/09/2010



(b) 22/02/2010

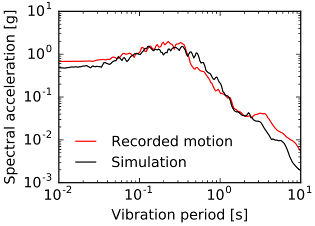


(c) 13/06/2011(b)

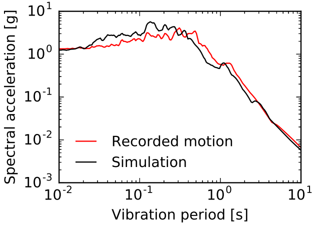


(d) 23/12/2011(b)

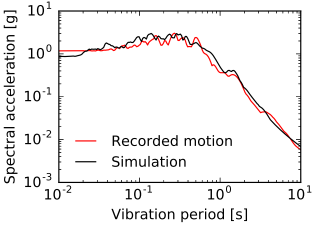
Simulation VS. Records: Response Spectra



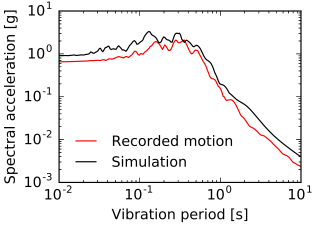
(a) 04/09/2010



(b) 22/02/2010

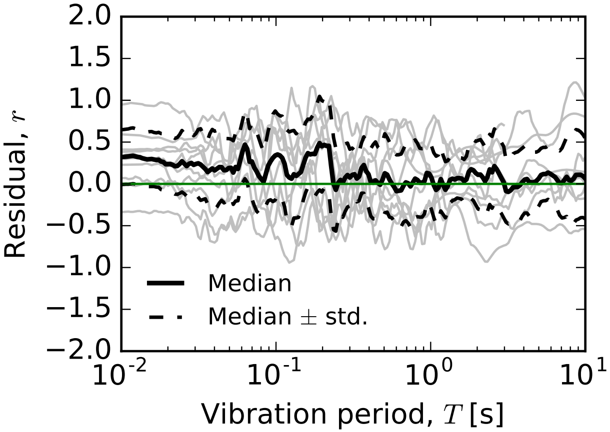


(c) 13/06/2011(b)

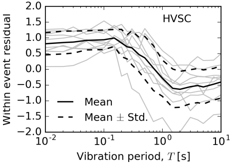


(d) 23/12/2011(b)

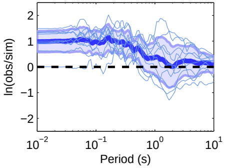
Spectral acceleration residuals



(a) 2D nonlinear site response analyses



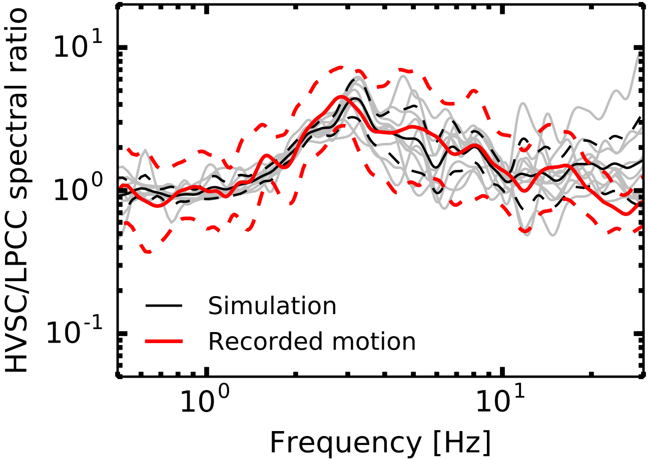
(b) Empirical model



(c) Ground motion simulation with 3D velocity model

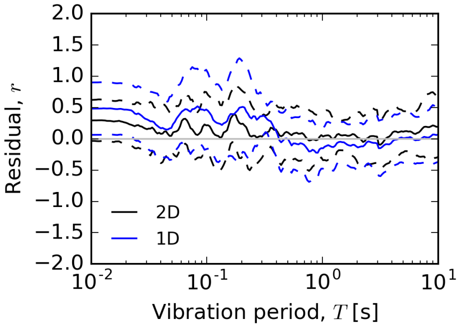
- The 2D Heathcote Valley site response model performs much better than the empirical model and the large-scale ground motion simulation

HVSC/LPCC spectral ratios

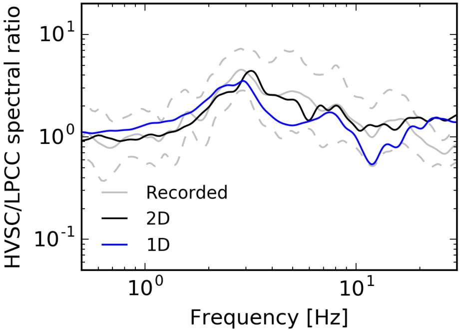


- Very good agreement between the observed and simulated spectral ratios
- Simulations show a large variability in the high frequencies ($f > 3Hz$), likely due to the event-dependent soil non-linear response

2D vs 1D simulations



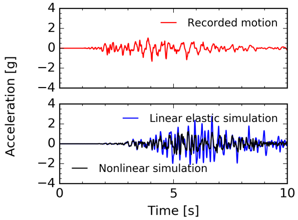
(a) Spectral acceleration residual



(b) HVSC/LPCC spectral ratio

- 2D simulations outperform 1D simulations
- 1D simulations overestimate long period motions ($T > 0.5s$ or $f < 2Hz$): Topography effect?
- 2D simulations and the recorded motions are further amplified in short periods ($T < 0.5s$ or $f > 2Hz$), likely caused by the Rayleigh waves generated near the basin edge

Effects of non-linear soil response



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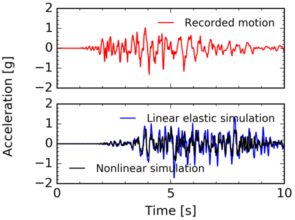
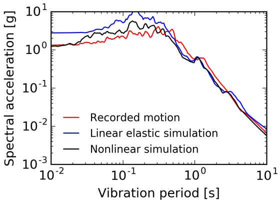


(b) 13/06/2011(b)



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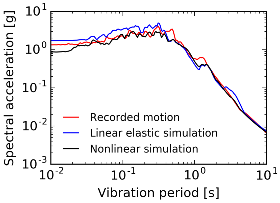
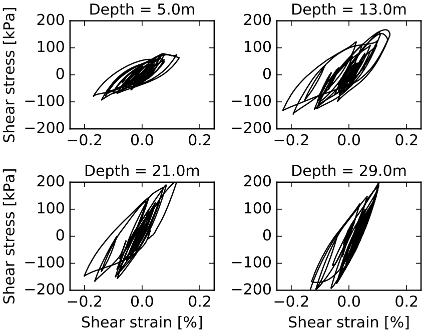


(b) 13/06/2011(b)

- Linear elastic simulations overestimate the ground motion amplitudes for strong events

Effects of non-linear soil response



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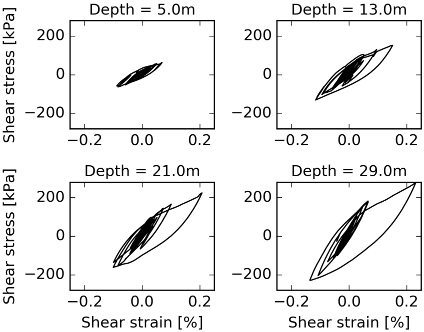
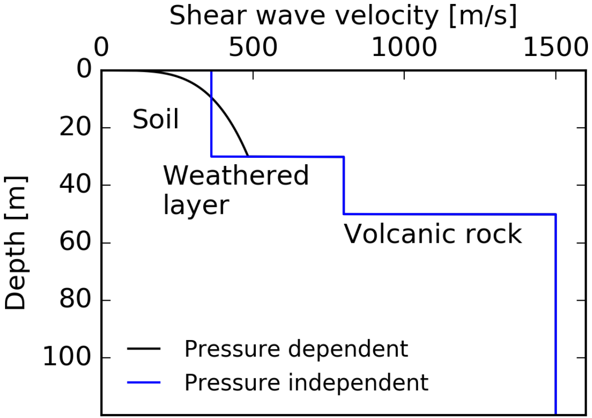


(b) 13/06/2011(b)

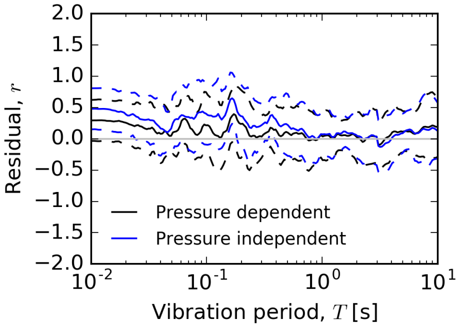
- Significant amount of energy is dissipated via the hysteretic response of soils during strong ground shaking events
- Improper modelling of such behaviour can lead to significant overestimation of ground motion amplification, caused by the waves trapped within the soil layer

Role of the depth dependent soil velocities

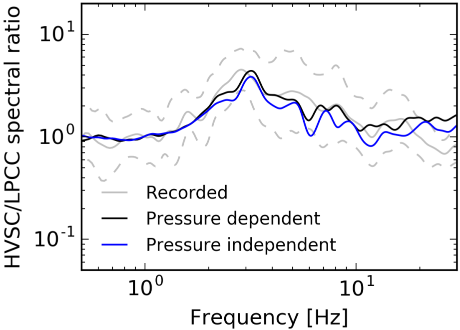


- Pressure dependent vs depth invariant soil moduli and strengths
- The two models have identical site periods and similar fundamental model amplification factors

Role of the depth dependent soil velocities



(a) Spectral acceleration residual



(b) HVSC/LPCC spectral ratio

- The equivalent homogeneous soil model underestimates the ground motion amplitude (at $T > 0.5s$ or $f < 2Hz$)
- The steep near surface velocity gradient of pressure dependent model results in much larger high frequency amplification; it may also affect how the surface waves propagates

Conclusion

- 2D non-linear site response simulation of Heathcote Valley shows a good agreement with observed ground motions and performs significantly better in high frequencies than the empirical model and the large scale ground motion simulation
- The strong impedance contrast at the soil-rock interface at Heathcote Valley significantly amplifies the ground motions near $f = 3Hz$
- Simulations suggest that the Rayleigh waves generated near the basin edge further amplify the ground motions at $f > 3Hz$
- Improper modelling of soil non-linear response may significantly overestimate the ground motion intensities for strong earthquake events
- Assumption of a depth-invariant soil velocity (and strength) may underestimate the amplification at frequencies higher than the site fundamental frequency