Use of SPAC, HVSR and strong motion analysis for site hazard study over the Tamar Valley in Launceston, Tasmania.

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Abstract

The geology of Launceston (Tasmania) is characterised by the presence of soft Tertiary and Quaternary sediments filling the Tamar rift valley. Damage has occurred to buildings in the city due to earthquake activity in the Bass Strait. We use microtremor (passive seismic) survey methods, and strong ground motion analysis to characterize the resonance pattern over the Tamar valley. The spatially averaged coherency method (SPAC) gives a shear wave velocity to depth profile at two sites; site *GUN* located over an assumed 1D geology, and site *KPK* located inside the Tamar valley. We then use horizontal to vertical spectral ratio (HVSR) to estimate the period of resonance at *GUN* and *KPK*. We finally compare HVSR observations with ellipticity modelling and strong ground motion analysis using the shear wave velocity profile obtained by SPAC. HVSR observations at *GUN* fit the ellipticity curve calculated with a layered model, while some discrepancies between HVSR and modelled strong ground motion analysis can be explained by the input of damping and modulus reduction factors in the strong ground motion analysis. HVSR observations at *KPK* do not fit the ellipticity curve computed with the shear wave velocity profile. 2D effects from the Tamar valley could be the cause of this difference. We explain the difference between HVSR and strong ground motion analysis at *KPK* by a combination of potential 2D effects from the valley, and the use of damping and modulus reduction curves in the strong ground motion analysis.

Keywords: microtremor, shear-wave velocity profile, period of resonance, amplification factors, strong ground motion.

1. INTRODUCTION

Past earthquakes have induced damage to buildings in Launceston, even if the city is located several hundreds kilometres away from any active seismic region (Michael-Leiba, 1995).

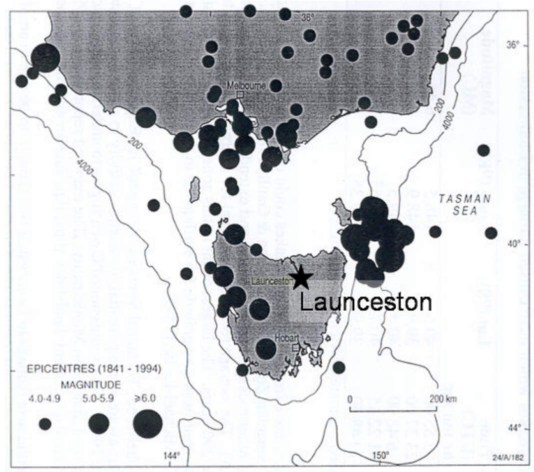


Figure 1. Epicentres of earthquakes (Magnitude = 4.0+) from 1884-1994 in the Tasmanian region. (modified from Michael-Leiba, 1995).

The geology of Launceston is characterised by the presence of the Tamar rift valley, which traverses the city in the NNW-SSE direction. It is filled with soft Tertiary and Quaternary sediments (Leaman, 1994), which provide a soft base for foundations. We postulate likelihood of existence of 2D effects, and study the site to see if evidence exists for them. The bedrock is a hard fractured dolerite of Jurassic age, which provides limited seismic risk and better than satisfactory conditions for foundations (Leaman, 1994). Interpretation of gravity data by Leaman (1994) suggests that the Tamar valley is 700m to 1000m wide, with a maximum thickness of 250m.

The objective of this paper is to better understand the seismic resonance pattern induced in the Tamar valley, using passive seismic microtremor survey methods. We first use spatially averaged coherency method (SPAC) to generate 1D shear wave velocity to depth profiles at separate sites in the city. We then use horizontal to vertical spectrum ratio (HVSR) and strong ground motion analysis to study the resonance pattern and site amplification inside and outside the valley.

2. SHEAR WAVE VELOCITY TO DEPTH PROFILES

We determine shear wave velocity to depth profiles in Launceston using a centred hexagonal array of 7 Mark L28 - 4.5Hz geophones to record microtremors. We analyse the microtremor with the SPAC method, introduced by Aki (1957). SPAC makes use of the hypothesis of spatial and time stationarity of microtremor to calculate an azimuthally averaged coherency over different radii.

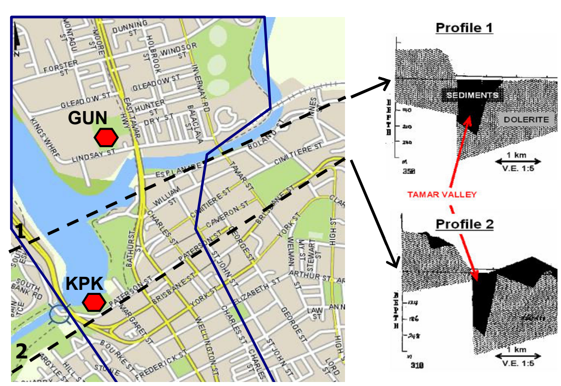


Figure 2. Map of Launceston. Hexagons are locations of SPAC array. Dashed lines represent 2 gravity profiles from Leaman (1994). Full line represents the approximate limits of Tamar valley.

We present the results obtained over an assumed 1D geology (*site GUN*; Gunn's Company), and at one site located inside the valley (*site KPK*; King's Park), as shown in

Figure 2. Averaged over all directions, the coherency has the shape of a Bessel function of first kind and zero order (Aki, 1957):

$$C(\omega) = J_0\left(\frac{2\pi f r}{V(f)}\right), \tag{1}$$

where $C(\omega)$ is the spatially averaged coherency, J_0 the Bessel function of first kind and zero order, f the frequency and r the radius of the array. $V(f)$ is the shear-wave velocity dispersion curve associated with a 1D layered earth geology. We directly fit the coherency curves to the appropriate Bessel function by iterative forward modelling (Hermann, 2002) to obtain the shear wave velocity profiles (Asten *et al.* 2004; Asten, 2006).

2.1 *GUN* Site

We used 15m and 30m radius arrays at *GUN*. We determine the shear wave velocity profile by joint analysis of both sets of SPAC curves. Figure 3 presents the results obtained from the 15m radius array.

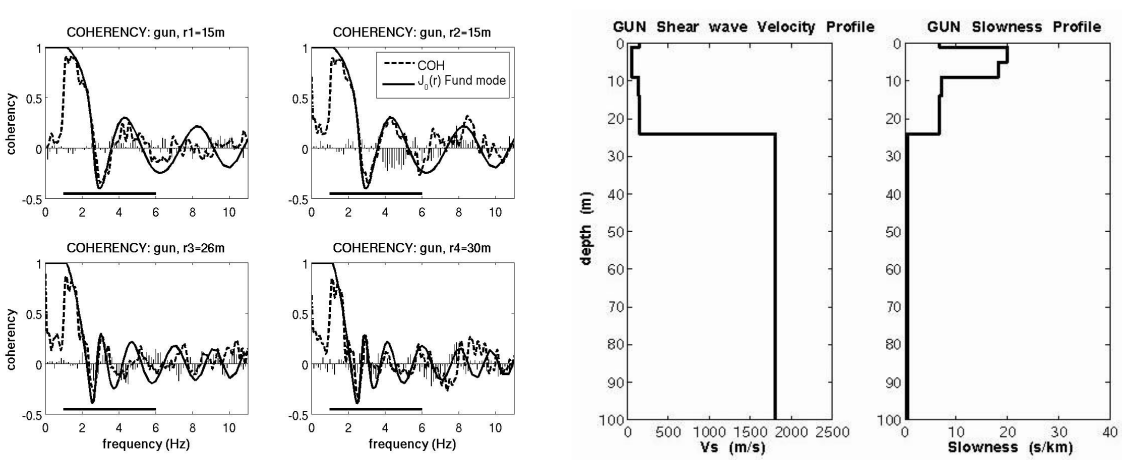


Figure 3. SPAC spectra for *GUN* site. Real part (thick line) and imaginary part (thin bars) of SPAC spectrum, with superimposed model SPAC spectrum (dashed line) computed from layered-earth model on the right. Straight lines at bottom of coherency graphs show the frequency range considered in the forward modelling process.

The utilisation of 2 arrays at GUN allows enhanced precision on the velocity profile for a broader range of frequencies. Forward modelling suggests a shallow bedrock interface at approximately 25m, with overlying sediments composed of a thin layer of filling, underlain by 10m of very low velocity (as low as 50m/s) alluvial sediments (clay and silt). 10m of more coherent silty clay to clayey sand is found between the alluvial sediments and the dolerite bedrock. Information from nearby borehole logs confirms SPAC interpretation.

2.2 *KPK* Site

Due to access limitations, only one 28m radius array was laid out at King's Park (site *KPK*). The results are presented in Figure 4. We interpret the upper layers as being composed of clay and silt from the Quaternary period. They are underlain by a thick layer of low velocity (400-500m/s) sands from the Tertiary period. The use of high-frequency sensors (4.5Hz) for SPAC observations limits the resolution at depth. We fail to locate accurately the interface between the tertiary sediments and the dolerite, but we interpret it must be at a minimum depth of 150m. Using further information from HVSR analysis and the gravity survey from Leaman (1994), we suggest that the interface should be located at approximately 250m. In October 2007, we conducted a second survey in Launceston (data is presently being analysed) with four 30s and 60s Guralp CMG-3ESP geophones and larger arrays (40m to 150m radius) which should provide us better resolution at depth.

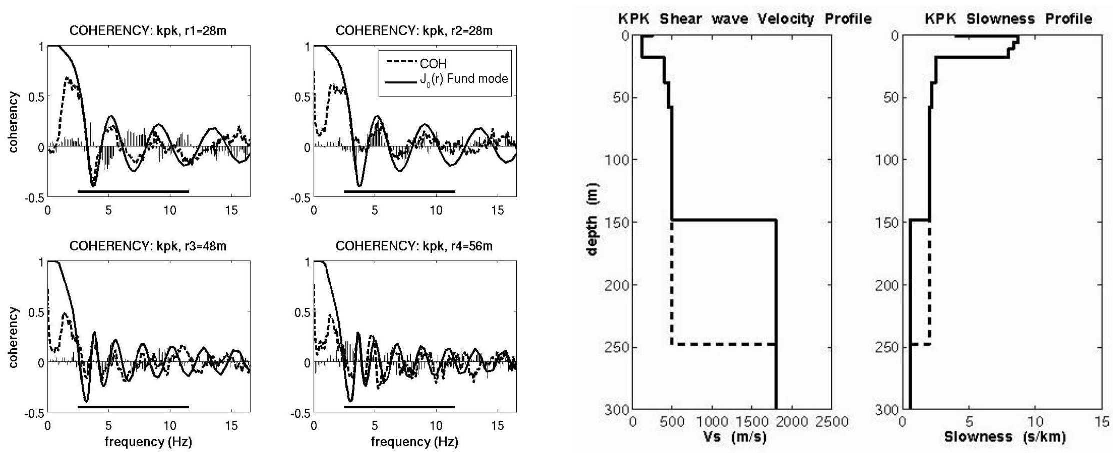


Figure 4. SPAC spectra for *KPK* site. Same legend as Figure 3. Full lines on the velocity/slowness model represent the minimum possible depth of the interface interpreted by SPAC. Dashed lines represent the depth suggested by HVSR observations and gravity survey.

3. PATTERN OF RESONANCE IN LAUNCESTON

3.1 Methodology

We use three approaches to analyse the pattern of resonance at Launceston. First, we model the particle motion of the Rayleigh waves (R_o for fundamental mode), using the shear wave velocity profiles interpreted by SPAC in Figures 3 and 4. This elliptical motion is proportional to the wave period and the elastic parameters of the earth. It tends to degenerate into a dominantly horizontal motion at the period of resonance (Asten *et al,* 2002). We use the Rayleigh wave's ellipticity to determine the period of resonance of a layered site (Tokimatsu, 1997).

We then use the horizontal to vertical spectrum ratio (HVSR), introduced by Nakamura (1989), to estimate the period of resonance of a site. In a layered medium, the HVSR peak is empirically found to be a reliable estimation of the Rayleigh wave's ellipticity (Lachet and Bard, 1994; Scherbaum *et al*, 2003).

The third approach consists of modelling the site amplification with strong ground motions, using the package *SUA* developed by Robinson *et al* (2006). This equivalent linear site-response analysis models regolith site-response to generate amplification factors, using spectral acceleration observed from strong ground motion on rock (Robinson *et al*, 2006). We select two specific strong ground motions to model site amplification at Launceston; one with high energy at high frequency, and one with high energy at low frequency. This allows us to better compare strong ground motion and microtremor analyses, since microtremor are composed of waves from the whole spectrum of frequency (Okada, 2003). We use two acceleration time series from the Northridge earthquake in 1994 to complete the strong ground motion analysis.

Following Robinson *et al* (2006), we include damping and modulus reduction curves to represent the non-linearity of the sediments to percentage strain. Using the information available on the geology of Launceston, we input the appropriate damping and modulus reduction curves from the software ProShake (http://www.proshake.com/userman.pdf). We compute an amplification factor to represent the site responses (Dhu and Jones, 2002), which we compare with the Rayleigh wave's ellipticity and the HVSR observations. Tables 1 and 2 present the parameters used in strong ground motions analysis for *GUN* and *KPK* respectively.

Table 1. Geological Parameters, *GUN* Site.

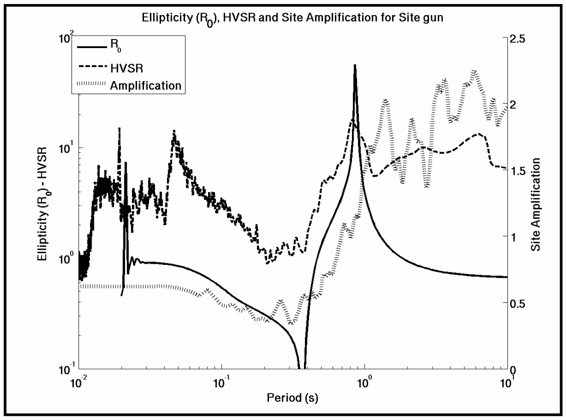
ID	**Thick. (m)**	**Vs (m/s)**	**ρ (g/cm^3)**	**Geology**	**Damping Curve**	**Modulus Reduction**
1	1	150	1.5	Filling	Linear	Linear
2	4	50	1.5	Clay	Clay – Average (Sun et al.)	Clay PI=20-40 (Sun et al.)
3	4	55	1.5	Clay	Clay – Average (Sun et al.)	Clay PI=20-40 (Sun et al.)
4	5	140	1.5	Clay	Clay – Upper Bound (Sun et al.)	Clay PI=40-80 (Sun et al.)
5	10	150	2.0	Sand	Sand (Seed & Idriss) – Lower Bound	Sand (Seed & Idriss) – Lower Bound
6	∞	1800	2.9	Dolerite	Rock	Rock

Table 2. Geological Parameters, *KPK* Site.

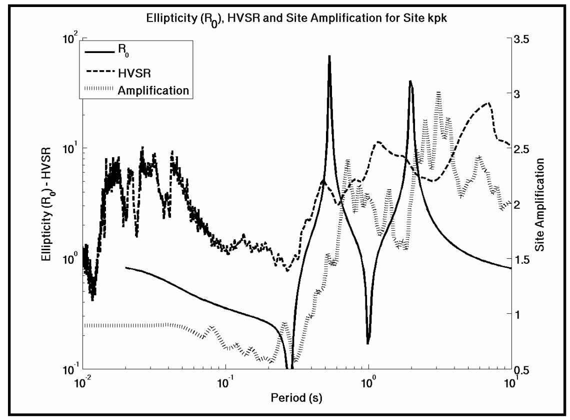
ID	**Thick. (m)**	**Vs (m/s)**	**ρ (g/cm^3)**	**Geology**	**Damping Curve**	**Modulus Reduction**
1	1	250	1.5	Filling	Linear	Linear
2	2	115	1.5	Clay	Clay – Average (Sun et al.)	Clay PI=20-40 (Sun et al.)
3	3	115	1.5	Clay	Clay – Average (Sun et al.)	Clay PI=20-40 (Sun et al.)
4	5	120	1.5	Clay	Clay – Upper Bound (Sun et al.)	Clay PI=40-80 (Sun et al.)
5	7	125	2.0	Clay	Clay – Upper Bound (Sun et al.)	Clay PI=40-80 (Sun et al.)
6	20	400	2.0	Sand	Sand (Seed & Idriss) – Average	Sand (Seed & Idriss) – Average
7	20	450	2.0	Sand	Sand (Seed & Idriss) – Average	Sand (Seed & Idriss) – Average
8	190	500	2.0	Sand	Sand (Seed & Idriss) – Average	Sand (Seed & Idriss) – Average
9	∞	1800	2.9	Dolerite	Rock	Rock

3.2 Results for Site Amplification Study

Figure 5 shows the results obtained from HVSR observations, Rayleigh wave ellipticity and site amplification modelling from strong ground motion at *GUN* and *KPK*.



(a) *GUN*



(b) *KPK*

Figure 5. Modelled ellipticity (R_0, full line), observed HVSR (dashed line), and modelled site amplification factors (dotted lines) for a) *GUN* and b) *KPK*. Ellipticity and HVSR are plotted with the logarithmic left axis; site amplification is plotted with the linear right axis.

The peaks on observed HVSR and modelled ellipticity curve agree well for *GUN*, with a period of resonance $T_h = 0.90$s. This suggests that HVSR can adequately estimate resonance pattern when using microtremor survey method over a layered geology. The period of resonance is shifted to higher period for the strong ground motion analysis. We suggest that the input of damping and modulus reduction factors are responsible for this shift in the period of resonance. Modelling with no damping and modulus reduction curves generates a period of resonance which agrees well with observed HVSR and modelled ellipticity (results not presented).

We see discrepancies between the observed HVSR and the modelled ellipticity at King's Park *KPK*. We recognise 2 peaks in both the ellipticity and HVSR. The HVSR peak at $T_{h1} = 0.50$s, which is thought to correspond to the interface between Quaternary and Tertiary sediments, agrees well with the ellipticity peak. The second peak on HVSR ($T_{h2} = 1.10$s) does not agree with the peak on the modelled ellipticity (2.00s). As observed at *GUN*, the periods of resonance computed by the strong ground motion analysis are shifted to longer periods when compared with HVSR observations and modelled ellipticity (Asten *et al*, 2002).

4. CONCLUSIONS

We demonstrate that microtremor survey method is a reliable tool to conduct a resonance study. Analysis at *GUN* shows good agreement between the observed HVSR and the modelled ellipticity. This is good evidence that geology at *GUN* can be approximated by a layered geology. The discrepancy between the modelled ellipticity and the strong ground motion analysis can result from the consideration of a non-linear and inelastic medium in the strong ground motion analysis. Microtremor survey method assumes a linear and elastic medium due to the low level of strain involved in ambient vibrations. Site *KPK* being located inside the Tamar valley, we postulate the presence of 2D effects in the resonance pattern at *KPK*, shifting the peak on HVSR to lower period of resonance. This effect was studied by Bard and Bouchon (1985), and later observed in Roten *et al*, 2006.

We conclude from this study that microtremor survey methods (both array technique SPAC and single station method HVSR) and strong ground motion analysis can be used conjointly to analyse resonance pattern induced by low velocity sediments over hard bedrock.

REFERENCES

Aki, K. (1957). Space and time spectra of stationary stochastic waves, with special reference to microtremors. *Bulletin Earthquake Research Institute*, *35*, 415-456

Asten, M. (2006). On bias and noise in passive seismic data from finite circular array data processed using SPAC methods. *Geophysics*, *71*, no.6, V153-V162.

Asten, M., Dhu, T. and Lam, N. (2004). Optimised array design for microtremor array studies applied to site classification; comparison of results with SCPT logs. In *13th World Conference on Earthquake Engineering*, Paper No.2903, Vancouver, B-C, Canada.

Asten, M., Lam, N., Gibson, G. and Wilson, J. (2002). Microtremor survey design optimised for application to site amplification and resonance modelling, *in* Total Risk Management in the Privatised Era, edited by M. Griffith, D. Love, P. McBean, A. McDougall, B. Butler, Proceedings of Conference, Australian Earthquake Engineering Society, Adelaide, Paper 7.

Bard, P.-Y. and Bouchon, M. (1985). The two-dimensional resonance of sediment-filled valleys. *Bulletin of the Seismological Society of America*, *75*, 519-541.

Dhu, T. and Jones, T. (2002). Earthquake risk in Newcastle and Lake Macquarie. *GA Record 2002/15*, Canberra, Australia, 271pp.

Hermann, R. (2002). Computer programs in seismology: An overview of synthetic seismogram computation. Saint-Louis University, USA, version 3.30 2002 edition.

Lachet, C. and Bard, P.-Y. (1994). Numerical and theoretical investigations on the possibilities and limitations of Nakamura's technique. *Journal of Physics of the Earth*, *42*, 377-397.

Leaman, D. (1994). Assessment of gravity survey City of Launceston. Technical Report, Leaman Geophysics, Hobart, Tasmania, Australia, for Launceston City Corporation Seismic Zonation Study.

Michael-Leiba, M. (1995). Microtremor survey and seismic microzonation Launceston, Tasmania. Technical report, Australian Geological Survey, Canberra, ACT, Australia, for Launceston City Council.

Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quarterly Report of Railway Technical Research Institute*, *30*, 25-33.

Okada, H. (2003). The microtremor survey method. *Number 12 In Geophysical Monograph Series*, Edited by Michael W. Asten, Society of Exploration Geophysicists, USA, 135pp.

Robinson, D., Dhu, T. and Schneider, J. (2006), SUA : A computer program to compute regolith site-response and estimate uncertainty for probabilistic seismic hazard analyses. *Computer & Geosciences*, *32*, 109-123.

Roten, D., Fäh, D., Cornou, C. and Giardini, D. (2006). Two-dimensional resonances in Alpine valleys identified from ambient vibration wavefields. *Geophysical Journal International*, *165*, 889-905.

Scherbaum, F., Hinzen, K.-G. and Ohrnberger, M. (2003). Determination of shallow shear wave velocity profiles in the Cologne, Germany area using ambient vibrations. *Geophysical Journal International, 152*, 597-612.

Seed, H.B. and Idriss, I.M. (1970). Soil moduli and damping factors for dynamic response analyses. *Report No. EERC 70-10*, Earthquake Engineering Research Center, University of California, Berkeley, USA.

Sun, J.I., Golesorkhi, R. and Seed, H.B. (1988). Dynamic moduli and damping ratios for cohesive soils. *Report No. EERC-88/15*, Earthquake Engineering Research Center, University of California, Berkeley, USA.

Tokimatsu, K. (1997). Geotechnical site characterization using surface waves. *Earthquake Geotechnical Engineering: Proceedings IS-Tokyo 95*, Edited by K. Ishihara, The First International Conference on Earthquake Geotechnical Engineering, 1333-1368.