Shear Wave Velocity measurement at Australian Ground Motion Seismometer Sites by the Spectral Analysis of Surface Waves (SASW) Method

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ABSTRACT

Near-surface shear-wave velocity profiles were acquired at eighteen permanent and temporary seismograph sites in Western Australia, South Australia, Victoria and New South Wales. These data were obtained to support ground-motion modelling in Australia by characterising the near-surface response at sites used to record ground-motion from Australian earthquakes. Geoscience Australia contracted the US Geological Survey to obtain shear-velocity data using the Spectral Analysis of Shear-Waves (SASW) technique. Velocity profiles were calculated down to maximum depths between 100-200m. Apart from two sites on alluvium, all sites were located on hard rock at or near the surface. The average velocity to 30m depth (V_{s30}) ranges from 257 m/s for alluvial sites to 1652 m/s for Proterozoic metasediments.

INTRODUCTION

Geoscience Australia (GA) has an ongoing program to develop models of ground-motion generated by earthquakes in Australia. Ground-motion models are essential for estimating the risk to buildings and infrastructure from earthquakes and for developing codes for building and engineering design. The potential amplification of the ground motion due to the characteristics of the near-surface rock or soil, particularly the stiffness, has a major influence on the ground-motion. The stiffness can be characterised by the seismic shear-wave velocity, but the paucity of near-surface shear-wave velocity data in Australia makes it difficult to quantify these amplification effects.

With the exception of limited surveys at the Lucas Heights replacement reactor site (Coffey, 1998), and recent site-specific SPAC surveys (Asten and Roberts, 2005), there is little or no data available to characterise near-surface shear wave velocity in bedrock-dominated terranes in Australia. A number of measured shear wave velocity profiles acquired by seismic cone penetrometer testing in two major centres (Newcastle and Perth) are held by GA, but these predominantly characterise unconsolidated near-surface regolith materials to a maximum depth of 30 m.

To address this problem, GA contracted a team from the US Geological Survey (USGS) to acquire near-surface shear-wave velocity data using the Spectral Analysis of Shear-Waves (SASW) technique (Kayen and Carkin, 2006). This non-invasive technique is an inexpensive and efficient means for estimating the stiffness properties of the ground, typically within the upper 10's-to-100 metres. The equipment is highly portable, enabling measurements to be made at remote sites. Other methods, such as direct measurements in boreholes or penetrometer tests are expensive or of limited use in very stiff soils or on rock.

SASW data were acquired at eighteen seismograph sites located in four distinct regions in Western Australia, South Australia, Victoria and New South Wales (Figure 1). These sites are operated by GA, Primary Industry and Resources South Australia (PIRSA) and Environmental Systems and Services (ESS) of Melbourne. In two cases the data were acquired a short way from the seismograph site due to a lack of access, but were located on the same geological unit. Most of these sites have little or no quantitative characterisation of site amplification effects or natural frequency. At all eighteen sites micro-tremor measurements were also made to assess the resonance characteristics of the ground for comparison with the shear wave velocity structure (Nakamura, 1989). These data are not yet processed or analysed and are not presented here.

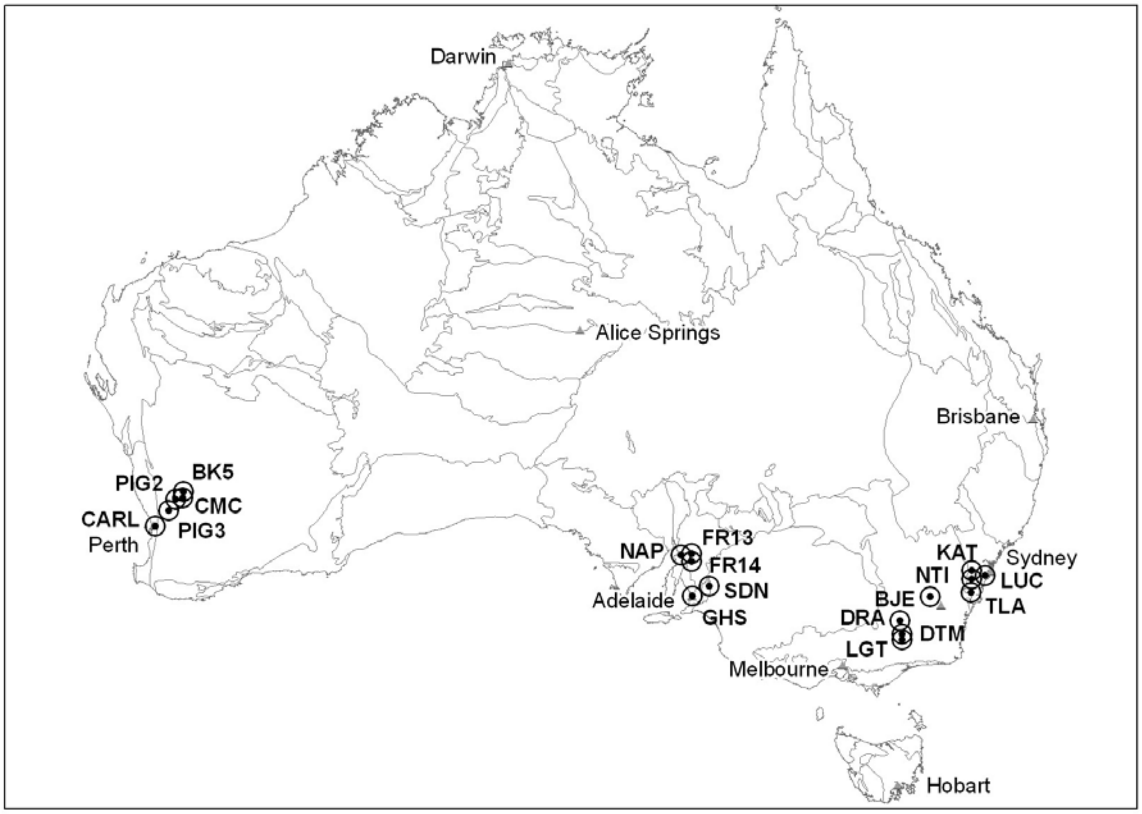

Figure 1. Location of SASW test sites

THE SASW METHOD

The field acquisition system comprises two 1-Hz Kinemetrics vertical seismometer receivers, two computer-controlled APS Dynamics Model 400 electro-mechanical harmonic-wave sources (shakers) and their amplifiers, a low frequency spectrum analyser, and a 4.0 kW generator (Figure 2). The spectrum analyser produces a sine wave signal that is split into a parallel circuit, and two separate power amplifiers produce an in-phase continuous harmonic-wave which drives the shakers in vertical motion to excite the ground. A fast Fourier transform (FFT) is performed on each of the receiver signals. In near-real time, the linear spectra, cross power spectra, and coherence are computed. The ability to perform near real-time frequency domain calculations and monitor the progress and quality of the test permits adjustment of various aspects of the test to optimise the capture of the phase data. These aspects include the source-wave generation, frequency step-size between each sine wave burst, number of cycles-per-frequency, total frequency range of all the steps, and receiver spacing.

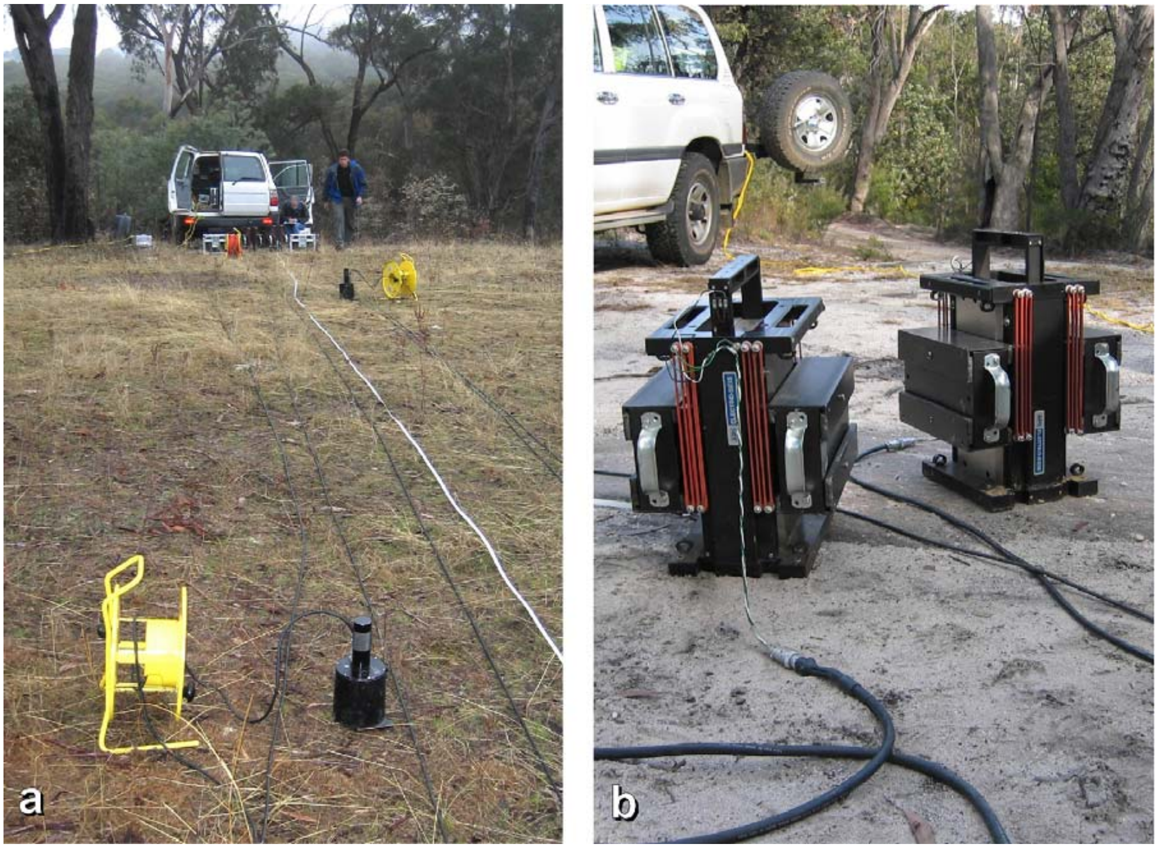

Figure 2. SASW field data acquisition. a) Traverse with two 1 Hz Kinemetrics seismometers, and b) the source array comprising two electro-mechanical shakers

The dual sources are arrayed orthogonally to the seismometer line. The test steps through a suite of frequencies and, for each frequency, phase computations are made. This method sweeps through a broad range of low frequencies in order to capture the surface wave-dispersion characteristics of the ground. This approach is a modification of the

Continuous Sine-wave Source - Spectral Analysis of Surface Waves (CSS-SASW) test presented by Kayen et al. (2004a; 2004b). Spacing of the receivers stepped geometrically from 1 m to 100 m. The two seismometers are separated by a given distance, d, and the source is usually placed at a distance of d from the inner seismometer. Rayleigh wave wavelengths are computed by relating the seismometer spacing and the phase angle (determined from the cross-power spectra) between the seismometers. The Rayleigh wave surface wave velocity is computed as the product of the frequency and its associated wavelength.

The inversion code used to determine the model at each site hunts for the best-fit shear wave velocity profile whose theoretical dispersion curve is the closest match with the averaged field dispersion curve. The term “best-fit” refers to the minimum sum of the squares of residuals from the differences between the theoretical and experimental dispersion curves. The inversion algorithm, WaveEq of OYO Corp. (Hayashi and Kayen, 2003) uses an automated-numerical approach that employs a constrained least-square fit of the theoretical and experimental dispersion curves.

RESULTS

Eighteen sites were occupied in Western Australia, South Australia, Victoria and New South Wales. The shear wave velocity structures for the uppermost 100-200 m of the ground at these sites are presented in Figure 3 and Table 1. Typically, a ten to fifteen layer model was used for the inversion, with layer thicknesses geometrically expanding with depth. The increasing layer thicknesses correspond with decreasing dispersion information in the longer wavelength (deeper) portion of the dispersion curve. The profiles generally increase in stiffness with depth, though low velocity layers are present in several of the profiles.

The simplest way of characterising the overall site condition is to compute the average shear wave velocity in the uppermost 30 m or 100 m of the subsurface (V_{S30} and V_{S100}) from the layer interval velocities. The average V_{S30} velocities ranged from 257 to 1652 m/s, which fall within NEHRP categories “D” through “A”. The average V_{S100} velocities ranged from 434 to 2335 m/s.

Most of the Western Australian sites (at temporary seismograph stations CMC, BK5, PIG2, PIG3) are located on Archaean granites, while CARL (a permanent strong-motion station) is located in the city of Perth on soils and alluvium above Perth Basin (Permian to Quaternary) sediments. Two sites in South Australia (at temporary seismograph stations FR13, FR14) are located on Proterozoic metasediments of the Flinders Ranges, and one (at permanent station NAP) on alluvial fan sediments derived from the adjacent Flinders Ranges. The permanent station at SDN is located on Cambrian metasediments of the Mount Lofty Ranges and the permanent strong-motion station GHS is located in Adelaide on alluvium. The sites located in the Lachlan Fold Belt of Victoria and New South Wales (permanent stations DTM, LGT, DRA, BJE) lie on granites, volcanics and metasediments of Devonian to Ordovician age. The sites in the Sydney Basin (permanent stations TLA, NTI, KAT LUC) are all on Hawkesbury Sandstone.

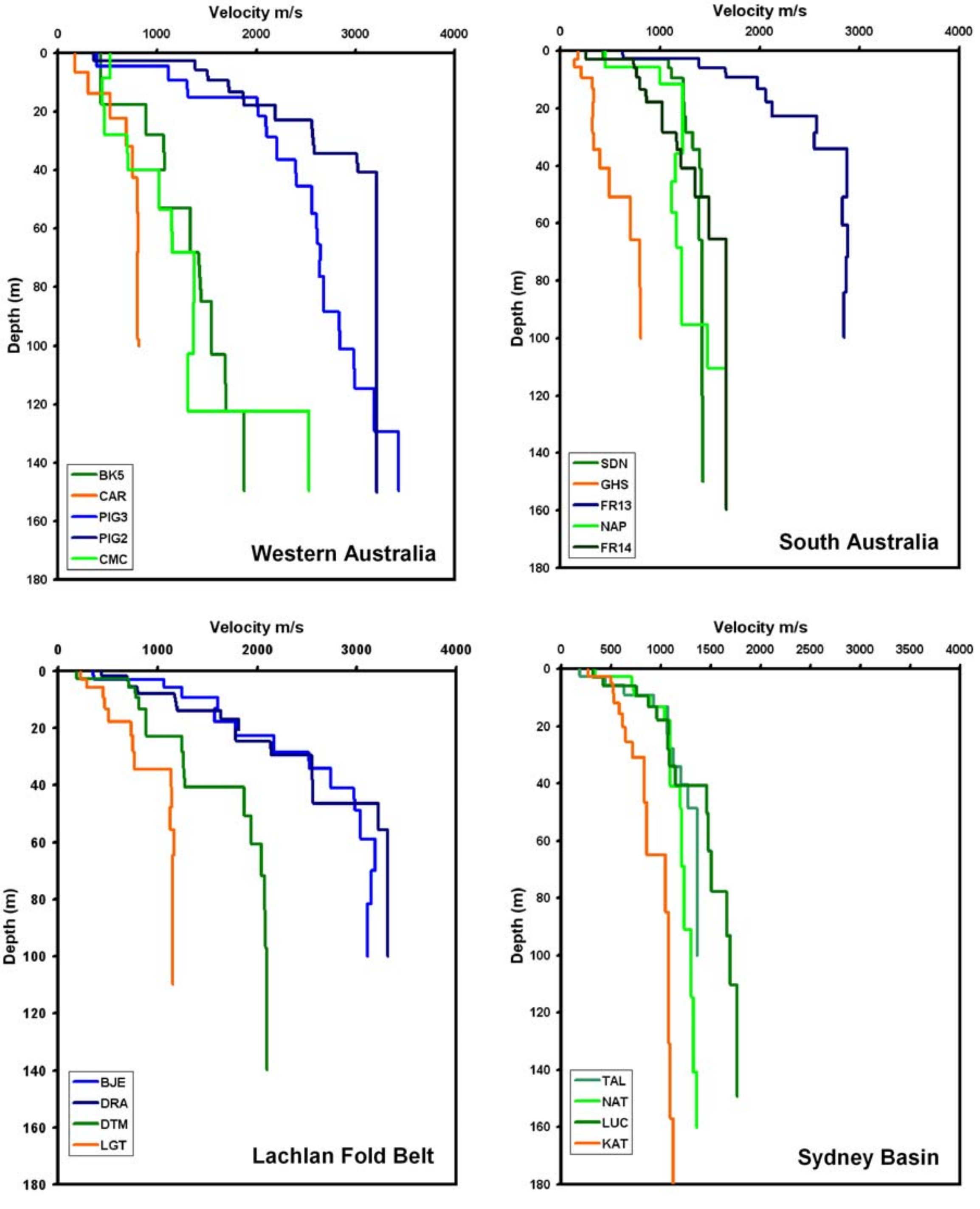

Figure 3. Shear-wave velocity profiles

Table 1. SASW station details with their computed average 30 and 100 metre shear wave velocities and corresponding NEHRP site class.

Site	Geology	Location	V_{S30}	V_{S100}	NEHRP Class
Western Australia					
CMC	Archean Granite	Cadoux, WA	474	785	C
BK5	Archean Granite	Burakin, WA	565	928	C
PIG2	Archean Granite	Macardy Hill, WA	1232	2196	B
PIG3	Archean Granite	Bolgart, WA	1101	1836	B
CARL	Alluvium	Carlisle, WA	338	563	D
South Australia					
SDN	Cambrian Metasediments	Sedan, WA	1026	1267	B
FR14	Proterozoic Sediments	Flinders Ranges, SA	725	1131	B
FR13	Proterozoic Sediments	Flinders Ranges, SA	1652	2335	A
NAP	Proterozoic Sediments	Napperby, SA	893	1087	B
GHS	Alluvium	Adelaide, SA	257	434	D
Eastern Australia (Lachlan Fold Belt)					
DTM	Granite	Dartmouth Dam	659	1194	C
LGT	Ordovician Sst/shale	Lightning Creek, VIC	458	778	C
DRA	Granite	Dora Dora, NSW	1148	2048	B
BJE	Devonian Andesite	Burrinjuck Dam, NSW	1194	2070	B
Eastern Australia (Sydney Basin)					
TLA	Hawkesbury Sst	Tallowa, NSW	643	1001	C
NTI	Hawkesbury Sst	Nattai, NSW	804	1050	B
KAT	Hawkesbury Sst	Katoomba, NSW	536	766	C
LUC	Hawkesbury Sst	Lucas Heights, NSW	728	1121	B

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REFERENCES

Asten, M. and Roberts, J., 2005. Final Report – Microtremor Array Survey of the Burakin Area, WA. Centre for Environmental and Geotechnical Applications of Surface Waves, Monash University.

Coffey Partners International Pty Ltd, 1998. Replacement Reactor Site, Lucas Heights, Geophysical Study. Report No. GY617/1-AC, April 1998.

Hayashi, K. and Kayen, R., 2003. Comparative test of three surface wave methods at Williams Street Park in San Jose, USA. Paper S051-009, 2003 Joint Meeting of Japan Earth and Planetary Science, University of Tokyo, Tokyo, Japan 2003 Joint Meeting, May 26-29, 2003.

Kayen, R. and Carkin, B., 2006. Preliminary Report on the Shear Wave Velocity of Australian Strong Motion Seismometer Sites by the Spectral Analysis of Surface Waves Method (SASW) with Parallel-Arrayed Harmonic-Wave Sources and H/V Microtremor Method. United States Geological Survey, Administrative Report 2006-2.

Kayen, R., Seed, R. B., Moss, R.E., Cetin, O., Tanaka, Y., and Tokimatsu, K., 2004. Global Shear Wave Velocity Database for Probabilistic Assessment of the Initiation of Seismic-Soil Liquefaction. Proceedings of the 11th Int'l. Conf. On Soil Dynamics and Earthquake Engineering, January 7-9, 2004, Berkeley, CA, p. 506-512.

Kayen, R., Thompson, E., Minasian, D., Moss, R.E.S., Collins, B.D., Sitar, N., Dreger, D., Carver, G., 2004. Geotechnical Reconnaissance of the November 3, 2002 M7.9 Denali Fault Earthquake, Earthquake Spectra, 20(3) p. 639-667.

Nakamura, Y., 1989. A method for dynamic characteristics estimation of subsurface using micro-tremor on the ground surface, Quarterly Report of RTRI 30, 25–33, Railway Technical Research Institute, Tokyo, Japan.