

SOME EMPIRICAL RELATIONS FOR ATTENUATION OF GROUND-MOTION SPECTRAL AMPLITUDES IN SOUTHWESTERN WESTERN AUSTRALIA

TREVOR ALLEN¹, TREVOR DHU¹, PHIL CUMMINS¹, JOHN SCHNEIDER¹ AND GARY GIBSON²
GEOSCIENCE AUSTRALIA¹, ENVIRONMENTAL SYSTEMS AND SERVICES²

AUTHORS:

Trevor Allen is a seismologist with the Risk Research Group, GA. He is currently working to develop spectral ground-motion attenuation models for the Australian crust.

Trevor Dhu is a geophysicist with the Risk Research Group, GA. His research is focused on national scale earthquake risk maps as well as developing site response and strong-motion models for Australia.

Phil Cummins is Leader of the Earthquake Hazard and Neotectonics Project at GA. He oversees GA's earthquake monitoring activities and earthquake hazard research.

John Schneider is the Leader of the Risk Research Group, Geoscience Australia. His interests are in the development of natural hazard risk assessment methods for applications to urban centres, with particular emphasis on earthquake hazards.

Gary Gibson established the Seismology Research Centre in 1976 and is an Honorary Research Associate at Monash University. His interests lie in observational seismology and its practical applications.

ABSTRACT:

A dataset comprising some 260 seismograph and accelerograph records from 67 events of the Burakin 2001-02 earthquake sequence was compiled to develop regional ground-motion models for southwestern Western Australia. Events range in size from moment magnitude $2.3 \leq \mathbf{M} \leq 4.6$. The decay of spectral amplitudes can be approximated by a geometrical spreading coefficient of $R^{-1.05}$ within 80 km of the source. The associated model for the regional seismic quality factor can be expressed as $Q(f) = 290f^{1.09}$.

These attenuation parameters are subsequently used to evaluate average source parameters for the 67 earthquakes. For the observed magnitude range, data demonstrates a seismic moment (M_0) – local magnitude (M_L) relation following: $\log M_0 = 1.14 M_L + 10.45$, where M_0 is in N-m. Average corner frequencies for these events do not vary significantly with M_0 particularly for events $\mathbf{M} > 3.0$, chiefly ranging between 2-3 Hz. This gives rise to anomalously low stress drops for lower magnitudes ($\mathbf{M} < 4.0$) that increase at larger magnitudes.

Fourier spectral amplitudes corrected for geometric spreading and anelastic attenuation were regressed with \mathbf{M} to obtain attenuation coefficients. Modelled horizontal-component displacement spectra fit the observed data well. Amplitude residuals (predicted – observed amplitudes) are, on average, relatively small and do not vary significantly with hypocentral distance. The results from this study provide an important framework for developing ground-motion relations in Australia. These regional attenuation parameters will provide key inputs for the generation of stochastic ground-motions.

INTRODUCTION:

Australian earthquake hazard and risk assessments currently suffer from considerable uncertainty since they are forced to rely on ground-motion attenuation models derived in other regions [e.g. eastern North America (ENA)] (Dhu and Jones, 2002; Robinson *et al.*, 2004). These uncertainties can lead to undesirable outcomes, including unrealistically high loading standards in the design and construction of critical infrastructure such as large dams.

Attenuation relations appropriate for the Australian crust have, in the past, been difficult to quantify owing to a lack of ground-motion data from moderate-to-large local earthquakes. Geoscience Australia (GA), in association with Environmental Systems and Services (ES&S) and the Australian National Committee on Large Dams (ANCOLD) are presently collaborating to assemble an Australian ground-motion database suitable for attenuation studies. This paper examines data acquired during the 2001-02 Burakin, Western Australia (WA), earthquake sequence (Leonard, 2003). The dataset represents the largest resource of high sample-rate digital data in WA that is useful for detailed spectral studies of this kind. We estimate source and path parameters, and subsequently perform regressions to define a Fourier spectral attenuation model for the Archean shield region of southwestern WA. For intraplate regions with low levels of seismicity, empirical studies such as this provide key input parameters for stochastic ground-motion generation of larger earthquakes (e.g. Atkinson and Boore, 1995; Toro *et al.*, 1997).

These data present a unique opportunity to study small-to-moderate magnitude earthquakes recorded at very small hypocentral distances. Moreover, the work described will provide a useful framework for developing regional ground-motion relations for Western Australia and the continent as a whole.

TEMPORARY NETWORK AND DATA:

At the onset of activity at Burakin in 2001-02, GA made a concerted effort to deploy a temporary seismic network in the region. The primary objective of this network was to collect high-quality strong-motion data for use in attenuation studies. Of the many thousands of located events, we analyse a subset of 67 earthquakes of M 2.3 and greater recorded from 30 September 2001 to 6 August 2002. The dataset comprises some 260 seismograph and accelerograph records, including strong-motion data for seven earthquakes of moment magnitude M 4.0 and greater at hypocentral distances less than 10 km.

The temporary Burakin deployment comprised a combination of triaxial short-period seismographs and accelerographs located at a range of distances from near the earthquake epicentres, out to approximately 160 km. In addition to the temporary network, data were also obtained from four government funded, permanent Joint Urban Monitoring Program (JUMP) strong-motion sites located in and around Perth. Sites located in Perth are approximately 190 km from the Burakin sources. All data were recorded at a sample rate of either 100 or 200 Hz and band pass filtered between 0.5 and 30 Hz. No data from Geoscience Australia's National Seismograph Network (ANSN) were used in the present analyses.

All of the earthquakes in the swarm had focal depths less than 2.5 km. Because of the shallow depths, several sites indicated strong radially propagating *Rg*-phase components. The amplitude of this phase was observed to be highly dependent on focal depth, with the shallowest events indicating the highest degree of *Rg*-phase contamination. To minimise surface effects from this phase, waveforms were rotated in the horizontal plane to obtain the transverse-component. Windowed transverse shear-waves were used for all subsequent Fourier source and path analyses.

REGRESSION METHODOLOGY:

Analysis of the present dataset largely follows the methods adopted by Atkinson (2004). Fourier amplitude spectra are fitted for 15 discrete frequencies between $0.79 \leq f \leq 19.95$ Hz following an equation of the general form

$$\log A_{ij} = c_1 + c_2(M - 4) + c_3(M - 4)^2 - b \log R_{ij} - c_4 R_{ij}, \quad (1)$$

where A_{ij} is the predicted spectral amplitude at site j for event i , R_{ij} is hypocentral distance, b is the geometrical spreading coefficient (i.e. R_{ij}^{-b}), and c_1 through c_4 are parameters to be determined (Atkinson, 2004). Ideally, M is moment magnitude \mathbf{M} , however it can be any measure of magnitude provided that both the magnitude type used in the regression and in the prediction of ground-motion are internally consistent.

The anelastic attenuation coefficient c_4 , is inversely related to the *seismic quality factor*, Q following

$$c_4 = (\pi f) / [\ln(10) Q \beta], \quad (2)$$

where β ($= 3.6 \text{ km s}^{-1}$) is the shear-wave velocity.

Atkinson (2004) states that the geometrical spreading coefficient b is a function of the source-receiver distance. This is largely due to the arrival of other phases within the shear window, corresponding with postcritical reflections from the mid-crustal and Moho discontinuities and *Lg*-wave arrivals. Consequently, Atkinson (2004) suggests that geometrical spreading in ENA can be described by a hinged trilinear attenuation model.

Once corrected for geometrical spreading and anelastic attenuation, spectral amplitudes can be regressed for quadratic coefficients c_1 , c_2 and c_3 to define an empirical spectral attenuation model dependent on magnitude. In the present study, we regress against magnitude \mathbf{M} as calculated by Allen *et al.* (in prep.).

GEOMETRICAL SPREADING:

Since we have a limited number of data to perform regressions in any one magnitude range, Fourier amplitude spectra were normalised to obtain a geometrical spreading model for the Burakin dataset. Windowed shear-wave displacement spectra were calculated and the low-frequency spectral level Ω_{ij} was manually picked for each record. Observed Fourier spectra were smoothed and a series of 22 discrete amplitudes $A_{ij}(f)$, logarithmically distributed from 0.78 to 25 Hz were extracted from each record.

Given the paucity and spatially clustered nature of the Burakin dataset, low-frequency spectral levels are source-corrected for sites with a hypocentral distance of $10 \leq R_{ij} \leq 105$ km. We assume that low-frequency source spectra ($f \leq 2.3$ Hz) can be estimated for all records in this distance range by multiplying by a geometrical spreading coefficient R_{ij} (Atkinson, 2004). Sites within 10 km of the source were ignored in the regression since their spectral amplitudes are susceptible to near-field saturation and radiation pattern effects, coupled with uncertainties in location. The normalising factor Ωn_i for the i th event is defined by averaging Ω_{ij} over the valid hypocentral distance range

$$\log \Omega n_i = (1/N_i) \sum_{j=1}^{N_i} [\log \Omega_{ij} + \log R_{ij}] \quad \text{for all } j, 10 \leq R_{ij} \leq 105 \text{ km.} \quad (3)$$

N_i is the number of stations that satisfy the hypocentral distance criterion stated above. This procedure is performed assuming that low frequencies are relatively unaffected by anelastic attenuation and scattering at short source-receiver distances ($R_{ij} \leq 105$ km). Each site j over all R_{ij} are subsequently normalised following

$$\log An_{ij}(f) = \log A_{ij}(f) - \log \Omega n_i, \quad (4)$$

where An_{ij} is the normalised spectral amplitude for earthquake i at the j th site. This method assumes that the logarithm of normalised spectral amplitude is equal to zero at $R = 1$ km. If we assume Ω_{ij} can be approximated by $A_{ij}(1.5 \leq f \leq 2.3 \text{ Hz})$, horizontal-component Fourier spectral amplitudes for $10 \leq R_{ij} \leq 105$ km appear to decay as approximately $R^{-1.05}$. Geometrical spreading coefficients with gradients steeper than -1 have also been empirically observed for sites $R \leq 70$ km in ENA (Atkinson, 2004). For sites less than 10 km, normalised spectral amplitudes for the Burakin dataset appear to plateau near the source. Unfortunately, the short hypocentral distance range ($R < 200$ km), coupled with the limited number and spatially clustered nature of the dataset, make it difficult to quantify a hinged geometrical spreading function similar to that of Atkinson (2004). In subsequent analyses, we assume a geometric spreading coefficient $G(R)$ following

$$\log G(R_{ij}) = \begin{cases} 1.06 \log R_{ij} & R_{ij} \leq R_0 \\ 1.06 \log R_0 + 0.5 \log(R_{ij}/R_0) & R_{ij} > R_0 \end{cases} \quad (5)$$

where R_0 is taken to be 80 km; the approximate distance where geometrical spreading becomes less severe owing to surface-wave arrivals from shallow events. R_0 is merely an approximation based on prior studies (e.g. Atkinson, 2004). This relation is employed for subsequent calculations of earthquake source parameters (Allen *et al.*, in prep.).

ANELASTIC ATTENUATION:

In addition to effects from the R_g -phase, strong resonance peaks in the 6-10 Hz band corrupted observed spectra at many of the sites within a hypocentral distance range of 7 to 20 km despite all instruments being located on hard-rock. This phenomenon further complicated attempts to resolve the frequency-dependent quality factor, $Q(f)$. To avoid

these problems, we only use horizontally-rotated, transverse-component data that appear to be relatively unaffected by site effects and complex phase arrivals. This limited the number of data we were able to use to estimate anelastic attenuation and may have introduced azimuthal, distance and instrument dependent biases into our calculations.

The quality factor typically follows the frequency-dependent power law $Q(f) = Q_0 f^\eta$, where Q_0 is the intrinsic quality factor at 1 Hz and η is a numerical constant. The two-station spectral ratio method (Kvamme and Havskov, 1989) was subsequently applied to our data. For frequencies $1.1 \leq f \leq 12.7$ Hz, regression analysis yields the frequency-dependence

$$Q(f) = 290 f^{1.09}. \quad (6)$$

The horizontal-component intrinsic quality factor in equation (6) is relatively low compared to other stable continental regions [e.g. $Q_0 = 893$ for ENA (Atkinson, 2004)], however, the large frequency exponent in equation (6) gives rise to large values of Q at higher frequencies. The value of Q_0 is slightly higher than crustal values identified by Bowman and Kennett (1991) for central Australia of $Q_0 = 230$.

EARTHQUAKE SOURCE PARAMETERS:

Allen *et al.* (in prep.) calculate moment magnitudes for the Burakin dataset employing the empirical relation of Hanks and Kanamori (1979): $\mathbf{M} = 2/3 \log M_0 - 6.03$, where M_0 is the seismic moment measured in N-m. Magnitudes for the present dataset range between $2.3 \leq \mathbf{M} \leq 4.6$ and demonstrate an M_0 - M_L relationship following

$$\log M_0 = 1.14 M_L + 10.45. \quad (7)$$

Local magnitudes M_L were calculated using the relation of Gaull and Gregson (1991). Further spectral analysis of the Burakin dataset indicates that the average corner frequencies for these events do not vary significantly with M_0 , chiefly ranging between 2-3 Hz (Allen *et al.*, in prep.) for events $\mathbf{M} > 3.0$. This gives rise to relatively low stress drops for the lower magnitudes ($\mathbf{M} < 4.0$) that increase at larger magnitudes. Average stress drops for the larger magnitude events ($\mathbf{M} > 4.0$) appear to be relatively high (approximately 10 MPa) and are consistent with values obtained from southeastern Australian earthquakes (Allen *et al.*, in press).

RESULTS AND DATA ANALYSIS:

Table 1 provides regression coefficients for the fit of horizontal-component spectral amplitudes. Predicted Fourier acceleration spectral amplitudes for earthquakes of magnitude $2.3 \leq \mathbf{M} \leq 4.6$ based on these coefficients can be written as

$$\begin{aligned} \log A_{ij} = c_1 + c_2 (\mathbf{M}_i - 4) + c_3 (\mathbf{M}_i - 4)^2 \\ - 1.05 \log R_{ij} - c_4 R_{ij} \end{aligned} \quad \text{for } R_{ij} \leq 80 \text{ km} \quad (8a)$$

$$\begin{aligned} \log A_{ij} = c_1 + c_2 (\mathbf{M}_i - 4) + c_3 (\mathbf{M}_i - 4)^2 \\ - 1.05 \log(80) - 0.5 \log(R_{ij}/80) - c_4 R_{ij} \end{aligned} \quad \text{for } R_{ij} > 80 \text{ km} \quad (8b)$$

Table 1. Coefficients of regression for horizontal-component Fourier amplitudes for Burakin, WA, earthquakes of magnitude $2.3 \leq \mathbf{M} \leq 4.6$ [equation (8)].

Frequency (Hz)	c_1	c_2	c_3	c_4	Q
0.79	1.169	1.529	0.0757	0.00133	226
1.00	1.341	1.526	0.0272	0.00131	290
1.26	1.534	1.464	-0.0240	0.00128	373
1.58	1.666	1.389	-0.0558	0.00125	479
2.00	1.768	1.295	-0.0783	0.00123	616
2.51	1.815	1.252	-0.0828	0.00120	791
3.16	1.853	1.224	-0.0777	0.00118	1017
3.98	1.860	1.199	-0.0656	0.00115	1307
5.01	1.840	1.152	-0.0549	0.00113	1680
6.31	1.806	1.069	-0.0480	0.00111	2160
7.94	1.767	1.001	-0.0421	0.00108	2776
10.00	1.757	0.945	-0.0330	0.00106	3568
12.59	1.748	0.897	-0.0153	0.00104	4586
15.85	1.704	0.882	0.0117	0.00102	5894
19.95	1.616	0.850	0.0456	0.00100	7575

Values describe Fourier acceleration spectra in mm s^{-1} .

Figure 1 compares some observed spectra (for two magnitude and distance ranges) with the predicted spectral amplitudes of this study and with Atkinson's (2004) model derived for ENA. Modelled spectral amplitudes are calculated at the mid-point of the distance range. Predicted amplitudes are plotted using the upper and lower magnitude limits. In general, our empirical attenuation model fits the observed data quite well. Outliers will be expected since the model is an average representation of observed ground-motion. The WA model appears to predict higher Fourier amplitudes at low frequencies than Atkinson (2004), particularly at short source-receiver distances. The disparity between the two models at low frequencies most likely arises from issues concerning differences in geometrical spreading. The magnitude scales used for each study appear to be consistent since the low-frequency level ($f < 2$ Hz) of the source spectrum (i.e. at $R = 1$ km) is equivalent for both models¹.

Residuals of modelled WA ground-motions are plotted against hypocentral distance (Figure 2). Residuals at sites j are defined as the logarithm of predicted spectral amplitudes, less the logarithm of observed spectra for an event of magnitude \mathbf{M}_i at R_{ij} km. Modelled spectra appear to slightly overestimate observed horizontal-component ground-motions between 10-20 km at 1 Hz, however, residuals at greater distances are generally quite low.

CONCLUSIONS:

Regression analysis of Fourier spectra indicates that the decay of spectral amplitudes can be approximated by a geometrical spreading coefficient of $R^{-1.05}$ within 80 km of the source. Beyond 80 km, we use theoretical cylindrical spreading of $R^{-0.5}$ (Herrmann and Kijko, 1983). The associated model for the regional seismic quality factor can be expressed as $Q(f) = 290 f^{1.03}$.

¹ Note: we convert \mathbf{M} for modelled spectra to m_1 using equation (12) in Atkinson (2004) and substitute into the ENA ground-motion model (Figure 1.).

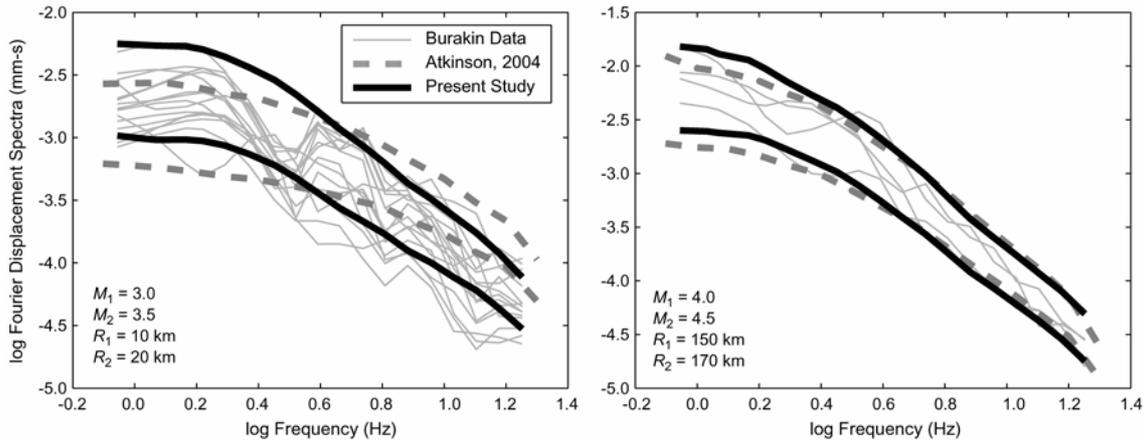


Figure 1. Comparison of Fourier Displacement Spectra derived from the Atkinson (2004) attenuation model and the present study. The two sets of heavier lines in each plot indicate the bounds of the maximum and minimum magnitudes (M_1 and M_2) calculated at the mid-distance of the data range (R_1 and R_2). Thin lines represent observed spectra recorded within the prescribed magnitude and distance range.

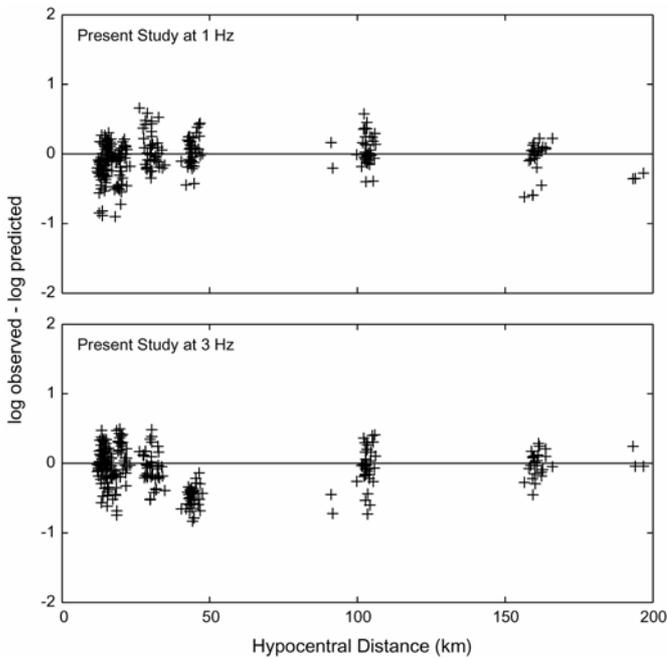


Figure 2. Residuals of modelled WA ground-motions plotted against hypocentral distance. Note that the site at approximately 45 km indicated anomalous frequency decay beyond 2 Hz. Consequently no data from this site were used in the regression of the ground motion model indicated in Table 1. Similarly, sites at $R > 190$ km were located in the geologically dissimilar Perth Basin and were not considered suitable to be included in the regressions either.

Using the coefficients derived in Table 1, modelled horizontal-component displacement spectra appear to fit the observed data very well. Spectral amplitude residuals are on average, relatively small and do not appear to vary significantly with hypocentral distance. Given the narrow magnitude range of the data ($2.3 \leq M \leq 4.6$), **we cannot be certain of the model's behaviour if extrapolated to larger magnitudes**. Furthermore, since the Burakin dataset comprise an earthquake swarm, results of Allen *et al.* (in prep.) suggest that all but the largest of these swarm events appear to have anomalously low corner frequencies and stress drop. We are therefore concerned that an attenuation model based on such events may have limited application for predicting ground-motions of isolated crustal events. This gives added impetus for the need to include more data in our work and to expand this research into different seismotectonic regions within the Australian continent.

This preliminary work provides an important framework for developing regional ground-motion relations in Australia. Attenuation parameters derived in these empirical studies are used as key inputs for stochastic models to predict ground-motions for larger magnitude events.

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