CRUSTAL AND SUBDUCTION ZONE ATTENUATION RELATIONS FOR NEW ZEALAND EARTHQUAKES

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SUMMARY

Attenuation relations have been developed for 5% damped acceleration response spectra in New Zealand earthquakes. The models take account of the different tectonic types of earthquakes in New Zealand, i.e., crustal, subduction interface and dipping slab, and of the faster attenuation of high-frequency components in the volcanic region. The study used all available data from the New Zealand earthquake accelerograph network that satisfied various selection criteria, supplemented by selected data from digital seismographs. The latter provide additional records from moderate- to high-strength rock sites, and of motions involving propagation paths through the volcanic region. Most of the accelerograph sites are on soil, with the few accelerograph rock sites generally being on weak rock. The data have been further augmented by seismograph records from a temporary deployment in the volcanic region. To constrain the model at short distances where New Zealand records are lacking, overseas peak ground acceleration data recorded less than 10 km from the source were included. It was found that New Zealand earthquake motions are mostly similar to those from other parts of the world for the same tectonic class, especially for crustal earthquakes, but that crustal and subduction zone earthquake motions have different spectral shapes.

INTRODUCTION

Response spectrum attenuation relations relevant to New Zealand have been required for the revision of the New Zealand Loadings Standard currently underway, the construction or retrofitting of major buildings, and design reviews and strengthening of hydro-electricity dams. Of relevance to the Loadings Standard is that Wellington, the capital city of New Zealand, and some other cities are located close to major active faults that have estimated recurrence intervals of a few hundred years for earthquakes causing surface-fault rupture. Many dams are located near faults that are less active, with recurrence intervals of several thousand years, but which are still critical for the 10,000 year return period motions usually considered as the Maximum Design Earthquake motions for these structures. The plate boundary interface at the Hikurangi subduction zone lies beneath Wellington and other cities, at depths of 20 to 30 km. Accordingly both crustal and subduction zone earthquake motions, including near-source motions, must be considered in the seismic design for major centres and important infrastructure facilities.

We present an acceleration response spectrum (SA) attenuation model for New Zealand that will be published in detail shortly, and also refer to an earlier peak ground acceleration (PGA) attenuation study (Zhao et al., 1997).

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NEW ZEALAND DATASET

The PGA study used records from 51 New Zealand earthquakes between 1966 and 1994 for which moment magnitudes M_w and PGAs are available. The data contained 24 crustal events, 7 interface events and 20 slab events. Magnitudes ranged from M_w 5.08 to M_w 7.23, and source-to-site horizontal distances from 11 km to 573 km. Centroid depths ranged from 4 km to 149 km, with only 9 of the 51 events at depths greater than 50 km. Deep slab data were excluded if they involved travel paths through the highly attenuating mantle. A total of 461 New Zealand strong-motion records were used, from ground sites or the bases of buildings. The largest New Zealand horizontal acceleration is 0.58g recorded in the 1968 Inangahua earthquake (M_w 7.2), 15 km from the modelled rupture surface.

There were fewer records available for the SA modelling than for the PGA study, because acceleroscope records and undigitised film records contribute PGAs but not spectra. Records from the bases of buildings more than four storeys high were excluded from the SA study. Also excluded were response spectra from very soft soil sites, that is those with shear-wave velocities less than 150 m/s for depths of about 10 metres or more. The SA study used 224 New Zealand response spectra, further reduced at long periods to 166 records judged to be above noise-level at 2.0s.

To constrain the model at short distances where New Zealand records are lacking, near-source overseas PGA data consisting of 66 records from 17 crustal earthquakes with moment magnitudes ranging from 5.1 to 7.4 were included. These data were restricted to source-to-site distances of 10 km or less. The PGAs of the selected overseas records ranged from 0.11g to 0.98g, with 18 of the 66 recordings having PGAs stronger than the largest value (0.58g) in the New Zealand dataset. The overseas data were not intended to be comprehensive for the 0-10 km distance range, but were felt to be representative, and included data from Northridge and Kobe. We are now compiling the response spectra for the overseas records, to provide near-source data constraint at all spectral periods.

Rapid attenuation of earthquake waves in the volcanic region has been recognised for many years (Mooney, 1970; Haines, 1981; Pancha and Taber, 1997), both at depth and in the crust. The volcanic path effects are potentially important for several towns and dam sites. Also, earthquake motions at sites on moderate- to high-strength rock may be considerably different to those at sites on weak rock (Cousins, Zhao and Perrin, 1999). In particular, dams are often located on rock in at least the moderate-strength category. To obtain sufficient rock-site and volcanic-path data for the SA study, records from digital seismographs installed as part of the New Zealand National Seismograph Network since 1990 were used to supplement the accelerograph data. Seismograph records from a temporary deployment in the volcanic region from January to May 1995 were used to further augment the data.

CLASSIFICATION OF SITE CONDITIONS

The site classification has been retained as close as possible to that of the three subsoil categories (a)-(c) of the current New Zealand Loadings Standard NZS4203:1992 (Standards New Zealand, 1992). Category (a) nominally corresponds to rock or very stiff soil sites with estimated natural periods less than 0.25s, category (b) corresponds to intermediate soil sites and category (c) corresponds to flexible or deep soil sites with natural periods greater than 0.6s. In this study, category (a) has been subdivided into: rock sites, or sites with soil layer of thickness not exceeding 3 metres overlying rock (Class A); and category (a) sites with soil layer of thickness greater than 3 metres overlying rock (labelled AL). The AL sites were combined with the category (b) sites to form Class B. Separation of the AL sites from rock sites and their combination with intermediate soil sites was justified by statistical studies of their residuals at an early stage of the study. Category (c) of NZS4203:1992 carried over directly into Class C.

In a modification primarily intended for dam studies, the Class A category was divided further into Weak Rock (WA), Moderate-strength Rock (MA) and Strong Rock (SA), corresponding essentially to the NEHRP (1994) categories A (hard rock), B (rock) and C (soft rock). Classifications of the rock sites were made mostly on the basis of geological descriptions rather than measured shear-wave velocities, as there have been very few shear-wave velocity measurements at New Zealand seismograph or accelerograph sites. In the regression analysis, Moderate-strength and Strong Rock sites were combined.

DEVELOPMENT OF THE RESPONSE SPECTRUM ATTENUATION MODEL

Limited ranges of magnitude and distance and insufficient records in the SA dataset prevent the development of a robust model purely from the data. Instead, we selected as "base models" overseas attenuation models that provided reasonable matches to the New Zealand data, one for crustal earthquakes and another for subduction-zone earthquakes and then modified some of their coefficients to improve the matches. Constraints were imposed so that the selected models controlled the behaviour at short distances where New Zealand data were lacking.

Residual analyses of New Zealand data with respect to available models were used to identify relations that gave good representations of either crustal or subduction-zone New Zealand spectra. Figure 1 shows residuals for soil sites for the Abrahamson and Silva (1997) crustal-earthquake model, and for rock and soil sites for the Youngs et al. (1997) subduction-zone model. The Idriss (1991), Boore et al. (1997) and Sadigh et al. (1997) crustal models and Crouse (1991) subduction-zone model were also included in the comparisons. All four crustal models gave adequate fits to the New Zealand data. Both subduction zone models matched the deep-slab data well, but were poor for the interface and shallow-slab data, overpredicting at short periods, and underpredicting at long periods.

The Abrahamson and Silva (1997) (A&S) model was used as the base model for crustal earthquakes, and the Youngs et al. (1997) model as the base model for subduction zone earthquakes. The form of the model for the median response spectrum values is given in Table 1. Free coefficients in the regressions are shown in bold. Parameters subscripted $_{AS}$ and $_{Y}$ were held to A& S or Youngs et al. values, respectively. M is moment magnitude, r is the shortest distance from the site to the fault rupture, and r_{VOL} is the length of the part of the source-to-site path that lies in the volcanic zone. SA(T) and SA′(T) are 5% damped response spectrum accelerations at period T for the larger horizontal component. The equations apply for moment magnitudes 5 to 7.5, and distances up to 400 km.

The near-source constraint used in this study was to require that the crustal and subduction zone expressions for rock sites match the magnitude-dependence of the base models at zero distance (r=0). The values of two of the coefficients, $C_4(T)$ and $C_6(T)$, of the crustal model governed by the near-source constraint differed insignificantly from their A&S values, so they were left unchanged. The constraint required that the quadratic magnitude term be as for A&S, i.e. $C_3(T)=C_{3AS}(T)$. For subduction zone earthquakes, the r=0 constraint led to a relationship shown in Table 1 for $C_{12}{}^{*}(T)$ linking the coefficients of the linear magnitude and ln(distance) terms, and the cubic magnitude term had to be the same as in the Youngs et al. model. Also, coefficients that occurred nonlinearly in the attenuation equations were constrained to their values in the base models.

Simplifying changes to the Abrahamson and Silva model are that the large-magnitude values of the coefficients of the linear magnitude term and of the reverse/oblique mechanism term for crustal earthquakes are used for all magnitudes, with the elimination of the small-magnitude coefficients. An anelastic attenuation term, $C_5(T)r$, has been added for crustal earthquakes to allow good matches of the data for the distance range up to 400 km used in the regression analysis. This distance range has been used to obtain sufficient rock records and volcanic path records. An anelastic attenuation term $C_{14}(T)r$ was considered for subduction earthquakes, but was found to be statistically insignificant for the dataset containing source-to-site distances up to 400 km.

Separate additive terms with respect to shallow-slab earthquakes were considered for interface earthquakes and deep-slab earthquakes, but were statistically significant only for interface earthquakes, as in the Youngs et al. model. Differences in attenuation rates for shallow-slab, deep-slab and interface earthquakes were not statistically significant. Consequently, modelled spectral accelerations for shallow- and deep-slab earthquakes differ only by the effect of the depth term.

Increased attenuation in the volcanic region has been modelled by the term $C_{46}(T)\ r_{VOL}$ applied for crustal, shallow-slab and interface earthquakes, where the source-to-site path includes a distance r_{VOL} through the volcanic zone. Similar effects occur at depth (e.g. Mooney, 1970), but in this study have been ignored for deep-slab earthquakes because of the difficulties of modelling the high attenuation zone in three dimensions. Deep-slab records likely to have been affected by high attenuation in the mantle under the volcanic region were omitted from the analysis, and the model should not be used for source-site combinations likely to involve propagation through the highly attenuating mantle. While the geometric attenuation term dominates for nonvolcanic paths at distances less than 100-200 km, the anelastic attenuation is of similar importance for volcanic paths. The total anelastic term halves PGA values over only 16 km in the volcanic region, while requiring more than 70 km to have the same effect on its own (i.e. neglecting the geometric attenuation) outside the volcanic zone. The volcanic path effect is less severe for periods exceeding 0.5s.

The model has different attenuation rates for the moderate-to-strong rock site class than for the other site classes. This distinction overcomes a magnitude-dependence that was apparent in the residuals between recorded and predicted rock motions for a simpler model in which a period-dependent site factor $C_{44}(T)$ alone represented the difference between motions at weak and moderate-to-strong rock sites. The simple site factor approach produced much lower estimates for moderate-to-strong rock motions than for weak-rock motions, with the ratios at the extreme limit of the ranges suggested by overseas studies. The preferred model has less difference between weak and moderate-to-strong rock motions at levels of motion important for seismic hazard assessments (PGAs greater than approximately 0.05g), although the ratios are large for some magnitude and distance combinations. According to the preferred model, the PGAs for these two site classes are similar at short distances, but the moderate-to-strong rock motions attenuate more rapidly, and show a greater magnitude-dependence with increasing distance. Also, the near-source estimates for the preferred model are more in line with overseas data.

The crustal and subduction zone models were linked through sharing common site effect terms, with the soil response factors being nonlinear functions of weak rock PGAs, as in the A&S model. The nonlinear part of the site response term of the A&S model was eliminated for site class B, because the regression produced unacceptable (positive) values of the coefficient of this term for short periods, and constraint to negative values produced poorer fits than given by a linear model excluding this term. Some New Zealand site class B sites fall into the A&S "rock" class, and some into their "soil" class, so the base models give no clear guidance as to what values to use for these coefficients. Class C is similar to the A&S deep soil class, so the coefficient of the nonlinear site response term for this class was fixed at the A&S value, because it was not well-constrained by the New Zealand data.

For some subsets of earthquake motions, notably on rock or deep soil sites for crustal earthquakes, the PGA estimates SA´(0) from the response spectrum dataset were considerably smaller than the estimates SA(0) derived from the complete PGA dataset, particularly near-source. As the SA(0) values were more in line with those from models from western US data, it was decided to scale the SA´(T) values by the ratio SA(0)/SA´(0) of the PGAs from the two models to obtain the final values of SA(T).

The standard error for each period has a magnitude-dependent intra-event component and an inter-event standard error that is independent of magnitude. A pleasing result is that the standard errors were generally similar to those of the A&S model and much smaller than those of the Youngs et al. model (Figure 2).

EXAMPLES OF PREDICTED SPECTRA

As examples of large-magnitude, near-source spectra, site class WA (weak rock) and B (intermediate soil) spectra for magnitude 7.5 reverse-mechanism crustal earthquakes at a distance of 10 km are shown in Figure 3 compared to the A&S rock & shallow soil spectrum. The different character of crustal, interface and shallow-slab spectra are indicated in Figure 4, for site class B at 30 km and magnitude 7.0, with interface and slab centroid depths of 20 km.

Crustal spectra for Class B are generally similar to the "rock" spectra of Abrahamson and Silva, and those of Class C to their "soil" spectra. Crustal weak-rock spectra are generally weaker than those of A&S, apparently because of the combination of rock and shallow soil sites in the A&S "rock" class (e.g. Figure 3). Using the A&S site classifications for the New Zealand data leads to spectra not very different from those of A&S. The New Zealand spectra require smoothing, especially for the rock categories and Class C, for which there are fewer data than for Class B.

Near-source, large magnitude spectra for Class B appear unrealistically strong at around 0.2s. This may result partly from our inability so far to establish an appropriate nonlinear site response factor for this class. Class B sites will probably show less nonlinearity than many Class C sites, but are unlikely to remain linear at very high amplitudes. The peaked shape for Class B is most acute for subduction zone earthquakes at large magnitudes where there is no data. This may be due to the greater attenuation rates than in the Youngs et al. model demanded by the New Zealand data also increasing the magnitude coefficient through the linking of these terms by the near-source constraint. If the Youngs et al. magnitude coefficient is retained and the attenuation rate allowed to be free, we obtain fitted spectra that appear unconservatively weak.

CONCLUSIONS

Considerable progress has been made in developing attenuation expressions for response spectra appropriate to New Zealand. The techniques of judicious combination of world-wide and local data, and modifying existing attenuation relations to better fit local data, may be applicable in other regions with strong-motion catalogues that are sizeable but not sufficient to develop robust attenuation models. It has been found that generally New Zealand earthquake motions are similar to those from other parts of the world for the same tectonic class, especially for crustal earthquakes. This suggests the possibility of combining world-wide data for regions with similar tectonic regimes. The results show that shallow crustal and subduction zone earthquake motions have different spectral shapes.

The problems that remain in the models developed for New Zealand are most evident at magnitude and distance combinations for which data are lacking. Large-magnitude data for subduction zone earthquakes and large-magnitude, near-source data for crustal earthquakes are still required to improve reliability of estimates of response spectra and PGAs at the large amplitudes of most interest in seismic design.

ACKNOWLEDGEMENTS

The research reported in this paper was funded by the New Zealand Foundation for Research, Science and Technology under Contract CO5506, and by the Electricity Corporation of New Zealand Ltd. We thank Jim Cousins for providing processed data, and Nick Perrin for assisting with the classification of sites.

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TABLE 1: Equations for the New Zealand Response Spectral Acceleration Model
(includes different attenuation for medium/strong rock class and a volcanic path term)

<table>
<tr><td colspan="2">First step: $SA_i'(T)$, i = MA/SA, WA, B, C fitted from response spectrum dataset</td></tr>
<tr><td>CRUSTAL EARTHQUAKE
with strike-slip mechanism
for site class WA("weak rock")
(includes volcanic path term)

and site class MA/SA ("moderate-to-strong rock")</td><td>$\ln SA_{WA}'(T) = C_1(T) + C_{4AS}(M-6) + C_{3AS}(T)(8.5-M)^2 + C_5(T)\, r$
$+ (C_8(T) + C_{6AS}(M-6)) \ln(r^2 + C_{10AS}{}^2(T))^{½} + C_{46}(T)\, r_{VOL}$

$\ln SA_{MA/SA}'(T) = \ln SA_{WA}'(T) + C_2(T)\, r + C_{44}(T)$
$+ (C_9(T) + C_7(T)(M-6))(\ln(r^2 + C_{10AS}{}^2(T))^{½} - \ln C_{10AS})$</td></tr>
<tr><td>CRUSTAL EARTHQUAKE MECHANISM TERM
CN: normal
CR: reverse, reverse-oblique</td><td>$+ C_{32}\, CN + C_{33AS}(T)\, CR$

CN = -1 for normal mechanism, 0 otherwise
CR = 0.5 for reverse/oblique, 1.0 for reverse, 0 otherwise</td></tr>
<tr><td>HANGING WALL TERM</td><td>As in Abrahamson and Silva (1997)</td></tr>
<tr><td>SUBDUCTION ZONE EARTHQUAKE
for site class WA ("weak rock")

(includes volcanic path term for shallow slab and interface events)

for site class MA/SA ("moderate-to-strong rock")</td><td>$\ln SA_{WA}'(T) = C_{11}(T) + \underline{C_{12}{}^*(T)}(M-6) + C_{13Y}(T)(10-M)^3$
$+C_{17}(T) \ln(r + C_{18Y} \exp(C_{19Y} M)) + C_{20}(T)\, H_C$
$+ C_{24}(T)\, SI + C_{46}(T)\, r_{VOL}(1-DS)$
where $\underline{C_{12}{}^*(T)} = C_{12Y} + (C_{17Y}(T) - C_{17}(T))\, C_{19Y}$
$C_{17Y}(T) = C_{15}(T)$

SI = 1 for subduction interface, 0 otherwise
DS = 1 for deep slab, 0 otherwise

$\ln SA_{MA/SA}'(T) = \ln SA_{WA}'(T) + C_{44}(T) +$
$C_{16}(T)(\ln(r + C_{18Y} \exp(C_{19Y} M)) - \ln(C_{18Y} \exp(C_{19Y} M)))$</td></tr>
<tr><td>SITE TERM
(crustal & subduction zone)

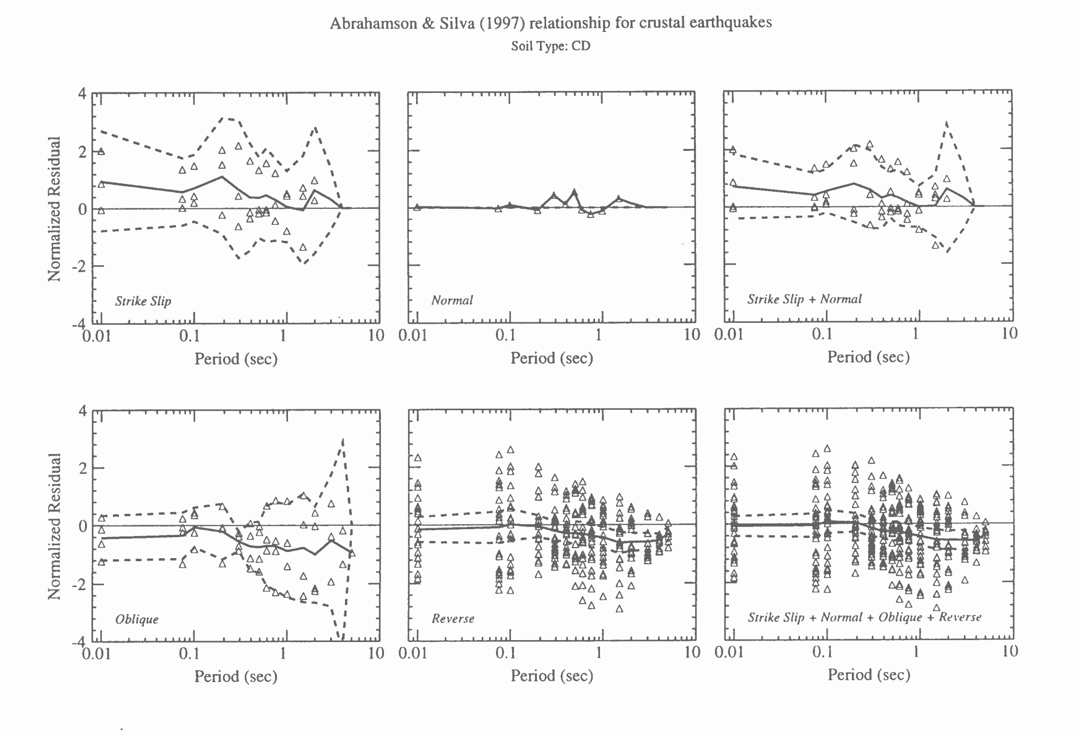
for site classes B and C</td><td>$\ln SA_B'(T) = \ln SA_{WA}'(T) + C_{29}(T)$

$\ln SA_C'(T) = \ln SA_{WA}'(T) + C_{30AS}(T) \ln(PGA_{WA}'+0.03) + C_{43}(T)$

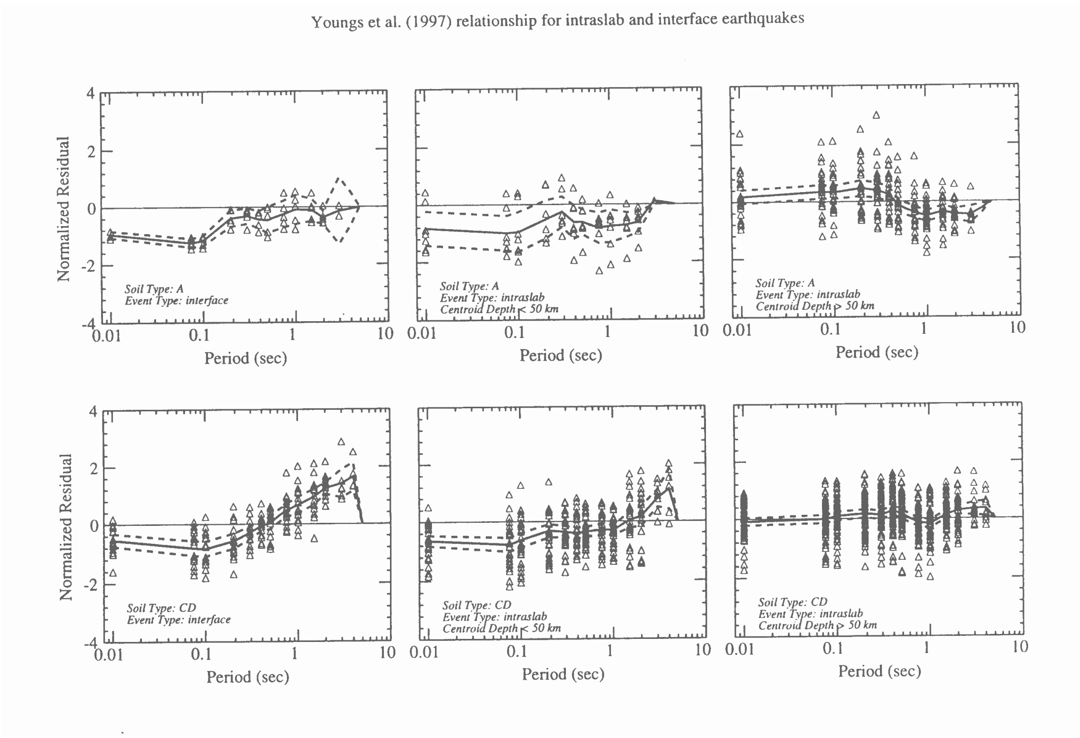
where $PGA_{WA}' = SA_{WA}'(T=0)$</td></tr>
<tr><td colspan="2">Second step: $SA_i(T)$ based on using larger PGA dataset for $SA_i(0)$</td></tr>
<tr><td>SCALING BY PGA RATIO
(for difference between PGAs estimated from response spectrum and PGA datasets)</td><td>$SA_i(0)$ same model form as above, fitted from larger PGA dataset i.e. including "PGA only" data

$SA_i(T) = SA_i'(T) * (SA_i(0)/SA_i'(0))$, $T \neq 0$

i = MA/SA, WA, B, C</td></tr>
</table>



(a)



(b)

Figure 1. Residuals between (a) the Abrahamson and Silva model and New Zealand crustal data for deep soil sites and (b) the Youngs et al. model and New Zealand subduction zone data for rock (A) and deep soil (CD) sites.

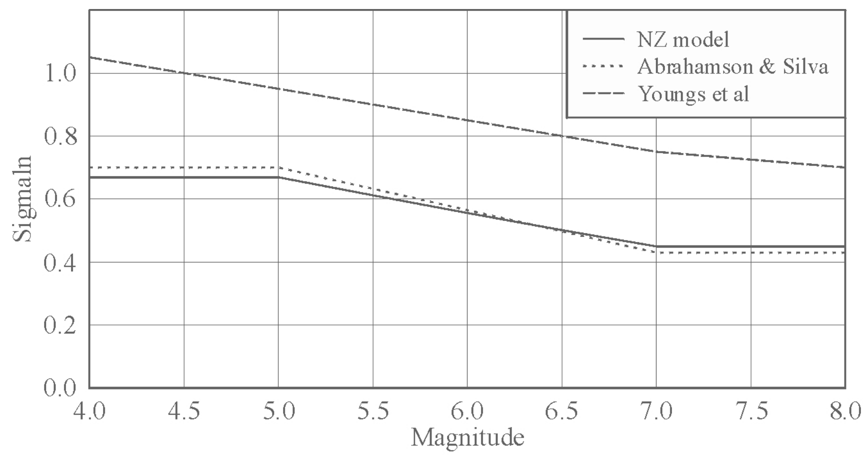


Figure 2. Standard errors of ln SA(T) for NZ and base models for T=0s.

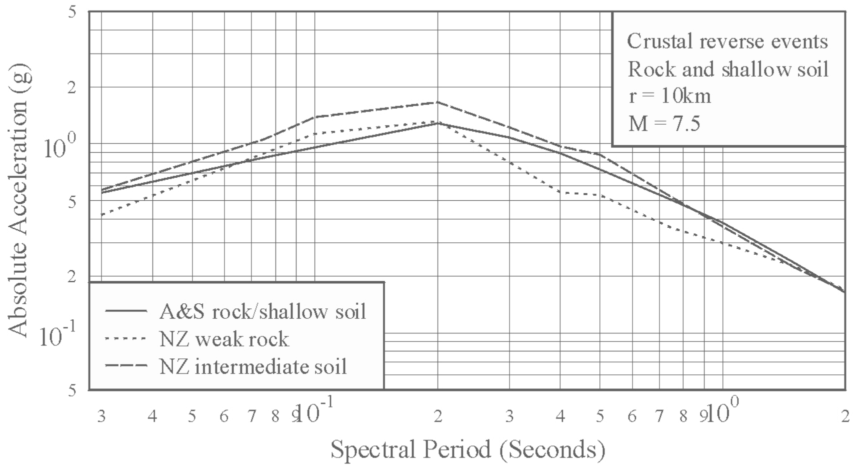


Figure 3. Near-source spectra at 10km for weak rock and shallow soil.

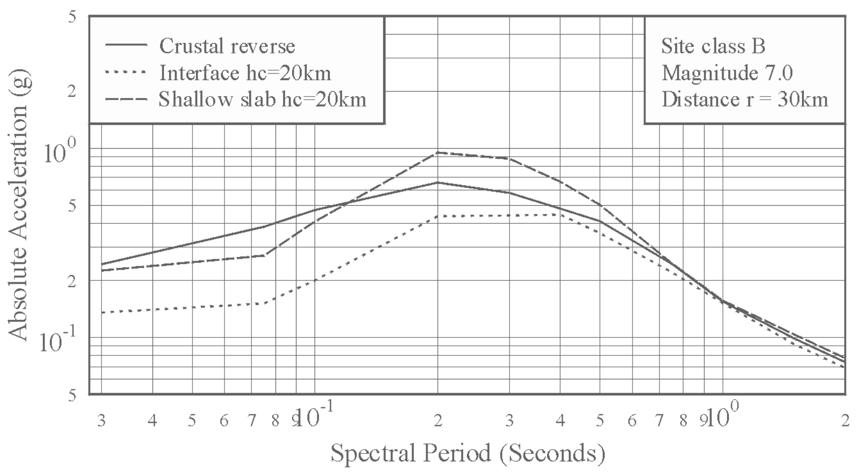


Figure 4. Comparison of reverse crustal, interface, and shallow slab spectra.