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From hazard maps to code spectra for New Zealand

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ABSTRACT: The development of the New Zealand seismic coefficients of the draft Australia/New Zealand Loadings Standard from a probabilistic seismic hazard analysis (PSHA) is presented. The hazard factors Z arise directly from a scaling of the 500-year return period estimates of the 5% damped response spectral accelerations SA(T) for period T of 0.5s. Truncation of Z to the range corresponding to rock peak ground accelerations of 0.13g to 0.6g is justified on deterministic grounds. Normalisation at the intermediate period T of 0.5s avoids the need for the U.S. practice of mapping multiple spectral values to construct spectra. The code spectral shapes for the various site classes give near upper bounds across New Zealand to mapped 500-year ratios of SA(T)/SA(0.5s) resulting from the PSHA, leading to code spectra that are near-envelopes of the hazard spectra. Hazard curves for most locations are fitted well by the risk factor R that scales the 500-year spectra to other return periods. The new near-fault factor N(T,D) caters for systematic near-fault directivity effects for longer-period structures at distances D less than 20 km from New Zealand's most active faults. This factor is based on results calculated from published empirical near-source modification factors.

1 INTRODUCTION

1.1 New Zealand probabilistic seismic hazard model

The New Zealand seismic coefficients of the draft Australia/New Zealand Loadings Standard (Standards New Zealand 2002) have been developed from a probabilistic seismic hazard analysis by Stirling et al. (2000, 2002). For the first time, the seismicity model underlying a New Zealand loadings standard includes fault sources, rather than smearing the seismicity over large regional sources (e.g. Smith & Berryman 1983, 1986). Another new feature is that the hazard analyses for the draft Standard used the “magnitude-weighting” approach of Idriss (1985), rather than the standard uniform-hazard approach used in the published results of Stirling et al. (2000, 2002). In addition, the draft standard includes a near-fault factor to account for systematic near-source directivity and polarisation effects for longer spectral-period components that are not included in the standard hazard estimates.

The new hazard model produces a greater range of hazard values over New Zealand than earlier models. The very high hazard estimates near the most active faults are well in excess of values that have been considered in previous New Zealand codes, especially for short-period structures. A continuous rather than discrete-region treatment of distributed seismicity reduces the estimates in the least seismic parts of the country. For example, the 5% damped acceleration for 0.2s period at the peak of the uniform-hazard 500-year spectrum for shallow soil varies from about 0.12g to over 3g in the new model. This compares with about 0.3g to 1.3g in the Matuschka et al. (1985) study that served as the basis for the present code, NZS4203:1992 (Standards New Zealand 1992), with the range truncated to 0.6g-1.2g in the NZS4203 code zone factors. The greatest 500-year SA(1s) estimate for the shallow soil class of about 0.8g is nearer the current code maximum of 0.6g. Hazard values for the main cities are less extreme, but in places exceed the maxima of the current code in the short-period range. For the capital city of Wellington, with the highest estimated hazard of any New Zealand city, the 500-year spectrum peaks at 1.6g, with an SA(1s) value of 0.40g.

There is also great variation in the recurrence intervals of the largest earthquakes expected in different parts of the country. Along part of the Alpine Fault, with an average recurrence interval in the hazard model of 200 years for surface-rupturing earthquakes of magnitudes up to 8.1, the 500-year spectral peak value of over 3g corresponds to about 84-percentile motions for this fault. For Wellington, the 500-year spectrum corresponds approximately to the median spectrum for a characteristic earthquake of about magnitude 7.3 on the Wellington Fault at 2-3 km from the city centre. For Dunedin, the 2500-year spectrum approximates the median spectrum for a magnitude 7.1 earthquake on the Akatore Fault, modelled with an average recurrence interval of 3000 years. Near Auckland, the 2500-year spectra are only about median spectra for magnitude 5.0-5.5 earthquakes at 20km distance.

These factors complicate the selection of appropriate motions for addressing the code objective of "withstanding the most severe earthquake shaking that the structure is likely to be subjected to, with a low probability of collapse."

1.2 **Magnitude-weighted spectra**

A criticism of uniform-hazard spectra is that they tend to be dominated by contributions from moderate-magnitude earthquakes, and do not reflect the effect of duration in causing structural damage. To address this issue, the hazard analyses performed for the development of the spectra in the draft Standard used the "magnitude-weighting" method of Idriss (1985) that is long-established for liquefaction analyses, in place of standard "uniform-hazard" spectra. In Idriss's method, response spectrum values for magnitude M are scaled by a factor $(M/7.5)^{1.285}$ for periods between 0s and 0.5s. This factor is intended to produce estimates that are equivalent to magnitude 7.5 values in terms of damage-potential, recognising that damage-potential increases with magnitude for a given amplitude of earthquake-induced motion because duration of shaking generally increases with magnitude.

1.3 **Selection of the hazard levels to use as the basis for the code**

The proposed design-level "ultimate limit state" earthquake motions for New Zealand are based on the 500-year return period magnitude-weighted spectra, but with upper and lower bounds on the required spectra. Except where the lower-bound limits apply, the design-level earthquake motions are those associated with damage limitation, rather than collapse avoidance. It is assumed that adoption of the requirements of the proposed Loadings Standard and appropriate materials standards provides a sufficient margin against collapse in the 500-year return-period design motions to survive 2500-year motions. Adoption of two hazard levels to be specifically considered for two limit states, with return periods of 500 years for damage-limitation and 2500 years for collapse-avoidance, was rejected by the code committee, although a map of the 2500-year hazard factors is to be added to the Commentary of the Standard. Some consideration was given to using the 2500-year spectra scaled by two-thirds to represent design-level motions, as in recent U.S. codes, to provide a constant factor between design-level motions and the maximum motions that are reasonable to consider for standard structures. As the ratio of the 2500-year to 500-year motions is 1.5 or greater for most locations in New Zealand (Fig. 2), this approach would have provided design-level motions with a return period of approximately 500 years for high-hazard locations, but longer return periods at lower-hazard locations.

1.4 **Basis for draft code seismic coefficients**

In the draft Standard, the elastic site hazard spectrum for horizontal loading, C(T), for a given return period is defined in terms of the product of four factors, namely the spectral shape factor $C_h(T)$, the hazard factor Z, the return period factor R and the near-fault factor N(T,D):

$$C(T) = C_h(T) Z R N(T,D) \qquad (1)$$

This paper presents the derivation of these four factors.

2 DEFINITION OF SPECTRAL SHAPES

2.1 Site classes

Spectral shape factors $C_h(T)$ are defined for five site classes: A Strong Rock, B Rock, C Shallow Soil, D Deep or Soft Soil, and E Very Soft Soil sites. For New Zealand, the Strong Rock and Rock classes share the same spectral shape factors. The Strong Rock class caters for the prevalence of sites in Australia with shear-wave velocities that are higher than for typical New Zealand rock. In a change from the current New Zealand code, statistical differences in spectra have led to rock sites being classed separately from very stiff or dense soil sites, which are now combined with other soil sites.

The site-class definitions are based on site period, to account for both the shear-wave velocity and the depth of soil, rather than using just the average shear-wave velocity to 30m depth as in recent U.S. codes. The site-period approach recognises that spectra from deep deposits of stiff or dense soil are stronger at long periods than those from shallow sites of the same material. In practice, for both Australia and New Zealand, the site class is assigned largely from descriptive terms, rather than from measured geotechnical properties. Measured shear-wave velocity profiles are available only very rarely.

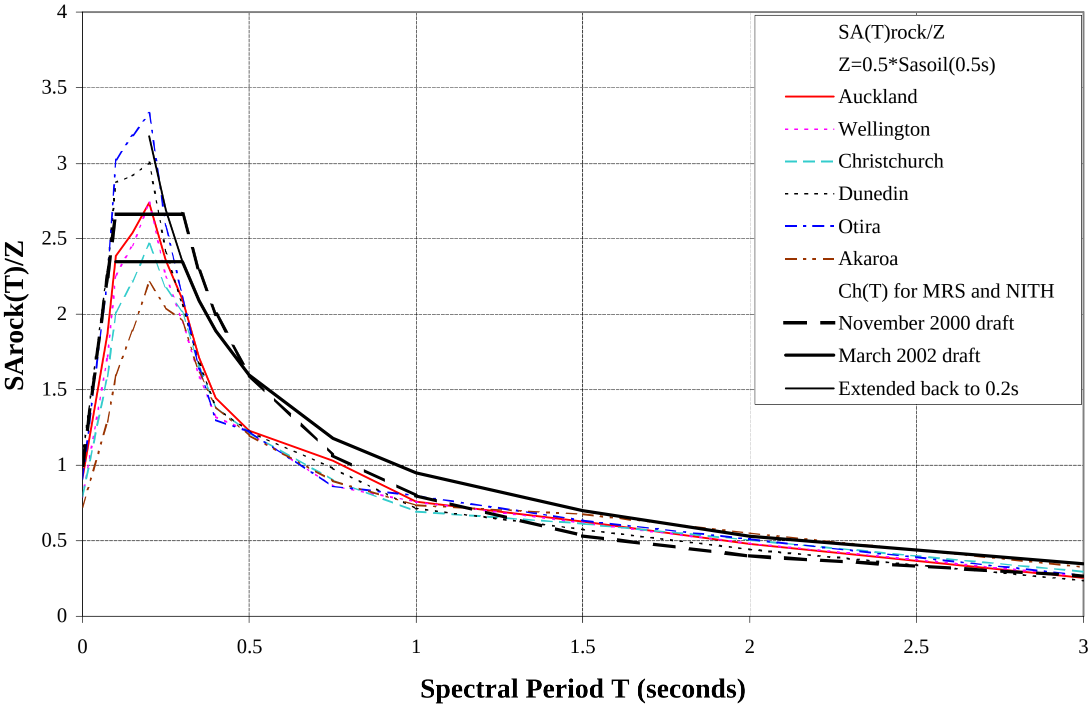
The new Class E for Very Soft Soil sites has been introduced for sites with about 10 metres or more depth of materials with shear-wave velocities less than 150 m/s. Such sites are often associated with amplifications for low-to-moderate levels of earthquake shaking that are considerably greater than those assigned to Classes C and D, especially for longer spectral periods.

2.2 Spectral shape factors Ch(T)

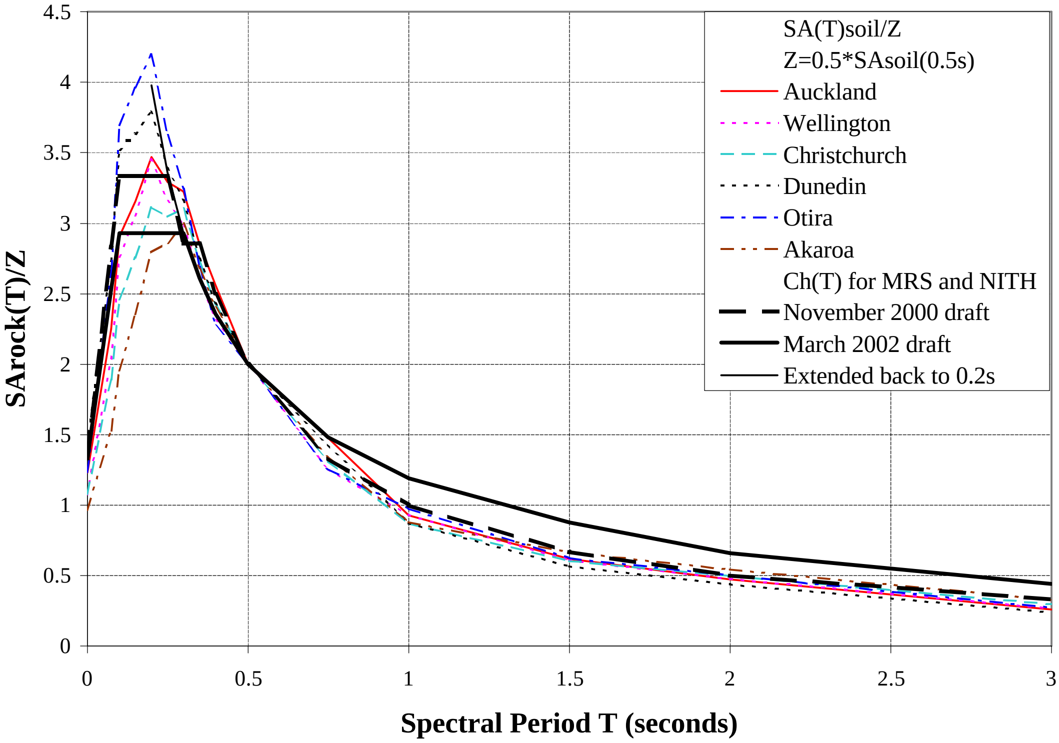
The spectral shape factors have evolved considerably since the November 2000 draft code (Standards Australia/Standards New Zealand 2000), because of review comments and problems revealed by trial designs. In the 2000 draft, the constant spectral-velocity branches for Classes A, B and C extended from 3s period back to 0.3s, rather than being truncated at 0.45s by the short-period plateaux as in the current NZS4203:1992 spectra. This made the acceleration coefficients for short-period structures highly dependent on the fundamental period, which is difficult to estimate accurately for structures with periods less than about 0.5s. There were difficulties identifying accelerograms for response-history analysis that have short-period peaks as strong relative to the longer-period values as the 2000 draft code spectra. The higher modes had much more influence than for the NZS4203:1992 spectra, because of the relatively greater strength of $C_h(T)$ at short periods relative to long periods in the draft code. Also, it was found that the draft code spectra underestimated the hazard spectra for Class A and B Rock Site conditions through most of the country for periods in excess of about 1s.

These problems have been addressed with a reduced falloff with period, proportional to $T^{-0.75}$ rather than T^{-1}, from the corner period of the plateau to 1.5s, together with increased corner periods.

Spectral shape factors (i.e. response spectrum values SA(T) from hazard analyses normalised by the hazard factor Z, as discussed in Section 3) for the main centres and some other locations are shown in Figures 1a (Class A & B Rock) and 1b (Class C Shallow Soil). These examples span the range across New Zealand of the spectral shapes for classes A/B and C, as determined from maps of the spectral ratios SA(T)/SA(0.5s) for several spectral periods T. These figures also show the spectral shapes proposed in the November 2000 and March 2002 drafts. The exponent of –1 of the 2000 draft closely matches the falloff of the Class C Shallow Soil spectra (bold dashed line in Fig. 1b). However, the T^{-1} decay is too rapid for the Class A/B rock spectra (Fig. 1a), with the November 2000 curve falling below all the actual spectral shapes for periods greater than about 1.25s. The March 2002 curve (bold solid line) corresponding to the –0.75 exponent for the descending branch of the spectrum to 1.5s virtually envelopes the rock spectral shapes (Fig. 1a), although overestimating the soil spectral shapes at intermediate and long periods (Fig. 1b). The value of –0.75 is governed by the upper envelope of the spectral shapes for rock sites around 1.5s, and by the peaks of the spectra around 0.2s for both rock and shallow soil conditions. The locations that govern the envelope at 1.5s are in the eastern part of the Canterbury Plains and on Banks Peninsula, e.g. Akaroa (Fig. 1a), while those controlling the envelope around the peak of the spectrum are adjacent to the Alpine Fault, e.g. Otira (Figs 1a and 1b).



(a)



(b)

Figure 1 Normalised spectra and Ch(T) factors for the modal response spectrum (MRS) and numerical integration time-history (NITH) methods for (a) Site Classes A&B Rock and (b) Site Class C Shallow Soil.

The hazard spectra for rock and shallow soil site conditions generally peak around 0.2s. Taking the short-period end of the $T^{-0.75}$ branch to 0.2s provides a near-envelope of the peaks of estimated 500-year return period spectral shapes across the country, especially for rock sites (Fig. 1a). However, truncating the peaks of the coefficients $C_h(T)$ for the Modal Response Spectrum (MRS) and the Numerical Integration Time-History (NITH) methods at 0.3s as in the March 2002 draft makes them much closer to recorded spectral shapes from large-magnitude earthquakes that are appropriate for consideration for ultimate loading conditions for the more seismic parts of New Zealand. For the equivalent static method, the spectral shape factors are truncated at their 0.4s values over the whole period band 0s to 0.4s, the longer truncation period for this method being selected to overcome problems with estimating short fundamental periods accurately.

The resulting spectral shapes are very similar to those of the rock and very stiff soil class of NZS4203:1992 for classes A/B, to the NZS4203:1992 intermediate soil class for class C and to the deep or flexible soil class for class D. The main difference from NZS4203 is the truncation of the peaks of the spectra at 0.3s for classes A/B and C, rather than at 0.45s as in NZS4203:1992. Class E Very Soft Soil is a new site class that has been obtained by subdividing the deep or flexible soil class, and its spectral shape is stronger at long periods than any in NZS4203:1992. Its spectral shape factor has been derived by extending the Class D plateau out to a corner period of 1s for Class E, recognition that such sites often show very strong motions in the long-period band. This selection results in a scaling up of the long-period branches (beyond T_c) for this site class by a ratio of 1.55 with respect to Class D, typical of the ratio of the long-period site-factors for Classes D and E in the NEHRP 2000 code (BSSC 2000). Comparison with spectra of recorded motions suggested that records from Class E sites generally exhibit significant amplification with respect to Class D sites only in the longer-period ranges. Accordingly, the amplitudes for the short-period plateau and for peak ground accelerations (i.e. 0s period) have been taken the same for classes D and E.

In the attenuation model used in the New Zealand hazard analyses, the ratios of the spectra for Class D sites (Deep or Soft Soil) to the spectra for Class A/B sites (Rock) are functions of the rock peak ground acceleration, as well as the spectral period T. This was reflected in the November 2000 draft by spectral-shape factors for Class D that were functions of the zone-factor Z. The use of nonlinear, period-dependent site factors is consistent with recent U.S. codes. However, in further review, it was decided that the amount of variation was insufficient to justify the extra complication of the dependence of the spectral shape on the Z factor.

3 THE HAZARD FACTOR Z

The variation in normalised spectra around New Zealand is sufficiently modest (Fig. 1), especially when the spectra are truncated at the 0.3s period values, that a judicious choice of the hazard-factor parameter Z in terms of the intermediate-period spectral value of SA(0.5s) for shallow soil allows a single factor to be retained, as in the current standard NZS4203. This is simpler than the U.S. approach that requires both short- and long-period factors, allowing spectral shapes to vary with location. Shallow soil was chosen as the reference class because it provides most New Zealand response spectra data, and hence the response spectrum model is most reliable for this class. The mapped hazard factor Z for scaling normalised code spectra is defined as 0.5 times the 500-year magnitude-weighted SA(0.5s) value for the shallow-soil class, except where the minimum and maximum Z-values govern (Section 3.1). This parameter corresponds to the codified value of the rock peak ground acceleration (pga), as demonstrated by the axis intercept at 1.0 in Figure 1a. Rock pga is a more standard hazard parameter than SA(0.5s) for shallow soil. Since the March 2002 draft, spatial smoothing has been applied to the proposed Z-values by use of a half-cosine arch filter of 1° width.

3.1 Minimum and maximum Z-values

A minimum allowable value of $Z = 0.13$ has been set to ensure compliance in low seismicity areas with the performance objective to withstand the most severe shaking that the structure is likely to be subjected to with a small margin against collapse. This defines a minimum level of earthquake motion that is to be withstood by any return period factor R=1 structure in New Zealand, corresponding to the estimated 84-percentile motions in a magnitude 6.5 normal-mechanism earthquake at a distance of 20 km. This sort of earthquake could occur randomly anywhere in New Zealand. Without a minimum allowable Z-value, it was felt that the lowest design levels may be insufficient to withstand the significant earthquake shaking that any structure in New Zealand could be exposed to in its lifetime. A Z-value of 0.13 is greater than its estimated value of 0.1 for Auckland, and its estimated minimum value in New Zealand of 0.08 at North Cape. The selection of a minimum Z-value departs from the probabilistic basis used for deriving the site hazard spectra, imposing instead a deterministically defined minimum level of earthquake motion that any normal-use (i.e. R=1) structure in New Zealand should be specifically designed to survive.

The maximum Z-value of 0.6 required for New Zealand corresponds to the 50-percentile near-source spectrum for a magnitude 8.1 strike-slip earthquake. With an assumed margin of safety of 1.8 for the ultimate limit-state, Z=0.6 corresponds to collapse-avoidance motions that are equivalent to the estimated 90-percentile motions at near-fault sites in the magnitude of earthquake expected on the Alpine Fault, the source of the strongest earthquake motions expected in New Zealand.

4 RETURN PERIOD FACTOR R

The Return Period Factors R scale the 500-year spectra (R=1) to other return periods as required for some classes of structure depending on their importance, and also to address the serviceability limit state, corresponding to return periods of about 20 years or greater. Hazard curves for shallow soil for magnitude-weighted SA(0.5s) values normalised by the 500-year return period values are shown in Figure 2 for several locations. They are compared to the proposed Return Period Factor curve for New Zealand, which is similar to the hazard curves for Auckland and Wellington. In general, the hazard increases more slowly than R for high-hazard sites (e.g. Otira). The rapid increase in hazard for Dunedin is associated with the increasing influence of the Akatore Fault (3000-year average recurrence interval) at longer return periods.

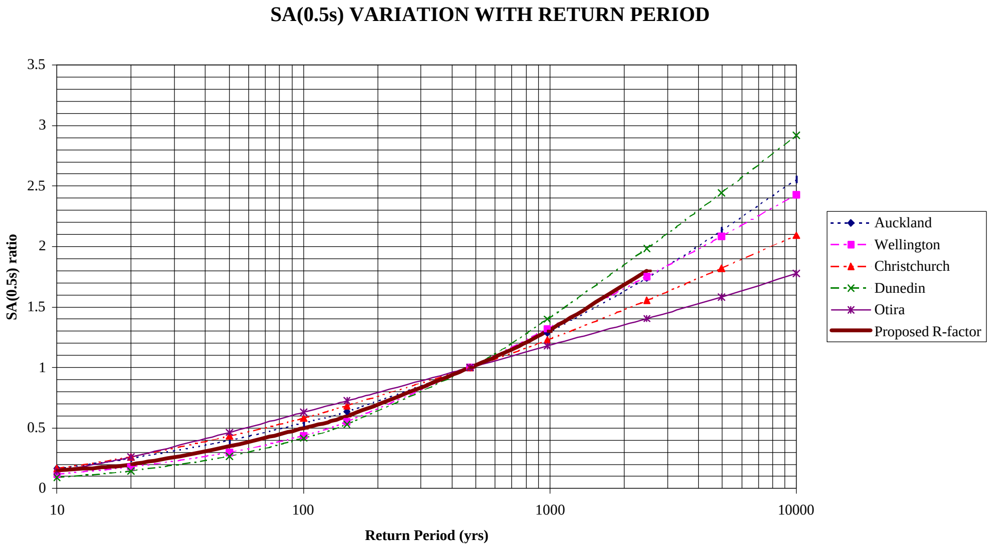


Figure 2 Comparison of proposed return-period factors R with hazard curves for 0.5s spectral accelerations.

5 NEAR-FAULT FACTOR N(T,D)

The near-fault factor N(T,D) was introduced in the March 2002 draft to account for systematic near-fault rupture directivity and polarisation effects that are not included in the standard hazard estimates. It varies from 1.0 only for structures with periods greater than 1.5s within 20 km of one of New Zealand's most active major strike-slip faults, and then only for structures and limit states requiring consideration of return periods of 200 years or greater.

The near-fault factor accounts for two systematic near-source effects related to propagation from a moving rupture: forward-directivity, and the polarisation of long-period motions in the near-source region. Somerville et al. (1997) provided models for adjusting estimates from standard attenuation models for these effects. Forward-directivity pulses are important because they produce large ground velocities, typically 1.0-1.5 m/s, and displacements that are likely to generate large amplitude inelastic response in structures experiencing them. For example, Bertero et al. (1978) showed that this type of pulse, rather than the strong high-frequency accelerations perhaps exceeding 1g that arrived later, was likely to have been the main cause of damage to the Olive View Hospital in the 1971 San Fernando earthquake. The San Fernando earthquake had reverse faulting, but similar features were recorded in the 1979 Imperial Valley, 1996 Kobe and other strike-slip earthquakes. Among effects not taken into account in the draft code is "fault-fling" i.e. the growth of the permanent displacement caused by fault offset.

Only the most active major faults in New Zealand have recurrence intervals short enough and magnitudes large enough that they dominate hazard estimates for return periods of a few hundred to a few thousand years that are of interest for code design. A convenient specification of those faults to be subject to the Near-Fault Factors is provided by the Californian Type A fault criteria (Petersen et al. 2000) used in the 1997 UBC (ICBO 1997). Type A faults are those assessed as capable of producing earthquakes of magnitudes of 7.0 or greater, and having slip rates of 5mm/year or greater. When these criteria are applied to the preferred estimates of New Zealand fault parameters, rather than upper-bound magnitude or slip-rate estimates, the selected faults are limited to New Zealand's most active major strike-slip faults, namely the Alpine, Awatere, Clarence, Hope, Kakapo, Kekerengu, Kelly, Mohaka, Wairarapa, Wairau and Wellington. No normal or reverse faults qualify.

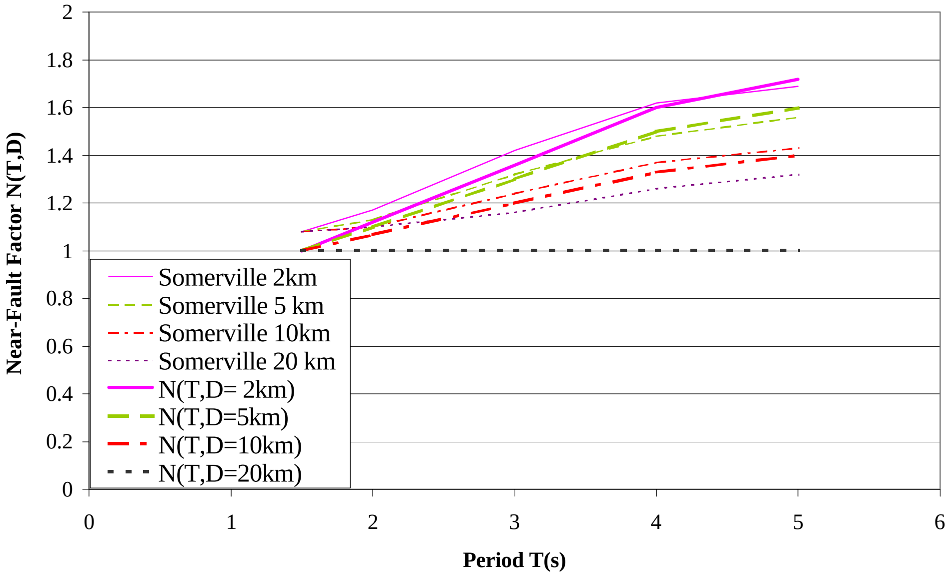


Figure 3 Near-fault factors N(T,D) compared with results calculated using the Somerville et al. (1997) models.

The values of the near-fault factors included in the proposed code are based on results obtained by specifying the values of various parameters in the simple models developed by Somerville et al. (1997). For the sites of most interest which lie close to the rupturing fault, the cosine of the angle between the strike of the fault and the line from the site to the epicentre can be taken as 1 for most possible epicentres. The fraction X of the fault rupture that propagates towards the site was taken as 0.75, the average across sites of its maximum possible value for each site. The magnitude M was taken as 7.5, the magnitude beyond which the Somerville factors are at their maximum values and close to the magnitudes appropriate for the faults to which it is to be applied. It is assumed that near-maximum directivity at a given location occurs for about one earthquake in three, with near-neutral directivity for the other two-thirds of earthquakes on the fault. With these assumptions about the values of the governing parameters, the results calculated from the Somerville et al. expressions can be represented by expressions that are tractable for code use. The near-fault factors N(T,D) are taken to vary linearly with shortest fault distance D from the value $N_{max}(T)$ at D=2 km to 1.0 at D=20km. The results were fitted well by piecewise linear variations with period T of $N_{max}(T)$. As shown in Figure 3, the resulting factors N(T,D) are good approximations to the results from the Somerville et al. expressions for distances up to 10km. The discrepancy between the N(T,D) factors and the Somerville et al. factors at 20 km arise from constraining N(T,D) to attenuate to 1.0 at 20km, while the Somerville et al. directivity factor, which is independent of distance, applies out to 50 km. Although the N(T,D) factor is 1.0, forward directivity effects may be important for long-period structures located off the end of but in line with strike-slip faults or updip of dip-slip faults.

6 CONCLUSIONS

It has been shown that the four factors contributing to the New Zealand elastic site hazard spectrum for horizontal loading C(T) in the draft Australia/New Zealand Loadings Standard are based on results from probabilistic seismic hazard modelling. The spectral shape factors for Class A/B rock sites, Class C shallow soil sites and Class D deep or soft soil sites are near upper bounds to the normalised spectra obtained from hazard analyses. The hazard factor Z is a direct scaling of the estimated 500-year return period value of the 5% damped response spectrum value at 0.5s period for shallow soil, except at locations governed by deterministically-based minimum and maximum values of 0.13 and 0.6. For most locations in New Zealand, the return period factor R is a good fit to the hazard curves normalised by their 500-year values. The near-fault factors N(T,D) to be applied within distances D of 20 km of New Zealand's most active strike-slip faults were derived by fitting results calculated using the Somerville et al. (1997) directivity and polarisation factors.

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