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Site-effect terms as continuous functions of site period and Vs30

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ABSTRACT: New site-effect terms that are a continuous function of site period *Tsite* are proposed to replace the spectral shape factors of the New Zealand structural design standard NZS1170.5. The new terms eliminate the 63% jump in shape factor between Class C Shallow Soil and Class D Deep or Soft Soil for spectral periods *T* beyond the peak of the Class D spectrum at about 0.6s. The proposed changes involve a gradual transition from the current shallow soil to deep soil factors over the site-period range 0.25s to 1.5s.

The new model represents the site-effects with respect to rock of the 5% damped spectrum by the simple form *lnSiteEffect(T)= a(T) + b(T)*Tsite*, where *a(T)* and *b(T)* are period-dependent fitted coefficients. Site-effect terms based on *Vs30*, the average shear-wave velocity to 30m depth, were also considered.

This site-period model fits the New Zealand attenuation model dataset better for spectral periods of 0.5s and longer than the original site-class model and the *Vs30* model. For New Zealand earthquake records, *Vs30* is a poor site-effects parameter at long spectral periods because long-period sites of the New Zealand strong-motion network are often associated with considerable depths of stiff gravels, rather than low *Vs30* materials.

1 INTRODUCTION

Currently there is an amplification of 63% between NZS1170.5 design spectra for Site Classes C Shallow Soil and D Deep or Soft Soil for periods of 0.56s and greater, as illustrated in the spectral shape factors of Figure 1 (Standards New Zealand 2004). This step change causes practical difficulties, as it results in similar differences in the cost of a structure. In addition, it is often difficult to determine which site class a borderline site falls into, potentially leading to considerable differences in the structural design forces for the same site depending on the site class assigned.

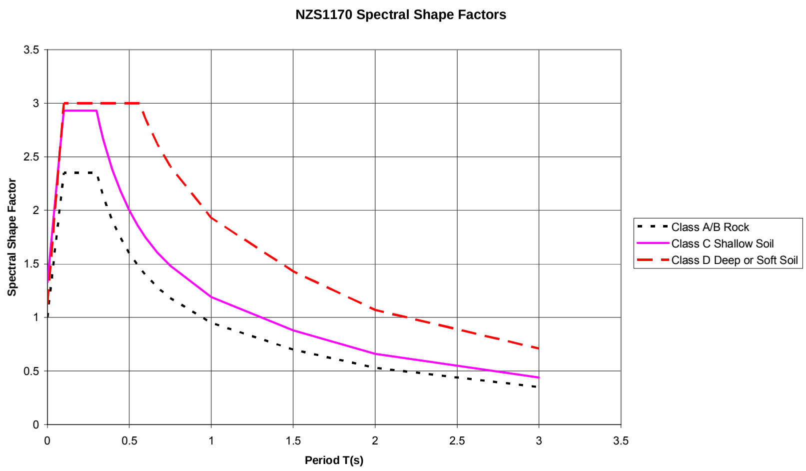

Figure 1 Spectral shape factors of the New Zealand Standard NZS1170, showing the large jump between Class C Shallow Soil and Class D Deep or Soft Soil.

The boundary between Classes C and D corresponds to a site period *Tsite* of 0.6s. The site period map presented by Semmens *et al.* (2011) at this conference, developed as part of the *It's Our Fault* study, shows that many sites in the central business district and Thorndon regions of Wellington have estimated periods lying between the *Tsite*=0.4s and 0.8s contours, close to the site class C/D boundary.

The aim of this study is to develop a site-effects term that is a continuous function of parameters such as site period, the average shear-wave velocity to either 30m depth (*Vs30*) or to rock (*Vave*), or a combination of *Vave* and depth to bedrock *Hrock* (to account for different amplifications arising from sites with the same periods but different average shear-wave velocities).

The approach is to reanalyse the New Zealand strong-motion dataset to replace the site-class terms in the response spectrum attenuation model of McVerry *et al.* (2006) with terms that are continuous functions of site parameters. The McVerry *et al.* model was used to develop the spectral shape factors and hazard factors *Z* of the New Zealand earthquake design standard NZS1170.5. The use of the McVerry *et al.* model to construct the NZS1170.5 spectra suggests that any modification of the site-effect terms should be able to be carried over into the NZS1170.5 spectral shape factors.

2 SITE-CHARACTERISATION PARAMETERS

2.1 New Zealand site class definitions

The McVerry *et al.* (2006) attenuation model and this study use the NZS1170.5 site classes, namely Class A/B Strong Rock/Rock, Class C Shallow Soil, Class D Deep or Soft Soil and Class E Very Soft Soil. The soil classes are based on site period, usually taken as four times the estimated shear-wave travel time from rock to the surface. The shear-wave velocities are generally assigned layer-by-layer from site descriptions rather than measured velocities. The site-period approach accounts for both the type and depth of soil at a site. It differs from US practice of using the average shear-wave velocity to 30m depth (*Vs30*). The main difference occurs for stiff soil sites that are deep enough to be assigned to Class D, which are characterised by shorter-period spectra in the *Vs30* approach.

2.2 Alternative site parameters

The current study aims to use measures of the site conditions that are continuous functions, rather than discrete site classes. Given that the NZS1170.5 site classes are nominally based on site period *Tsite*, this parameter was an obvious candidate. It can be determined using the current NZS1170 procedures for determining site class, except that specific estimates of *Tsite* need to be carried out.

Another continuous measure is *Vs30*. This parameter is widely used in US earthquake design codes and is the primary descriptor of site conditions in the NGA (Next Generation Attenuation) models (Stewart *et al.* (eds) 2008), sometimes in conjunction with other parameters to improve prediction of long-period components. The average shear-wave velocity *Vave* to rock has also been considered.

2.3 Parameters of sites used in this study

The current study required the estimation of *Tsite*, *Vs30*, *Vave* and *Hrock* for all sites throughout New Zealand that contributed spectra to the dataset used for derivation of the McVerry *et al.* model. For Wellington city and Hutt Valley sites, these parameters were estimated from the profiles developed by Semmens *et al.* (2010) and Boon *et al.* (2010, 2011) as part of the *It's Our Fault* project (Van Dissen *et al.* 2010). Nick Perrin of GNS Science compiled the information for sites outside these regions.

Figure 2a shows that *Vs30* ranges from about 150m/s to slightly over 800m/s for the Class C and D sites used in this study. Lower *Vs30* values are not present because Class E Very Soft Soil sites were excluded from the analysis. Sites with periods up to 0.6s (i.e. Class C Shallow Soil) have *Vs30* values that cover most of the 150-800m/s range. The *Vs30* range is more restricted for Class D Deep or Soft Soil sites, from about 150m/s to 620m/s, with most values less than 400m/s. The higher-velocity Class D sites are deep gravel deposits (200-300m), combining high *Vs30* values and long site periods. Figure 2b shows that there is not a strong correlation between the two velocity parameters, *Vs30* and *Vave*.

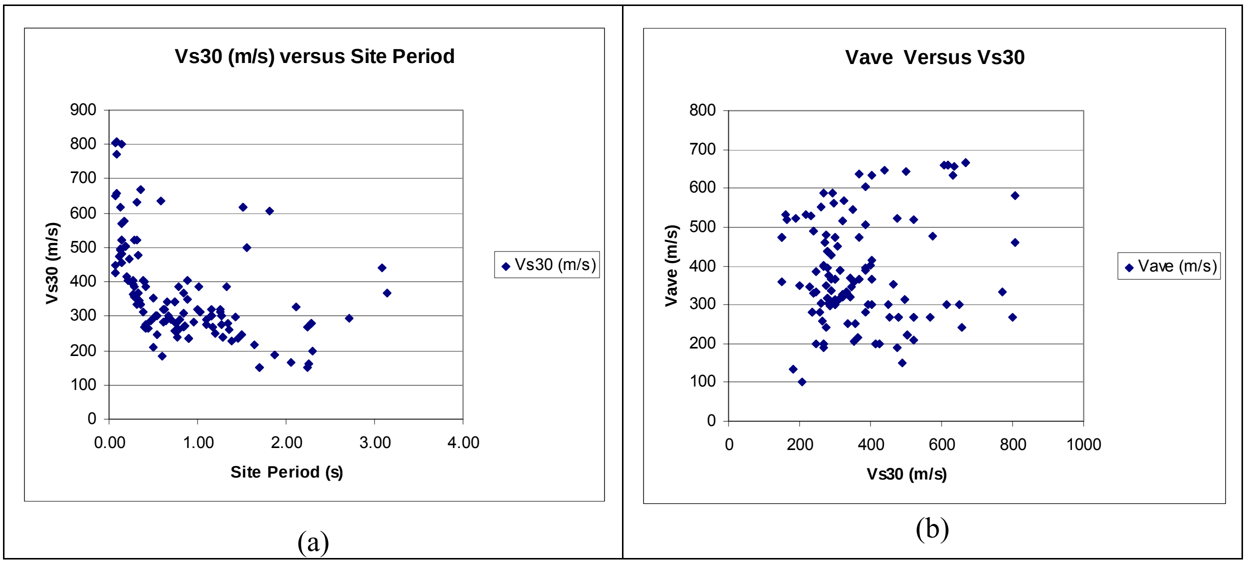

Figure 2 (a) *Vs30* (m/s) versus site period *Tsite*, and (b) *Vave* versus *Vs30*, for all soil sites in the analysis.

3 NEW ZEALAND RESPONSE SPECTRUM MODEL

3.1 Current site-effect terms and residuals

The site-effect terms of the current New Zealand response spectrum model (McVerry *et al.*, 2006) are

$$\ln SA_C(T) = \ln SA_B(T) + C_{29}(T) \tag{1}$$

$$\ln SA_D(T) = \ln SA_B(T) + C_{30AS}(T)\ln(SA_B(T) + 0.03) + C_{43}(T) \tag{2}$$

$SA_B(T)$, $SA_C(T)$ and $SA_D(T)$ are the 50-percentile estimates of the 5% damped response spectrum accelerations at period T for site classes B, C and D. C_{29}, C_{43} and C_{30AS} are coefficients of the model.

Trends of residuals (i.e. recorded data minus predicted values) of the McVerry *et al.* model (Figs 3 and 4) with site period *Tsite* and *Vs30* show that the motions depend on these parameters, suggesting that they may be useful as alternative site-effect parameters.

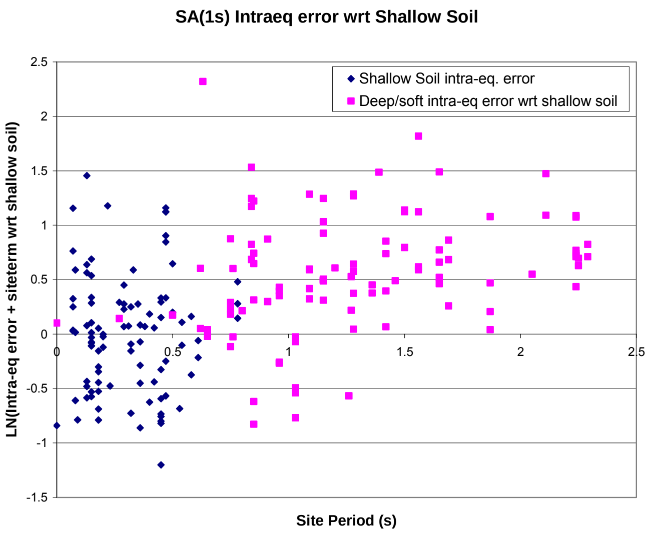

Figure 3 Intra-earthquake residuals at 1s period with respect to shallow soil increasing with site period *Tsite*.

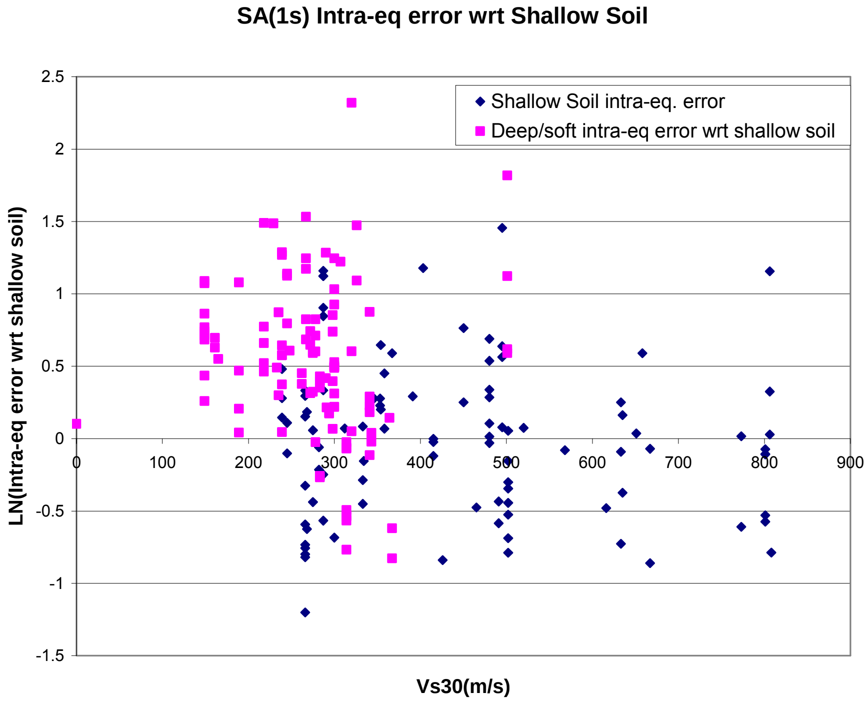

Figure 4 Intra-earthquake residuals at 1s period, generally decreasing with increasing *Vs30*.

3.2 **Proposed site-effect terms**

Several different combinations of the linear and nonlinear site-effects terms have been considered in place of equations (1) and (2). Table 1 summarises the particular functional forms that are discussed here. The combinations are denoted by *SiNj*, where the indices *i* and *j* correspond to *ISEtype* and *INONLINtype*, for the site-effect type and nonlinear response type. The functional form for the rock model is identical to that of the existing McVerry *et al.* model, although all free coefficients of the rock model were re-determined as part of the regression for deriving each of the various new models.

The overall model takes the form

$$\ln SA(T) = \ln SA_B(T) + ISE(T, site\_parameters) + INONLIN(T, SA_B(T)) \quad (3)$$

Table 1 Functional forms of site-effect and nonlinear site-response terms

ISEtype	ISE	INONLINtype	INONLIN
0 (site class model)	$C_{29}(T)\delta C + C_{43}(T)\delta D$ δC=1 for Class C, else 0 δD=1 for Class D, else 0	0 (linear)	0
1 (site-period)	$C_{48}(T) + C_{49}(T)\ T_{site}$	1	$C_{51}(T)\ \ln(SA_B(T) + 0.03)$
4 (V_{s30})	$C_{48}(T) + C_{49}(T)\ \ln(V_{s30})$	2	$[C_{51}(T) + C_{52}(T)\ T_{site}]^* \ln(SA_B(T) + 0.03)$

Model Code	Description
S0N0,S0N1	Site class based: N0 linear, N1 nonlinear (as in McVerry et al., 2006)
S1N0, S0N2	Site-period based: N0 linear, N2 site-period dependent nonlinear term
S4N0	Vs30-based, linear

3.3 **Goodness-of-fit of models**

The goodness-of-fit of the various models was determined in terms of the Akaike Information Criterion value *AIC* (Akaike 1974), which accounts for both the closeness-of-fit in terms of the log-likelihood *LL* and the number of parameters (unconstrained coefficients) *P* of the model

$$AIC = -2LL + 2P \tag{4}$$

The best fit corresponds to the model that minimizes *AIC*. Increasing the number of parameters by one requires an increase in the LL by 1.0 or greater to improve the model. *AIC* values within 2.0 of each other indicate a similar measure of fit, and *AIC* values within 1.0 can be considered very close. The differences in *AIC* values of various models are plotted in Figure 5. Positive values of the *AIC* difference correspond to improved models compared to the *S0N1* (McVerry *et al.* site-class nonlinear) model when the numbers of free coefficients are taken into account.

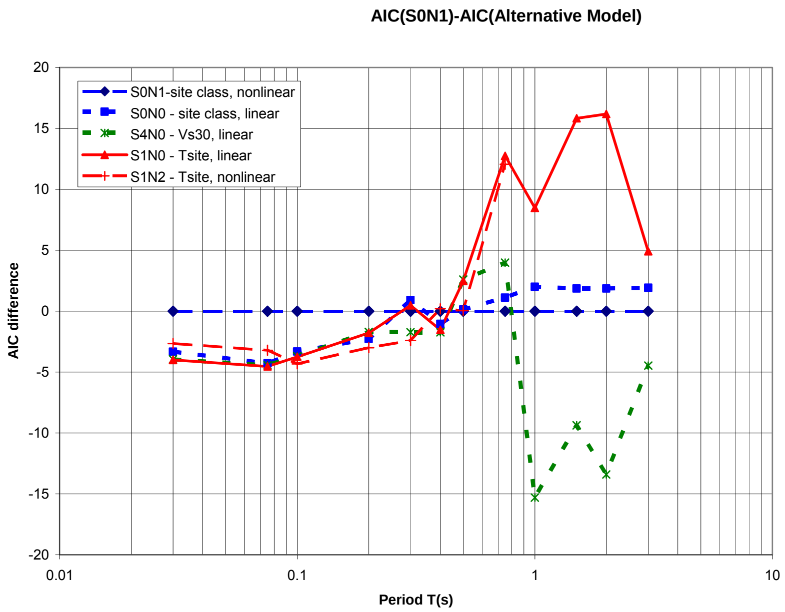

Figure 5 *AIC* values relative to original McVerry *et al. S0N1* (site-class, nonlinear) model for the *S0N0* (site class, linear), *S4N0* (*Vs30*, linear), *S1N0* (*Tsite*, linear) and *S1N2* (*Tsite*, nonlinear) models. Positive values of the *AIC* difference correspond to improved models when the numbers of parameters are taken into account.

For periods of 0.5s and greater, the *S1N0* (linear site-period based) model, shown as a solid red line, is an improvement over the *S0N1* site-class nonlinear model. It also gives a slight improvement at 0.3s, and its *AIC* is within 2.0 at 0.4s. Although not shown here, the *S1N0* model overcomes the trend of increasingly positive residuals with longer periods that is apparent in Figure 2 for the *S0N1* model.

The *S4N0* (*Vs30*-based) model, shown as a dotted green line, is an improvement over the *S0N1* site-class model only for 0.5s and 0.75s periods, and becomes much worse than the site-class model at longer periods. For practical purposes, the site-period based model *S1N0* can be taken to be as good as the *Vs30*-based *S4N0* model for periods up to 0.5s, and far superior for longer periods. The lack of success of *Vs30* in characterising site-effects in this study is possibly because New Zealand long-period sites are often associated with considerable depths of stiff gravels, rather than low *Vs30* materials. Also, the full *Vs30* range is not included in the data analysed, as *Vs30* has not been used as a site-effects parameter for rock sites, and Class E Very Soft Soil sites were excluded.

The linear site-period model *S1N0* is recommended for periods of 0.3s and longer, where the NZS1170 deep soil spectral-shape factors diverge from the shallow soil shape factors. For shorter periods, the nonlinear site-class model *S0N1* has the best *AIC* value, but the nonlinear *Tsite* model *S1N2* gives similar log-likelihood *LL* values. The *S1N2* model is suggested as appropriate for periods of 0s (pga) to 0.2s, to obtain a *Tsite*-based model that retains nonlinear response as in the *S0N1* model.

4 SITE-RESPONSE FACTORS

Figure 6 compares the site-response factors *SA(T,Tsite)/SA*$_B$*(T)* of the *S1N0* model for site periods *Tsite* from 0.1s to 2.25s with those for Classes C and D of the existing site-class *S0N1* model. The plots for site periods up to 0.6s, corresponding to Class C sites, are shown as dashed lines, while those for longer site periods, corresponding to Class D sites, are shown as solid lines. Similarly, Figure 7 compares site-response factors of the *Vs30*-based *S4N0* model with those of the *S0N1* model.

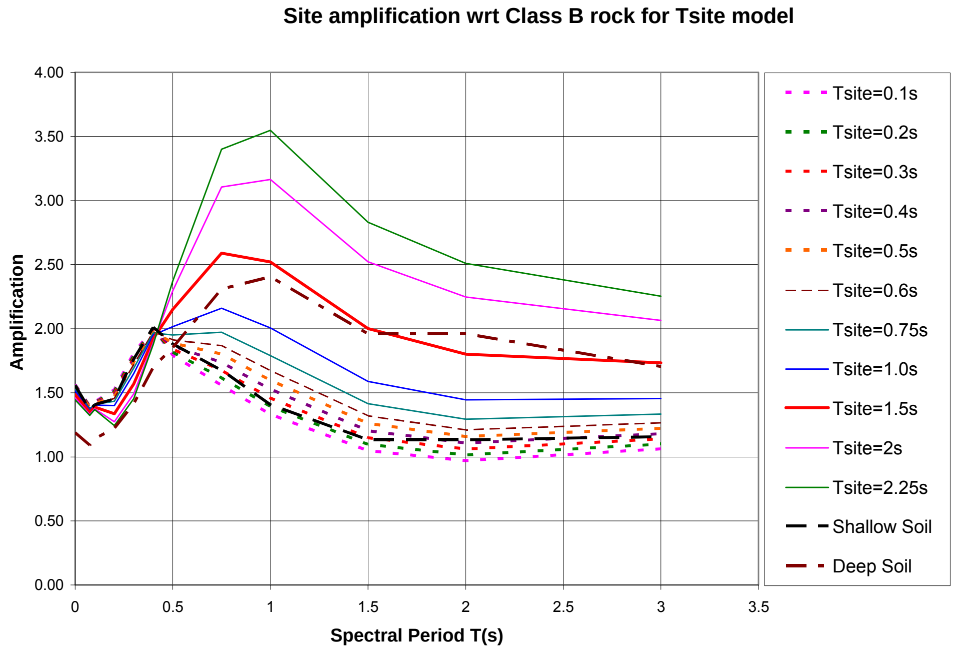

Figure 6 Comparison of the site-response factors of the *S1N0* model for various site periods *Tsite* and those for NZS1170 Classes C and D of the existing site-class model *S0N1* of McVerry *et al.* (2006).

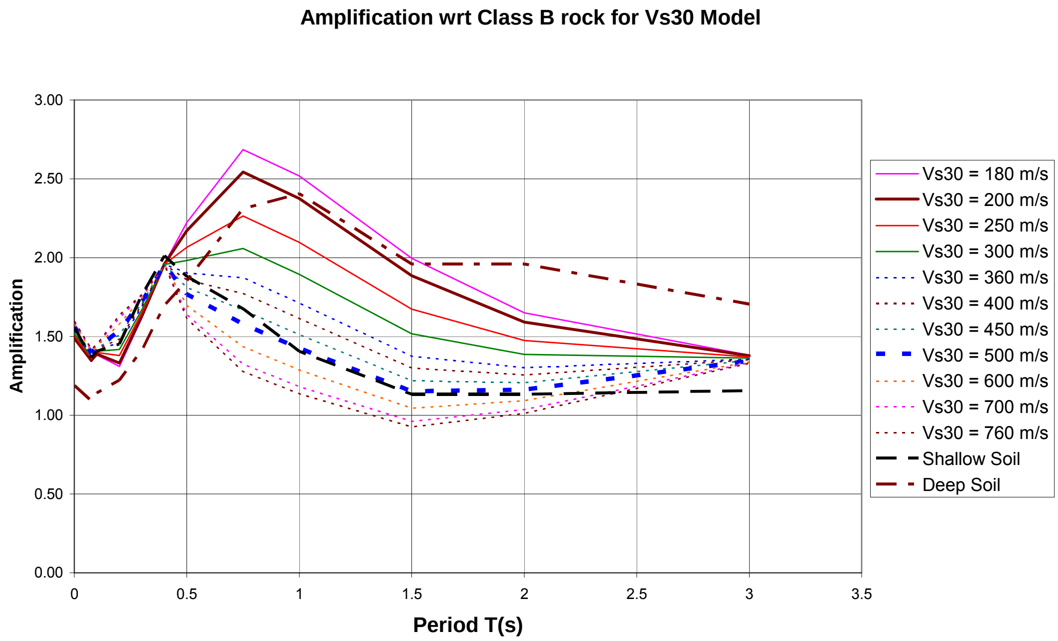

Figure 7 Comparison of the site-response factors of the *S4N0* model for various *Vs30* values and the factors for NZS1170 Class C and Class D of the existing site-class model *S0N1* of McVerry *et al.* (2006).

A feature of Figure 6 is the similarity of the site-class and site-period based factors for some *Tsite* values. The Class C curve resembles those for site periods of 0.2s or 0.3s, at least for spectral periods *T* up to about 1.5s. The Class D curve is similar to that for *Tsite*=1.5s, although the comparison is poorer than for Class C. Curves for site periods from 0.6s to 1.5s generally lie below the Class D curve, while those for longer site periods exceed it, quite considerably by a site period of 2s.

For spectral periods up to 1.5s, the Class C and *Vs30*=500m/s curves correspond reasonably well, while the Class D curve is similar to the *Vs30=200m/s* curve (Fig. 7). At longer spectral periods, the *Vs30* curves converge towards each other, unlike the site-class or *Tsite*-based curves.

5 PROPOSED MODIFIED NZS1170 SPECTRAL SHAPE FACTORS

The site-effect term of the McVerry *et al.* model for Class C Shallow Soil corresponds closely to the *Tsite*-based term for a site period of about 0.2s to 0.3s, while that for Class D Deep or Soft Soil approximates the *Tsite* term for a site period of 1.5s. The same properties apply to the spectra themselves for the site-class and site-period based models, and leads to proposed modifications of the NZS1170.5 spectral shape factors $C_h(T)$ shown in Figure 8 and explained below.

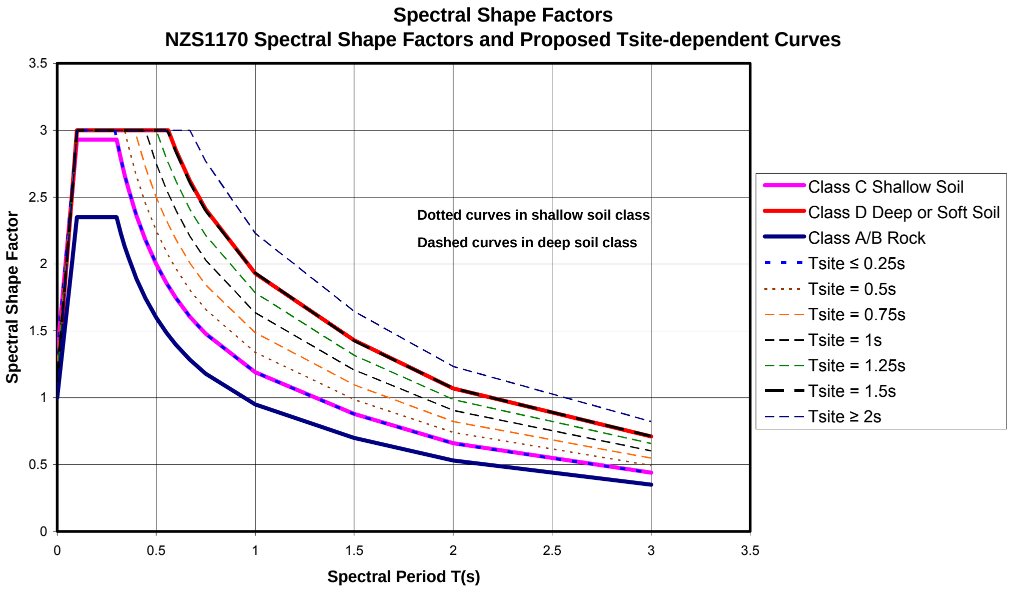

Figure 8 Proposed modified spectral shape factors as a function of site period *Tsite* to avoid the jump between Class C and Class D. Dotted curves correspond to Class C site periods, and dashed ones to Class D site periods.

The linear variation with site period of *lnSA(T,Tsite)* can be approximated by a linear variation of *SA(T,Tsite)*, which can be written in terms of its values at site periods *Ts1* and *Ts2*

$$SA(T,Tsite) = SA(T,T_{s1})\left[1+\left(\frac{SA(T,T_{s2})-SA(T,T_{s1})}{SA(T,T_{s1})}\right)\left(\frac{Tsite-T_{s1}}{T_{s2}-T_{s1}}\right)\right] \quad (5)$$

The NZS1170 Class D and Class C spectral shape factors $C_h(T)$ exhibit a constant ratio of 1.63 for periods *T*>0.56s. Selecting *Ts1* as 0.25s and *Ts2* as 1.5s, the bracketed term in equation 5 becomes *[1+0.5(Tsite-0.25)]*.

Modifying the peak value of the Class C spectral shape factor from 2.93 to the Class D value of 3.0, a modified spectral shape factor for Classes C and D (Fig. 8) is recommended as

$$C_h(T,Tsite) = Min\left[3, C_h(T)_{shallow\_soil} * (1+0.5(Tsite-0.25))\right]$$

$$for\ 0.25s \le Tsite \le Tmax,\ T \ge 0.1s \quad (6)$$

Possible values of the maximum period of application *Tmax* are 2s or 2.25s. At longer site periods, the C_h value for *Tmax* applies. In Figure 8, the maximum C_h curve is plotted for a site period of 2.0s.

There is a small penalty for overcoming the jump at the Class C/D boundary at *Tsite*=0.6s, in that the factors for site periods between 0.25s and 0.6s increase from the current Class C factors by up to 17.5%. However, between 0.6s and 1.5s the proposed factors decrease from the Class D factor. For site periods greater than 1.5s, the modified spectral shape factors exceed the current one for Class D.

6 CONCLUSIONS

- Site period *Tsite* has been shown to be an effective predictor of site effects as a replacement for site-class terms in the McVerry *et al.* (2006) acceleration response spectrum model that was used in New Zealand to develop the hazard spectra of the NZS1170 earthquake standard.
- The widely-used parameter *Vs30* is better than the original site-class terms only for periods of 0.5s and 0.75s for the New Zealand dataset considered, and generally worse than *Tsite*.
- A revised response spectrum model has been derived using *Tsite* as the site-effects parameter.
- It is recommended that the 63% jump between the NZS1170 Class C and Class D spectral shape factors at a site period *Tsite* of 0.6s can be overcome by a simple linear interpolation with site period between the Class C factor at *Tsite*=0.25s to the Class D factor at *Tsite*=1.5s.
- The new parameter *Tsite* that is required in place of site class can be approximated by procedures already described in NZS1170 to determine the site class, and maps of *Tsite* are available for Wellington city and the Hutt Valley (Semmens et al. 2010; Boon et al. 2010).

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