COMPARISON BETWEEN V_{S30} AND SITE PERIOD AS SITE PARAMETERS IN GROUND-MOTION PREDICTION EQUATIONS FOR RESPONSE SPECTRA

John X. Zhao
GNS Science
Lower Hutt
New Zealand

ABSTRACT

V_{S30}, the average soil shear-wave velocity of the top 30m, has been used to represent site effect in the Next Generation Attenuation (NGA) models and other recent models for different parts of the world. However, while V_{S30} has been found to be a reasonable parameter to represent site effect in some studies, it is not in others. In the present study, a systematic comparison will be carried out using a large dataset from Japan. The approach is to compare the standard deviations in the modelling of site effect by using site period or using V_{S30} and the amplitudes of amplification ratios. The site effect modelled includes site amplification ratios between the surface and borehole records from the Kik-net and the site effect (site class term plus intra-event residuals) from a ground-motion prediction equation (GMPE). For Kik-net data, site predominant period (4 times the shear-wave travel time from the bedrock to the ground surface) is a better parameter than V_{S30} for deep soil sites, while the two parameters lead to very similar variability of amplification ratios for the other sites. For the site effect from the GMPE, V_{S30} and site period perform statistically equally well for all site classes at most periods, while V_{S30} leads to smaller variability than site period at some spectral periods. The conflict between the Kik-net surface/borehole records and the results from GMPE is likely to be a result of large variability in the GMPE.

INTRODUCTION

Site condition is one of the most important ground-motion parameters for engineering designs and is often characterized by a set of simplified parameters, such as site class based on site predominant period (Zhao et al. 2006a and 2006b), site class based on geological and geotechnical description of soil layers and site period (McVerry et al. 2006), and the average soil shear-wave velocity down to a depth of 30m (V_{S30}) used by many recent ground motion prediction equations (GMPE), including the Next Generation of Attenuation (NGA) models (Abrahamson and Silva 2008, Boore and Atkinson 2008, Campbell and Bozorgnia 2008 and Chiou and Youngs 2008). However, there are ample research articles that demonstrate the limitations and the breakdown when using V_{S30}, as reviewed by Catellaro et al. (2008). McVerry (2011) shows the improvement in the prediction for response spectra by using site period as the site parameter in a GMPE, and the inappropriateness of V_{S30} as a site parameter for New Zealand strong-motion recording stations. Site predominant period (referred to as "site period" hereafter) is considered as a better site parameter from theory and practice (Zhao et al. 2006a and 2006b, Catellaro et al. 2008, and McVerry 2011).

Most studies for assessing site parameters used a limited number of strong-motion records and the effect of the variability of the GMPE was often not fully accounted for. In the present study, two large sets of strong-motion records from Japan are used, and the large number of records allows very detailed assessment of the appropriateness of site period and V_{S30} as the site parameter in a GMPE. The borehole strong-motion records from Kik-net sites are also used because the amplification ratios between the surface and borehole records are less affected by the variability associated with source and path effect than GMPE results.

To assess whether site period and V_{S30} can be equally appropriate site parameters in a GMPE, it is important to examine the correlation between the V_{S30} and site period for a large number of strong-motion recording stations. If these two site parameters are highly correlated, either can be used as a site parameter. To make a simple comparison, $T_{VS30}=120/V_{S30}$ (unit for V_{S30} is m/s), the site period for a site where bedrock is reached at 30m depth, is used in the present study. Figure 1 shows the correlation of the two site

parameters, with the solid line being a function of site period for calculating T_{VS30}. The correlation is excellent for site periods up to about 0.4s. The standard deviation is 0.266 on a natural logarithm scale for all sites and 0.173 for sites with a site period of 0.4s or less, much less than the model prediction standard deviation of most GMPEs. The good correlation for short-period sites suggests that either site period or V_{S30} can be equally good site parameters for a GMPE. The scatter for sites with a natural period over 0.5s is considerable and may lead to different model predictions between the two site parameters. The important point is whether the large scatter in Figure 1 for long period sites can lead to statistically and practically different site amplification ratios and associated variability in a GMPE. The small standard deviation in the correlation between the two site parameters means that difference in the site effect between the two site parameters can be obscured by the large model prediction variability, typically 0.6-0.8, of a GMPE.
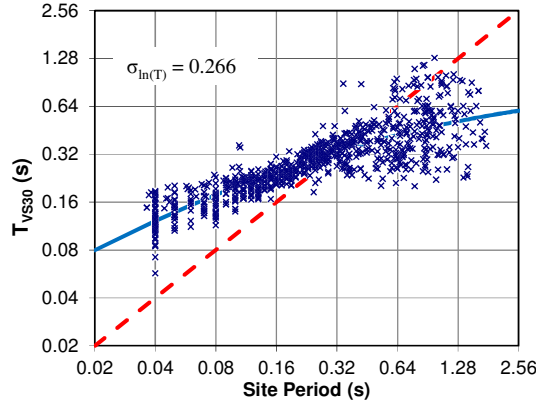

Figure 1   Correlation between site period and T_{VS30} for strong-motion recording stations in Japan. The site period for Kik-net sites is computed to the borehole depth, e.g. four times the shear-wave travel time to the borehole depth. For those sites with a site period less than 0.035s, the site period was set as 0.035s.

METHODOLOGY

The best way to assess the suitability of a site parameter, such as V_{S30} and/or site period, to represent site effects in a GMPE, is to use a large strong-motion dataset suitable for developing GMPE. We need to have not only all necessary earthquake parameters, but also the shear-wave velocity profiles of the recording stations, preferably measured values down to the depth of engineering bedrock. Records from the strong-motion network Kik-net, operated by the Institute of Earth Science and Disaster Prevention in Japan, and a small number of stations from the Port and Harbour Research Institute (PHRI) with the necessary site information, are assembled. Most Kik-net stations have a 3-component accelerometer at the surface and a 3-component accelerometer at the bottom of a borehole, and many boreholes reach engineering bedrock. Most stations have measured shear-wave and compression-wave velocities to the depth of the borehole accelerometer.

First, the response spectral amplification ratios between the surface and borehole records are used. These spectral amplification ratios differ from the response spectral amplification ratios between the ground surface record and a nearby rock site surface record, if the impedance ratio between the soil layer above the borehole accelerometer and the rock beneath the borehole accelerometer is not large, or the shear-wave velocity of the rock beneath the borehole accelerometer is not large. For site class (SC) I sites (Zhao 2006a), the amplification ratios derived from surface and borehole records for most stations are not relevant to the GMPE of Zhao et al. (2006a) and Zhao (2010). For SC II, III and IV sites, the amplification ratio derived from the surface and borehole records can be similar to the amplification ratios between these soil sites and seismological rock site, again if the borehole reaches the seismological bedrock. The amplification ratios between the surface and borehole records are always larger, on average, than the amplification ratios between a soil site and an SC I rock site (outcrop) as the effect of radiation damping (Zhao 1997) is excluded. However, if a particular site parameter models the amplification ratio between surface and borehole records very well, it should also characterize the response spectral ratios between the surface motion of a soil site and that of a nearby rock site very well. The suitability of a site parameter can also be checked by

$$A_{site}(T_{site}, T_{SP}) = \frac{A_{SB}(T_{site}, T_{SP})}{A_{SB}(T_{rock}, T_{SP})} \qquad (1)$$

where A_{site} is the amplification ratio for a soil site over a rock site, e.g., the amplification ratio in a GMPE, A_{SB} is the average amplification ratio between the surface and borehole response spectra, T_{site} is a site parameter, either site period or T_{VS30}, T_{SP} is spectral period, and T_{rock} is the site parameter for rock site, either site period or T_{VS30}, for a rock site in a GMPE.

The variability of the response spectral rations from a site with a borehole record is still too large to allow assessment of the suitability of a site parameter by comparing the spectral amplification ratios with theoretical results from simple models. Instead, an empirical method is used. The average amplification ratio is calculated for each site and a simple function of a site parameter, such as site period or T_{VS30}, is fitted to the average amplification ratio from all sites. The residuals between the average amplification ratio of a site and the value from the fitted equation are referred to as inter-site residuals. The residuals between the amplification ratio of each record and the average amplification ratio from all records at this particular site are referred to as intra-site residuals. The definition of inter-site residual is not strictly consistent with random effects methodology. A rigorous separation of residuals into the inter- and intra-site parts requires a random effects model to be fitted to the amplification ratios and the inter- and intra-site errors can be estimated simultaneously, but a rigorous model is not necessary for a preliminary study to assess the suitability of a site parameter. The standard deviation of the inter-site residuals is used to gauge the suitability of the site parameter. The conclusion may be reached by a simple statistical test, such as the *F-test,* between the two sets of inter-site residuals by using the site period or T_{VS30} on the hypothesis that the two sets of residuals have the same standard deviation. If the hypothesis is rejected at a significantly low probability, such as 5 or 10%, the site parameter that leads to the smaller standard deviation is assumed to be the better one. The comparison and the statistical tests will be carried out for all data and also the data grouped together according to the site classes used by Zhao et al. (2006a, 2006b) and Zhao (2010) based on site period. It is important to test the data in each site class, because a site parameter that appears to be better for all sites in one group may not be the better parameter for all site classes. The standard deviation of the intra-site residuals would represent the variability that contributes to the standard deviation of the amplification ratios in a particular site and should be similar to the variability in the amplification ratios from numerical simulation using simple site models in many studies).

The second approach is to model the site class terms plus the intra-event residuals as derived by the Zhao (2010, 2011) studies. Theoretically the inter-event residuals are associated with earthquake source parameters only, and will not be used in the present study. In a similar manner, a simple function of either site period or T_{VS30} is fitted to the average site class term plus intra-site residuals from each site, and the standard deviation of the inter-site residuals is used to gauge the suitability of the site parameter. Statistical tests are performed for all data in one group and for each group of sites according to their site classes.

STRONG-MOTION DATASET

Two sets of strong-motion records are used. The first dataset has 3018 pairs of strong-motion records, ground surface and borehole, obtained by the Kik-net stations from earthquakes for which moment magnitude, reliable focal depth and tectonic source types were available. The earthquakes have a moment-magnitude range of 4.9 – 9.5 and a focal depth up to 130km. The records are from 10 shallow crustal earthquakes, 31 subduction interface earthquakes and 54 subduction slab events. The source distance (the closest distance to the fault rupture model for large earthquakes and hypocentral distance for the others) is up to 300km and a magnitude-dependent cutoff distance is used to avoid the effect of un-triggered stations. 959 pairs of records are from SC I sites, 678 from SC II sites, 399 from SC III sites and 982 from SC IV sites. These records will be used for the analysis of the response spectral amplification ratios between the surface and the borehole accelerograms. The second dataset consists of 2014 records, many from the first dataset, including 669 records from SC I sites, 467 from SC II sites, 200 from SC III sites and 678 from SC IV sites, and the earthquakes have similar magnitude and focal depth range to those of the first dataset. All records are from ground surface stations and they have been used by Zhao (2010 and 2011) for deriving ground-motion prediction equations. The records are from 39 crustal earthquakes, 64 subduction-interface earthquakes and 37 subduction slab earthquakes. The records from a small number of stations in the strong-motion network of the Port and Harbour Research Institute (PHRI) and K-net stations were used. These stations have either a measured shear-wave velocity profile or their site periods (all from SC IV site class) can be estimated by H/V ratios with reasonable confidence by the method of Zhao et al. (2006b). The rest of the records in Zhao (2010 and 2011) are not used because the site periods of the recording stations are not available. The strong -motion records from the M_W=9 Tohoku 2011 event were used in both datasets.

ANALYSES OF KIK-NET RESPONSE SPECTRAL AMPLIFICATION RATIOS

Figure 2 shows the variation of peak ground acceleration (PGA) amplification ratios between the surface and borehole records with earthquake magnitude and source distance for SC I and SC II sites. The trend lines represent the magnitude- and source-distance dependence of the average amplification ratios in each site class. Clearly the PGA amplification ratio depends on earthquake magnitude and source distance, consistent with the results from numerical simulations by Zhao et al. (2009) and Zhao and Zhang (2010) using 1-D models. The amplification ratios tend to decrease with increasing magnitude and source distance for both site classes. The effect of magnitude on PGA amplification ratios appears to be similar for all data while the distance tends to have less effect on the PGA amplification ratios for the long-period sites than for short period sites. The scatter of the amplification ratios is very large. The amplification ratios for SC III and SC IV sites show similar dependence on earthquake magnitude and source distance, but are not presented here.
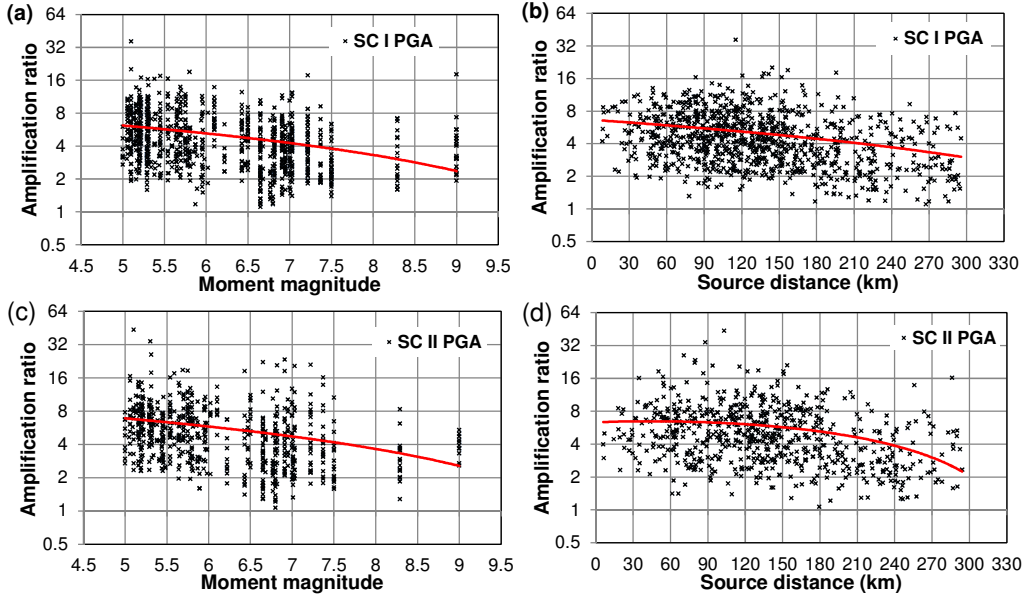
Figure 2   Variation of PGA amplification ratio between the Kik-net site surface and borehole records with respect to (a) magnitude, and (b) source distance for SC I sites, and (c) magnitude, and (d) source distance, for SC II sites
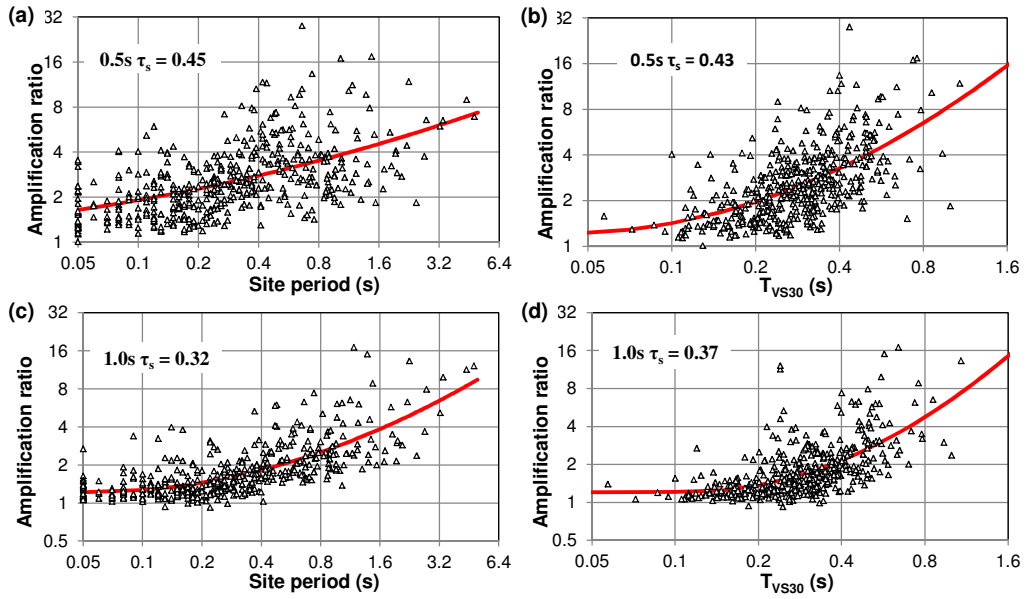

Figure 3   Amplification ratios between the Kik-net site surface and borehole records for 0.5s spectral period (top row) and 1.0s (bottom row). The left plots use site period as the site parameter and the right plots use T_{VS30}.

The average spectral amplification ratios are computed for each site, and for those sites that have a large number of records the effect of magnitude and source distance can be minimized by taking the average amplification ratio for all records in each site. A small number of stations have only one record, and the amplification ratio for this record is taken as the "average" ratio. Therefore, the average amplification ratios still contain, to a certain extent, the effect of earthquake magnitude and source distance. The following simple function of a site parameter T, is fitted to the site amplification ratios between the surface and borehole response spectra,

$$\ln[A_{SB}(T, T_{SP})] = a_{SB}(T_{SP})T + b_{SB}(T_{SP})\ln(T) + c_{SB}(T_{SP})[\ln(T)]^2 + d_{SB}(T_{SP}) \qquad (2)$$

where T is either the site period or T_{VS30}, T_{SP} is spectral period, and $a_{SB}(T_{SP})$, $b_{SB}(T_{SP})$, $c_{SB}(T_{SP})$ and $d_{SB}(T_{SP})$ are regression coefficients for a given value of T_{SP}. Only the terms with a statistically significant estimate will be used. The differences between the natural logarithm of the amplification ratios and those calculated from Equation (2) are then referred to as inter-site residuals for the simple model and their standard deviation is referred to as inter-site variability (τ_s). Figure 3 shows the amplification ratios for 0.5s (the top

tow) and 1.0s (the bottom row) spectral periods. The corresponding curves characterized by site period are in the left panel and T_{VS30} are in the right panel. For 0.5s spectral period, the standard deviation for the fitted equation is 0.45 when site period is used and 0.43 when T_{VS30} is used, suggesting that both parameters can be used to characterize the site effect equally well. For 1.0s spectral period, the standard deviation for the fitted equation is 0.32 for site period and 0.37 for T_{VS30}, suggesting that site period is slightly better than T_{VS30}. Figure 4 shows amplification ratios for 2.0s (the top tow) and 4.0s (the bottom row) spectral periods; the corresponding curves characterized by site period are in the left panel and by T_{VS30} are in the right panel. The scatter in the right panel is clearly larger than that in the left panel of Figure 4. For both spectral periods, the standard deviation for the fitted equation of site period is less than that for T_{VS30}, suggesting that site period is a better site parameter.
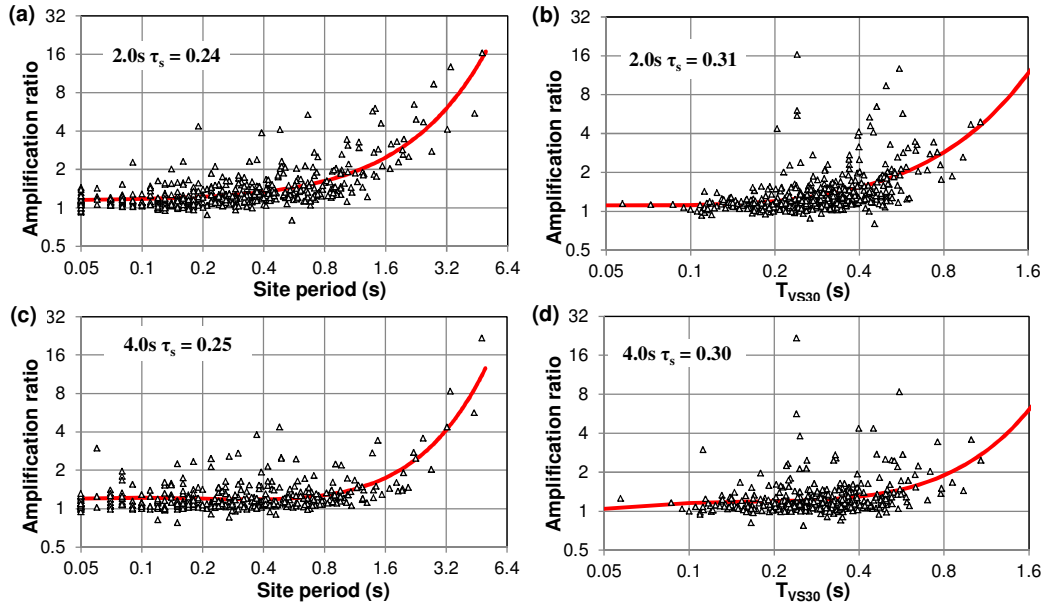

Figure 4   Amplification ratios between the Kik-net site surface and borehole records for 2.0s spectral period (the top row) and 4.0s for the bottom row. The left panel uses site period as the site parameter and the right panel uses T_{VS30}.
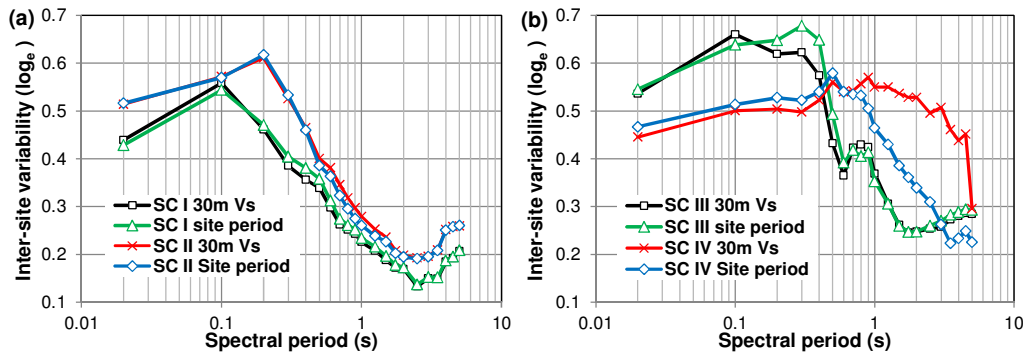

Figure 5   Comparison of inter-site variability derived by using site period and T_{VS30} for site classes I and II in (a) and site classes III and IV in (b), for the Kik-net site surface and borehole records

Figure 5 compares the inter-site standard deviations derived from Equation (1) by using T_{VS30} with those using site period as the site parameter, for four site classes. For three site classes, SC I (rock), SC II (hard soil), and SC III (intermediate soil), the standard deviations derived by using either site period or T_{VS30} are nearly identical for all spectral periods, although the inter-site standard deviation by using T_{VS30} is slightly smaller than that derived by using site periods for some spectral periods. For SC IV sites, the inter-site standard deviation using site period is slightly larger than that using T_{VS30} at short period but is much smaller than that using T_{VS30} at spectral periods over 1s, as shown in Figure 5(b). Figure 6(a) shows the inter-site standard deviation for all data. The standard deviation by using site period is similar to that using T_{VS30} at short period and is moderately smaller than that using T_{VS30} in a spectral period range of 1-4.5s. The probability of *F-test* on the hypothesis that the standard deviation by using site period is similar to that using T_{VS30} is less than 5% in a spectral period range of 0.9-4.5s, as shown in Figure 6(a), suggesting that site period is a statistically better site parameter than T_{VS30} in this period range. However, Figure 6(b) shows that the probability for the same hypothesis is less than 5% only for SC IV sites in the spectral period range of 1.25-5s and is less than 10% for spectral periods over 1s. These results

mean that the site period is a better site parameter than T_{VS30} for soft soil sites within a spectral period range of 1-5s. For other site classes and spectral period bands used in the present study, T_{VS30} and site period work equally well.
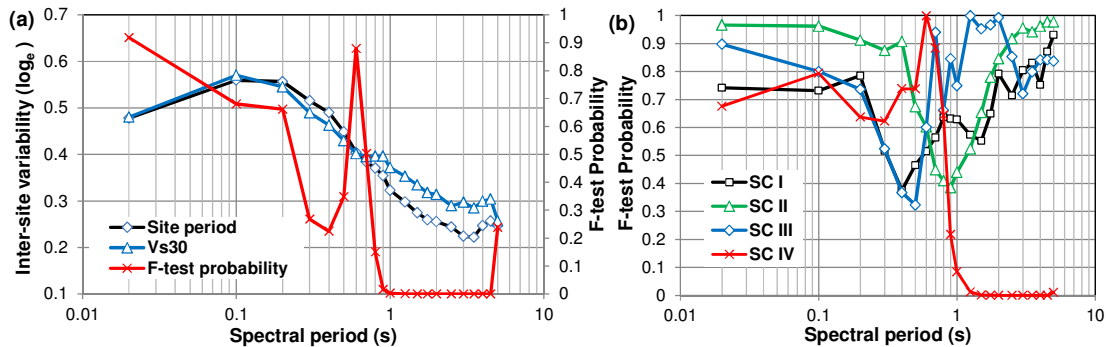

Figure 6   Probability from *F-test* for the inter-site residuals by using site period and T_{VS30}, (a) all data and (b) each site class for the Kik-net site surface and borehole records
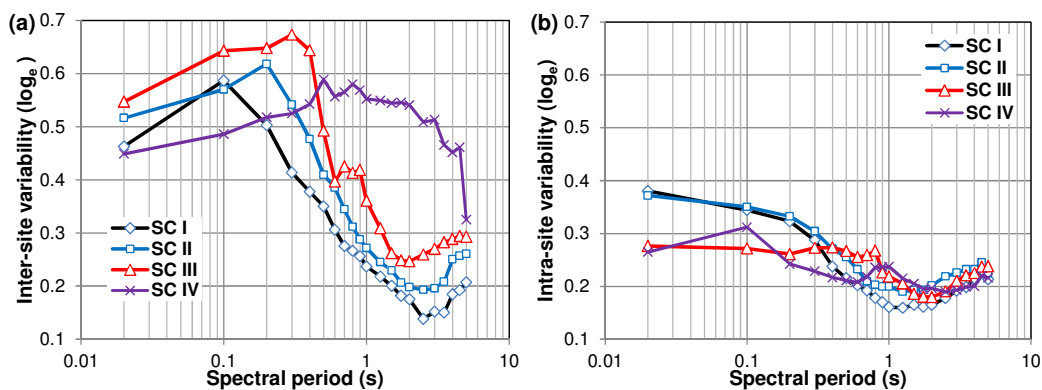

Figure 7   Inter-site variability in (a) and intra-site variability in (b) for response spectra amplification ratios, assuming constant amplification ratios in each site class for the Kik-net site surface and borehole records.

A hypothesis that statistically similar models in terms of model standard deviation can be derived by using site class or site period is also tested, and the results show that the probability for accepting this hypothesis is less than 10% for periods over 1.0s and less than 5% for periods over 1.25s for the soft soil site class (SC IV) only. This means that using site period as a site parameter can reduce the model standard deviation for soft soil sites but not for rock, hard soil and medium soil site class. However, using site period will avoid the step function of design response spectra for these site classes, as shown by McVerry (2011).

Alternative inter-site residuals can be defined as the differences between those of each record and the average amplification ratios in each site class. Figure 7(a) shows the standard deviation of inter-site variability assuming constant amplification ratio within each site class. For the first 3 site classes, SC I, II and III, the inter-site standard deviations for all spectral periods tend to increase with increasing site class, while for SC IV sites the inter-site standard deviations at short periods are smaller than those for the other three site classes but become much larger at long spectral periods. The standard deviations for the intra-site residuals in Figure 7(b) are generally much smaller than those of the inter-site residuals at short periods but they are similar at long periods for rock and stiff soil class sites (SC I and SC II). The intra-site residuals exclude the single-record sites for which the intra-site residuals are zero. For soft soil sites (SC IV) the standard deviation for intra-site residuals is much less than that for inter-event residuals at all spectral periods. The small intra-site standard deviation derived from the present study is probably one of the reasons why the standard deviation from the strong-motion records obtained at a particular site would be considerably smaller than that in the regional GMPE, as reported by Atkinson (2006).

ANALYSIS OF RESIDUALS FROM GROUND MOTION PREDICTION EQUATIONS

The analysis of a subset of the data in the Zhao (2010 and 2011) studies is presented next. All records are from a group of sites with reasonably well estimated site periods. The site class terms from the GMPEs of Zhao (2010, 2011) plus the intra-event residuals, that contain the variability from both site and path effects, are presented in Figure 8 for SC I and SC II class sites. The site class terms plus intra-event errors depend on magnitude and source distance for PGAs from SC I sites and SC IV sites (not presented here), while they

depend neither on magnitude nor on distance from SC II and SC III (not presented here) sites. The amplification ratios between any soil sites with respect to SC I class sites depend on magnitude and source distance because of the magnitude- and source-distance-dependent site terms plus intra-event residuals for the SC I sites. Note that average values of the site class terms plus intra-event residuals are not zero.
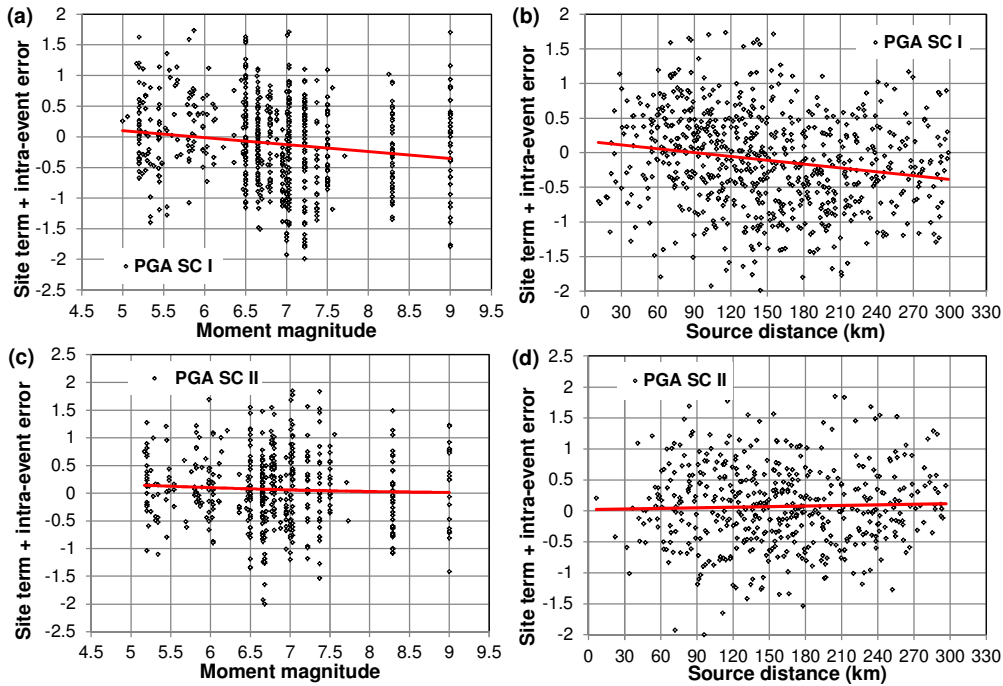

Figure 8   Variation of site class term plus the intra-event residuals for PGA from GMPE (Zhao 2010 and 2011) with respect to magnitude (left panel) and source distance (right panel). The top row is for SC I sites and the bottom row is for SC II
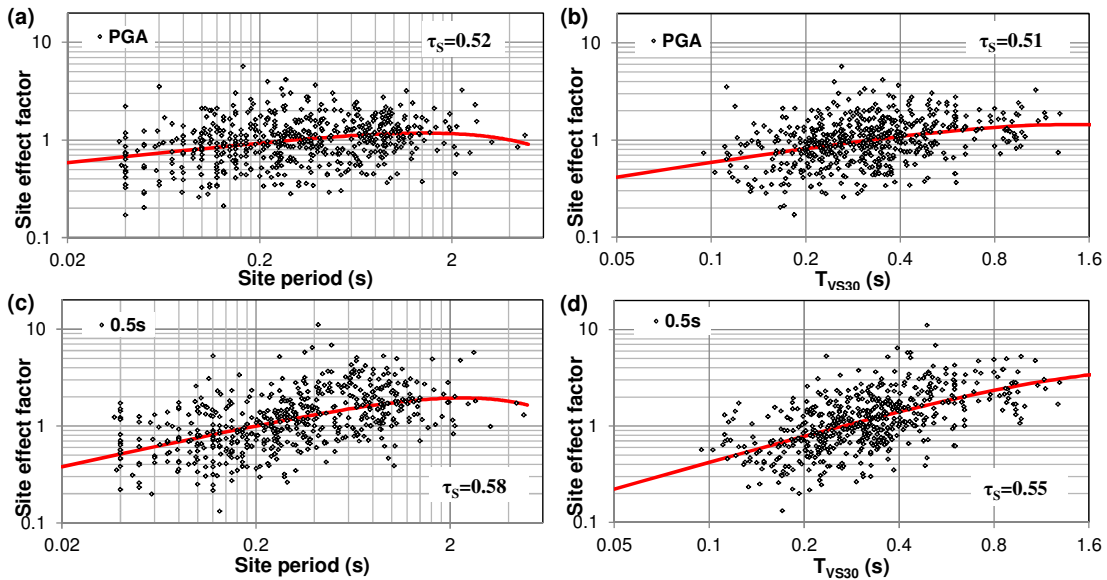

Figure 9   Site effect factor for each site and the simple functions fitted to the site effect factor using site period as the site parameter in the left panel and T_{VS30} in the right panel. The top row is for PGA and bottom row is for 0.5s spectral period.

Again, the average value of the site class terms plus intra-event residuals for each site is used so as to minimize the error associated with path effect. The exponential of the site class term plus intra-event residuals is referred to as the site effect factor. When the site has only one record, the site effect factor for this record is then taken as the "average" value for this particular site. The following

simple function of either site period or T_{VS30} is fitted to the average values.

$$\ln[B_{site}(T, T_{SP})] = a_{site}(T_{SP})T + b_{site}(T_{SP})\ln(T) + c_{site}(T_{SP})[\ln(T)]^2 + d_{site}(T_{SP}) \quad (3)$$

where B_{site} is the site effect factor, e.g., the number that is used to multiply the spectrum derived from a base model excluding the site effect so as to compute the spectrum for this particular site condition, and a_{site}, b_{site}, c_{site} and d_{site} are regression coefficients. The variability associated with the fitted empirical site model is again referred to as the inter-site variability. Figure 9 shows the average values for the site effect factor from the Zhao (2010 and 2011) studies in each site and values computed from Equation (3) for PGA and spectral accelerations at 0.5s, and Figure 10 shows the results for 4s period. The standard deviations for the empirical models described by Equation (3) by using site period or T_{VS30} are very similar with the T_{VS30} producing a slightly smaller standard deviation for PGA and 0.5s period. The standard deviations for 1.0s and 2.0s spectral periods are very similar between the two site parameters. This is also the case for 4s spectral period as shown in Figure 10.
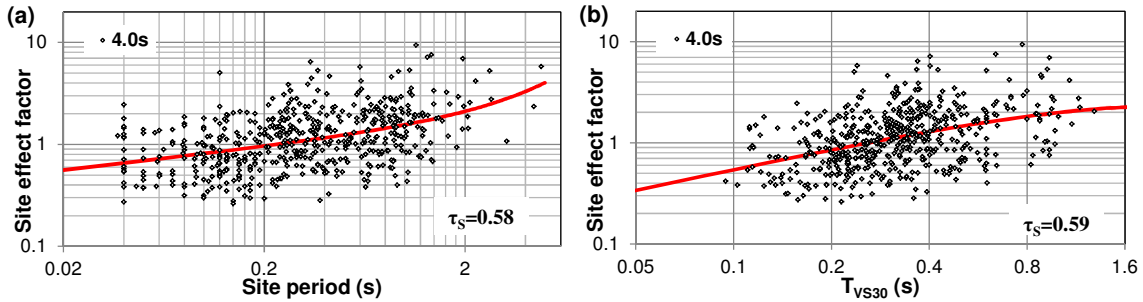

Figure 10   Site effect factor for 4s spectral period and the simple functions fitted to the site effect term using site period as the site parameter in (a) and T_{VS30} as the site parameter in (b).
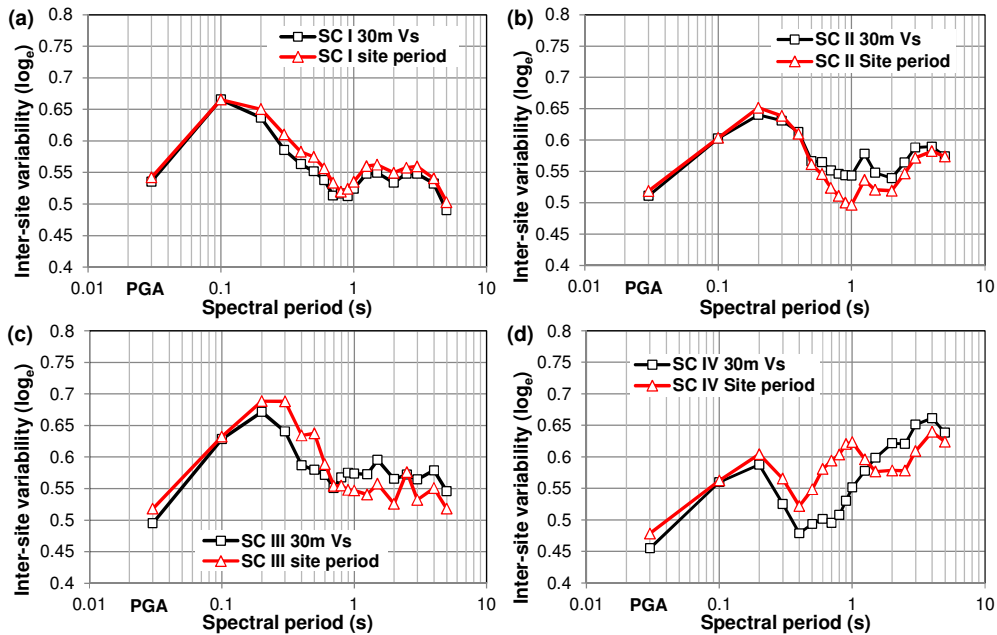

Figure 11   Comparison between the inter-site variability modelled by using T_{VS30} and site period as site parameters, (a) for SC I, (b) SC II, (c) SC III and (d) SC IV recording stations

Figure 11 compares the inter-site standard deviations derived from using site period or T_{VS30}. For SC I sites, the standard deviations from using site periods and T_{VS30} are very similar for most spectral periods. T_{VS30} leads to a slightly smaller standard deviation than site period, as shown in Figure 11(a). Figure 11(b) shows that, for SC II sites, site period leads to a smaller standard deviation in a spectral period range 0.8-3s, than T_{VS30}, and both site parameters lead to very similar standard deviations for other spectral periods. For SC III sites, Figure 11(c) shows that, at periods up to 0.6s, site period leads to slightly larger standard deviation than T_{VS30}, but leads to smaller standard deviations at a number of other periods. However, for SC IV sites, site period actually leads to a sizable increase in the inter-site standard deviations between spectral periods 0.3 and 1.0s compared with those using T_{VS30}, while site period leads to smaller standard deviations at spectral periods over 1.2s than T_{VS30}. The probability of *F-test* on a hypothesis that the inter-site

residuals have statistically similar standard deviations is less than 10% in a period range of 0.6-0.9s, where the site period actually performs worse than T_{VS30} does.

COMPARISON OF AMPLIFICATION RATIOS PREDICTED BY USING T_{VS30} AND SITE PERIOD

It is well known that even using appropriate site modelling parameters in GMPEs does not usually lead to significant reduction in the model standard deviations. However, the appropriate site modelling can lead to appropriate spectral shapes that are consistent with the definition of site classes. Zhao et al. (2006b) showed (in their Figure 13) that using the spectral amplification ratios for the spectra from SC II, SC III and SC IV site classes over SC I class, derived from GMPEs using site class based on predominant site period, leads to much more consistent amplification ratios than using the site classes based on geological and geotechnical description. Fukushima et al. (2003) found that using site classes based on site period for the European data led to little reduction in regression standard deviation but produced "better" spectral shape. A recent study (Di Alessandro et al. 2011) also found similar results. These results mean that achieving a consistent spectral shape is an important reason for using appropriate site parameters.
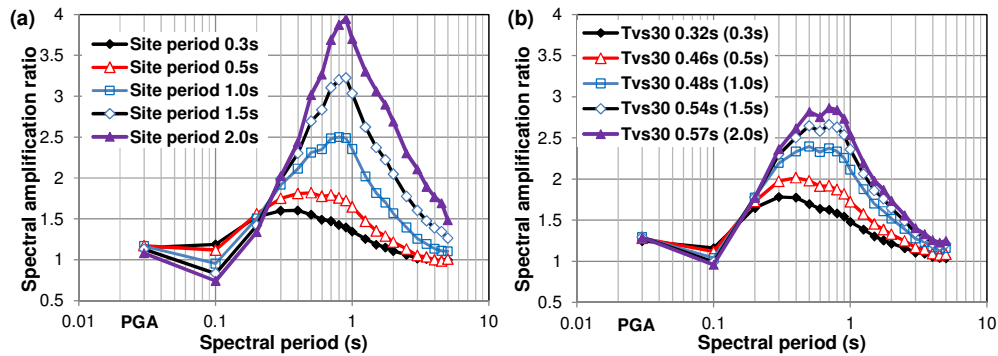

Figure 12   Spectral amplification ratios between a site with site periods or T_{VS30} of 0.3s, 0.5s, 1.0s, 1.5s, 2.0s and a site with a 0.1s period or T_{VS30}=0.2s derived by (a) using site period and (b) using T_{VS30}. The values for T_{VS30} are derived using the solid line in Figure 1 using the site periods in the brackets in (b).

Figure 12 shows the amplification ratio derived by using site period in Figure 12(a) or T_{VS30} in Figure 12(b) for sites with site periods or T_{VS30} of 0.32s, 0.46s, 0.48s, 0.54s and 0.57s relative to a site with a site period of 0.1s or T_{VS30}=0.2s. These values of T_{VS30} are derived from the correlation relationship represented by the solid line in Figure 1. These amplification ratios were computed from Equation (1) from the Kik-net strong-motion records. The site amplification ratios in Figure 12(a) have amplitudes generally similar, but not identical, to those presented by Zhao et al. (2006a) in their Figure 6(a) and Figure 13 in Zhao et al. (2006b). Figure 12(a) also shows that amplification ratios at spectral periods over 0.5s increase with increasing site periods when site period is used as the site parameter. For sites with a site period of 1s or shorter, the amplification ratios derived by using site period or T_{VS30} (Figure 12b) are comparable. However, for long period sites, the amplification ratios derived from T_{VS30} are much smaller than those using site periods, suggesting that T_{VS30} may not be an appropriate site parameter for a GMPE.

The results presented in Figure 12 suggest that peak response spectral amplification ratios for long period sites no longer occur at the site period, but tend to occur at a considerably shorter spectral period. This aspect will be investigated in the next section using a 1-D equivalent linear analysis.

BREAKDOWN OF SITE PERIOD AS A SITE PARAMETER TO MODEL SITE EFFECT

For response spectral amplification ratios, site period does not always work well as the sole site parameter to model site effects, because the peak amplification does not always occur at the site period. Two examples are presented here. For a very deep soil site with the shear-wave velocity profile presented in Table 1, the site has a soft soil layer with a thickness of 19.8m and a shear-wave velocity of 184.6m/s, overlying a thin layer of 1.2m thick with a shear-wave velocity of 300m/s. Underneath the soft soil layers, a 279m thick layer of stiff soil (layer 3) with a shear-wave velocity of 545m/s overlays another 250m thick gravel layer with a shear-wave velocity of 800m/s. The site period is 3.74s for four layers and T_{VS30} is 0.51s. Four times the shear-wave travel time in the soft soil layers (layer 1 and 2) is 0.44s which is referred to as T_{2L}. SHAKE91, an equivalent linear soil site modelling computer code, was used to analyse this 1-D soil site model. A set of shear-modulus reduction curves and damping ratio curves for sand and dense sand were used for the top 3 layers, and the 4th layer was modelled as soft rock with appropriate shear modulus reduction and damping ratio curves. The site is subjected to two sets of synthetic seismograms, one with a peak ground acceleration (PGA) of 0.018g (the geometric mean of the two horizontal components) for weak motion (with minor soil nonlinear response) and the other with a PGA of

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0.27g that leads to significant nonlinear soil response. Three values of shear-wave velocity for the bedrock were used to examine the sensitivity of the impedance ratios between the soil layer and the bedrock.

Table 1 Site parameters

Layer No.	1	2	3	4
Depth at the bottom of soil layer (m)	19.8	21.0	300.0	550.0
Layer thickness (m)	19.8	1.2	279.0	250.0
Shear wave velocity (m/s)	184.6	300.0	545.0	800.0
Shear wave travel time (s)	0.107	0.004	0.513	0.313

Figure 13(a) shows a prominent feature of the amplification ratios for weak motion (this would be the case for most strong-motion records used to develop a GMPE): the largest amplification ratio does not occur at the site period for all three impedance ratios, but instead two dominant amplification ratios appear at 0.44s and 0.77s respectively, which are quite close to T_{VS30} and also to T_{2L}. This means that T_{VS30} and T_{2L} are in fact better site parameters for the modelling of site effect in a GMPE than site period for this particular case. When the site is subjected to strong excitation, the dominant peak amplification ratios at periods less than 1s are reduced significantly and the peak application ratio is at 1.2s, still much shorter than the site period.
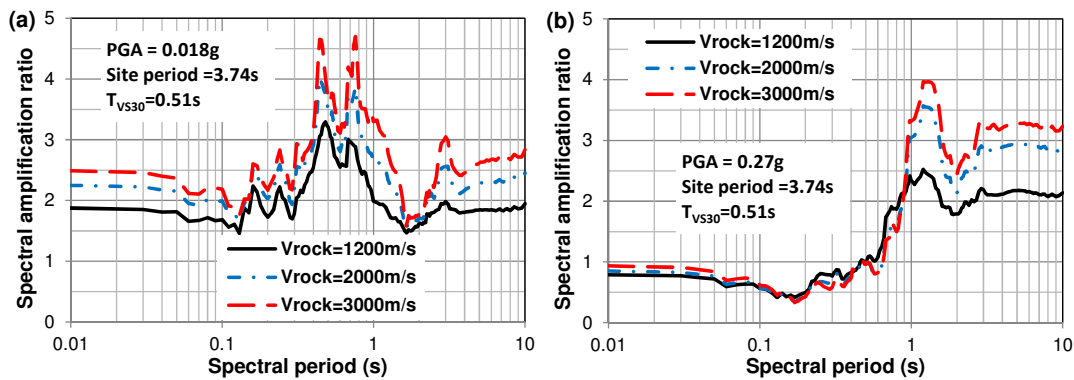

Figure 13   Amplification ratios of a deep soil site with a site period of 3.74s and a T_{VS30} of 0.51s. The site was analysed by 1-D equivalent linear model using SHAKE91, subjected to (a) weak rock motion, and (b) moderately strong rock motion

The second site has a shear-wave velocity profile as described in Table 2 and the amplification ratios under the same earthquake excitation are presented in Figure 14. The site period for this site is also 3.74s, the same as the first example, and the T_{VS30} is 0.61s. The period of the top layer over the stiff soil layer (four times the shear-wave travel time within the first layer) T_L is 1.08s. Figure 14(a) shows that the peak response spectral amplification ratio does not occur at the site period and, neither, of course, at the T_{VS30}. Rather, the peak amplification ratio occurs at about 1.3s spectral period, reasonably close to T_L for all impedance ratios between the bottom layer and the bedrock as shown in Figure 14(a). Clearly, the large impedance ratio between the top and the second layer may suggest that T_L is an "appropriate" site parameter while the site period and T_{VS30} are not. For strong excitation that leads to significant nonlinear soil response, the peak amplification ratios occur at a spectral period range of 1-2s, much greater than T_{VS30} and far shorter than the site period.

Table 2 Site parameters

Layer No.	1	2
Depth at the bottom of soil layer (m)	50	412
Layer thickness (m)	50	362
Shear wave velocity (m/s)	184.6	545.0
Shear wave travel time (s)	0.277	0.66

The reason for the breakdown of site period as a site parameter (i.e. the peak amplification ratio is no longer at the site period) may be the impact of radiation damping. Zhao (1997) shows that the radiation damping ratio is most effective in reducing site amplification ratio for the first mode and the effect decreases rapidly with increasing frequency, while the effect of material damping (including viscous damping and the energy dissipated by nonlinear soil response) is to reduce the amplification ratio most strongly at high

frequencies compared with radiation damping. The combined effects from the two damping mechanisms may lead to a peak amplification period that is much shorter than the site natural period.
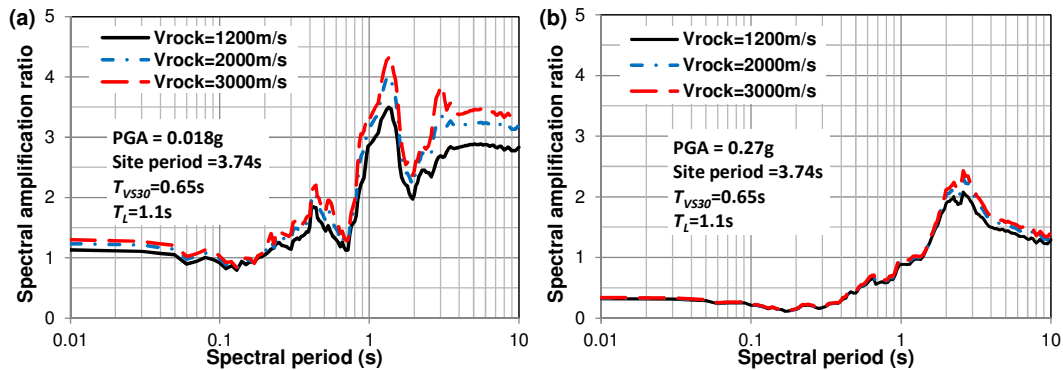

Figure 14   Amplification ratios of a deep soil site with a site period of 3.74s and a T_{VS30} of 0.65s. The site is modelled by 1-D equivalent linear model using SHAKE91, subjected to (a) weak rock motion, and (b) moderately strong rock motion

Without a rigorous investigation, it appears that the period of peak amplification ratio for a long period site can be considerably shorter than the site period, which therefore may not be the most "ideal" or "appropriate" site parameter for modelling site effect in a GMPE. The "alternative site period", computed to the depth where soil shear-wave velocity is significantly larger than the overriding soil layers, may be a possible alternative to the site period for long period sites.

CONCLUSIONS

The following conclusions can be reached in the present study:
1) The correlation between site period (four times the travel time of shear-wave velocity in the soil layers) and T_{VS30}, $120/V_{S30}$ (the average shear-wave velocity to a depth of 30m with a unit of m/s), is excellent for sites with a site period less than about 0.4s. This means that for short period sites, both V_{S30} and site period can be used as the site parameter to model the response spectral amplification ratios. Over about 0.5s, the variability in correlation between T_{VS30} and site period is considerable;
2) The modelling of response spectral amplification ratios between the surface and borehole records from Kik-net stations suggests that response spectral amplification ratios strongly depend on earthquake magnitude and source distance, consistent with the results of Zhao et al. (2009) and Zhao and Zhang (2010);
3) The standard deviation for inter-site errors, the difference between average residuals for each site and the empirical model used to estimate response spectral amplification ratios of the Kik-site data, are in a range of 0.1-0.6 in the natural logarithm scale. The larger value is associated with short spectral periods and the smaller value with long spectral periods;
4) The standard deviation of the intra-site errors that represents the variation of amplification ratios from different records in each station is much smaller than the standard deviation of inter-site residuals at short spectral periods but similar at long periods;
5) In terms of standard deviation for inter-site errors, site period is a better site parameter for modelling amplification ratios than V_{S30} for sites with predominant periods over 0.6s for Kik-net data. The variability of amplification ratios derived using site period or V_{S30} are statistically similar for sites with short and medium periods;
6) The site effect, the site class term plus the intra-event residuals from a ground-motion prediction equation (GMPE) derived by Zhao (2010 and 2011) also strongly depend on earthquake magnitude and source distance;
7) The standard deviations of inter-site error from the empirical model for site effect by using site period or V_{S30} are statistically similar except for long spectral periods for sites with a long period. Site period improves the site effect modelling at long spectral period only for long period sites;
8) For soil sites with a long period over about 1s, peak amplification ratios for both Kik-net records and a sub-dataset from the GMPE of Zhao (2010 and 2011) do not occur at site period, but at a considerably shorter period;
9) Theoretical modelling suggests that the shift of peak amplification period from the site period to shorter periods may be caused by material damping and radiation damping; and
10) The limited modelling results suggest that the site period computed for soil layers down to a depth where there is a significant shear-wave velocity increase, for example from 200m/s to 550m/s, may be a better site parameter than either site period, that is computed for all soil layers down to engineering bedrock, or V_{S30}.

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