Impact of site classification on deriving empirical ground-motion prediction equations: application to the west Eurasia dataset

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RÉSUMÉ. *Dans ce travail, nous avons classifié les sites en utilisant la période dominante à partir du rapport spectral moyen (H/V) des spectres de réponse et nous avons examiné l'impact de cette classification sur le calcul des modèles empiriques de prédiction du mouvement sismique. Cette procédure a été appliquée à la base de données compilée par Fukushima et al. (2003) dont les sites ont été classés comme étant au rocher ou au sédiment. En appliquant cette technique, les sites sur des sols mous ont clairement été identifiés. Avec cette nouvelle classification nous avons calculé des équations de prédiction empirique du mouvement sismique. La variabilité aléatoire de ces équations (mesurée par leur écart type) est légèrement inférieure à celle obtenue en utilisant une classification au rocher et au sédiment seulement. Cependant, l'effet le plus important est sur le spectre de réponse prédit, qui est très différent de celui calculé avec les deux classes rocher/sédiment. Les spectres prédits avec cette nouvelle classification montrent une différence importante entre sites mous, raides et rocheux.*

ABSTRACT. *We classify sites based on their predominant period computed using average horizontal-to-vertical (H/V) response spectral ratios and examine the impact of this classification scheme on empirical ground-motion models. We apply this classification scheme to the database of Fukushima et al. (2003), for which stations were originally classified as simply rock or soil. The calculation of average H/V response spectral ratios permits the majority of sites in the database to be unambiguously classified. Soft soil conditions are clearly apparent using this technique. Ground-motion prediction equations are then computed using this alternative classification scheme. The aleatoric variability of these equations (measured by their standard deviations) is slightly lower than those derived using only soil and rock classes. However, perhaps more importantly, predicted response spectra are radically different to those predicted using the soil/rock classification. In addition, since the H/V response spectral ratios were used to classify stations the predicted spectra for different sites show clear separation.*

MOTS-CLÉS : *H/V, rapport des spectres de réponse, classification de site, lois d'atténuation, période prédominante.*

KEYWORDS: *H/V, response spectral ratio, site classification, attenuation relation, predominant period.*

1. Introduction

It is well known that precise site classification is important in determining accurate empirical ground-motion prediction relations. However, possessing a good knowledge of site conditions is rather exceptional. Even well characterized sites do not always have complete geotechnical information down to the bedrock. For

example in Japan, the surface array K-net has geotechnical characterization down to a maximum depth of 20 m. Thankfully, its complementary borehole array KiK-net, has information down to 100 or 200 m depth depending on the site. This important, but expensive, information is almost non-existent for most strong-motion networks in the world, and Europe is not an exception. Some previous European empirical ground motion prediction relations (e.g. Fukushima et al., 2003) used a general rock/soil classification scheme due to this lack of detailed site information. This site classification, based mainly on geological information, came with the strong-motion data provided by the data contributing agencies. A general soil class, however, may contain both stiff and soft soils, and a general rock class may include sites with weathered rock or thin soil layers at the surface and hard bedrock stations. In addition, the difference between predicted ground motions at soil and rock stations computed by these relations is not remarkable, being less than 70% (Fukushima et al., 2003). Therefore, a better site classification is required for precise strong ground motion estimation.

In particular situations, an approximation of the theoretical site amplification can be computed using 1D multiple reflection theory. Yet, the cost of deep boring, down to the bedrock, at all sites is unrealistic. In the USA, average shear-wave velocity in the first 30 m, here after called Vs30, is used as an alternative parameter to classify soil conditions (Table 1). This parameter provides more information than surface geological data since impedance contrast at least down to this depth is reflected in the site classification. However, the transfer function should not be limited to the first 30m; on the contrary, it should be continued down to bedrock.

Site classes	Site natural period (s)	Average shear-wave velocity	NEHRP class
SC-I	$T_G < 0.2s$	$V_{s30} > 600$ m/s	A+B
SC-II	$0.2s \leq T_G < 0.4s$	300 m/s $\leq V_{s30} < 600$ m/s	C
SC-III	$0.4s \leq T_G < 0.6s$	200 m/s $\leq V_{s30} < 300$ m/s	D
SC-IV	$0.6s \leq T_G$	$V_{s30} < 200$ m/s	E

Table 1. *Site class definition used in Japan for engineering design practice (Japan Road Association 1980 and 1990) and the approximate correspondence with NEHRP site classes (BSSC, 2000). T_G of K-net station is simply estimated by T_G =4H/Vs, where H is thickness of upper layer than rock or stiff soil in m, and Vs is average S wave velocity of the layer in m/s.*

An alternative, but less well-known, site classification scheme originally proposed by Kanai and Tanaka (1961) is based on the site's predominant period. This is used in Japan for the seismic design code of highway bridges (Japan Road Association 1980, 1990), and it is also given in Table 1. This classification does not exactly correspond to the Vs30 scheme, but it represents a combination between Vs and the thickness of soil layers. One advantage of this classification is that deep geological profiles and high shear-wave velocities are mapped to the resonance frequency. A recent study using Japan data (Zhao et al., 2006) proposed four site categories using this method. These authors used this site classification rather than the traditional description based on Vs30 because thick stiff soil layers overlying hard rock amplify long-period motions. Conversely, thin soft soil layers amplify short periods. This means that Vs30 does not always capture the predominant period of the site, since it represents only the shallowest portion of the geological profile. Using a classification scheme based on predominant period presents two advantages. The first one is that strong-motion prediction will account for the entire site frequency content and not only shallow geological effects. In addition, at many sites easily available direct field measurements can be performed to estimate the site predominant period using either ambient noise measurements or H/V spectral ratios on earthquake data. Furthermore, when computing empirical ground-motion prediction relations, Lussou et al. (2001) showed that, for K-net data, site classification by a combination of Vs30 and H/V predominant period reduced the standard deviation of the computed equation. Zhao et al. (2006) classified K-net sites using average H/V response spectral ratios and obtained a relation that well modelled local site effects and also reduced the model's uncertainty. This

procedure potentially has application to data classified into general categories such as rock or soil, or that use no classification at all.

In the present study, we use the H/V response spectral ratio, which was proposed by Zhao et al. (2006), to attempt a site classification based on predominant period. It is not the objective of this paper to derive new empirical ground-motion estimation equations. We rather focus on the site classification procedure, its shortcomings and its general impact on the shape of the predicted response spectra. The data of Fukushima et al. (2003), which mainly comes from west Eurasia but with some near-source Californian and Japanese (Kobe) data, is used. The number of events considered in this study is 50 recorded at 341 strong-motion stations. The data ranges are, for distance, 0.5 to 235 km and, for magnitude, 5.5 and 7.4.

2. Site classification

Zhao et al. (2006) classified their sites according to the predominant period computed using the H/V response spectral ratio. They used the 5% damping response spectra ratio between the horizontal and vertical components as an approximation for smoothed Fourier spectral ratios. Their reasoning was that the response spectra are closer to engineering needs than Fourier spectra. Moreover, individual site H/V amplitudes are not important, but the predominant period is. In this way, they proposed four site categories for Japan.

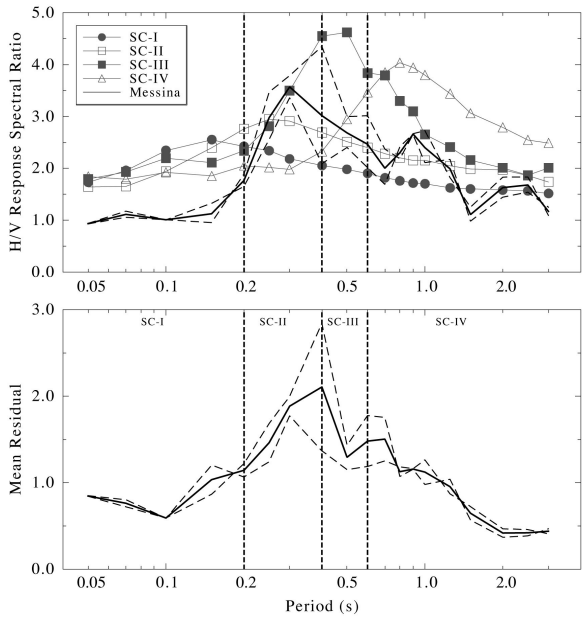


Figure 1. *Average H/V response spectral ratios for the Messina station in Italy (top) showing, for comparison, the results for the four Japanese four site classes. Mean residuals between observed and predicted response spectra from the Fukushima et al. (2003) model (bottom). In both plots, estimates for both components are shown (these are assumed to be independent).*

Following the same procedure in this article, only records having three components (two horizontal and one vertical) were used to compute the H/V response spectral ratio. In the present study, average H/V response spectral ratios were used to classify stations, and in this regard, the two horizontal components were considered individually. Mean residuals between observed and predicted response spectra from the equations of Fukushima et al. (2003) were subsequently inspected, since analysis of residuals proved to be useful when the observed response spectra showed amplification with respect to the predicted accelerations. A first attempt was made to classify the sites according to the Japanese soil classification. Figure 1 shows an example of H/V response spectral ratios (top) and residuals (bottom) (for the Messina station in Italy). The Japanese H/V response

spectral ratios from Zhao et al. (2006) are also plotted. This station is actually classified as a rock site in the original database of Fukushima et al. (2003). However, a peak around 0.3s is observed on the H/V plot as well as a remarkable amplification in the residuals near 0.4s. This station could then be classified as SC-II according to the Japanese spectral shapes.

Classification is, however, not always straightforward. The observed H/V response spectral ratio may not present a peak, but rather a broadband behaviour as shown in Figure 2 for the San Francisco Airport station. This site is located on soft ground (McGarr et al., 1991), therefore, complex soil amplification could be expected, such as nonlinear behaviour, and the current site classification does not account for such soil behaviour making this station impossible to classify. For stations that recorded the Kobe earthquake in Japan, the first author had a priori geotechnical information. However, in order to have a homogeneous procedure, all stations were classified as if only the H/V information was known. Since few (roughly 30%) stations have multiple records the average H/V response spectral ratio per site is not statistically robust and thus the automatic classification of Zhao et al. (2006) cannot be used. Therefore here, all sites were manually classified.

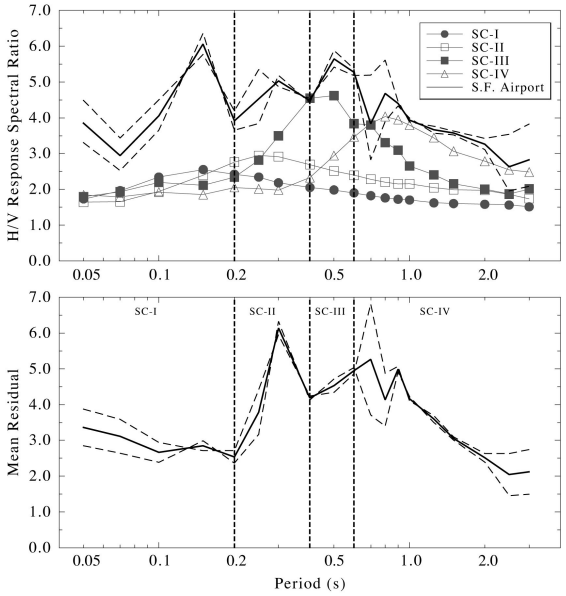


Figure 2. *Same as Figure 1, but for station at San Francisco Airport in the USA. Note the broadband site response. This kind of behaviour is not taken into account in the Japanese site classification; therefore the site cannot be classified.*

During the classification procedure, each co-author independently provided their opinion. It became apparent that the frequency band for soil class SC-III is too narrow, and for all purposes inapplicable. Therefore, we decided to combine SC-II and SC-III into a single class for our study. The final site categories are SC-1 (SC-I), SC-2 (SC-II plus SC-III), and SC-3 (SC-IV), respectively. Finally, those sites that could not be classified maintained their original denomination of rock (SC-4) and soil (SC-5), respectively (Table 2). These last two classes, however, are only retained so as to have enough data to compute ground-motion prediction equations.

Once the definitions of the site classes were finalized, each co-author manually classified each station. For roughly 90% of the stations, the classifications agreed with each other. Different classifications were made for stations close to the limits of the site classes. When opinions differed, stations were re-classified after further discussion. Final statistics of the classification are summarized in Table 3, which shows the number of stations that switched from original rock and soil categories to the new classes based on predominant period. Note that

sites originally classified as rock were reclassified into all three new categories, SC-2 being the more common. Similarly, the original soil category was composed of a combination of all three new types of sites; in this case, SC-2 and SC-3 classes are most represented. Note that we were able to classify 47 sites out of 91 rock sites and 171 sites out of 250 soil sites using the procedure (64% in total).

Site classes	Site natural period (s)	Average shear wave velocity	NEHRP class
SC-1	$T_G < 0.2s$	$V_{s30} > 600$ m/s	A+B
SC-2	$0.2s \leq T_G < 0.6s$	$200 \text{ m/s} \leq V_{s30} < 600$ m/s	C+D
SC-3	$0.6s \leq T_G$	$V_{s30} \leq 200$ m/s	E
SC-4	Unknown	$V_{s30} > 800$ m/s	A+B
SC-5	Unknown	$300 \text{ m/s} \leq V_{s30} < 800$ m/s	C

Table 2. *Site class definition used in this study and the approximate correspondence with NEHRP site classes (BSSC 2000). SC-4 and SC-5 are general rock and soil classes that were impossible to classify using the new procedure.*

Following Zhao et al. (2006), we computed the mean H/V response spectral ratio and its standard deviation for each site class (Figure 3). Note the remarkable similarity between the Japanese H/V averages and those derived here. It should be noted that less than 4% of Japanese stations belong to soil class SC-III (Zhao et al., 2006) suggesting that class SC-2 closely corresponds to class SC-II in Japan because, as noted above, SC-III was found to be too narrow, here, to use for classification of stations (i.e. very few stations fell within this category). With respect to the standard deviations, the ones computed in this study show less variation with respect to period than those of Zhao et al. (2006); however, their absolute levels are similar. This is rather surprising considering the fewer records used in this study compared to those used by Zhao et al. (2006).

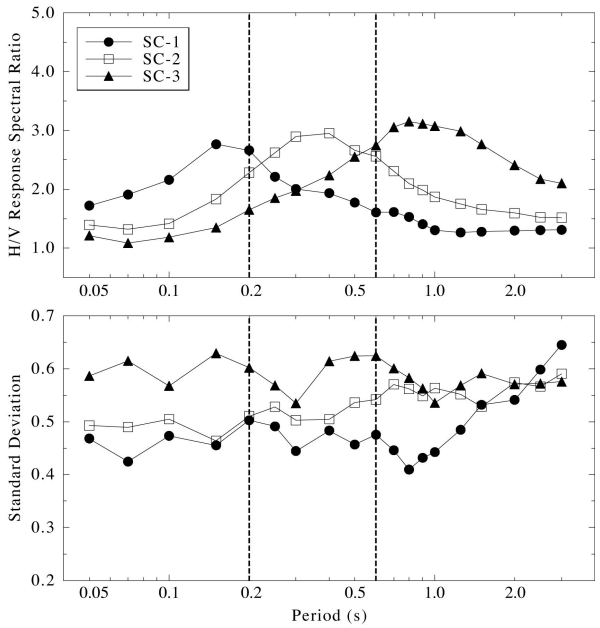


Figure 3. *Average H/V response spectral ratios (top) and standard deviations based on spectral ratios in natural logarithms (bottom) for the site classes used in this study.*

3. Results

Ground-motion prediction equations are derived using the functional form and regression method of Fukushima et al. (2003). Recall that we do not seek to derive a new ground-motion model for use in seismic hazard assessment. Therefore, we limit ourselves to commenting on the effect of the new site classification on: the derived site coefficients, the standard deviations of the model, and predicted response spectra. Data were band-pass filtered with cut-offs of 0.25 and 25Hz (Fukushima et al., 2003), therefore results are shown up to 3 s.

3.1. *Site coefficients*

Figure 4 shows the relative amplification of site classes SC-1, SC-2, and SC-3 with respect to the general rock site classification SC-4. The SC-1/rock ratio is close to unity, except for a slight increase at long periods, which indicates that the general rock class captures the main features of rock/stiff soil behaviour. The slight difference at long periods occurs since the general rock category also contains medium to soft soil sites, as mentioned above. Nonetheless, the overall effect of mixing site conditions within a general rock category is rather small. Conversely, the SC-2/rock ratio shows deamplification of 50% at short periods and an amplification of two at long periods. The SC-3/rock ratio demonstrates a slightly greater deamplification than the SC-2/rock results and, in addition, it clearly indicates an amplification factor up to 3.3 around 1s. Note that the general soil/rock ratio does not display deamplification and the maximum amplification is only about 70% at 1s. Another interesting result is the order of PGA amplification using this new classification: PGA at SC-3 sites is less amplified than at SC-2 stations, which, in turn, is less amplified than at sites in the SC-1 class. Unfortunately, this method has limitations since there are sites that do not exhibit clear H/V peaks, on the contrary they show broadband response, which is not captured by any of the classes. Site response at these stations remains difficult to quantify irrespective of the classification scheme.

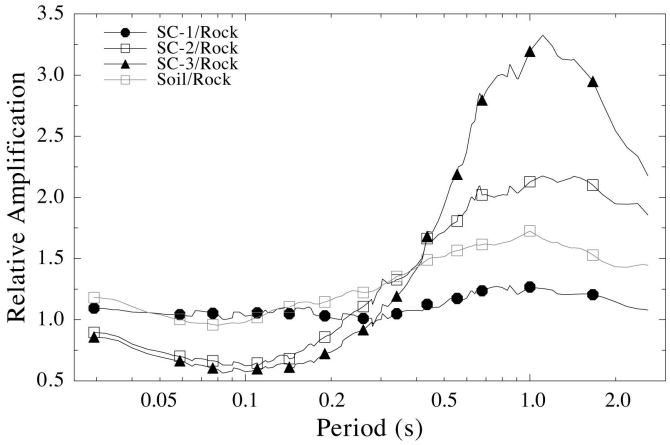


Figure 4. *Relative amplification of site classes used in this study, SC-1, SC-2, and SC-3, with respect to general rock site classification. For comparison, general soil-to-rock amplification is also shown. Note that amplification for SC-1 and general rock classes are similar.*

3.2. *Standard deviation*

The standard deviations using this new site classification scheme are slightly lower (on average 2%) compared to those using the original rock/soil classification scheme. This result suggests that better knowledge of local site conditions can reduce aleatoric variability in empirical ground-motion models. Therefore, more

effort should go into site characterization in order to derive more accurate strong-motion models with lower uncertainties

3.3. *Predicted response spectra*

Figure 5 shows that the shape of the predicted response spectra follows the shape of their corresponding average H/V response spectral ratios since these ratios were used in the classification process. This is less evident for SC-3 sites, although the amplification of spectral accelerations at long periods is remarkable. Incidentally, note that the period intervals defining such classes (Table 3) are apparent in the predicted response spectra. This suggests that site classification using predominant periods could be partially mapped into the site coefficients. This provides a useful link between strong ground motion predictions and earthquake-engineering design against soil-structure interaction.

Site classes	SC-1	SC-2	SC-3	SC-4	SC-5	Total
Rock	12	23	12	44		91
Soil	11	77	83		79	250
Total	23	100	95	44	79	341

Table 3 *Number of sites in each category using the proposed and original classification schemes.*

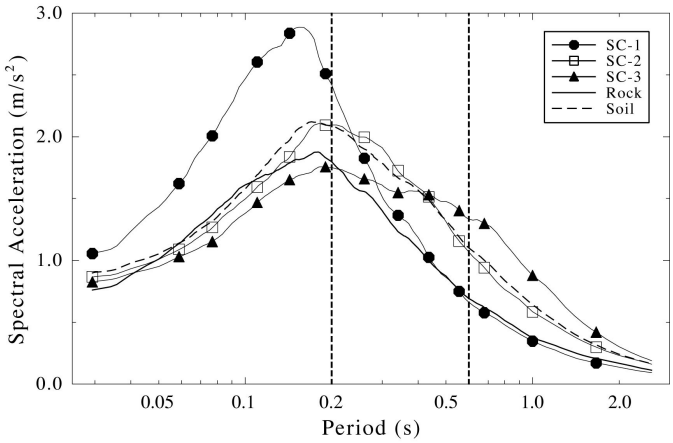


Figure 5. *Predicted response spectra for a magnitude 6.0 earthquake at 30 km using the site classes proposed in this study and general rock/soil categories.*

Predicted spectral accelerations at SC-1 sites are slightly higher than those at general rock sites. This is an interesting result considering that SC-1 and the general rock class are similar in terms of site amplification (Figure 4). This shows that the choice of site classification scheme has considerable impact on predicted ground motions. Most SC-1 sites are located in west Eurasia, thus these results may be regionally biased. Conversely, response spectra on sediments show distinct behaviour depending on whether the ground is composed of medium or soft material (SC-2 and SC-3 classes). Sites of the SC-3 class are almost equally represented in the three geographical regions, thus predicted response spectra may represent the average behaviour of such sites and tectonic environments.

Given the quality of these dataset and the lack of quantitative knowledge of the velocity profile at each site, we cannot say which empirical median predictions are more correct. Additional studies should be performed, in Japan for example, to help resolve this practical question. Nonetheless, we can see that this site classification clearly reproduces some seismological observations. For example, predicted PGA for the three site classes are well separated. This separation is also maintained at other periods, from high spectral accelerations at short

periods (stiff sediments) to low spectral amplitudes at long periods (soft soils). These results already show an improvement with respect to general rock/soil classes whose predicted spectral accelerations show little difference at short periods (Figure 5).

4. Conclusions

Good knowledge of site conditions is important for deriving accurate empirical ground motion prediction equations. In this study we used a site classification procedure based on the predominant resonance period computed from average H/V response spectral ratios and applied it to the database of Fukushima et al. (2003). The most remarkable result is the similarity of both spectral amplitudes and shapes of average H/V response spectral ratios to those found in Japan using the same technique (Zhao et al., 2006). This suggests that a common site classification scheme may be possible regardless of the geology and geographical location of a given site. However, the physical meaning of such shapes and their correspondence with Vs30 classification still remains to be clarified. We also found that previous general rock/soil categories are, in fact, composed of rock/stiff, medium and soft soils. The relative amplification of these new classes (SC-2 and SC-3) with respect to the general rock category is about 2.0 and reaches a maximum of 3.3 at 1s. On the other hand, SC-1 and general rock classes share similar amplification effects. The standard deviations of the derived ground-motion model using these new site classes are slightly lower than that obtained using general rock/site classes. Despite this small reduction, this result encourages the pursuit of a better site classification in order to improve the accuracy of empirical models. Predicted response spectra using the new classes have similar spectral shapes to the average H/V response spectral ratios that define each class. This is useful for predicting the period of the maximum spectral acceleration. This, however, represents a shortcoming of the method because sites having a broadband response cannot be accurately classified. In any case, this simple technique allows a fast evaluation of site effects when geotechnical characterization of the site does not exist. In addition, the method can allow the direct incorporation of effects involving deep soil structure and average shear-wave velocity of the whole soil deposit into empirical ground-motion prediction equations. Further details of this study are provided by Fukushima et al. (2007).

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5. Bibliography

Building Seismic Safety Council. “The 2000 NEHRP Recommended Provisions for New Buildings and Other Structures: Part I (Provisions) and Part II (Commentary)”, FEMA 368/369, Federal Emergency Management Agency, Washington, D.C., 2000.

Fukushima Y., Berge-Thierry C., Volant P., Griot-Pommera D. A., Cotton F. “Attenuation relation for west Eurasia determined with recent near-fault records from California, Japan and Turkey”, J. Earthq Eng., 7(3), 2003, 1-26.

Fukushima Y., Bonilla L.F., Scotti O., Douglas J. “Site classification using horizontal-to-vertical response spectral ratios and its impact when deriving empirical ground-motion prediction equations”, J. Earthq. Eng., 2007, in press.

Japan Road Association. “Specifications for Highway Bridges Part V, Seismic Design”, Maruzen Co., LTD, 1980.

Japan Road Association. “Specifications for Highway Bridges Part V, Seismic Design”, Maruzen Co., LTD, 1990.

Kanai K., Tanaka T. “On Microtremors. VIII, *Bull. Earthr. Res. Inst., Tokyo Univ.,* 40, 1961, 97-114.

Lussou,P., Bard P.Y., Cotton F., Fukushima Y. “Seismic design regulation codes: Contribution of K-net data to site effect evaluation”, J. Earthq. Eng., 5, 2001, 13-33.

McGarr, A., Çelebi M., Sembera E., Noce T., Mueller C. “Ground motion at the San Francisco international airport from the Loma Prieta earthquake sequence, 1989”, Bull. Seism. Soc. Am., 81, 1991, 1923-1944.

Zhao, J. X., Irikura K., Zhang J., Fukushima Y., Somerville P. G., Asano A., Ohno Y., Oouchi T., Takahashi T., Ogawa H., “An Empirical Site-Classification Method for Strong-Motion Stations in Japan Using H/V Response Spectral Ratio”, Bull. Seism. Soc. Am., 96, 2006, 914-925.