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Research Article

Estimation of Time-Averaged Shear Wave Velocity (SWV) to 30 m considering Site SWV Structural Characteristic

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The time-averaged shear wave velocity (SWV) to 30 m (V_{S30}) is a site condition parameter that has been widely used to specify the site class in building codes. However, the penetration depth of some building sites is less than 30 m, and thus, V_{S30} cannot be determined based on the velocity profiles. To estimate the site parameter V_{S30} accurately, we examined the effect of the velocity structural characteristic parameter of site profiles, β_H, on V_{S30} by performing a residual analysis. Further, a method to estimate V_{S30} was established considering the effect of β_H, and the validity of the proposed model was assessed based on site data pertaining to Japan and California (USA). The results show that the time-averaged shear wave velocity to the depth H ($H < 30$ m), V_{SH}, is weakly correlated with the parameter β_H. However, β_H has a significant effect on V_{S30}; for the same site V_{SH}, V_{S30} tended to increase with β_H. Compared with the extrapolation method, the proposed model can significantly reduce the standard deviation for the estimation of V_{S30}, while increasing the correlation between the estimated and measured values of V_{S30}. Thus, the estimation accuracy can be significantly improved by considering the effect of β_H.

1. Introduction

The local site effects have notable influence on the characteristic of the ground motion. To estimate site effects on ground motion, two general approaches are used [1]. The "site-specific" analysis that can be conducted using the numerical seismic response method is usually performed for sensitive buildings and large infrastructure [1]. For the site response analysis of soil, static and dynamic site characterizations are crucial points [2–4]. In order to obtain the geotechnical characteristics, laboratory and in situ investigations are usually carried out to measure material index, constrained modulus, undrained shear strength, horizontal stress, shear wave velocity, shear modulus, damp ratio, etc. [5–10]. Through the tests, the special attention is devoted to obtain the shear wave velocity (SWV) of the profiles [3] because it is very important in seismic wave amplification. In addition, the variation of the shear modulus and damping ratio with the shear strain level needs to be determined for the reason that nonlinearity of site response is also one of the major issues in evaluating site effects [3]. Alternatively, generic site factors are used for final design of typical buildings [1]. Developing site factors has been done by compiling ground motion data recorded at soil and rock sites during past earthquakes and examining dependence of amplification factor on certain site parameter, also known as site proxy [1]. Given that the site shallow SWV is a determining factor of the effect of the local site condition [11–13], the most commonly used site proxy is the time-averaged SWV to 30 m, V_{S30}.

To accurately determine V_{S30}, the SWV survey value to a depth of 30 m must be obtained; however, because the drilling depth of some building sites is less than 30 m, it is extremely difficult to measure the SWV at a sufficient depth. To overcome this, a number of scholars have proposed alternatives for the estimation of the site V_{S30}, e.g., the V_{S30} estimation model established using the topography, slope [14]. In addition, the SWV of the profiles can also be estimated from soil physical properties of the building site through the empirical correlations because the SWV depends significantly on soil physical properties [15–22]. The soil physical properties used generally include the cone tip resistance, liquidity index, standard penetration test blow counts, void ratio, etc., which should be determined by static and dynamic penetration tests [16–22]. Kuo et al. examined the estimation accuracy of V_{S30} using soil physical properties based on actual site data in Taiwan, and the results of this study show that this method is less accurate than the bottom-constant extrapolation method [23]. Further, the model using soil physical properties is region-dependent [24]. The bottom-constant extrapolation method is used to obtain V_{S30} using the measurement results of the shallow soil layer SWV, assuming that the magnitude of the SWV from the bottom of the borehole to the subsurface depth of 30 m is constant, and it is equal to the SWV at the bottom of the borehole.

The bottom-constant extrapolation method is one of the first methods used to estimate the site V_{S30}; however, the results still involve a few errors because the method does not consider the progressive increase in SWV with the depth. Given this, Boore [25] and Boore et al. [26] proposed the gradient extrapolation method and established an empirical model for the estimation of V_{S30} using the measured site data in California, Japan, and other areas. Several other scholars also engaged in the research of V_{S30} based on the subsurface SWV and obtained some meaningful results. Xie et al. [27] established and validated a V_{S30} estimation model for Beijing plain areas using the gradient extrapolation method. Dai et al. [28] proposed a V_{S30} estimation method based on the conditional independence property. Wang and Wang [29] and Wang et al. [30] estimated the site V_{S30} based on a given subsurface velocity, using the interpolation method by assuming the SWV profiles. Of the many V_{S30} estimation alternatives based on the subsurface velocity, the gradient extrapolation method is the most influential and has been widely used. For example, in the Next Generation Attenuation (NGA) project, the V_{S30} of some strong motion station sites was determined using this method.

The gradient extrapolation method is used to characterize the correlation between V_{SH} which is the time-averaged SWV to H ($H < 30$ m) and V_{S30} in the shallow layer. Although this method can reflect the common trend that the SWV of the profile increases progressively with the depth, the effect of the complexity of the SWV profile down to H ($H < 30$ m), especially its variability at depth, on the estimated results of V_{S30} is not considered. The current work attempts to examine the effect of the structural characteristics of SWV in the shallow soil layer ($H < 30$ m) on the estimated value of V_{S30}, in order to propose an alternative method for the estimation of V_{S30}. This study involves four main phases: introducing the parameter β_H, which characterizes the SWV structural characteristics; examining the correlation between β_H, V_{SH}, and V_{S30} using a residual analysis; establishing an estimation model for V_{S30}, considering the effect of β_H; and assessing the estimation accuracy of the proposed model. The results obtained herein can effectively indicate the effect of the SWV structural characteristics on the estimated value of V_{S30}, which is of great significance to improving the estimation accuracy of V_{S30}, so as to determine a reasonable design for the ground motion.

2. Research Method and Basic Data

To examine the effect of the SWV structural characteristics in the given shallow layer on the estimated value of V_{S30}, we first introduce the parameter β_H, which was first proposed by Regnier et al. [31] to characterize the behavior of the SWV profile with depth. The parameter β_H is defined as the slope of the linear regression between the common logarithm of the shear wave propagation velocity and the common logarithm of the depth as shown in the following equation:

$$\log_{10} V_S(H) = \beta_H \times \log_{10}(H) + \gamma, \quad (1)$$

where $V_S(H)$ characterizes the SWV at the depth H ,and β_H and γ are determined by fitting the relationship between $V_S(H)$ and the depth according to equation (1).

The parameter β_H can reflect the rate of increase in the SWV with depth. A lower β_H value means low velocity increases with depth; a higher β_H value indicates a rapid velocity increases with depth. To better specify the meaning of the parameter β_H, three sites from Japan, OKYH03, YMGH09, and AICH05, for which the values of V_{S30} are 307 m/s, 303 m/s, and 302 m/s, respectively, are selected. The SWV profiles down to 30 m for the sites selected are shown in Figure 1. The stratigraphic sections with the indication of geotechnical layers for the sites selected are shown in Figure 2. Although the three sites have almost the same values of V_{S30}, the SWV structures show quite different characteristics. The SWV increase of site OKYH03 is more rapid than those of other sites. The fitted curves of the SWV of the sites with depth from equation (1) are also given in Figure 1, and the values of β_{30} for OKYH03, YMGH09, and AICH05 are 1.02, 0.58, and 0.29, respectively. It is obvious that the differences of the SWV structural characteristics can be reflected by β_{30} because the site with larger β_{30} shows more rapid velocity increases with depth.

To investigate whether the estimation accuracy of V_{S30} is improved by introducing β_H into the gradient extrapolation method, the correlations between β_H and V_{SH}, V_{S30} were examined based on actual site SWV data. To examine the effect of β_H on V_{S30}, values of V_{S30} corresponding to actual sites in California and Japan were estimated from V_{SH} using the models proposed by Boore [25] and Boore et al. [26], respectively, with residuals obtained. The effect of β_H on V_{S30} was examined by analyzing the dependence of the residual on β_H.

In this thesis, the actual site SWV data were sourced from California and Japan (courtesy of KiK-net). For California, a dataset of SWV profiles compiled by Boore [32] was used. The selected sites were required to have a drilling depth of more than 30 m and definite SWV; the resulting number of selected sites in Japan and California was 646 and 135, respectively.

3. Correlation between β_H and V_{SH}

The correlation between β_H and V_{SH} determines whether they can be used to estimate V_{S30} simultaneously. A strong correlation implies that the accuracy of V_{S30} estimated using the two parameters is similar to that using one of the two parameters. For the convenience of engineering applications, it

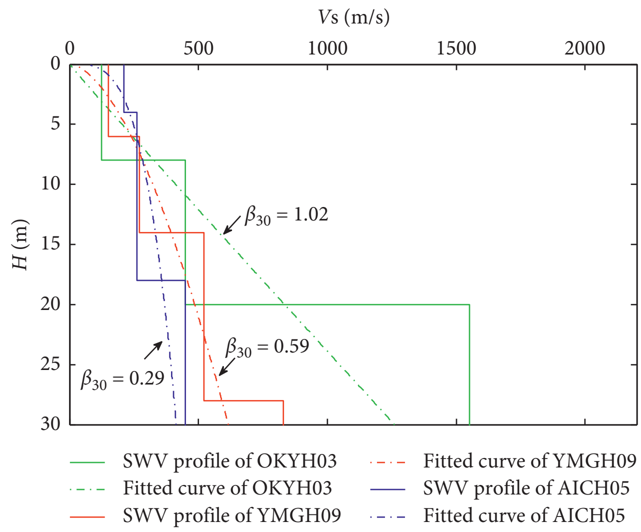

FIGURE 1: SWV profiles of OKYH03, YMGH09, and AICH05.

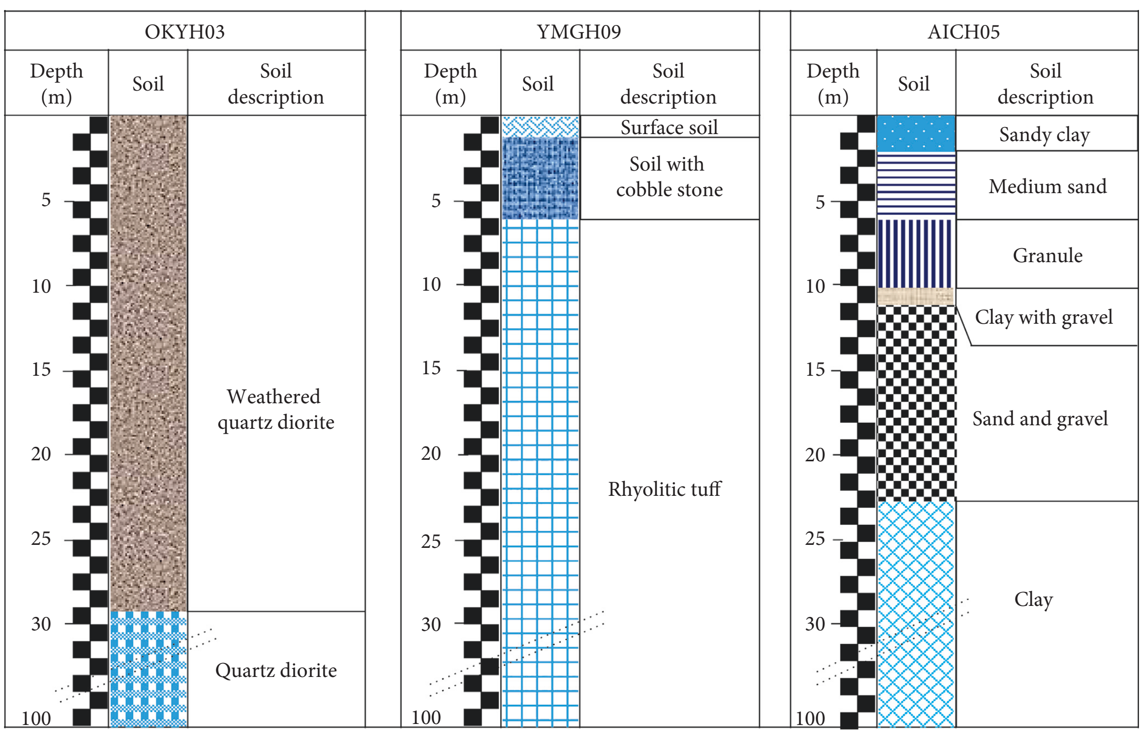

FIGURE 2: Stratigraphic sections of OKYH03, YMGH09, and AICH05.

is enough to use a single parameter to estimate V_{S30}. To examine the correlation between β_H and V_{SH}, the following depths were selected: $H = 10$, 15, 20, and 25 m. Subsequently, the β_H and V_{SH} at each depth were calculated using the actual drilling data to examine the variations of V_{SH} with β_H, as shown in Figure 3. Figures 3(a)–3(d) demonstrate the tendency of site parameters in Japan whereas Figures 3(e)–3(h) show the tendency of site parameters in California.

As noted from Figure 3, the value of β_H corresponds to three cases. If β_H is 0, the value of SWV within the depth H is constant. If β_H is less than 0, a soft interlayer exists as the depth increases. For Japanese sites, for H between 10 and 25 m, the variations of V_{SH} with β_H did not show a well-defined tendency. For sites in California, V_{SH} tended to slightly increase with β_H, progressively. In order to quantitatively examine the correlation between V_{SH} and β_H, the Pearson correlation coefficients were calculated and are listed in Table 1.

Table 1 shows that for Japanese sites, the correlation coefficient is extremely small, indicating a weak correlation between the two parameters. For California sites, the correlation coefficient is slightly larger. Further analysis of the data

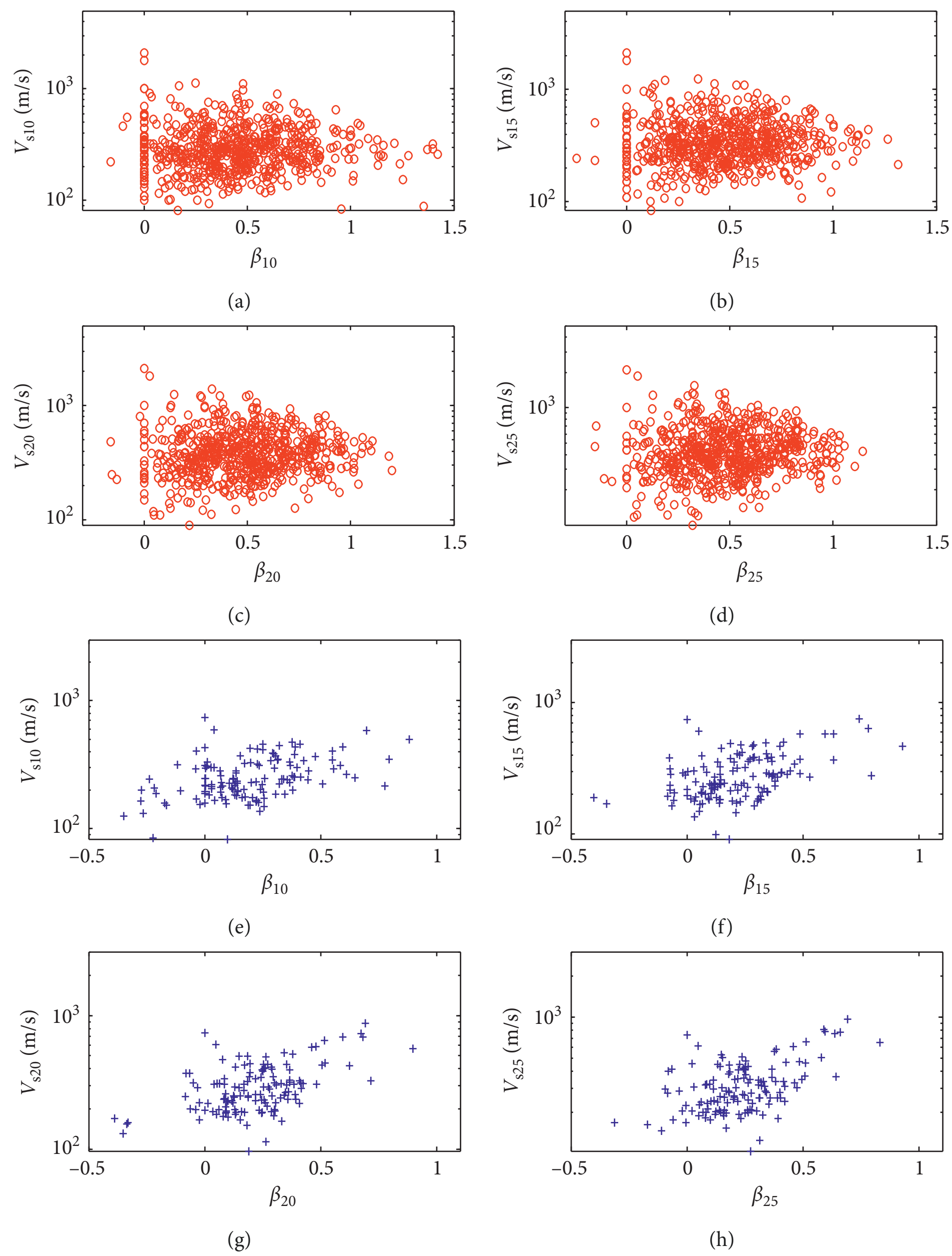

Figure 3: V_{SH} with respect to β_H. (a) Japan, $H = 10$ m. (b) Japan, $H = 15$ m. (c) Japan, $H = 20$ m. (d) Japan, $H = 25$ m. (e) California, $H = 10$ m. (f) California, $H = 15$ m. (g) California, $H = 20$ m. (h) California, $H = 25$ m.

Table 1: Pearson correlation coefficients.

H (m)	10	15	20	25
Japan	−0.065	−0.032	−0.013	0.0047
California	0.390	0.460	0.500	0.500

noted for sites in California shows that the presence of few data points corresponding to deviatory large and small values of β_H influences the correlation coefficient; the data for which the value of β_H is between 0 and 0.5 show the same tendency, indicating a weak correlation between the two parameters as those in Japanese sites. Thus, the correlation between V_{SH} and β_H is considered to be negligible in this study.

4. Effect of β_H on V_{S30}

The gradient extrapolation method was used to characterize the relationship between V_{SH} ($H < 30$ m) and V_{S30} using a single variable V_{SH}. According to the above analysis, the correlation between V_{SH} and β_H is very weak, and both parameters reflect the site characteristics in different aspects. To explore whether β_H can improve the estimation accuracy of V_{S30}, the effect of β_H on V_{S30} was examined by performing a residual analysis. Residuals were obtained by estimating the V_{S30} in sites in California and Japan, using the gradient extrapolation method by Boore [25] and Boore et al. [26], respectively. The empirical models proposed by Boore [25] and Boore et al. [26] do not consider the variable β_H.

According to the principle of residual analysis, if the obtained residual exhibits significant variations with respect to β_H, it can be inferred that β_H significantly influences V_{S30}. The estimation accuracy of V_{S30} can be improved by introducing β_H into the gradient extrapolation method.

To examine whether a strong dependence of V_{S30} on β_H exists, Figure 4 shows the variations of residual with β_H, where Figures 4(a)–4(d) show the data points in Japan and Figures 4(e)–4(h) show the data points in California.

It is noted that the data in the two areas exhibit similar tendencies. The residual for the estimation of V_{S30} tends to increase with β_H progressively. A smaller H implies more significant progressive increase; moreover, when β_H is high, the residuals tend to be greater than zero systematically. This indicates that V_{S30} tends to increase with β_H. The reason is that for most sites, provided V_{SH} is the same, the site with the higher rate of increase in the SWV with the depth will have a greater V_{S30}. Therefore, it is beneficial to introduce β_H into the gradient extrapolation method.

5. V_{S30} Estimation Model considering the Effect of β_H

According to the above analysis, the parameter β_H reflecting SWV structural characteristics in the shallow layer has a significant effect on the estimated result of V_{S30}. As observed from the distribution of data points in Figure 4, the residual tends to increase linearly with β_H. To reflect this law, the functional form including β_H was introduced into the gradient extrapolation method, and the V_{S30} estimation models for Japan and California sites can be expressed as equations (2) and (3), respectively:

$$\log V_{S30} = c_{0E}\delta_E + c_0 + c_1 \log V_{SH} + c_2 \left(\log V_{SH}\right)^2 + c_3\beta_H, \tag{2}$$

$$\log V_{S30} = a + b \log V_{SH} + c\beta_H, \tag{3}$$

where δ_E in equation (2) indicates the uniqueness of class E sites. $\delta_E = 1$ for class E, and $\delta_E = 0$ otherwise. The coefficients c_{0E}, c_0, c_1, c_2, and c_3 in equation (2) and coefficients a, b, and c in equation (3) are regression coefficients determined using site data in this study. The coefficients c_3 in equation (2) and c in equation (3) reflect the influence of β_H on V_{S30}. Regressions of equations (2) and (3) were conducted using the considered dataset to obtain the model coefficients and the residual standard deviations, as given in Tables 2 and 3, respectively. Unlike in Boore [25], the model coefficients for the estimation of V_{S30} according to the average SWV of 25 depths in the range of 5–29 m, at an interval of 1 m, were obtained.

6. Analysis and Discussion

6.1. Comparison of Residual Standard Deviations. The residual standard deviation is a key index used to measure the accuracy of model estimation. To validate the effect of introducing the SWV structural characteristic parameter, the residual standard deviations σ of results obtained using equation (2) and the model proposed by Boore et al. [26] and those obtained using equation (3) and the model proposed by Boore [25] for the estimation of V_{S30} were compared. The results of comparison are as shown in Figure 5. Figure 5(a) shows the data in Japan, while Figure 5(b) shows the data in California.

Figure 5 shows that the standard deviations of the models proposed by Boore [25] and Boore et al. [26] for the estimation of V_{S30} can be significantly reduced by introducing β_H. For Japan and California sites, the average reductions in the standard deviation were 29.8% and 10.4%, respectively. This indicates that the standard deviation for the estimation of V_{S30} in Japan sites could be more significantly reduced by considering the effect of β_H, which can be explained by analyzing the variations of the velocity gradient model residual with β_H, as shown in Figure 4. As shown from the comparison between Figures 4(b) and 4(f), a more obvious correlation exists between the residual and β_{15} for the estimation of V_{S30} in Japan; in other words, the V_{S30} in Japan sites has a stronger dependence on β_H.

To further analyze the effect of β_H on V_{S30} for sites from the two regions, β_H was divided into intervals to analyze the differences of V_{S30} between the intervals. For Japan sites, the intervals of $\beta_H < 0.2$ and $\beta_H > 0.8$ were selected for the comparison. Owing to the sparse data available in the California sites, to ensure a uniform number of samples in each interval, the intervals of $\beta_H < 0.1$ and $\beta_H > 0.3$ were selected for the comparison. The variations of individual intervals are as shown in Figure 6; Figures 6(a) and 6(b) correspond to the Japanese sites, while Figures 6(c) and 6(d) correspond to the California sites.

As shown in Figures 6(a) and 6(b), for Japan sites provided with the same V_{SH}, the V_{S30} of the sites with greater β_H are greater. The extent of such differences can be obtained from the coefficients given in Table 2. For the two sites with $\beta_{10} = 0.8$ and $\beta_{10} = 0.2$, the differences in the V_{S30} obtained from the same V_{S10} are 27%. However, because the gradient extrapolation method does not consider the effect of β_{10}, the estimated error is bigger than the result in this study. This indicates that the estimation accuracy of V_{S30} for Japan sites can be significantly improved by introducing β_H, and thus, a smaller estimation standard deviation of V_{S30} can be obtained.

For the California sites, the two intervals with the same V_{SH} have few samples, and therefore, the V_{S30} of the sample sites within the two intervals does not show a significant difference; further, the extent of reducing the V_{S30} standard deviation by introducing β_H is relatively insignificant. However, when V_{S10} is in the range of 200–320 m/s, the actual values of V_{S30} in the two intervals with the same V_{S10} but different β_{10} have some differences, which show the same variations as that with the data in Japan.

6.2. Comparison of Correlation Coefficients. The correlation coefficient can be used to effectively characterize the correlation between the estimated value and the actual value of V_{S30} in order to investigate the reliability of the proposed method. Using the boreholes in Japan and California, V_{S30} were calculated using equations (2) and (3) with V_{SH} at

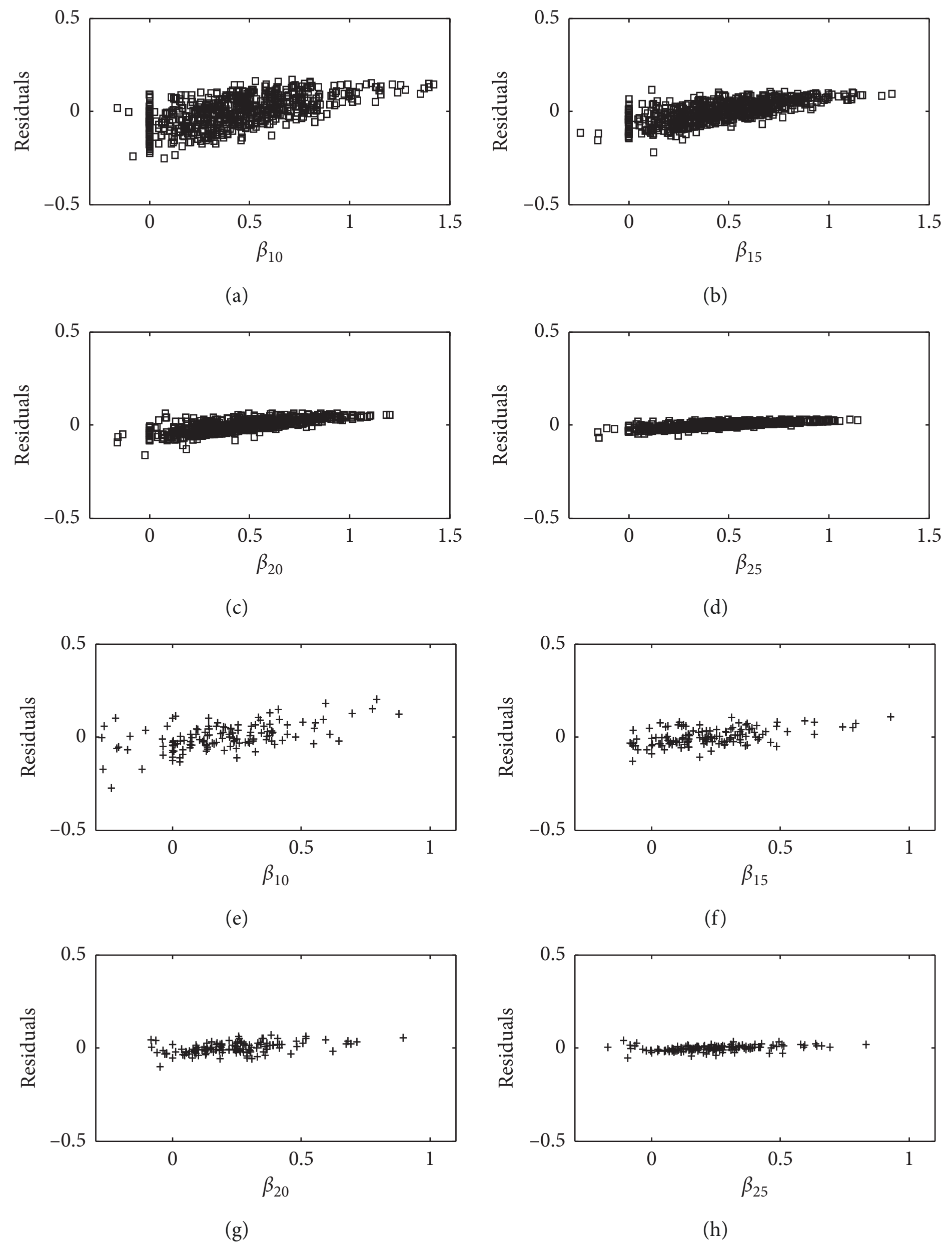

Figure 4: Distribution of residual V_{S30} with β_H. (a) Japan, $H = 10$ m. (b) Japan, $H = 15$ m. (c) Japan, $H = 20$ m. (d) Japan, $H = 25$ m. (e) California, $H = 10$ m. (f) California, $H = 15$ m. (g) California, $H = 20$ m. (h) California, $H = 25$ m.

Table 2: Model coefficients for Japan sites.

H (m)	Coefficients					Residual standard deviations
	c_{0E}	c_0	c_1	c_2	c_3	
5	−2.08E-01	1.03 E+00	5.79E-01	3.55E-02	1.60E-01	9.99E-02
6	−1.90E-01	9.45E-01	6.03E-01	3.68E-02	1.72E-01	9.12E-02
7	−1.76E-01	8.98E-01	6.09E-01	3.93E-02	1.67E-01	8.46E-02
8	−1.60E-01	9.19E-01	5.59E-01	5.28E-02	1.75E-01	7.76E-02
9	−1.44E-01	8.53E-01	5.82E-01	5.18E-02	1.72E-01	7.12E-02
10	−1.28E-01	8.52E-01	5.56E-01	5.98E-02	1.75E-01	6.51E-02
11	−1.11E-01	7.88E-01	5.82E-01	5.76E-02	1.71E-01	5.93E-02
12	−9.41E-02	7.53E-01	5.86E-01	5.94E-02	1.69E-01	5.41E-02
13	−7.53E-02	6.60E-01	6.37E-01	5.23E-02	1.63E-01	4.91E-02

Table 2: Continued.

H (m)	Coefficients					Residual standard deviations
	c_{0E}	c_0	c_1	c_2	c_3	
14	−6.05E-02	6.24E-01	6.46E-01	5.26E-02	1.59E-01	4.44E-02
15	−4.95E-02	5.91E-01	6.55E-01	5.29E-02	1.51E-01	3.99E-02
16	−4.03E-02	5.51E-01	6.71E-01	5.14E-02	1.45E-01	3.58E-02
17	−3.11E-02	4.71E-01	7.20E-01	4.37E-02	1.36E-01	3.19E-02
18	−2.40E-02	4.13E-01	7.54E-01	3.84E-02	1.27E-01	2.86E-02
19	−1.84E-02	3.61E-01	7.84E-01	3.39E-02	1.16E-01	2.55E-02
20	−1.43E-02	3.21E-01	8.05E-01	3.08E-02	1.06E-01	2.27E-02
21	−1.10E-02	2.58E-01	8.45E-01	2.42E-02	9.61E-02	1.94E-02
22	−8.57E-03	2.09E-01	8.75E-01	1.94E-02	8.57E-02	1.67E-02
23	−6.85E-03	1.72E-01	8.98E-01	1.60E-02	7.48E-02	1.41E-02
24	−5.41E-03	1.43E-01	9.14E-01	1.35E-02	6.42E-02	1.19E-02
25	−4.21E-03	1.24E-01	9.24E-01	1.22E-02	5.36E-02	9.63E-03
26	−3.54E-03	1.03E-01	9.35E-01	1.05E-02	4.31E-02	7.57E-03
27	−2.33E-03	7.15E-02	9.55E-01	7.35E-03	3.24E-02	5.42E-03
28	−1.39E-03	4.49E-02	9.72E-01	4.61E-03	2.16E-02	3.53E-03
29	−5.44E-04	2.01E-02	9.87E-01	2.09E-03	1.09E-02	1.65E-03

Table 3: Model coefficients for California sites.

H (m)	Coefficients			Residual standard deviations
	a	b	c	
5	4.96E-01	8.40E-01	2.11E-01	9.75E-02
6	4.01E-01	8.79E-01	1.90E-01	8.86E-02
7	3.54E-01	8.97E-01	1.73E-01	8.36E-02
8	3.49E-01	8.95E-01	1.73E-01	7.61E-02
9	3.24E-01	9.02E-01	1.78E-01	6.65E-02
10	2.86E-01	9.14E-01	1.73E-01	5.94E-02
11	2.36E-01	9.33E-01	1.57E-01	5.46E-02
12	2.04E-01	9.45E-01	1.41E-01	5.11E-02
13	1.89E-01	9.49E-01	1.30E-01	4.76E-02
14	1.66E-01	9.57E-01	1.18E-01	4.39E-02
15	1.45E-01	9.63E-01	1.06E-01	4.07E-02
16	1.23E-01	9.71E-01	9.14E-02	3.82E-02
17	1.07E-01	9.77E-01	7.62E-02	3.65E-02
18	9.93E-02	9.78E-01	6.86E-02	3.39E-02
19	9.14E-02	9.79E-01	6.52E-02	3.09E-02
20	8.69E-02	9.79E-01	6.31E-02	2.79E-02
21	8.26E-02	9.78E-01	5.97E-02	2.48E-02
22	7.92E-02	9.78E-01	5.63E-02	2.20E-02
23	6.73E-02	9.81E-01	5.08E-02	1.89E-02
24	5.43E-02	9.85E-01	4.40E-02	1.60E-02
25	4.18E-02	9.89E-01	3.69E-02	1.33E-02
26	2.97E-02	9.92E-01	2.92E-02	1.03E-02
27	1.84E-02	9.96E-01	2.08E-02	7.62E-03
28	1.09E-02	9.98E-01	1.35E-02	5.04E-03
29	5.40E-03	9.99E-01	6.91E-03	2.48E-03

depths ranging from 5 to 29 m and 10 to 29 m, respectively. Further, V_{S30} from the California and Japan sites were also calculated using the empirical relations suggested by Boore [25] and Boore et al. [26], respectively. The Pearson correlation coefficient r between the measured and estimated V_{S30} for the same region is calculated as shown in Figure 7. Figure 7(a) shows the data in Japan, while Figure 7(b) shows the data in California.

As shown in Figure 7, the data for the two regions show the same tendency; there is a stronger correlation between the estimated value and the actual value of V_{S30} obtained using the proposed method, especially when the depth H is smaller. This indicates that the estimation accuracy of V_{S30} can be significantly improved by considering β_H ($H < 30$ m).

7. Conclusions

We examined the effect of β_H on the estimated value of V_{S30}; established the V_{S30} estimation model considering the effect of β_H; and observed the estimation effect of the proposed model, based on data for the Japan and California sites:

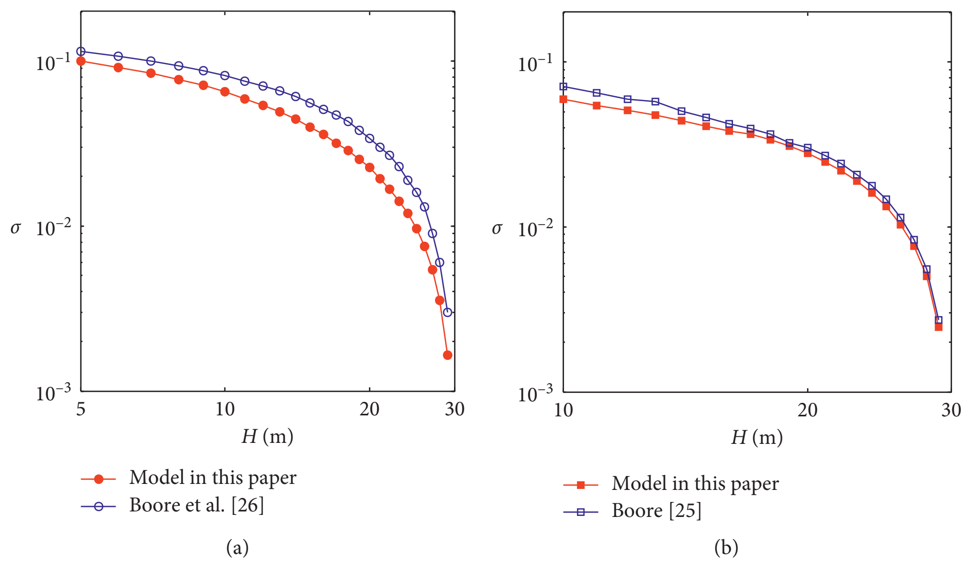

FIGURE 5: Comparison of standard deviations. (a) Japan. (b) California.

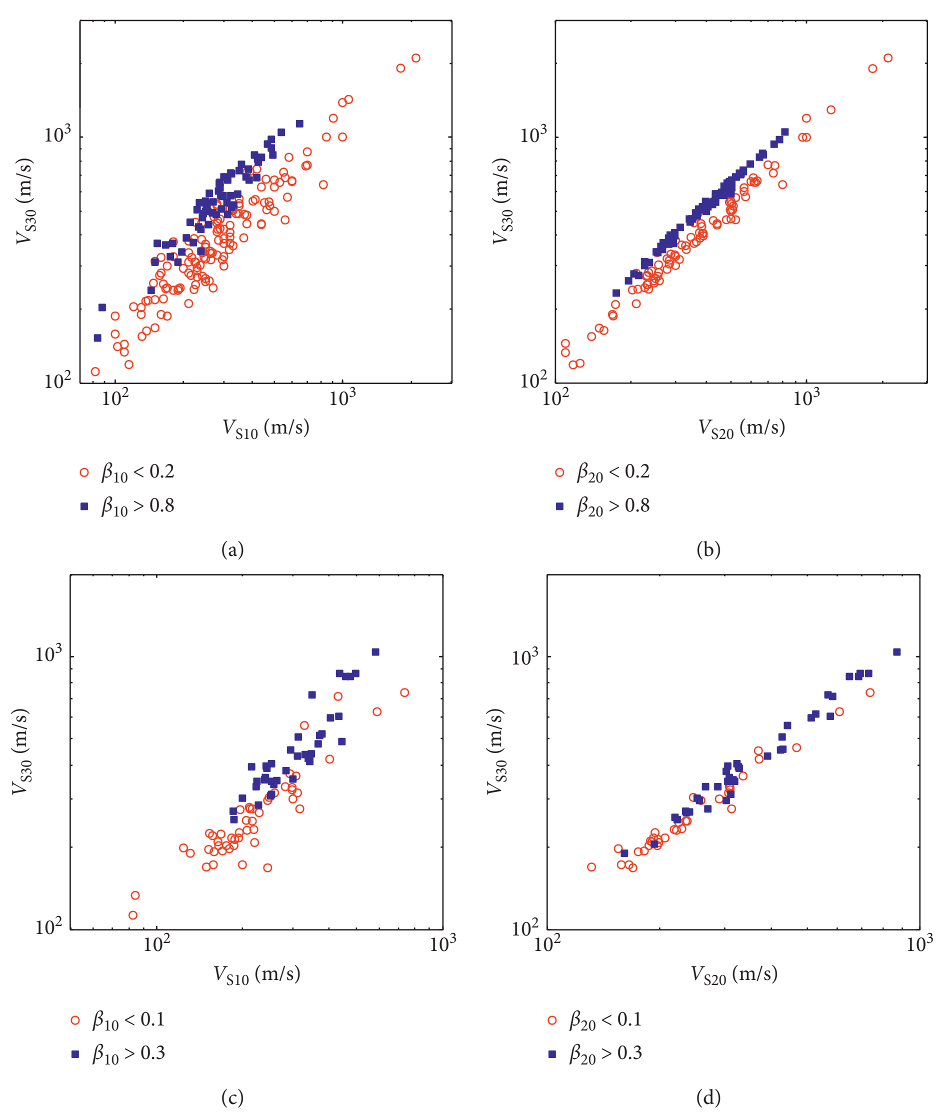

FIGURE 6: Comparison of variations of V_{S30} with V_{S10} and V_{S20}.

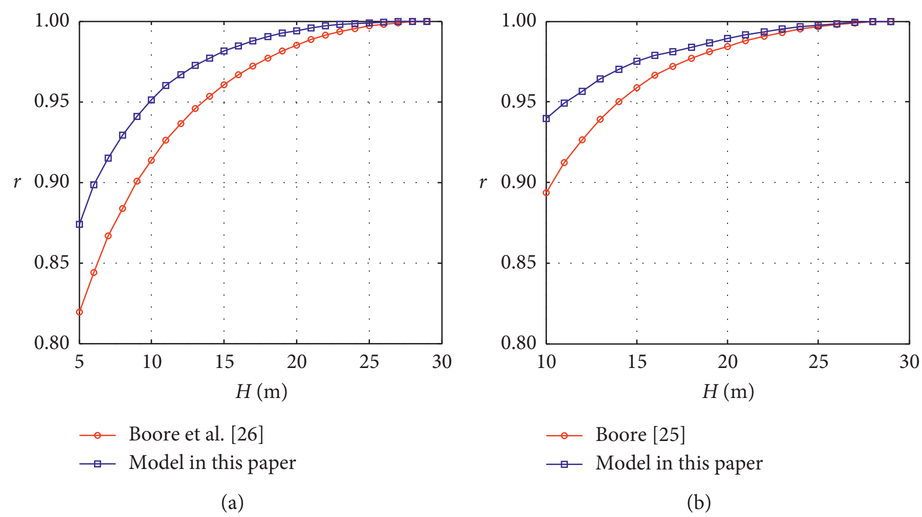

Figure 7: Comparison of correlation coefficients. (a) Japan. (b) California.

(1) For soil with depth less than H, β_H and V_{SH} are weakly correlated; these can be used as the variables to estimate V_{S30} simultaneously

(2) The parameter β_H has a significant effect on V_{S30}; for the same site V_{SH}, V_{S30} tends to increase with β_H

(3) Compared with the gradient extrapolation method, the proposed model can significantly reduce the standard deviation for the estimation of V_{S30} while increasing the correlation between the estimated value and the measured value of V_{S30}

Data Availability

The shear wave velocity profiles from 646 boreholes from the Japanese KiK-net network are from http://www.kyoshin.bosai.go.jp/kyoshin/db/index_en.html?all (last accessed February 2016). The shear wave velocity profiles of 135 boreholes from California are from a compendium of Boore [32], available from the online data section of http://www.daveboore.com (last accessed August 2016).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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