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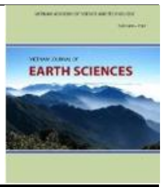

Methods for constructing V_{S30} maps from geology, borehole and topography data

Nguyen Thuy Linh, Bui Van Duan, Nguyen Anh Duong*

Institute of Geophysics, Vietnam Academy of Science and Technology

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ABSTRACT

The average shear wave velocity in the upper 30 meters of a soil profile (V_{S30}) is used in building codes to separate sites into classes for the purpose of earthquake engineering design. In this paper, a method of Thompson E.N. and Wald D.J. (2012) was applied to build a VS30 map of Ho Chi Minh city using, many different data such as geologic, topographic and shear wave velocities derived from the Standard Penetration Test (SPT) data of 104 boreholes. The V_{S30} values are mainly within two ranges of 0 -180 m/s and 180 - 240 m/s corresponding to two site classes of type D and C, respectively, according to the soil classification in Vietnam Construction Code TCVN 9386:2012. The site class of type C is mainly distributed in the districts located in the northern area of Ho Chi Minh city, while the soft soil with V_{S30} < 180 m/s is concentrated in the south of the city. This result shows that this method can reduce the uncertainty of V_{S30} map by up to 11.4% relative to the topography slope-only approach. Moreover, the average topographic slope of Ho Chi Minh city area is about 0.0024. It implies that Ho Chi Minh city area is in a stable continental region, which is suitable to apply ground motion prediction equations developed for seismic stable regions for the purpose of seismic hazard assessment. Our study is a prerequisite for the wide application of this method to build V_{S30} maps for other areas in Vietnam.

Keywords: V_{S30}, Ho Chi Minh city, geology, borehole, topography slope, soil classification.

1. Introduction

V_{S30} is the average shear wave velocity of the first 30 meters below surface ground. The value of V_{S30} is used in building codes (e.g., International Code Council, 2009; Vietnam Construction Code TCVN 9386:2012, 2012; Building Seismic Safety Council, 2015). It is also an important parameter to estimate site conditions used in ground motion prediction equations and seismic hazard assessments (e.g., Borcherdt, 1994; Abrahamson et al., 2008; Phan T.T. et al., 2013; Bozorgnia et al., 2014; Tran T.M.T et al., 2014, 2015). In the applications of engineering seismology, site response is estimated by using empirical correlations of V_{S30}. Those applications depend on the availability of V_{S30} measurement data at a certain point (such as the borehole, seismic exploration data) or various scales and resolutions of V_{S30} map.

*Corresponding author, Email: duongna@igp-vast.vn

When V_{S30} measurement points are sparse, it is necessary to have other methods to estimate V_{S30} values at any point without this data. Scientists have proposed a new method using the topographic slope to calculate the V_{S30} value. However, the calculated V_{S30} value is not close to reality due to the use of only topographic slope. In order to overcome this limitation, other data such as geological data, and measured V_{S30} data can be used jointly in V_{S30} calculation. In the early years of the twenty-first century, scientists studied the correlation between V_{S30} and other data such as surficial geology (e.g., Romero and Rix, 2001; Wills and Clahan, 2006); topographic slope (e.g., Wald and Allen, 2007; Allen and Wald, 2009); geomorphologic terrain mapping from satellite imagery (e.g., Yong et al., 2008; Yong et al., 2012). These studies tried to create more accurate and precise V_{S30} maps from the available data, then estimated the potential amplification due to site conditions in the affected or potentially affected area.

In the world, many countries (such as USA, Japan, Taiwan, and Italia,...) have built V_{S30} maps for small areas or for the entire territory (Lee and Tsai, 2008; Allen and Wald, 2009; Thompson and Wald, 2012). In Vietnam, the construction of V_{S30} map is only implemented in urban territories. Currently, there are V_{S30} maps for old Hanoi city, expanded Hanoi city, and Ho Chi Minh city. The site classification in Hanoi city was also implemented by using V_{S30} data collected from 157 boreholes (Bui T.N. and Nguyen H.P., 2015). For expanded Hanoi city (Ha Dong and Hoa Lac areas), microtremor measurements, borehole data, seismic exploration and geological data were used to construct V_{S30} map (Nguyen S.M. et al., 2014). For Ho Chi Minh city area, V_{S30} map was based on data of engineering geology and V_{S30} derived from the Standard Penetration Test (SPT) data (Cat N.H. et al., 2009). Their studies had not taken into account the quantitative correlation between the V_{S30} value and other used data, which would affect the accuracy of the final results. They simply plotted the contour map of V_{S30} by using the available V_{S30} measurement points. Moreover, the coverage of studied area and density of used data vary according to each approach, thus the final results have various precisions. Therefore, it is necessary to adopt an appropriate data processing method to achieve the best result at a given location. In this study, we rebuild V_{S30} map for Ho Chi Minh city by incorporating various data sources, such as geological data, topographic slope, and the SPT-derived V_{S30} values, with a hierarchic approach.

2. Data and Method

2.1. Topographic slope

The topographic slope is one of the most important parameters in this study. Topographic slope is derived from digital elevation model (DEM) with high resolution: 9 arcseconds (approximate to 270m resolution) or 30 arcseconds (approximate to 900 m resolution) (http://www2.jpl.nasa.gov/srtm/index.html). The structure of digital elevation data includes 3 columns (longitude, latitude, elevation) and n rows (each row is the information of a grid point within a study area). The topographic slope is calculated at each grid point in the study area as the same structure of DEM (Figure 1).

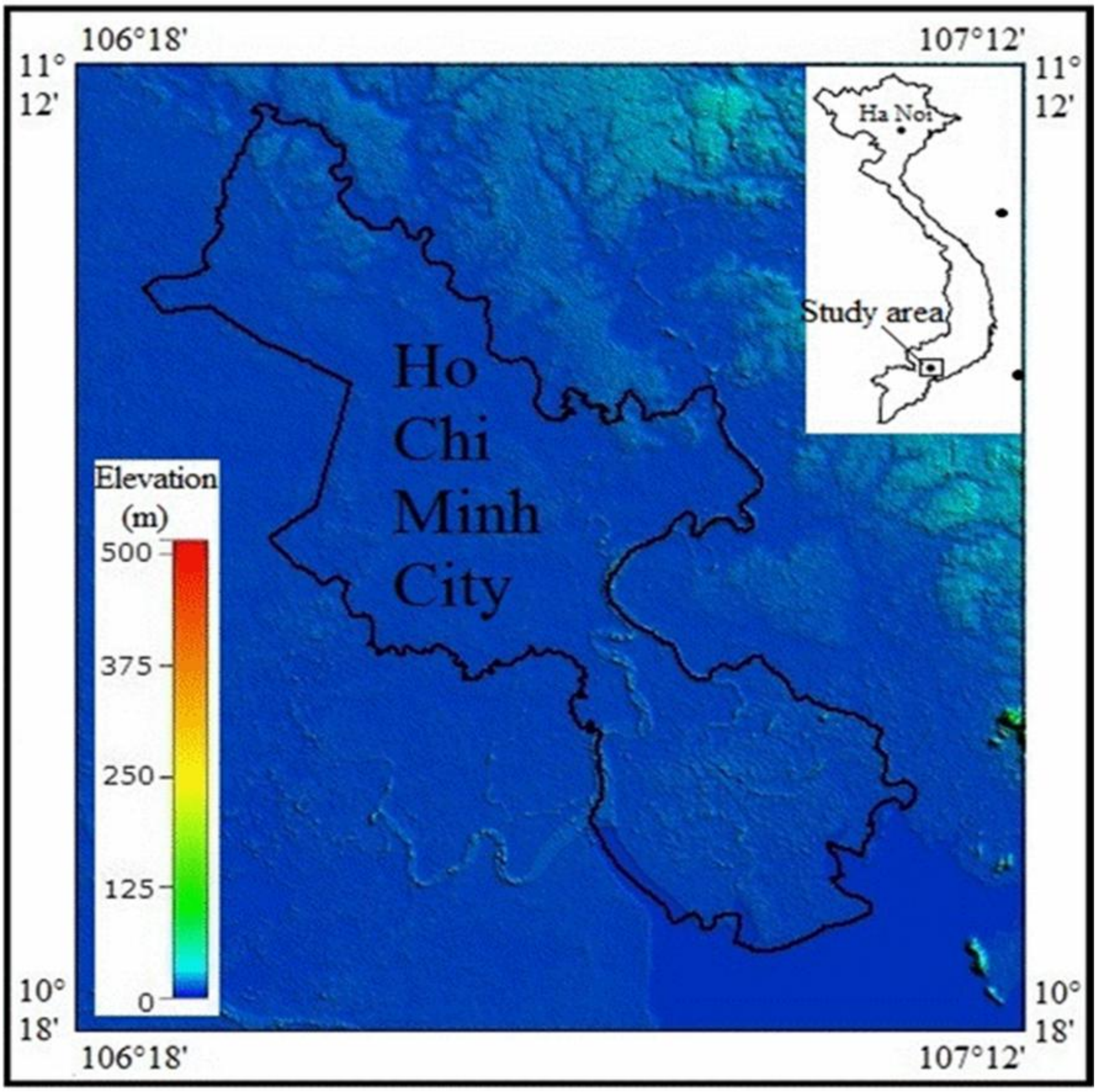

Figure 1. Landscape surface area of Ho Chi Minh City from digital elevation model of 9 arcsecond resolution

2.2. SPT-derived shear wave velocity

Shear wave velocity of a layer is calculated from SPT value (N_{SPT}) by using the Imai's formula (Imai, 1977):

$Vs = 91 * N_{SPT}^{0.337}$

V_{S30} is determined from the formula of CEN (CEN, 2004):

$$V_{S30} = \frac{30}{\sum \frac{T_{hi}}{V_{Si}}}$$

where: VSi and Thi are shear wave velocity and thickness of the ith layer, respectively.

The borehole data is collected from the report of Cat N.H. et al. (2009). V_{S30} data is derived from SPT values of 104 boreholes plotted in Figure 2 and summarized in Appendix.

2.3. Geological data

Geological data of Ho Chi Minh city is collected from “Geological and mineral map of Vietnam” on the scale of 1:200.000 (Ho

Chi Minh city sheet) (Nguyen N.H. et al., 1995). The exposed geological formation in the geological and mineral map of Vietnam was also used in the research of Bui V.D. et al. (2015) as a factor to explain the activity of reservoir-induced earthquakes occurred in the Song Tranh 2 hydropower reservoir area in the period of 2011-2014. The geological data is also widely used to assess geomorphic processes and active tectonics (Phan T.T. et al., 2012), and earthquake prediction (Nguyen et al., 2014). In Ho Chi Minh city area, we group the exposed geological formations into four categories of Holocene, Pleistocene, Pliocene and Jurassic (Figure 2).

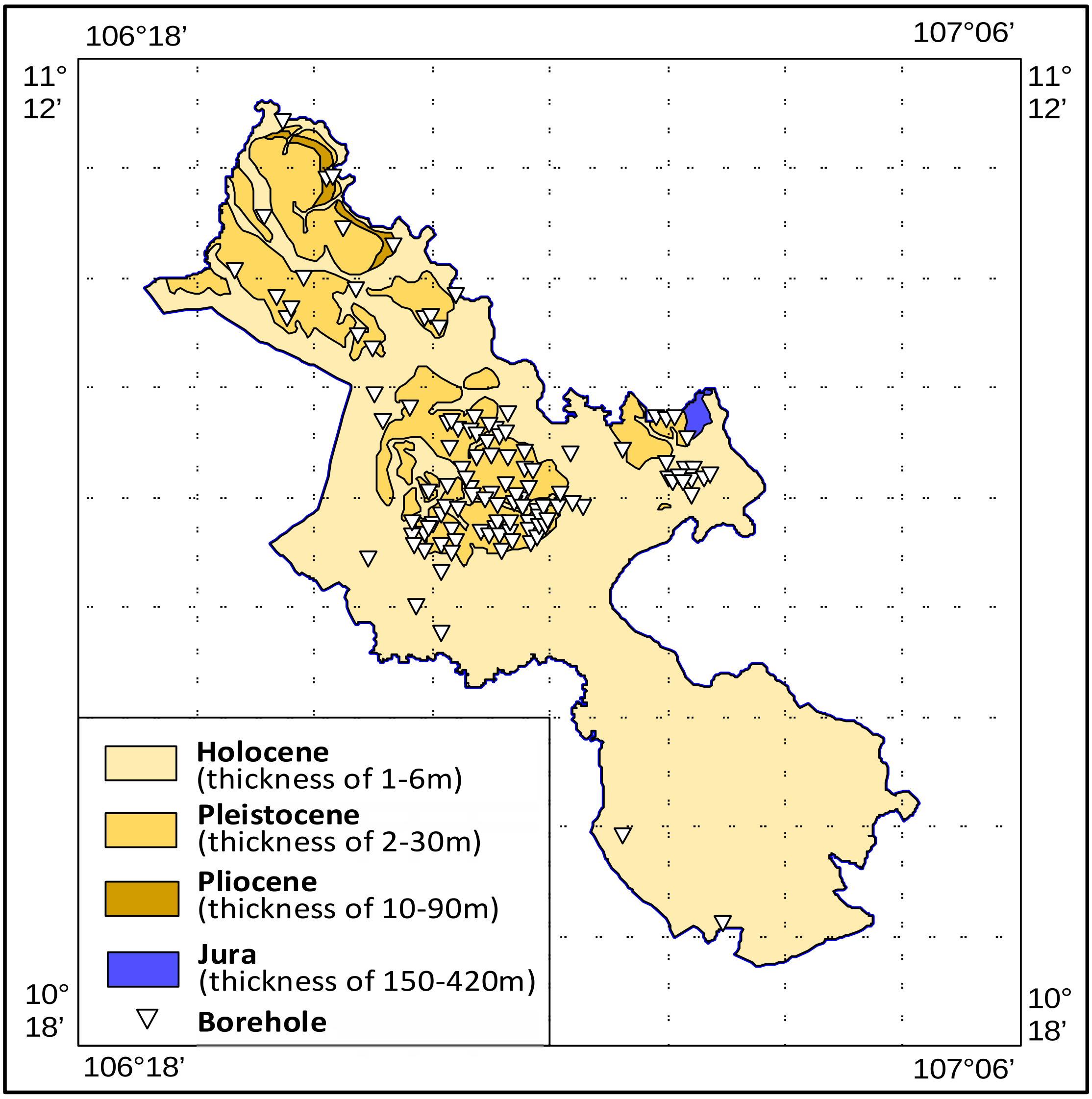

Figure 1. Landscape surface area of Ho Chi Minh City from digital elevation model of 9 arcsecond resolution

2.4. Constructing a V_{S30} map

In 2012, Thompson and Wald produced V_{S30} map for Taiwan area by using 447 V_{S30} measurements, topographic slope and geological data (Thompson and Wald, 2012). Similarly, we apply the geostatistical method of Kriging regression to calculate V_{S30} for Ho Chi Minh city from a set of geological data, topographic slope, and V_{S30} values at specific sites. Kriging interpolation algorithm trending to V_{S30} distribution is used to smoothen the resulting map at the locations with the dense coverage of measured V_{S30} points. The main procedure is as follows:

Step 1: Calculating topographic slope.

Step 2: Calculating V_{S30} in correlation with topographic slope.

Step 3: Calculating V_{S30} by incorporating topographic slope, geological data and the calculated V_{S30} from SPT values.

Step 4: the Kriging algorithm is used to establish V_{S30} map.

3. Results

3.1. Resolution in digital elevation model

We determine the correlation between topographic slope and V_{S30} at the borehole locations in two resolutions: 30 arcseconds (Figure 3) and 9 arcseconds (Figure 4). The correlation curves of Allen and Wald (2009) are also represented in Figure 3 and Figure 4. From these results, the resolution in the digital elevation model is chosen for calculating the topographic slope. We selected 9 arcsecond resolution of DEM in this study due to stronger correlation with V_{S30} than 30 arcsecond one and appropriate to the correlation of Allen and Wald (2009).

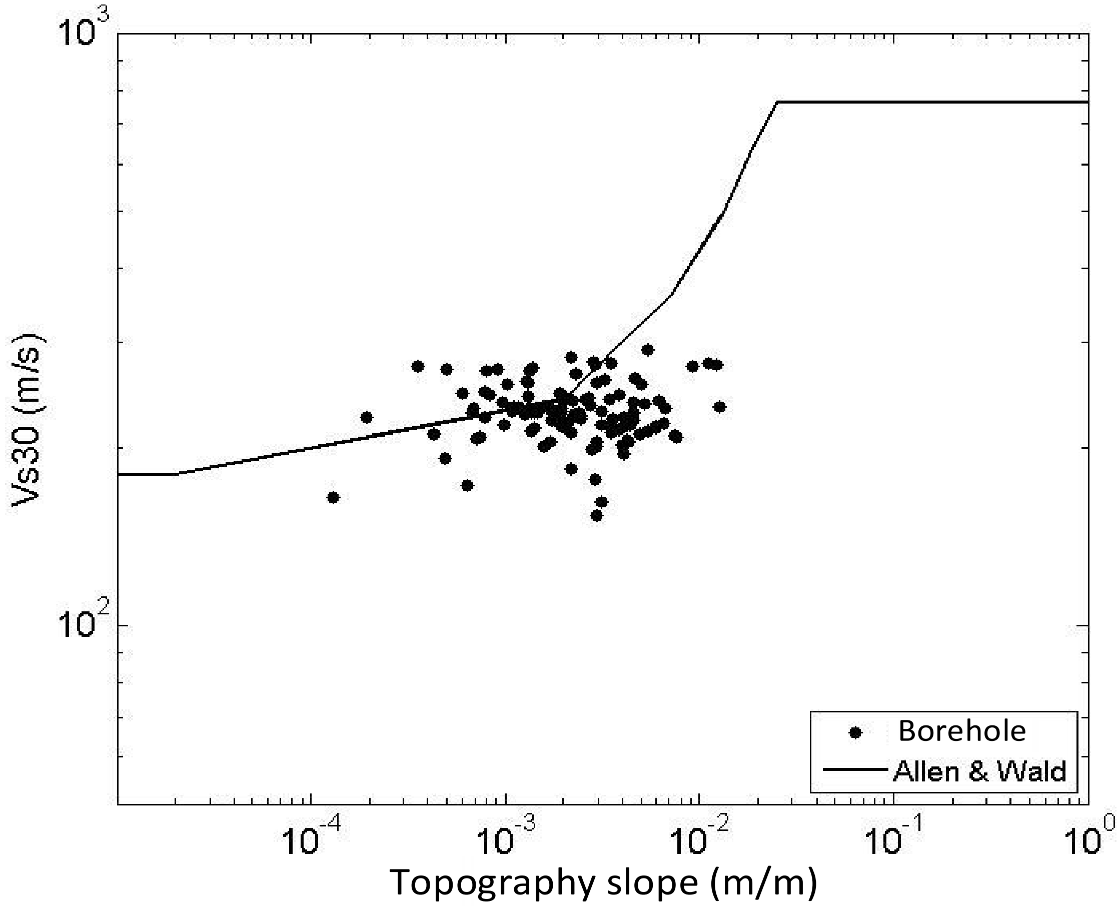

Figure 3. V_{S30} and topography slope computed from DEM 30 arcseconds at the borehole locations (Black dots). The solid line denotes the correlation curve of Allen and Wald (2009)

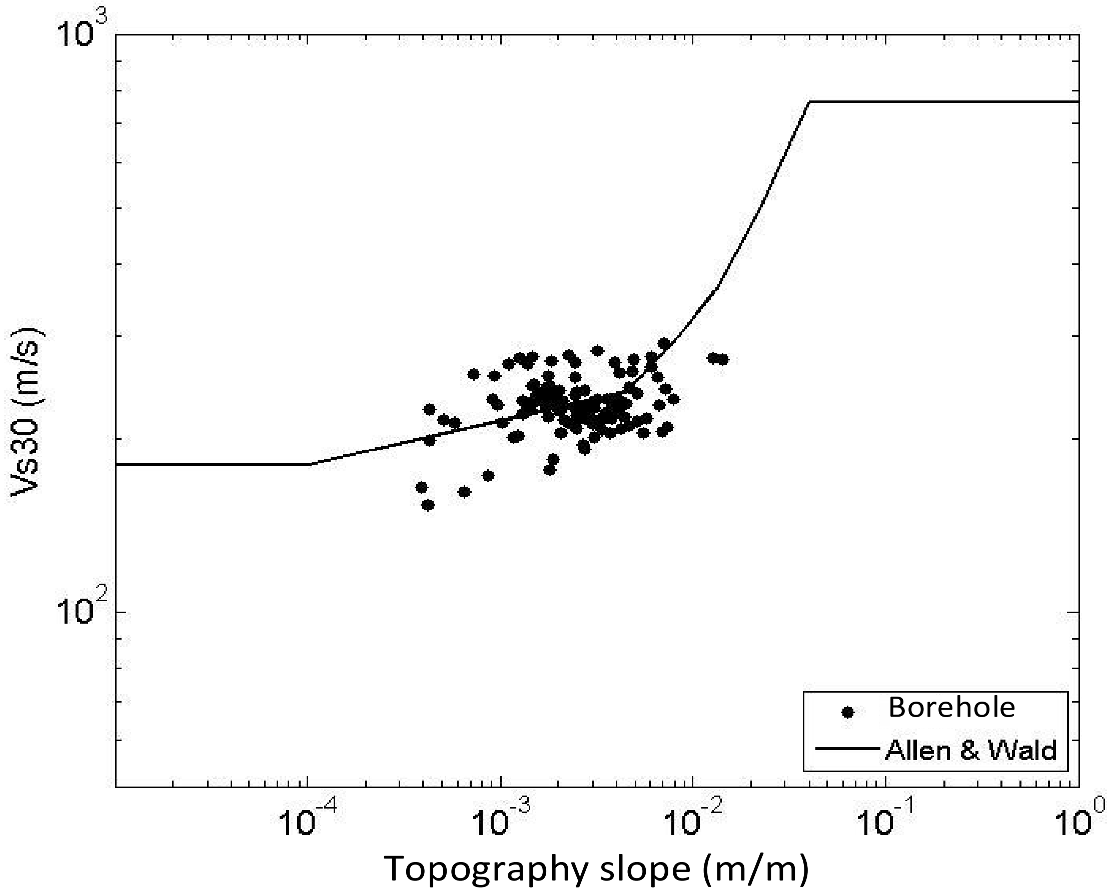

Figure 4. V_{S30} and topography slope computed from DEM 9 arcseconds at the borehole locations (Black dots). The solid line denotes the correlation curve of Allen and Wald (2009)

3.2. Topographic slope-derived V_{S30} value

From topographic elevation data inferred from the DEM of 9 arcsecond resolution, we have calculated the topographic slope at each grid point in the study area. According to the correlation between topographic slope and V_{S30} values in 9 arcsecond resolution of stable continental region proposed by Allen and Wald (2009) (Figure 4), we have computed V_{S30} values from the topographic slopes at the grid points. Then, V_{S30} results are shown in Figure 5.

3.3. Calculating V_{S30} value from geology, borehole and topography data

In order to improve the precision of V_{S30} map for Ho Chi Minh City, we combined the calculated results of V_{S30} from topographic slope with surficial geological data and V_{S30} data from SPT of the borehole in 2 strategies:

Strategy 1: we use geological units to adjust the residual of SPT-derived V_{S30} values and topographic slope-derived V_{S30} values in each geologic unit. This strategy is conducted as follows: (1) calculating V_{S30} from topographic slope for the study region (Figure 5); (2) computing the residual of V_{S30} values (SPT-derived V_{S30} value divided by topographic slope-derived V_{S30} one) at each borehole location; (3) computing mean residual for each geological unit;

(4) recomputing V_{S30} by using the mean residual of each geological unit and then constructing a new map of V_{S30} inferred from the topographic slope-derived V_{S30} values. The corrected V_{S30} results are shown in Figure 6.

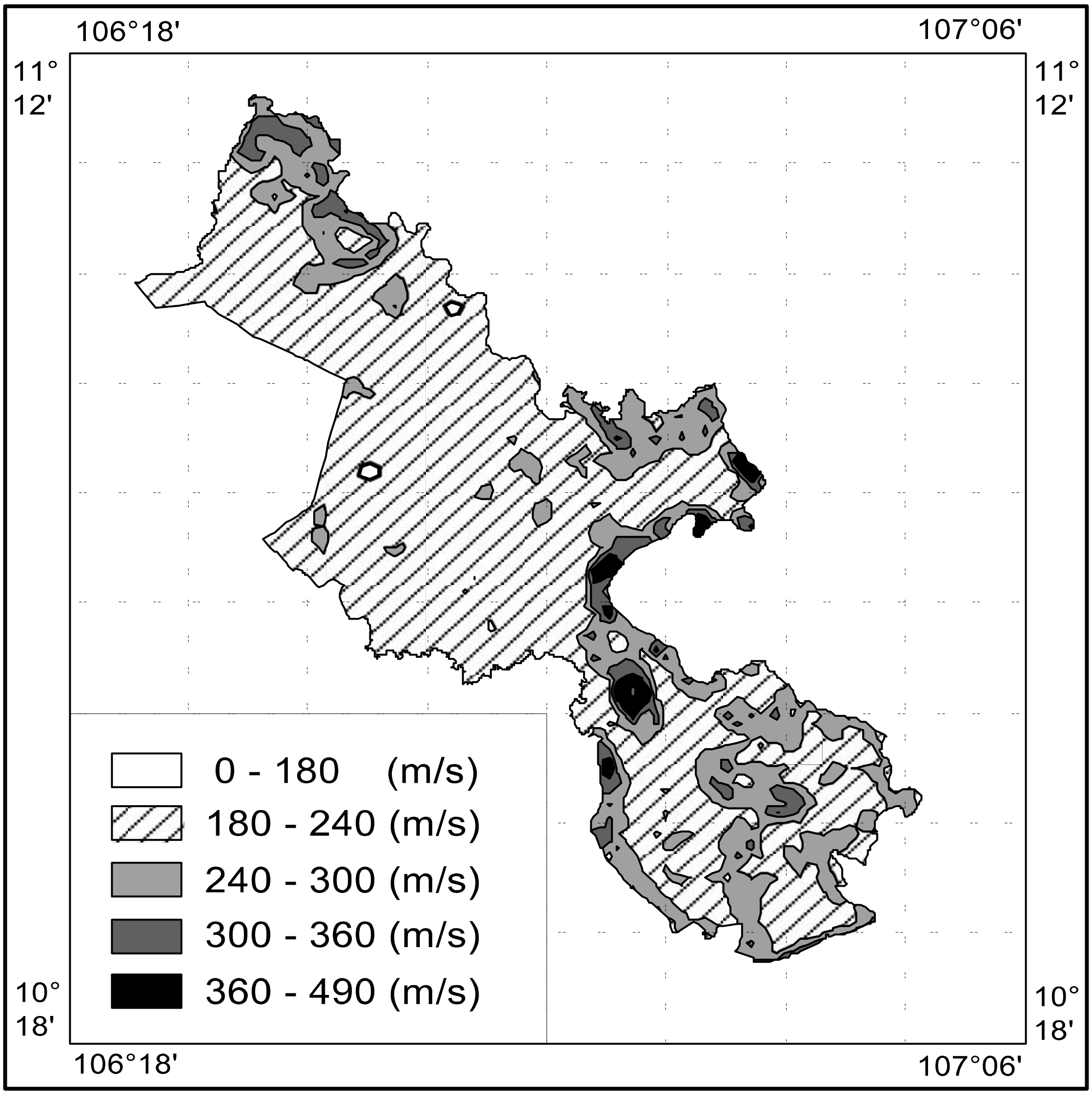

Figure 5. Distribution of V_{S30} calculated from the topography slope in Ho Chi Minh city

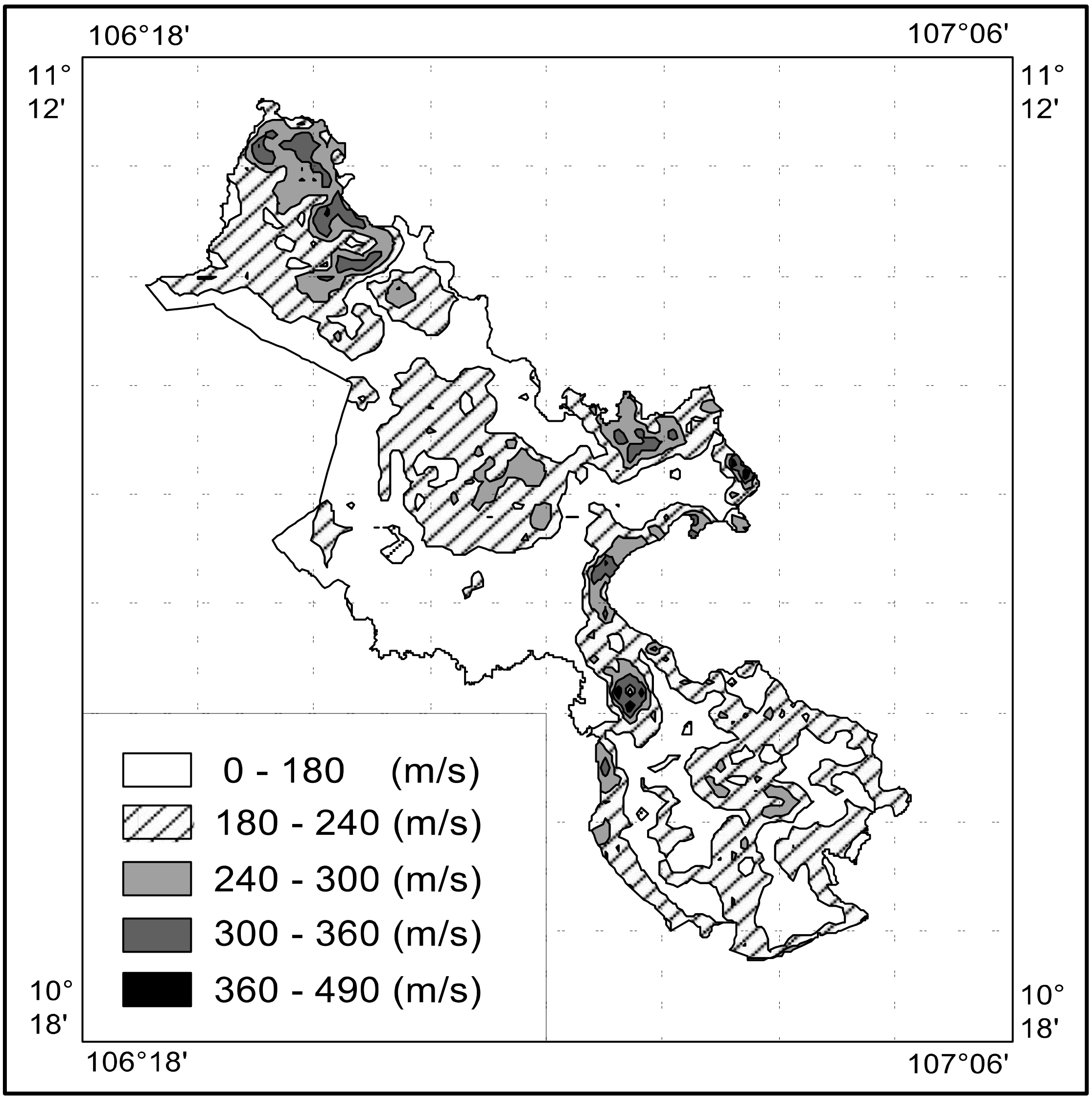

Figure 6. Map of V_{S30} that results from using geological units to adjust the residual of SPT-derived V_{S30} and topographic slope-derived V_{S30} in each geologic unit (Strategy 1)

Strategy 2: we determine the correlation of topographic slope and SPT-derived V_{S30} for each geological unit. This approach is implemented by defining V_{S30} as a simple function of the topographic slope for each geological unit (Figure 7). Figure 7 presents the relation between velocity and topographic slope for Holocene geological formation. Meanwhile, this relation does not exist in the geological formations of Pleistocene and Pliocene. Both of velocity and topographic slope, however, in Pliocene and Pleistocene formations have a tendency to greater than those in the Holocene. Therefore, we use the mean value of V_{S30} for the Pleistocene and the Pliocene. By using the relation between velocity and topographic slope for the Holocene, mean values of V_{S30} for the

Pleistocene and the Pliocene, and the Jura proposed by Allen and Wald (2009), we establish the V_{S30} map for the study area and show in Figure 8.

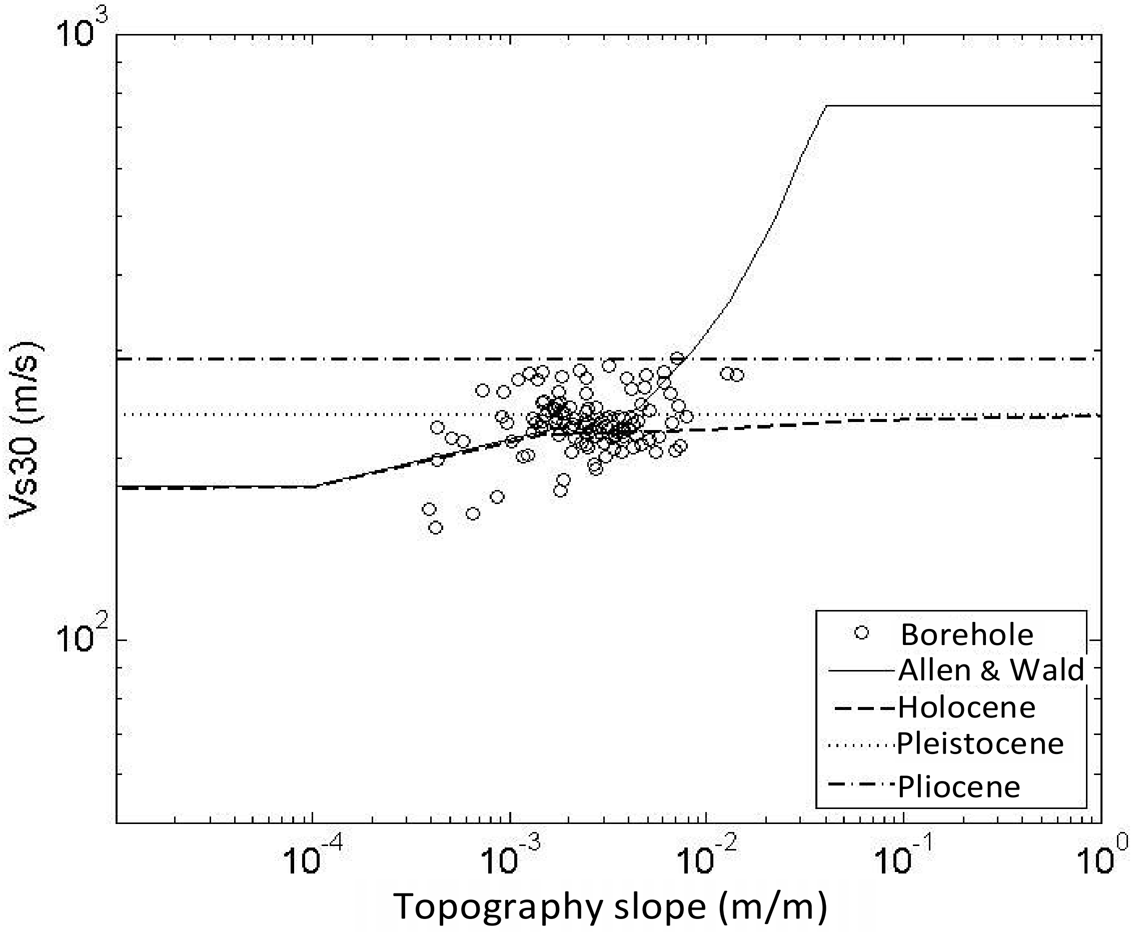

Figure 7. Relationships between V_{S30} and topography slope for Holocene, Pleistocene and Pliocene formations in Ho Chi Minh city inferred from the data at the borehole locations (Black dots). The solid line denotes that relationship proposed by Allen and Wald (2009)

3.4. Estimation of uncertainty for V_{S30} map

The uncertainty of V_{S30} map changes over space, so that we have estimated the error of V_{S30} map by standard deviation σ in the logarithm with base 10 from the formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(V_{S30_i} - \overline{V_{S30}})^2}{(n-1)}}$$

The result of an error of V_{S30} map is shown in Figure 9. The standard deviation σ calculated from the topographic slope (A&W), Strategy 1 (Stra1) and Strategy 2 (Stra2) for Ho Chi Minh City are 1.708, 1.685, and 1.513, respectively. The uncertainty of V_{S30} from Strategy 2 is about 10.2% and 11.4% smaller than that from Strategy 1 and from the approach of only using topographic slope, respectively.

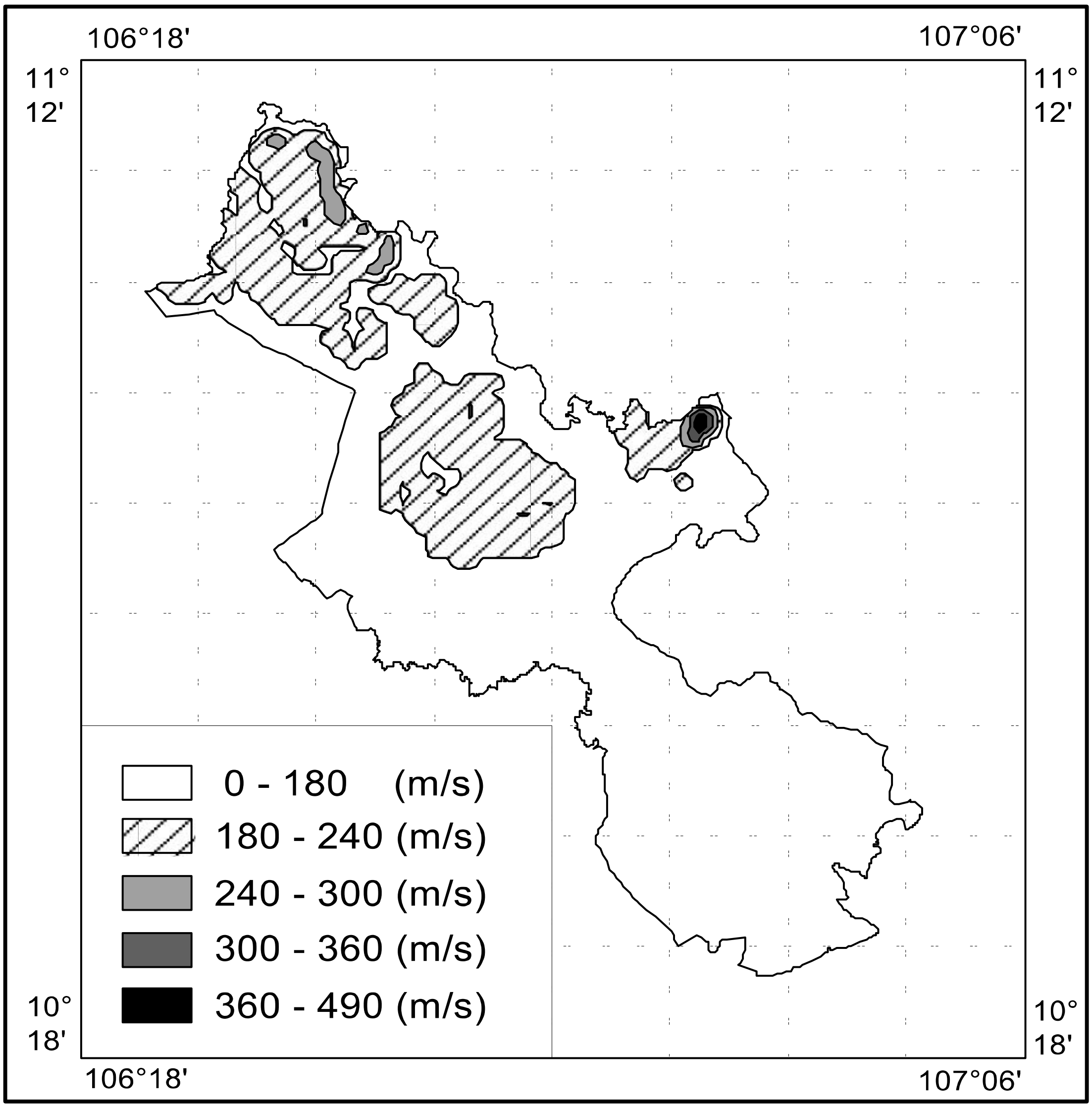

Figure 8. Map of V_{S30} that results from using the correlation of topographic slope and SPT-derived V_{S30} for each geological unit (Strategy 2)

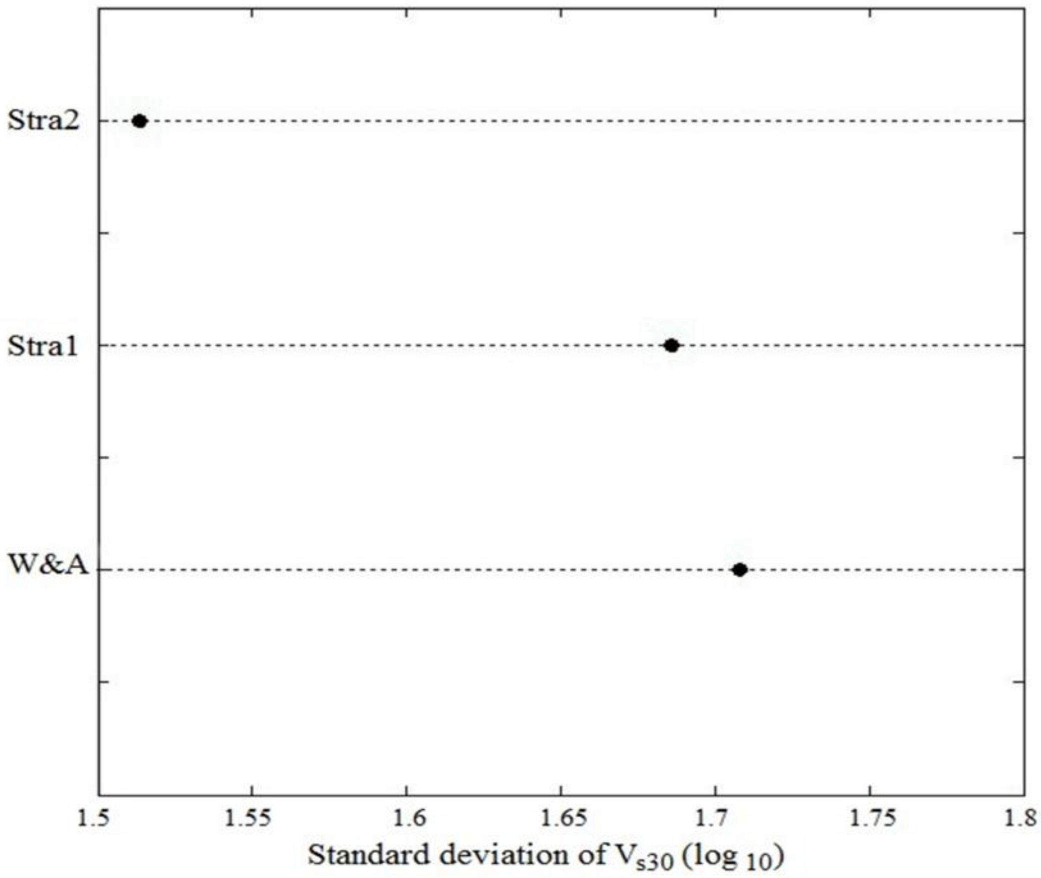

Figure 9. Standard deviation of residuals of V_{S30} resulted from different strategies. A&W refers to the Allen and Wald (2009) slope-based model. Stra 1 refers to Strategy 1 (Figure 6). Stra 2 refers to Strategy 2 (Figure 8)

4. Discussion

The average topographic slope of Ho Chi Minh city area calculated from the DEM of 9 arcsecond resolution is about 0.0024. This result shows that the study area is in a stable continental region (Wald and Allen, 2007). It is consistent with previous studies that the study area is in the stable Sunda plate (Petersen et al., 2007; Simons et al., 2007; Phan T.T., 2012; Nguyen A.D. et al., 2013). It indicates that the study area is suitable to apply ground motion prediction equations developed for seismic stable regions for the purpose of seismic hazard assessment. For example, the ground motion prediction equation developed by Toro et al. (1997) was used by Nguyen H.P. and Pham T.T. (2014) for the compilation of probabilistic seismic hazard maps of the South Central Vietnam region where Ho Chi Minh city is located.

There are major differences between the distribution of V_{S30} values in Figure 5 and the geological formations in Figure 2. Particularly, V_{S30} values in the north of the study area are little differentiation, however, many geological formations concentrate there such as Holocene, Pleistocene, Pliocene and Jura. On the other hand, there is only one geological formation (Holocene) in the south, but there has a large differentiation in V_{S30} values. This may be due to a relatively poor predictor of V_{S30} using the topographic slope at high resolutions of a small area (Wald and Allen, 2007; Allen and Wald, 2009). The differentiations in V_{S30} are sensitive to minor scale variations in elevation, so calculated V_{S30} values are poorly precision for the topographic slope approach only.

By comparing the calculated results in the two strategies (Figure 6 and Figure 8), it indicates that the result in Strategy 2 (Figure 8) is more compatible with the distribution of geological formations in the study area. Both results have the good fit in the trend of distribution of calculated V_{S30} with the locations of measured V_{S30} points and the geological features in the northern area of Ho Chi Minh city where is dense of V_{S30} measurement points. The result in Strategy 1 shows a hard ground in the southern area of the city, which is contrary to the fact that it is a soft ground area. Meanwhile, the result in Strategy 2 reflects the fact of ground in the south though it is sparse of measurement points.

The calculated V_{S30} from Strategy 2 shown in Figure 8 is the best and compatible with the distribution of the geological formations in the study area. Hence, the final calculated result of V_{S30} indicates that Ho Chi Minh City mainly consists of two average shear wave velocity ranges: V_{S30} = 0 - 180 m/s, and V_{S30} = 180 - 240 m/s corresponding to two types of soil: type D and type C, respectively, according to the soil classification in Vietnam Construction Code (TCVN-9386:2012). Type C mainly concentrates in the districts of Cu Chi, Tan Binh, Thu Duc, District 1, District 3, District 5, District 6, District 9, and District 11. Type D with V_{S30} < 180 m/s distributes in the area of District 2, District 4, District 7, District 8, District 10 and District 12, Can Gio, Nha Be, Hoc Mon, Binh Chanh, Phu Nhuan, Binh Thanh, and Go Vap districts.

By comparing the results of two documents reported by Cat N.H. et al. (2009) and Vu T.T. et al. (2010) with our final result (Figure 8), it is found that they are quite similar in terms of soil types as well as their distribution trending in general. However, our result shows more detail of high velocities (240 - 300 m/s) in northern part of the city, while the previous studies do not. Moreover, the resulted V_{S30} map in this study is more consistent with geological features than that of Cat N.H. et al. (2009). It is due to Cat N.H. et al. (2009) used only borehole data to draw the V_{S30} map and then classified the soil type by using the engineering geology map. Thus, our result clearly indicates that suitable data sources with an appropriate incorporating method should be taken into account rather than a single data source of topography slope or borehole only.

5. Conclusions

By using the topographic slope, the SPT-derived shear wave velocities (V_{S30}) of 104 boreholes and geology data, we implement two strategies to establish V_{S30} map for Ho Chi Minh City. It is found that the most reliable approach is Strategy 2, which determines the correlation of topographic slope and SPT-derived V_{S30} for each geological unit. The resulted map has two major ranges of V_{S30}, which are 0 - 180 m/s and 180 - 240 m/s, corresponding to two types of soil: type D and type C, respectively, according to the soil classification in Vietnam Construction Code (TCVN 9386:2012). The uncertainty of V_{S30} in this method reduces 11.4% compared with the approach of only using topographic slope. While, it is about 10.2% smaller than that from Strategy 1, which uses geological units to adjust the residual of SPT-derived V_{S30} values and topographic slope-derived V_{S30} values in each geologic unit. The final result of this study is consistent with geological, borehole data and has high reliability compared to the previous studies.

V_{S30} in the range of 180 - 240 m/s mainly concentrates in the northern area of Ho Chi Minh City including the districts of Cu Chi, Tan Binh, Thu Duc, District 1, District 3, District 5, District 6, District 9, and District 11. Meanwhile, the southern area including District 2, District 4, District 7, District 8, District 10, District 12, Can Gio, Nha Be, Hoc Mon, Binh Chanh, Phu Nhuan, Binh Thanh, and Go Vap districts has soft soils with V_{S30} <180 m/s. The final V_{S30} map can be used in related studies such as establishing of ground motion prediction equation, ground motion simulation, seismic hazard assessment, constructing of seismic micro-zoning map... Our study is a prerequisite for the wide application of this method to build V_{S30} maps for other areas in Vietnam.

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APPENDIX

SPT-derived V_{S30} data at boreholes in Ho Chi Minh City

No.	Longitude (o)	Latitude (o)	V_{S30} (m/s)
1	106.80	10.83	241.1
2	106.82	10.81	238.1
3	106.80	10.82	224.3
4	106.84	10.82	226.2
5	106.79	10.87	279.6
6	106.80	10.87	290.5
7	106.81	10.82	269.1
8	106.81	10.81	195.9
9	106.82	10.83	267.7
10	106.83	10.82	250.3
11	106.82	10.81	247.7
12	106.70	10.79	272.8
13	106.81	10.87	292.4
14	106.74	10.76	264.5
15	106.70	10.78	271.3
16	106.73	10.79	266.2
17	106.72	10.84	278.3
18	106.69	10.76	257.4
19	106.81	10.83	269.5
20	106.71	10.78	190.4
21	106.72	10.86	262.1
22	106.71	10.75	236.3
23	106.79	10.76	241.6
24	106.80	10.76	240.6
25	106.61	10.71	182.8
26	106.46	11.05	208
27	106.74	10.84	218.5
28	106.68	10.81	235.6
29	106.64	10.77	251.3
30	106.47	11.14	205.4
31	106.47	10.98	290.2
32	106.67	10.80	250.6
33	106.68	10.90	245
34	106.80	10.81	291.8
35	106.50	11.04	227.7
36	106.43	10.98	256.2
37	106.66	10.78	249.6
38	106.66	10.77	219.2
39	106.66	10.84	204
40	106.69	10.77	212.9
41	106.65	10.75	235.5
42	106.68	10.79	236.1
43	106.68	10.81	235.5
44	106.67	10.76	222.4
45	106.66	10.75	236.1
46	106.61	10.72	210.5
47	106.63	10.76	265.3
48	106.63	10.81	283.8
49	106.72	10.72	262.5
50	106.55	10.89	200.2
51	106.62	10.87	256.6
52	106.49	11.00	220.1
53	106.60	10.96	236.1
54	106.62	10.73	280
55	106.70	10.88	220.9
56	106.61	10.87	183.8
57	106.57	11.03	227
58	106.64	10.78	235.1
59	106.61	10.95	233.2
60	106.64	10.85	246.1
61	106.68	10.87	262.5
62	106.59	10.88	255.4
63	106.54	10.99	238.9
64	106.62	10.69	251
65	106.68	10.80	233.3
66	106.52	11.09	194.2
67	106.72	10.72	213.1
68	106.60	10.79	233.9
69	106.63	10.83	228.2
70	106.62	10.98	227.1
71	106.61	10.70	239.3

72	106.53	10.87	196.6	89	106.48	10.97	234.1
73	106.64	10.76	225.4	90	106.70	10.73	241.3
74	106.59	10.96	259.5	91	106.65	10.93	204.2
75	106.54	10.88	236.5	92	106.65	10.85	236.9
76	106.62	10.86	234.2	93	106.70	10.79	235.2
77	106.68	10.83	232.3	94	106.65	10.80	249.7
78	106.53	11.04	255.3	95	106.66	10.81	280.1
79	106.58	10.88	225.4	96	106.64	10.80	273.1
80	106.55	10.93	218.2	97	106.63	10.82	279.7
81	106.67	10.79	245.8	98	106.65	10.77	250.3
82	106.54	10.95	250.2	99	106.66	10.79	226.7
83	106.61	10.81	256.3	100	105.97	10.80	113
84	106.70	10.77	242	101	105.97	10.80	116.9
85	106.68	10.84	242	102	105.97	10.80	118.7
86	106.67	10.77	241	103	105.97	10.80	120.5
87	106.48	10.96	234.1	104	106.43	11.01	213.9
88	106.56	10.87	234.1				