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# ASSESSMENT OF THE SEISMIC SITE EFFECT IN THE HANOI URBAN AREA

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**SUMMARY OF GEOPHYSICS DOCTORAL THESIS**

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# INTRODUCTION

Hanoi is the capital of Vietnam, the political and administrative center of the country. According to the planning project to 2050, Hanoi consists of a central urban area and 5 satellite urban areas (Fig. 1). The central urban area plays the most important role as the nucleus of Hanoi. Previous studies [Nguyen Duc Dai et al., 1996, Vu Nhat Thang et al., 2003] showed that the ground of Hanoi is soft sediment. It is mainly composed of mud, clay and fine-grained sand. This ground often amplifies seismic waves more times. Furthermore, the study on seismic activity [Nguyen Dinh Xuyen et al., 1994] showed that Hanoi is located on the Red River fault zone (RRF). The seismic intensity can reach the level VIII (MSK-64 scale), which means that the seismic hazard is high, the risk of earthquake-induced damage is great. Therefore, this thesis aims at studying the ground motion amplification with the title of the Project: "**Assessment of the seismic site effect in the Hanoi urban area**", in order to determine the characteristic parameters related to the physico-mechanical properties of rock-soil layers to serve the planning and the design of structures for earthquake resistance in response to and mitigation of earthquake-induced damage for urban communities.

**The objective of the thesis:** The thesis aims to clarify that the amplification of seismic waves at the surface in the Hanoi urban area is due to local site conditions.

**The content of the thesis:** (1) Collecting, updating and synthesizing the data on microtremor measurement and engineering geology; (2) Additionally measuring single-station microtremor; (3) Researching and completing the procedure of the seismic site effect assessment by using microtremor technique; (4) Determining the ground motion amplification factor in the Hanoi urban area.

**New points of the thesis:** (1) Clarifying the relationship to between the characteristics of microtremor and local site conditions in the Hanoi urban area; (2) Constructing a zoning map of ground types A, B, C, and D according to shear-wave velocity in the top 30 m ($V_{S30}$) in the Hanoi urban area; (3) Determining the amplification factor of ground types B, C and D in the Hanoi urban area according to the technique of HVSR curve simulation by genetic algorithm.

**The structure of the thesis:** In addition to the introduction and conclusion, the thesis includes 5 chapters, namely: Chapter 1. Overview of seismic site effect research and ground condition of the study area; Chapter 2. Methodology of seismic site effect research; Chapter 3. Data source and analysis process; Chapter 4. Characteristics of microtremor in the Hanoi urban area; Chapter 5. Seismic site effect in the Hanoi urban area.

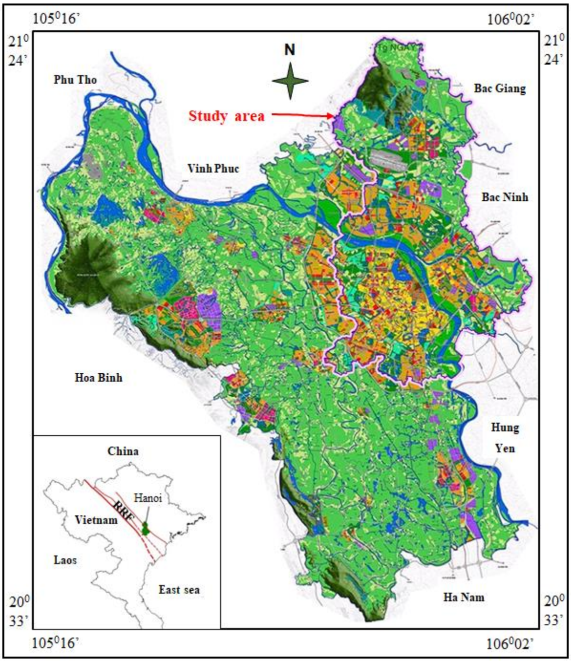



Figure 1. Map of the study area. Including 12 urban districts (Ba Dinh, Cau Giay, Dong Da, Ha Dong, Hai Ba Trung, Hoan Kiem, Hoang Mai, Long Bien, Tay Ho, Thanh Xuan, North Tu Liem and South Tu Liem) and 4 suburban districts (Dong Anh, Gia Lam, Soc Son and Thanh Tri). The total study area is about 1000km$^2$.

# CHAPTER 1: OVERVIEW OF SEISMIC SITE EFFECT RESEARCH AND GROUND CONDITION OF THE STUDY AREA

## 1.1. The seismic site effect research in the world and in Vietnam

The seismic site effect research began during the period of the second industrial revolution. Studies have shown that the different amplification is due to the different ground types [Milne, 1898] or the strong amplification occurs in the areas with thick alluvial deposits [Ohta and Goto, 1978; Singh et al., 1989; Fletcher and Wen, 2005]. This shows that the local site significantly amplifies seismic waves at the surface. Each local site has its characteristic parameters related to the physico-mechanical properties of rock-soil such as shear-wave velocity ($V_S$), density, vibration damping coefficient, H/V dominant frequency ($F_0$) and the layer thickness. In which, $V_S$ and $F_0$ are the two most important parameters because they are directly related to the seismic wave propagation speed and the resonant frequency for the buildings. Consequently, the standards of the design of structures for earthquake resistance are directly related to these parameters.

In Vietnam, the seismic site effect study is mainly carried out in the following directions: 1- Constructing the peak ground acceleration (PGA) maps for the outcrop with $V_{S30}$ is1100 m/s or for hard rock with $V_{S30}$ is 800 m/s, PGA values in other sites are interpolated according to this PGA value [Nguyen Dinh Xuyen, 2004; Nguyen Hong Phuong, 2006; Pham Dinh Nguyen et al., 2012]; 2- Calculating PGA values for some typical sites, the PGA values in other sites are interpolated according to this PGA value [Nguyen Ngoc Thuy, 2004]; 3- Determining the PGA value by simulating acceleration waveforms to serve the construction of response spectrum for the design of structures for earthquake resistance [Tran Thi My Thanh, 2007].

In Hanoi, the seismic site effect research has been carried out by many authors. Some of the main research directions can be mentioned as follows: 1- Regarding engineering geology, the studies [Nguyen Duc Dai, 1996; Vu Nhat Thang, 2003; Nguyen Huy Phuong, 2004] used borehole data to build engineering geological maps, ground site structure maps, etc. serving the classification of ground types or site structural characteristics; 2- Regarding seismology, the studies conducted by the Institute of Geophysics in 1964, 1973, 1978, 1990 and 1992-1994 have established the seismic microzoning map of Hanoi according to the seismic stiffness method. From 2003 to 2015, the studies by [Tulandhar et al., 2004; Nguyen Tien Hung, 2011; Nguyen Hong Phuong, 2014] have built the $T_0$ or $F_0$ distribution map from single-station microtremor data and processed by Nakamura technique (1989). Recently, Bui Thi Nhung (2017) classified the ground of Hanoi urban area according to the lithological characteristics, Pham The Truyen (2020) calculated the PGA value for 5 central districts by extreme earthquake sources, Giang Trung Kien (2022) calculated the PGA value in the west-east cross section by simulating the acceleration records. Thus, it can be seen that previous studies have only focused on determining the $T_0$ or $F_0$ value, the physico-mechanical properties of rock-soil or the ground motion amplification based on an extreme earthquake scenario, meanwhile research on the amplification caused by the local site in the Hanoi urban area has not yet been conducted comprehensively. Therefore, this study has classified the ground types, determined the ground motion amplification factor according to the $V_{S30}$ value calculated from the single-station microtremor data in Hanoi urban area.

## 1.2. General ground condition of the study area

There are 3 types of topography in the study area: Low mountain, hill and plain. According to the engineering geological data in previous reports [Nguyen Duc Dai, 1996; Vu Nhat Thang et al., 2003], the bedrock only outcrops in the northern mountainous area and then sinks under the near-surface sedimentary layer in the plains. The near-surface sedimentary layer is Quaternary sediment formed from the Early Pleistocene to the Late Holocene, including 5 formations from top to bottom, namely Thai Binh, Hai Hung, Vinh Phuc, Hanoi and Le Chi, respectively. It is mainly composed of fine-grained sand, clay, yellow sand, gravel and pebble. The near-surface sedimentary thickness (D) tends to increase gradually from north to south (reaching 0 m in Soc Son and 116 m in Hoang Mai) and from west to east (reaching 55 m in Bac Tu Liem and 100 m in Long Bien), Figure 1.10 .

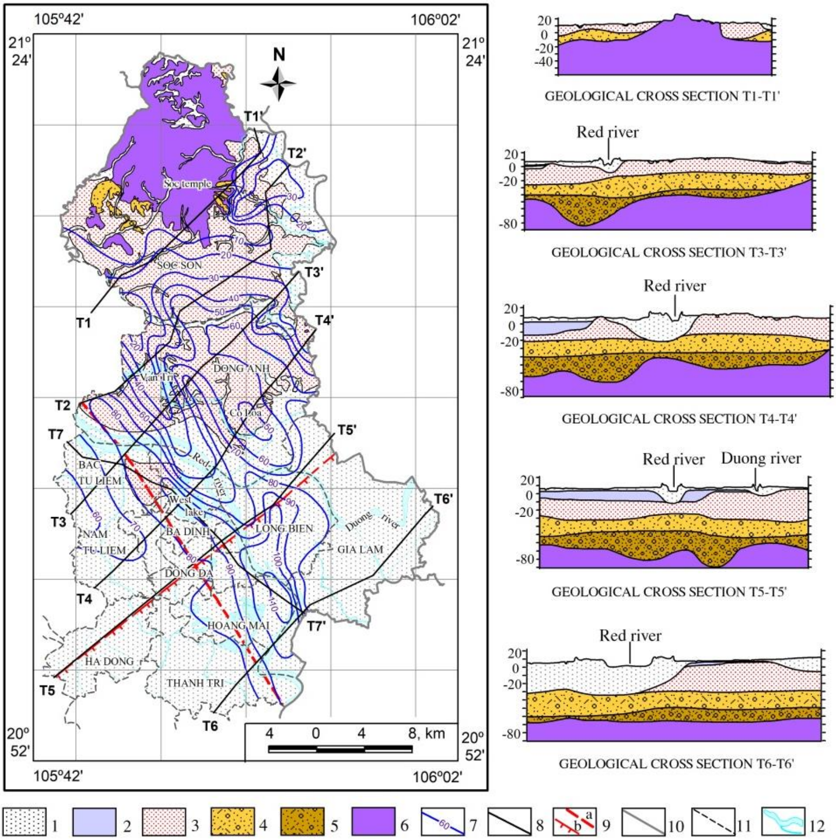



Figure 1.10. Map of engineering geology, distribution of near-surface sedimentary thickness and 2D geological sections of the study area. (1) Thai Binh Formation; (2) Hai Hung Formation; (3) Vinh Phuc Formation; (4) Hanoi Formation; (5) Le Chi Formation; (6) bedrock; (7) contours of near-surface sedimentary thickness and value in meter (Vu Nhat Thang et al., 2003); (8) geological cross-section; (9) tectonic fault: a. Vinh Ninh fault, b. Gia Lam-Chuong My fault; (10) provincial boundary; (11) district boundary and (12) river, stream or lake.

# CHAPTER 2: METHODOLOGY OF SEISMIC SITE EFFECT RESEARCH

## 2.1. Microtremor and survey techniques

Microtremors are very small near-surface natural vibrations, with the displacements amplitude from $10^{-7}$ to $10^{-5}$ m. They are generated from activities such as earthquake, ocean waves, wind, human activities, etc.

Microtremor is measured by some techniques as follows: The reference site technique is the measurement by 02 seismometers; Single-station technique is the one-time measurement using only one seismometer and Array technique is the simultaneous measurement by many seismometers.

## 2.2. Methodology of microtremor characteristics assessment

Microtremors at the surface are standing waves propagating from the boundary between the rock-soil layers below. Then, the microtremor wave frequency is:

$$f = (2k + 1)\frac{V}{4h} \quad (k=0, 1, 2, \ldots) \qquad (2.1)$$

where $f$ is microtremor wave frequency; $k$ is the number of microtremor wave packet; $V$ is the microtremor wave velocity; $h$ is the depth from the surface to the bottom of the layer.

The technique of H/V spectral ratio (HVSR) analysis was proposed by Nakamura (1989). This technique is used to determine H/V dominant frequency ($F_0$) from the single-station microtremor measurement. The general formula is as follows:

$$HVSR = \frac{\sqrt{(F_{NS}^2 + F_{EW}^2)/2}}{F_Z} \qquad (2.2)$$

where $F_{NS}$ is Fourier spectrum of north-south component; $F_{EW}$ Fourier spectrum of east-west component; $F_Z$ Fourier spectrum of vertical component.

The technique of assessing the relationship between $F_0$ and D was proposed by Seht and Wohlenberg (1999). The theoretical function is given by:

$$D = a * F_0^b \qquad (2.3)$$

where $a = \left[\frac{V_0(1-x)}{4}\right]^{1/(1-x)}$; $b = -\frac{1}{1-x}$ and depending on the local site

## 2.3. Methodology of seismic site effect assessment

According to SH-wave transfer technique by Haskell (1953, 1960), in a medium with n parallel, homogeneous and isotropic layers, the ratio of reflected wave amplitude ($\upsilon_n$') to incident wave amplitude of n layers ($\upsilon_n$'') and the ratio of wave amplitude at the free surface ($\upsilon_0$) and incident wave amplitude of n layers ($\upsilon_n$'') are given by:

$$\upsilon_n'/\upsilon_n'' = \frac{\mu_n r_{\beta n} A_{11} - A_{21}}{\mu_n r_{\beta n} A_{11} + A_{21}} \quad (2.4)$$

$$\upsilon_0/\upsilon_n'' = \frac{2\mu_n r_{\beta n}}{\mu_n r_{\beta n} A_{11} + A_{21}} \quad (2.5)$$

The genetic algorithm developed by Holland et al. (1975) is an advanced search engine, used to find the results that best consistent with practice. The correlation function used is 80% of linear correlation and 20% of $F_0$ correlation, which has the following form:

$$f = \left(\frac{r+1}{r}\right) \times 0.8 + \left(1 - \frac{|F_{SH} - F_{HV}|}{0.3 \times F_{HV}}\right) \times 0.2 \quad (2.6)$$

where $F_{SH}$ is the dominant frequency according to the theoretical transfer function; $F_{HV}$ is $F_0$ determined at the microtremor measurement point and r is the linear correlation coefficient between the transferred SH-wave chart and the actual measured HVSR curve.

The ground motion attenuation function was established by Campbell and Bozognia (2008), suitable for the conditions of Vietnam, with the general form: $Ln(GM) = f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed}$ (2.7)

where $f_{mag}$ is a function related to the moment magnitude ($M_W$); $f_{dis}$ is a function related to distance from the epicenter zone to the measuring point, $f_{flt}$ is a function related to the fault mechanism, $f_{hng}$ is a function related to the measuring point location and the rupture plane of a fault, $f_{site}$ is a function related to the local site condition, and $f_{sed}$ is a function related to the basin structure in the study area.

Ground motion amplification factor (K): $K = \frac{GM_S}{GM_R}$ (2.8)

where GMs and $GM_R$ are ground motion indexes of the measured according to actual $V_{S30}$ and $V_{S30}$ is 800 m/s.

## 2.4. Assessment standards

Vietnam national standard TCVN 9386:2012, ground classification according to $V_{S30}$ value.

German standard DIN 4149:2005, zoning according to motion frequency.

# CHAPTER 3: DATA SOURCE AND ANALYSIS PROCESS

## 3.1. Seismometer

The seismometers used are 7 sets of microtremor measuring device manufactured by Tokyo Sukushin, Japan. Each set includes a SAMTAC-801H recorder and a VSE315D or VSE355EV sensor. The recorder has a 24bit resolution and the sensor has 6 components (3 velocity components and 3 acceleration components) with a frequency range from 0.1 to 50 Hz, Figure 3.1. At each point, measurements were made continuously over a period of 20 minutes. The sampling frequency of the measurement is 200 samples/second. The data used for analysis are the three velocity components (NS, EW, Z) of microtremor vibration tapes. Measurement points are precisely located using a handheld global positioning system (GPS).


Figure 3.1. Microtremor measurement device and field implementation

## 3.2. Data source for research

The main data used include 834 single-station microtremor measurement points, with 497 measurement points carried out in this study and 09 microtremor array measurement points [Wen et al., 2012; Nguyen Hong Phuong, 2014], Figure 3.4.

Additionally, other data are also collected, including:

- 157 values of near-surface sedimentary thickness (D) according to borehole in studies [Nguyen Duc Dai, 1996, Vu Nhat Thang et al., 2003; Nguyen Dinh Thong et al., 2012];
- 39 boreholes with $N_{SPT}$ index and lithological characteristics in the research by Nguyen Huy Phuong (2004);
- 36 $V_{S30}$ values synthesized in studies [Trinh Viet Bac et al., 2011; Nguyen Sinh Minh et al., 2015; Lai Hop Phong et al, 2020];
- Engineering geological atlases, 06 Quaternary sedimentary cross-sections and 02 engineering geological cross-sections by Nguyen Duc Dai (1996); The Quaternary sediment thickness map by Vu Nhat Thang et al. (2003); The ground site structure map of Hanoi at 1:25.000 scale by Nguyen Huy Phuong et al. (2004).
- The reliability of single-station microtremor measurement data and engineering geological cross-sections is also verified and assessed in this study. The results show that: 1- The HVSR curve established from the single-station microtremor measurement does not change with the measurement time and the measurement device, which means that the single-station microtremor data used are synchronous and reliable; 2- The near-surface sedimentary thickness values of the engineering geological cross-sections by Nguyen Duc Dai (1996) and the new boreholes [Vu Nhat Thang et al., 2003; Nguyen Dinh Thong et al., 2012] are significantly different, therefore the near-surface sedimentary thickness used in this study is that of the boreholes.

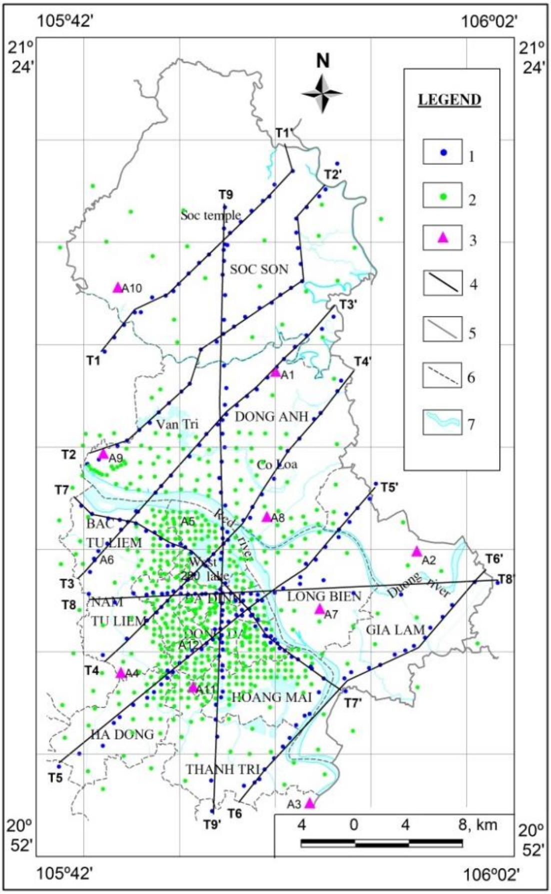



Figure 3.4. Distribution map of microtremor measurement points. (1) single-station microtremor measurement points according to the profile; (2) single-station microtremor measurement points according to the area; (3) microtremor array measurement points; (4) microtremor survey profile; (5) provincial boundary; (6) district boundary and (7) river, lake, or stream.

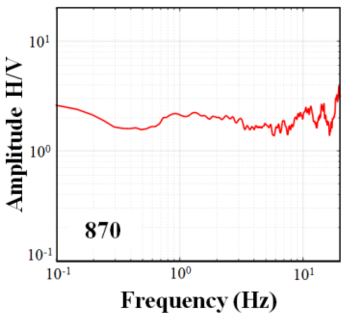
## 3.3. Analysis process

From the $V_{S30}$ values calculated by single-station microtremor measurement data, the analysis process consists of the following main steps: Step 1: Correcting the earthquake source parameters; Step 2: Calculating $GM_S$ and $GM_R$ values of each earthquake scenario; Step 3: Determining the factor K by the equation (2.8) at single-station microtremor measurement points; Step 4: Determining the amplification factor of ground types for each scenario; Step 5: Calculating the average amplification factor of ground types; and Step 6: Analyzing and assessing the results.

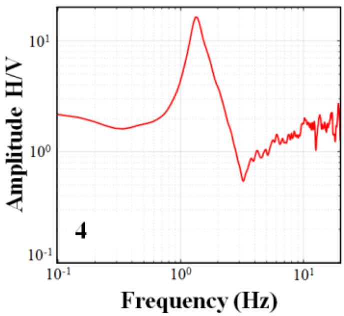
# CHAPTER 4
# CHARACTERISTICS OF MICROTREMOR IN THE HANOI URBAN AREA

## 4.1. Characteristics of the HVSR curve shape in Hanoi urban area

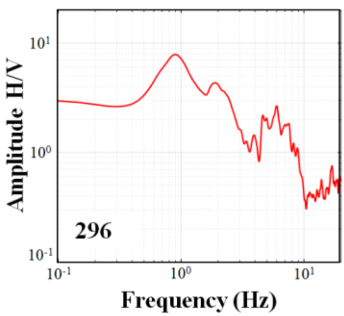
The Nakamura technique (1989) was applied to 834 single-station microtremor measurement points to obtain 831 corresponding HVSR curves. These HVSR curves are classified into 3 shapes as follows: 1- Flat (no obvious peak), including 03 curves, only found at the exposed outcrop in the north of Soc Son district; 2- Bell-shaped (single peak), consisting of 529 curves, mainly in the stable plains of the north, the west and the south; and 3- Saddle-shaped (multiple peak), including 302 curves, mainly in the unstable plains of the east, along the Red River or the strongly weathered rock zones in the northern mountain foot zones of Soc Son district, Figure 4.1.




(a)




(b)




(c)

Figure 4.1. The characteristics of the HVSR curve shape in Hanoi urban area. (a) Flat HVSR curve; (b) Bell-shaped HVSR curve; and (c) Saddle-shaped HVSR curve.

## 4.2. Characteristics of the H/V dominant frequency ($F_0$) in Hanoi urban area

From 834 HVSR curves, 834 $F_0$ values are determined. The $F_0$ value reached 0.37 to 11.67 Hz (Fig. 4.3). According to DIN 4149:2005 standard, 834 $F_0$ values are divided into 4 different dominant frequency domains: high dominant frequency domain, $F_0$ greater than 3.5Hz; medium dominant frequency domain, $F_0$ from 1.3 to 3.5 Hz; low dominant frequency domain, $F_0$ from 0.8 to 1.3 Hz and very low dominant frequency domain, $F_0$ less than 0.8 Hz (Fig. 4.4).

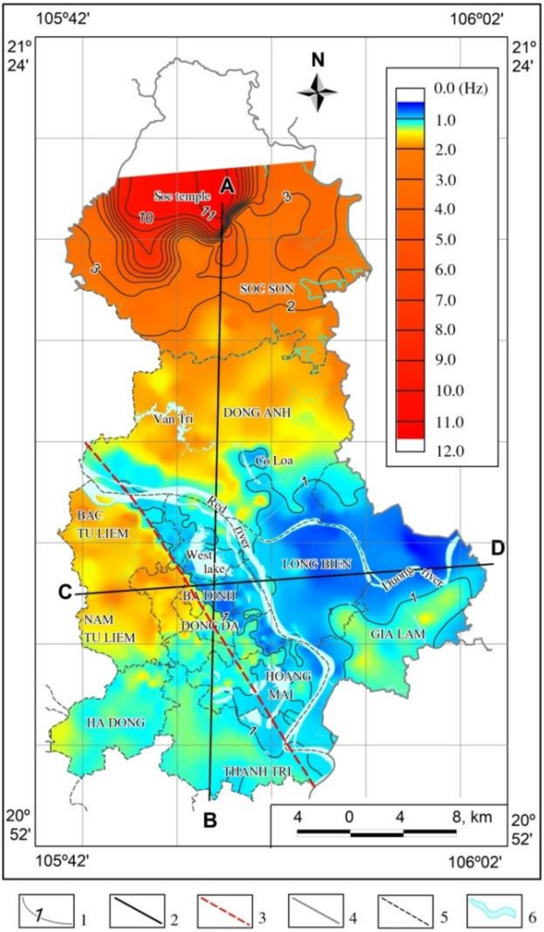



Figure 4.3. H/V dominant frequency distribution map in Hanoi urban area. (1) contour lines of $F_0$ and values in Hz; (2) $F_0$ value survey profiles (AB and CD); (3) Vinh Ninh fault; (4) provincial boundary; (5) district boundary; and (6) rivers, lakes, or streams

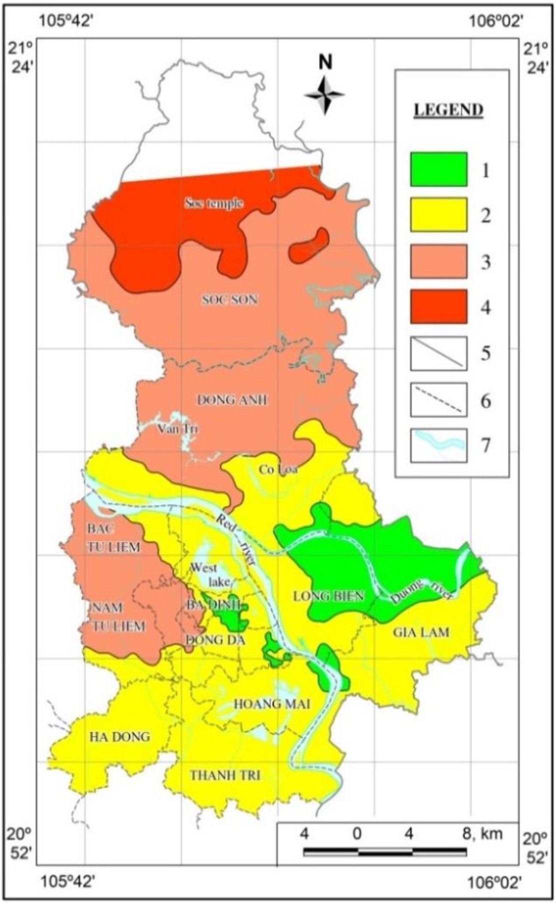
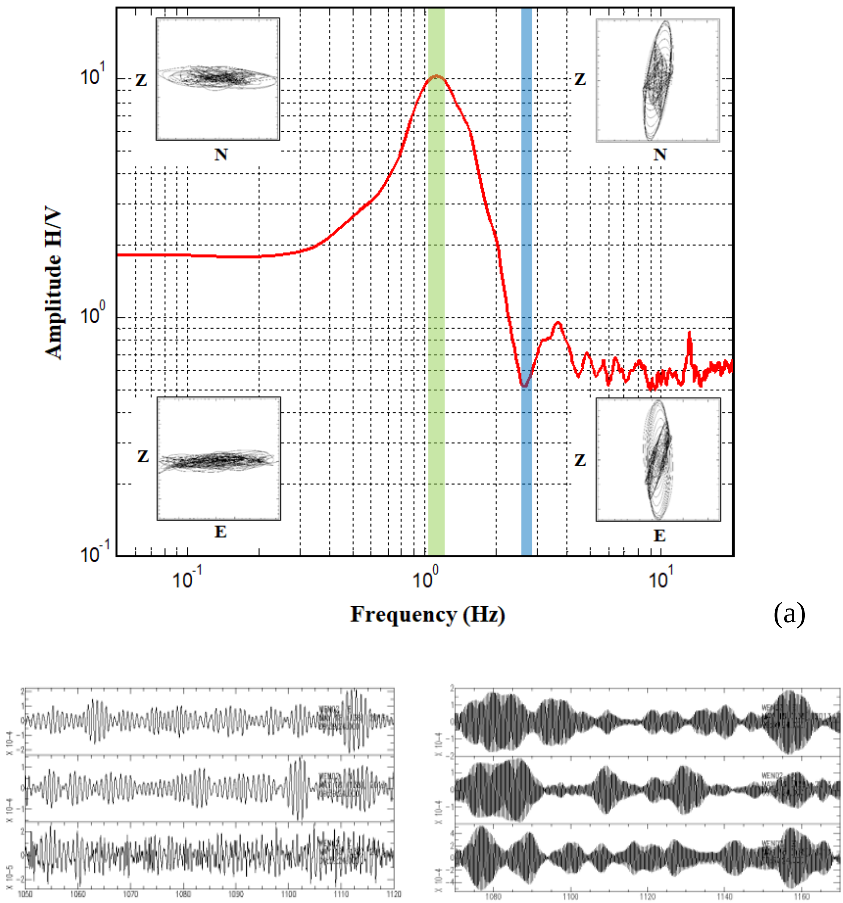



Figure 4.4. H/V dominant frequency zoning map in Hanoi urban area. (1) $F_0$ less than 0.8 Hz; (2) $F_0$ from 0.8 to 1.3 Hz; (3) $F_0$ from 1.3 to 3.5 Hz; (4) $F_0$ greater than 3.5 Hz; (5) provincial boundary; (6) district boundary; and (7) river, lake, or stream.

**4.3. Microtremor characteristics in the special frequency domain in Hanoi urban area**

The types of microtremor presented in two special narrow frequency domains show that: 1- The motions in the frequency domain around the dominant peak (two insets on the left) are mainly in horizontal direction (N or E axis) similar to SH-wave motion (Fig. 4.6b); 2- In contrast, the motions in the frequency domain around the trough point (two insets on the right) are mainly in vertical direction (Z axis) similar to Rayleigh wave motion (Fig. 4.6c).




(a)

(b) (c)

Figure 4.6. Microtremor characteristics in two special frequency domains in Hanoi urban area. (a) HVSR curve, special frequency domains (green denotes the special narrow frequency domain around the dominant peak, blue represents the special narrow frequency domain around the trough point) and types of motion polarized in vertical and horizontal directions; (b) Microtremor record filtered in the narrow frequency domain around the dominant peak, (c) Microtremor record filtered in the narrow frequency domain around the trough point.

### 4.4. Relationship between the H/V dominant frequency ($F_0$) and the near-surface sedimentary thickness (D) in Hanoi urban area

From 64 pairs of D values according to boreholes have the depth to bedrock ($D_K$) and $F_0$ values measured next to these boreholes, the empirical coefficients of the equation (2.3) found by non-linear regression are a=81,851 and b=-0.942, with a correlation coefficient of 0.84 (Figure 4.7). Then the relationship between $D_K$ in meter and $F_0$ in Hz in Hanoi urban area is given by:

$$D_K = 81{,}851 * F_0^{-0{,}942} \qquad (4.1).$$

The correlation coefficient of 0.84 shows that the relationship between $D_K$ and $F_0$ is reliable, therefore the equation (4.1) is used to find D based on $F_0$ ($D_T$) at the remaining microtremor measurement points. Based on $D_T$ values, the zoning map of $D_T$ values in Hanoi urban area was built (Fig. 4.9). Figure 4.9 shows that the smallest $D_T$ is less than 20 m in the northern mountainous zones of Soc Son district, the largest $D_T$ is over 100 m in the central and eastern areas, meanwhile $D_T$ along the Red River and the southern area is over 70 m. This result is also consistent with the borehole result [Vu Nhat Thang et al., 2003].

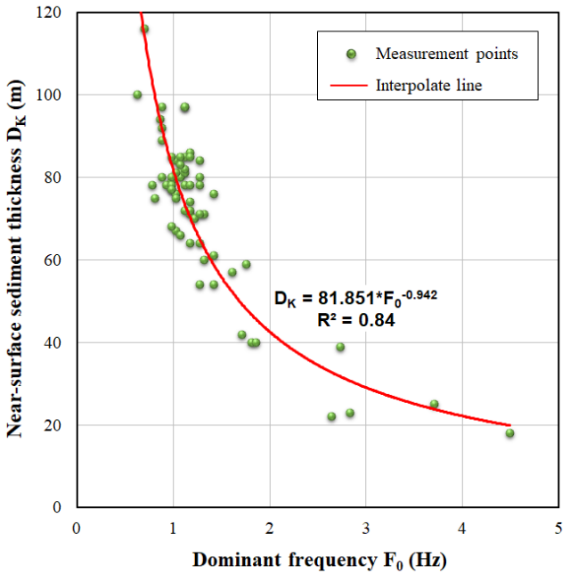



Figure 4.7. The empirical correlation between the near-surface sedimentary thickness ($D_K$) and microtremor dominant frequency ($F_0$) in Hanoi urban area.

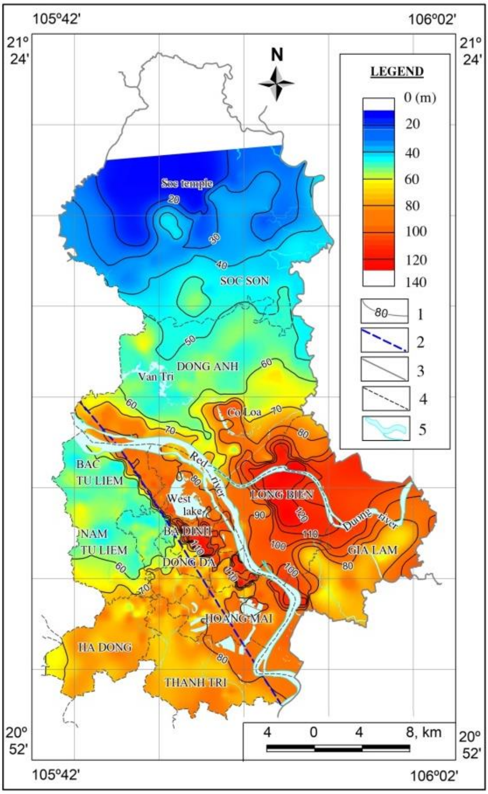



Figure 4.9. The near-surface sedimentary thickness zoning map in Hanoi area obtained from microtremor data. (1) the near-surface sedimentary thickness and value in meter; (2) tectonic fault; (3) provincial boundaries; (4) district boundaries and (5) river, stream, or lake.

# CHAPTER 5
# SEISMIC SITE EFFECT IN HANOI URBAN AREA

## 5.1. Initialization models

$V_S$ value of near-surface soil layers is selected according to borehole data and $V_S$ value of deep rock layer is selected according to microtremor array measurement data. Using engineering geological database, 03 initialization models were built corresponding to 03 typical ground types of the study area.

## 5.2. Near-surface $V_S$1D structure charts in Hanoi urban area

From 816 HVSR curves, 816 $F_0$ values and 03 initialization models, 2448 optimal $V_S$1D structure charts were established according to the technique of HVSR curve simulation by genetic algorithm (GA). The obtained simulation results show that the shape and position of dominant peaks are comprehensively simulated.

**5.3. Ground classification in Hanoi urban area**

From 2448 optimal $V_S$1D structure charts, 816 $V_{S30}$ values were determined. Applying TCVN 9386:2012 standard, the studied area is divided into 3 different ground types: 1- The type B ground corresponding to the area with $V_{S30}$ from 360 to 800 m/s, only found in the mountainous or the mountain foot delta in the northern of Soc Son district; 2- The type C ground corresponding to the area with $V_{S30}$ from 180 to 360 m/s, occupying most of the plains, and 3- The type D ground corresponding to the area with $V_{S30}$ less than 180 m/s, distributed along Long Bien-Hoan Kiem-Hoang Mai-Thanh Xuan (Fig. 5.8).

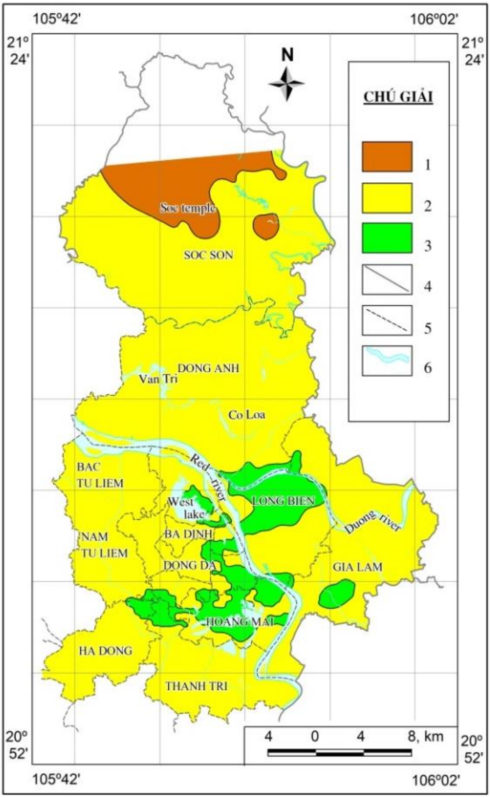



Figure 5.8. The ground classification map established in Hanoi urban area. (1) type B ground, $V_{S30}$ from 360 to 800 m/s; (2) type C ground, $V_{S30}$ from 180 to 360 m/s; (3) type D ground, $V_{S30}$ less than 180 m/s; (4) provincial boundary; (5) district boundary and (6) river, lake, or stream.

## 5.4. Ground motion amplification factor in Hanoi urban area

Scenario parameters are determined from 03 earthquakes (Thanh Hoa 1635; Vinh Phuc 1958; Bac Giang 1961) with different $M_W$ and shaking directions. The ground motion amplification factors of 03 scenarios ($K_1$, $K_2$, $K_3$) are calculated by the equation (2.8). The distribution of $K_1$, $K_2$, $K_3$ values is depicted in Figure 5.12, Figure 5.16, Figure 5.20, respectively. Based on 816 $V_{S30}$ values and $K_1$, $K_2$, $K_3$ values, their relationship diagrams are built as shown in Figure 5.13, Figure 5.17, Figure 5.21. From $K_1$, $K_2$, $K_3$ values, the average ground motion amplification factors according to 03 scenarios ($K_{1tb}$, $K_{2tb}$, $K_{2tb}$) and that of 03 scenarios (K) are calculated for ground types B, C, D as described in Table 5.9. The relationship between the pairs of ground motion amplification factors according to the scenarios in the Hanoi urban area is illustrated in Figure 5.22. Figure 5.22 shows that their relationship is good, with the correlation coefficient of above 0.89. This confirms that the ground motion amplification factors in the Hanoi urban area is less dependent on the magnitude of seismic source and the shaking direction.

Table 5.9. Amplification factor of ground types calculated according to 3 scenarios in Hanoi urban area.

| **GROUND TYPE** | **GROUND MOTION AMPLIFICATION FACTOR** | | | |
|---|---|---|---|---|
| | $K_{1tb}$ | $K_{2tb}$ | $K_{3tb}$ | K |
| B | 1.28 | 1.27 | 1.24 | 1.26 |
| C | 1.48 | 1.47 | 1.45 | 1.47 |
| D | 1.68 | 1.68 | 1.63 | 1.66 |

***Note:*** $K_{1tb}$, $K_{2tb}$, $K_{3tb}$ are the average ground motion amplification factors according to the scenarios 1, 2, 3 respectively; K is the average ground motion amplification factor of 03 scenarios.

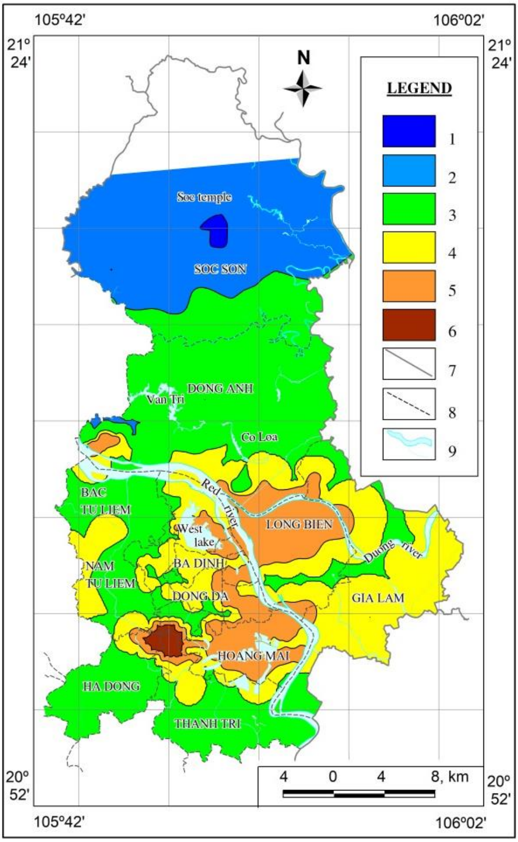



Figure 5.12. Distribution map of ground motion amplification factor according to the scenario 1. (1) $K_1$ less than 1.3; (2) $K_1$ from 1.3 to 1.4; (3) $K_1$ from 1.4 to 1.5; (4) $K_1$ from 1.5 to 1.6; (5) $K_1$ from 1.6 to 1.7; (6) $K_1$ greater than 1.7; (7) provincial boundary; (8) district boundary and (9) river, lake and stream.

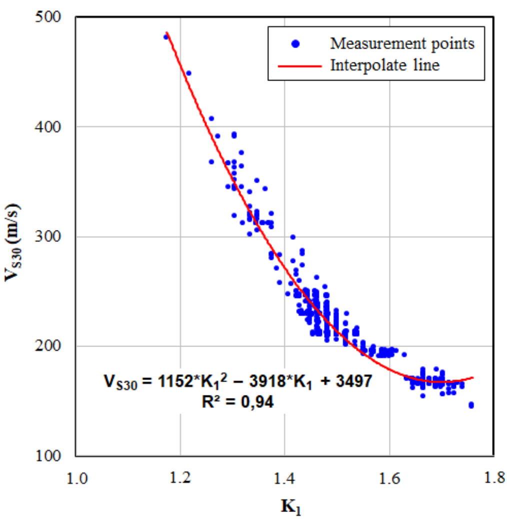



Figure 5.13. Diagram of relationship between $K_1$ and $V_{S30}$ in the Hanoi urban area.

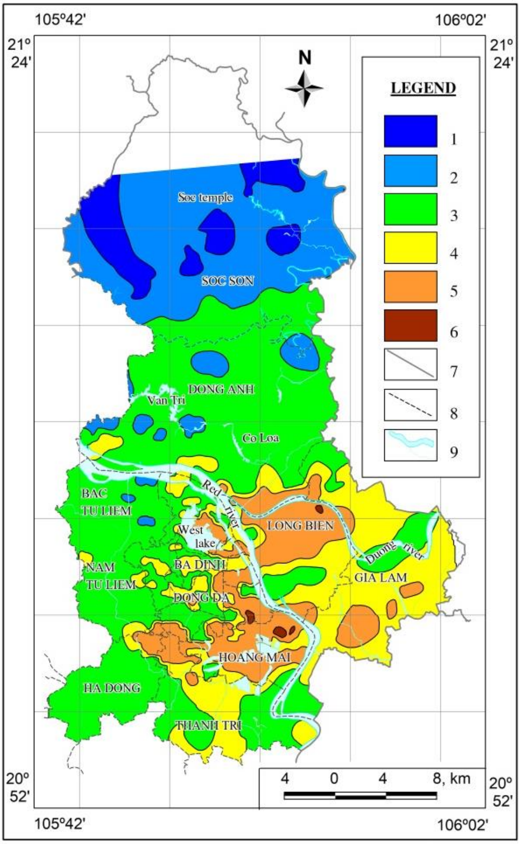



Figure 5.16. Distribution map of ground motion amplification factor at measurement points according to the scenario 2.
(1) $K_1$ less than 1.3;
(2) $K_1$ from 1.3 to 1.4;
(3) $K_1$ from 1.4 to 1.5;
(4) $K_1$ from 1.5 to 1.6;
(5) $K_1$ from 1.6 to 1.7;
(6) $K_1$ greater than 1.7;
(7) provincial boundary;
(8) district boundary and (9) river, lake, stream.

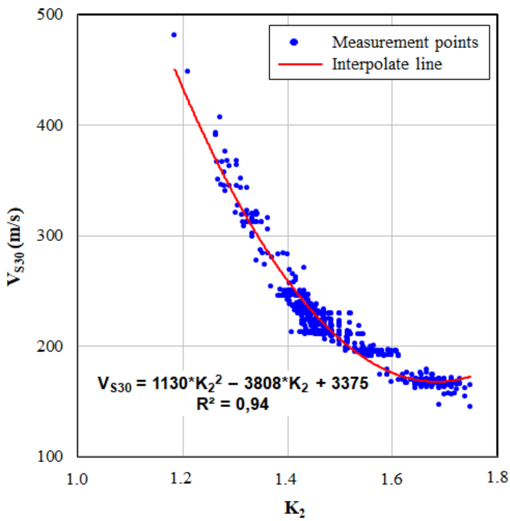



Figure 5.17. Diagram of relationship between $K_2$ and $V_{S30}$ in the Hanoi urban area.

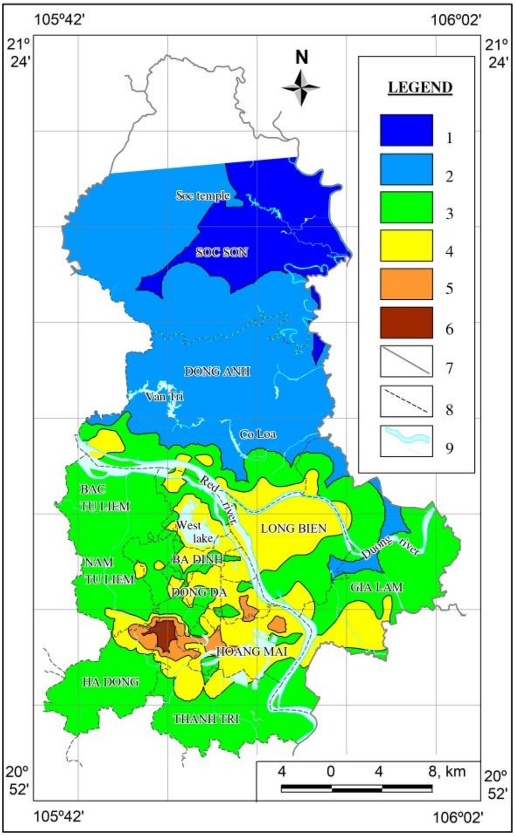



Figure 5.20. Distribution map of ground motion amplification factor at microtremor measurement points according to the scenario 3. (1) $K_1$ less than 1.3; (2) $K_1$ from 1.3 to 1.4; (3) $K_1$ from 1.4 to 1.5; (4) $K_1$ from 1.5 to 1.6; (5) $K_1$ from 1.6 to 1.7; (6) $K_1$ greater than 1.7; (7) provincial boundary; (8) district boundary and (9) river, lake, stream.

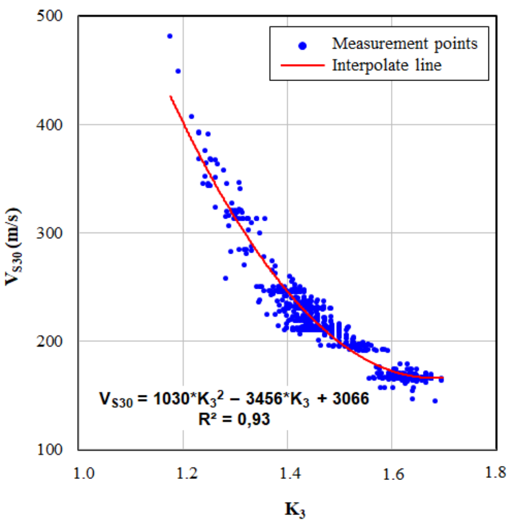



Figure 5.21. Diagram of relationship between $K_3$ and $V_{S30}$ in the Hanoi urban area.

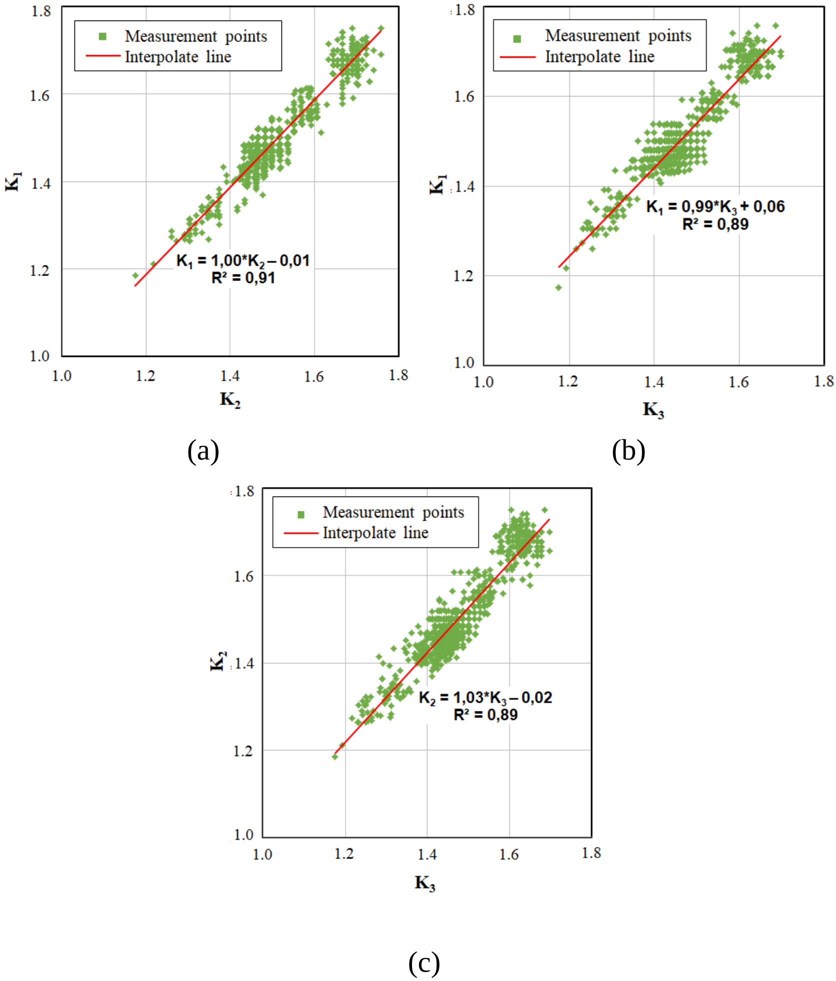



Figure 5.22. Diagrams of relationship between ground motion amplification factors in Hanoi urban area. (a) Relationship between scenario 1 and scenario 2; (b) Relationship between scenario 1 and scenario 3; (c) Relationship between scenario 2 and scenario 3.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

The study on seismic site effect has been carried out at 834 single-station microtremor measurement points and 03 earthquake scenarios in Hanoi urban area. On the basis of the above results, the following conclusions can be drawn:

1/ The thesis has completely built the process of estimating the seismic site effect based on the source of microtremor measurement and geological data in Hanoi urban area combined with the technique of H/V spectral ratio analysis, the technique of H/V spectral ratio curve simulation by genetic algorithms and determined the ground motion amplification factor was using in the world and Vietnam.

2/ The results of assessment of microtremor characteristics have clarified the relationships between the microtremor characteristics and the local site conditions in Hanoi urban area. The shape characteristic of HVSR curves is mainly related to the physico-mechanical properties of underlying rock-soil layers below the measurement point. The H/V dominant frequency is related mainly to the near-surface sedimentary thickness cover above the hard rock. The empirical function between the H/V dominant frequency ($F_0$) in Hz and near-surface sedimentary thickness (D) in meter in the Hanoi urban area is given by $D_K$=81,851*$F_0^{-0.942}$. The microtremors on around the dominant frequency are mainly similar to SH-wave in the horizontal direction, while the microtremors on around the trough frequency are mainly similar to Rayleigh wave in the vertical direction.

3/ The classification of the ground classification has established the ground classification map in Hanoi urban area on the basis of 834 single-station microtremor measurement points actual survey. The ground classification map has clearly shown the relationship between the ground types and the characteristics of rock-soils in Hanoi urban area. Type B ground found in the mountainous zones or the mountain foot delta zones in the northern of Soc Son district. Type C ground occupying most of the stable plain zones of Hanoi urban area. Type D scattered in low plains containing thick soft soil in the north of Long Bien district, south of Thanh Xuan district, the strip along the Red River from West Lake to Yen So and a small area in Dong Anh district.

4/ The results of the seismic site effect assessment have shown a strong ground motion amplification (over 1.6 times) in soft soils (type D ground) in Thanh Xuan district, Hoang Mai district, the strip along the Red River from West Lake to Yen So and north of Long Bien district. This strong amplification is mainly due to the local site conditions in Hanoi urban area. The amplification factor of ground types B, C, D in Hanoi urban area is calculated as 1.26, 1.47, and 1.66 respectively. This factor is less dependent on the magnitude of seismic source and the shaking direction.

**Recommendations**

1/ The study on seismic site effect only focuses on the top 30 m of rock-soil layers to serve the design of civil earthquake-resistant buildings. It is necessary to extend the research depth to apply to underground or special buildings, high-rise and super-high-rise buildings.

2/ The set of detailed $V_S$1D structure diagrams at a depth of up to 200 m will continue to be studied according to 2D and 3D ground structure sections to serve the seismic hazard assessment and the seismic site effect simulation in the Hanoi urban area in the next stages of research.

3/ It is essential to continue the study on seismic site effect using single-station microtremor measurement data in densely populated areas and other large cities in order to minimize the damage caused by strong earthquakes in the future.

# LIST OF PUBLICATIONS

1) **Hung Nguyen-Tien,** Phuong Nguyen-Hong, Minh Nguyen-Le, Lin Che-Min, Nguyen Tran-An, Truyen Pham-The, Duong Nguyen-Van, Establishment of the correlation between the near-surface sedimentary thickness and the microtremor dominant frequency in the Hanoi area, Vietnam Journal of earth sciences, 1-17, https://doi.org/10.15625/2615-9783/17569.
2) **Hung Nguyen-Tien**, Phuong Nguyen-Hong, Minh Nguyen-Le, Wen Kuo-Liang, Nguyen Tran-An, Investigation of microtremor motion variation by Nakamura's H/V spectral ratio method, Journal of Marine Science and Technology; Vol. 17, No. 4B; 2017: 68-74 DOI: 10.15625/1859-3097/17/4B/12994.
3) **Nguyen Tien Hung**, Ha Thi Giang, Nguyen Le Minh, Satoru Tanaka, Yasushi Ishihara, Ha Vinh Long, Le Quang Khoi, Group velocity estimation of Rayleigh wave of crust and upper mantle based on the broadband seismic data in Vietnam East Sea, Journal of Marine Science and Technology; Vol. 17, No. 4B; 2017: 198-207 DOI: 10.15625/1859-3097/17/4B/13008 (in Vietnamese, with abstract in English).
4) Nguyen Cong Nghia, Nguyen Van Duong, Ha Thi Giang, Dinh Quoc Van, Nguyen Le Minh, Bor-Shouh Huang, Pham The Truyen, **Nguyen Tien Hung**, Le Quang Khoi, Nguyen Huu Hung (2022), Automatic earthquake detection and phase picking in Muong Te, Lai Chau region: an application of machine learning in observational seismology in Vietnam, *Vietnam Journal of Earth Sciences*, 1-17, https://doi.org/10.15625/2615-9783/17253.