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Subsoil Variability in the Bangkok Metropolitan Area of Thailand Identified through Ambient Noise Measurement

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Abstract - This paper presents the variations in subsoil conditions of the Bangkok Metropolitan Area of Thailand. The study was initiated by measuring ambient noise with a seismometer. A total of twenty sites was investigated by microtremor measurements. The typical subsoils of Bangkok were presented on the basis of site investigation reports. Furthermore, inversion analysis was conducted to determine subsoil properties in Bangkok. Geotechnical parameters for seismic analyses, such as soil layer thickness, undrained shear strength (s_u), unit weight, time-averaged shear wave velocities at 30 m (V_{s30}), 100 m (V_{s100}), and 500 m (V_{s500}), and engineering bedrock surface depth were reported. Results shows that clay layer thickness varies from 17 - 25 m with the s_u of approximately 10 - 60 kPa and unit weight of approximately 15 - 17.5 kN/m^3. The results also show that V_{s30}, V_{s100}, and V_{s500} fall in the ranges of 100 - 225, 175 - 300, and 325 - 450 m/s, respectively. Engineering bedrock with the V_s of 760 m/s is found at 375 - 625 m below the ground. This result also indicates that a thick sediment is generally found in the Bangkok Metropolitan Area. In general, the results of this work could be used for civil engineering practice, especially seismic design and analysis in the studied area.

Keywords: ambient noise, microtremor, soft clay, engineering bedrock, earthquake

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Introduction

In civil engineering practice, site investigation should be prioritized before construction. Information on subsoils is needed for several engineering purposes, especially foundation design and ground response analysis (Mase, 2020). Therefore, technologies for investigating subsoil properties have been considerably developed (Clayton *et al*., 1995; Mase *et al*., 2019). In addition, the subsoil properties are also important to investigate understanding on the soil behaviour during dynamic loads (Mase, 2017; Mase *et al*., 2021). For ground response analysis, the information related to the soil profile as well as physical and engineering properties should be obtained in addition to the information on ground motion (Mase *et al*., 2020). Likitlersuang *et al.* (2020) reported that seismic responses induced by earthquakes occured more frequently at sites with a thick soft clay layer, such as the Bangkok Metropolitan Area, than at other sites. Therefore, investigating underground conditions in detail by obtaining subsoil measurements, especially those related to shear wave velocity, is important.

Several geophysical methods for obtaining the shear wave velocity of soils have been proposed by various researchers. In general, two main methods are used to measure shear wave velocity (Mase *et al*., 2020). The first one is an ambient noise measurement, a passive method wherein a seismometer is used as the medium for measurement (Kanai, 1961). The second one is an active method in which the spectral analysis of surface waves (Nazarian and Stoke, 1984) and the multichannel analyses of surface waves (Park *et al*., 1999) are applied. The passive method is generally preferred because it is easy to perform, cheap, and practical. However, inversion analysis should be initially performed to generate shear wave velocity profiles (Garcia-Jerez *et al*., 2016). Therefore, *a priori* knowledge related to the general condition of the soil structure and the physical properties of the materials should be acquired before inversion. In other words, geotechnical investigation should be used as a guideline for obtaining reliable shear wave velocities for specific purposes (Mase *et al*., 2021a).

Depicting the soil profiles in Thailand is an important and necessary issue. The Bangkok Metropolitan Area, the capital city of Thailand, is a basin area with a very thick clay layer and deep bedrock (Sinsakul, 2000; Likitlersuang *et al*. 2013, 2014; Nguyen and Likitlersuang 2021). Ashford *et al*. (2000); Poovarodom and Jirasakjamroomsri (2016) reported that earthquake effects could influence the performance of structural buildings in the Bangkok Metropolitan Area, because the city stands on a very thick clay layer. Likitlersuang *et al*. (2020) and Qodri *et al*. (2021) reported that the effect of long-distance earthquakes could influence buildings, for the clay layer tends to amplify the seismic waves during earthquakes. Several parameters for foundation design and seismic ground response analysis, such as the average of undrained shear strength (s_u), the average of the unit weight of clay (γ), and the depth of engineering bedrock should be known. However, the cost of obtaining these parameters is quite expensive. The alternative approach is estimating geophysical and geotechnical parameters by using numerical analyses on the basis of ambient noise measurement combined with geotechnical investigations.

This article presents a study on the variability of soil properties based on the inversion analysis of ambient noise. A total of twenty sites were investigated for the measurement of ambient noise. The inversion analysis was then performed to obtain the variation in soil properties. The inversion analysis provided the shear wave velocity profile, the variations in shear strength and unit weight as well as the engineering bedrock depth. Those results were then interpreted in the form of contour maps to observe their distribution. In general, this study could provide necessary information on subsoil characteristics for engineering practice by using a simple method. Its results can also be used by local engineers as the preliminary justification of foundation design and seismic ground response analysis for the Bangkok Metropolitan Area.

Geological Condition of the Studied Area

This study focuses on the Bangkok Metropolitan Area, which is the capital city of Thailand, and one of biggest cities in Southeast Asia. The city is located in the plain of Chao Phraya River Basin in the upper area of the Gulf of Thailand (Sinsakul, 2000; Surarak *et al.*, 2012). According to Poovarodom and Jirasakjamroonsri (2016), the plain is dominated by Quaternary deposits with generally uniform subsoils inside the basin. Sinsakul (2000) reported that this Quaternary sediment was very thick with the thickness of almost 200 m. In line with the geophysical measurement, Figure 1 presents the layout of the sites investigated in this study. The Bangkok Metropolitan Area is surrounded by several provinces, such as Nonthaburi, Pathumthani, Ayuthaya, Chachoengsao, Samut Prakan, Samut Sakhon, and Nakhon Pathom. A total of twenty locations inside the studied area were investigated. These locations are spread throughout the studied area

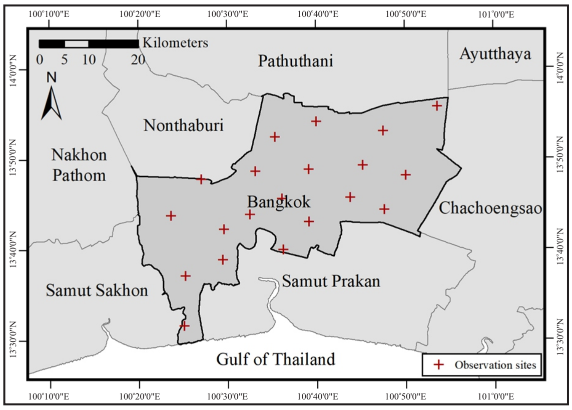

Figure 1. Location of investigation (basic map modified from Likitlersuang *et al.*, 2020).

and are considered in reference to the study of Poovarodom and Jirasakjamroonsri (2016). Ambient noise at the investigated locations was measured by using a seismometer.

Several studies related to the typical subsoil conditions of the Bangkok Metropolitan Area have also reported by Shibuya *et al*. (2003). Qodri *et al.* (2021) reported that sedimentary materials were generally found in the basin. Very soft clay that is classified as high-plasticity clay or CH, found at the depths of 1 - 10 m. Medium-stiff clay that is classified as high-plasticity clay or CH is found at the depths of 10 - 15 m. Stiff clay that is also classified as CL occurs at the depths of 15 - 25 m. The first sand layer, which is classified as the silty sand layer or SM, is found at the depths of up to 35 m below the stiff clay layer. A very stiff clay that is classified as CL is present at the depths of 35 - 45 m. The second sand layer, which is classified as SM, occurs at 7 m below this layer (Surarak *et al*., 2012; Likitlersuang *et al*., 2013).

Shibuya *et al*. (2003) revealed that in the Bangkok Metropolitan Area, the existence of soft sediment deposits, such as soft clay, could play an important role in increasing propagation waves. This phenomenon is known as the amplification effect. The Bangkok Metropolitan Area itself is situated far away from earthquake sources as reported by Tanapalungkorn *et al*. (2020) and Mase *et al*. (2022). Despite the absence of the direct shaking effect of earthquakes, several studies, such as those conducted by Warnitchai *et al*. (2000), Mase *et al*. (2018), Likitlersuang *et al*. (2020), and Qodri *et al*. (2021), have revealed that the amplification factor during remote earthquakes is relatively large. Therefore, investigating the subsoil information of the studied area is important.

Method

Ambient Noise Measurement Using Microtremor

The passive geophysical measurement method for the measurement of ambient noise has widely been used in a geotechnical engineering practice. This measurement is implemented by using an equipment called a seismometer. Numerous researchers, such as Gosar (2010), El-Hady *et al.* (2012), Mase *et al*. (2018), Farid and Mase (2020), and Mase *et al.* (2021b), have utilized this method to observe the geophysical characteristics of many sites. This measurement method was originally proposed by Kanai and Tanaka (1954). Subsequently, Nakamura (1989) widely introduced the application of this method for geophysical and geotechnical investigations. Ambient noise is used to measure the spectral ratio, namely the *H/V* ratio and fundamental frequency (f_0). The curve of the *H/V* ratio is obtained from the ambient noise measurement. The curve is then validated on the basis of the criteria for reliable curves and clear peaks suggested by SESAME (2004). The details related to the criteria can be found in the SESAME (2004).

In this study, the microtremor apparatus called DATAMARK JU410 equipped with a 24-bit AD type digital acquisition unit was used to measure ambient noise. The equipment consists of three accelerometers with three direction components, *i.e.* east–west, north–south, and up–down (vertical). According to Kockar and Ackgun (2012), this equipment was developed for observing weak and strong motions. Hence, this equipment has lower sensitivity than seismometer sensors. Mase *et al*. (2020) mentioned that electricity noise was low during the measurement and could therefore be ignored. The data logger of this equipment may be operated over a dynamic range of up to 130 dB at 100 Hz. In general, compared with accelerometer sensors, the digitizers of this equipment are more sensitive in detecting ambient noise levels for spectral ratios.

During the site investigation, each measurement was conducted for thirty minutes. Firstly, the machine was allowed to warm up for five minutes to avoid the problem of the low-frequency range and to obtain the reliable waveform quality (Kockar and Ackgun, 2012). Next, the noise was removed. SESAME (2004) suggested that the quiet section was the ambient section that could be used to determine the *H/V* ratio. Another benefit of ambient noise measurement is that the *H/V* ratio can be used for inversion analysis to generate a soil profile in one-dimensional model. In this study, the computer code HV-Inv developed by Garcia-Jerez *et al.* (2016) was used to analyze ambient noise for inversion. The inversion of the *H/V* curve was computed on the basis of Monte Carlo simulated annealing (Mase *et al*. 2020).

The model suggested by Garcia-Jerez *et al.* (2016) consists of five parameters that include soil thickness ranges, pressure wave velocity (V_p), shear wave velocity (V_s), material density (ρ), and Poisson's ratio (v). The general ground surface modelling used in this study is presented in Table 1. The soil profile thickness, density, and Poisson's ratio shown in Table 1 are obtained under the typical geological condition. The typical geological condition of the Bangkok Metropolitan Area is acquired on the basis of the studies of Surarak *et al.* (2012), Qodri (2019), Likitlersuang *et al.* (2020), and Qodri *et al.* (2021). The Quaternary geological profile in the Bangkok Metropolitan Area is generally found at depths of up to 500 m (Sinsakul, 2000). Elastic half-space is assumed at the bottom of the soil profile model (Mase *et al.,* 2020). Several assumptions have been suggested by Mase *et al.* (2020). The V_s profile is obtained from the seismic downhole measurement based on the study of Qodri *et al.* (2021). Mase *et al.* (2020) suggested that because V_p, V_s, and v were interdependent, the elastic theory proposed by Salencon (2001) combined with the velocity ratio (V_p/V_s) suggested by Tatham (1981) could be used to predict V_p. The parameters listed in Table 1 were arranged from their minimum to maximum values and were considered on the basis of *a priori* knowledge. The inversion was initiated by starting the Monte Carlo search with the starting-guess model. The parameters of the model are randomly listed in Table 1. During the inversion, the geotechnical properties for the best profile models were repeatedly calculated until the measured *H/V* curve was consistent with the inversion *H/V* curve. The detailed procedure for running the inversion technique by using the model of Garcia-Jerez *et al*. (2016) can be found in the article by Mase *et al*. (2020).

V_{s30}, V_{s100}, and V_{s500}

The main objective of this study is to interpret shear wave velocity profiles based on the inversion analysis on ambient noise measurement. Therefore, observing several parameters related to the time-averaged shear wave velocity is important. In this study, V_{s30}, V_{s100} and V_{s500} were calculated on the basis of the V_s profile. The formulae used to estimate these parameters are:

$$V_{s30} = \frac{30}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}}, \quad \text{..(1)}$$

$$V_{100} = \frac{100}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}}, \quad \text{..(2)}$$

$$V_{500} = \frac{500}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}}, \quad \text{..(3)}$$

where:

V_{s30}, V_{s100}, and V_{s500} are the time-averaged shear wave velocities at the first 30, 100, and 500 m depths, respectively;

d_i is the thickness of each layer;

V_{si} is the V_s value of each layer, and

n is the total number of layers.

Table 1. Ground Models for Inversion Analysis Based on Studies by Surarak *et al*. (2012), Qodri (2019), Likitlersuang *et al*. (2020), and Qodri *et al*. (2021)

Soil Type	Layer	Minimum Thickness (m)	Maximum Thickness (m)	Min V_p (m/s)	Max V_p (m/s)	Minimum V_s (m/s)	Maximum V_s (m/s)	Minimum Density (□) (kg/m³)	Maximum Density (□) (kg/m³)	Minimum Poisson's Ratio (□)	Maximum' Poisson's Ratio (□)
Clay	1	1	20	120	300	60	123	1800	2000	0.400	0.495
	2	1	20	400	400	100	164	1800	2000	0.400	0.495
	3	1	20	600	600	200	245	1800	2000	0.400	0.495
	4	1	20	500	700	250	286	1800	2000	0.400	0.495
Sand	5	1	20	500	700	250	327	1800	2000	0.300	0.400
Clay	6	10	50	600	800	300	327	1800	2000	0.400	0.495
	7	1	20	700	900	300	327	1800	2000	0.400	0.495
Sand	8	1	20	500	700	300	327	1800	2000	0.300	0.400
Clay	9	1	20	600	800	300	327	1800	2000	0.400	0.495
Sand	10	10	50	600	800	350	368	1800	2000	0.300	0.400
	11	10	100	700	900	350	368	1800	2000	0.300	0.400
Clay	12	10	50	700	900	350	368	1800	2000	0.400	0.495
Sand	13	10	100	900	1100	450	550	1800	2000	0.300	0.400
Sand	14	10	50	900	1100	450	550	1800	2000	0.300	0.495
Sand	15	10	100	100	1200	500	600	1800	2000	0.300	0.400
Sand	16	10	100	1100	1300	550	650	1800	2000	0.300	0.400
Sand	17	10	200	1300	1500	650	750	1800	2400	0.300	0.400
Sand	18	50	500	2000	5000	800	2500	1800	2400	0.300	0.400
Sand	19	0	0	3000	6000	1000	3000	1800	2400	0.300	0.400

Given that inversion analysis can generate shear wave velocity profiles, the information on engineering bedrocks may be obtained by using this method. Miller *et al.* (1999) reported that the engineering bedrock surface could be identified on the basis of a surface with the V_s of 760 m/s. Several researchers, such as Pamuk *et al.* (2017), Mogren (2020), and Mase *et al.* (2022) have suggested use this value to identify engineering bedrock surfaces in case studies in Izmir (Turkey), Jeddah (Saudi Arabia), and Mae Sai (Thailand), respectively.

Research Framework

The research framework of this study is summarized as a flowchart in Figure 2. The research was initiated by identifying the problem of ground uncertainty in the Bangkok Metropolitan Area. The idea to study subsoil variation was proposed on the basis of the influence of ground uncertainty on geotechnical engineering and seismic ground response analysis. Data, including geological conditions, topographical conditions, and ambient noise measurements were collected. Previous studies conducted on the Bangkok Metropolitan Area that specifically explained soil variations and their effects on the soil structure in the Bangkok Metropolitan Area were also reviewed. Ground geophysical measurement was conducted on the basis of microtremors. In this study, twenty locations in Bangkok were selected to perform the microtremor measurements. The curve of the horizontal-to-vertical spectral ratio (*H/V*) was generated on the basis of ambient noise measurements that were also validated in accordance with the criteria for reliable curves and clear peaks suggested by SESAME (2004). When a curve did not fulfil the criteria, the ambient noise was remeasured.

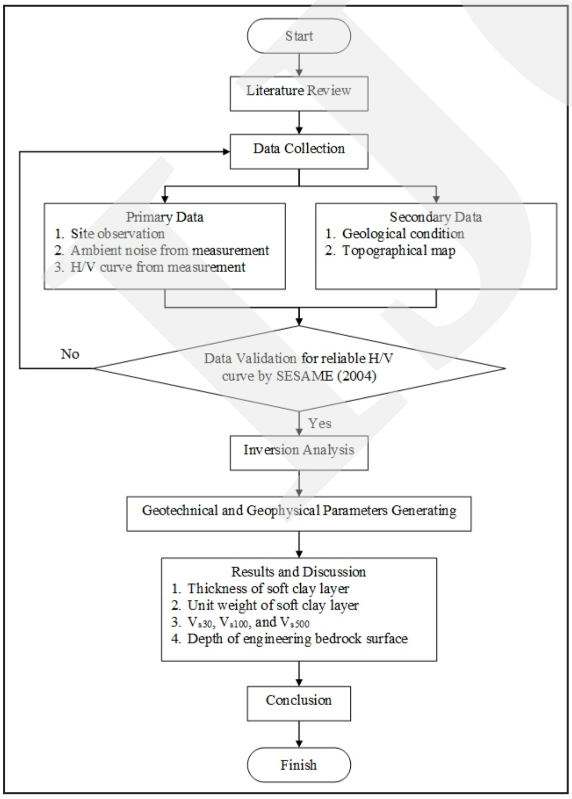

Figure 2. Research flowchart.

After data checking, inversion analysis was conducted by using the model proposed by Garcia-Jerez *et al.* (2016). The initial model based on the previous studies of authors are summarized in Table 1. The model randomly selected the first starting-guess model through Monte Carlo simulated annealing. The best model was determined in consideration of the consistency of the *H/V* curve and *H/V* inversion. From the inversion, several geotechnical and geophysical parameters, such as the thickness of the clay layer, the unit weight of the clay layer, the time-averaged shear wave velocity values for the first 30, 100, and 500 m depths represented as V_{s30}, $V_{s100,}$ and V_{s500}, respectively, and the depth of the engineering bedrock surface, were obtained. Those parameters were mapped onto contour maps and discussed.

For engineering bedrock, the minimum V_s of 760 m/s was used as the indicator where engineering bedrock surface existed. Also, s_u for Bangkok clay layer in this study was determined based on empirical equations from Likitlersuang and Kyaw (2010) as expressed below:

$$V_s = 187\left(\frac{s_u}{p_a}\right)^{0.372} \quad \text{lower boundary} \quad ......(4)$$

$$V_s = 187\left(\frac{s_u}{p_a}\right)^{0.510} \quad \text{upper boundary} \quad ......(5)$$

where:

V_s is shear wave velocity,

s_u is undrained shear strength, and

p_a is the atmospheric pressure (100 kPa).

In this study, the average value of those two equations were used to estimate the V_s for Bangkok clay, as recommended by Likitlersuang *et al.* (2013). In general, the results of the study could reflect the variabilities in subsoil properties in the Bangkok Metropolitan Area, Thailand, based on geophysical measurements that could be used for further geotechnical engineering purposes.

Results And Discussion

Thickness of Clay Layer

Figure 3 presents the thickness of the clay layer in the Bangkok Metropolitan Area. The inversion analysis shows that the thickness of clay layer varies from 17 m to 23 m. Five zones based on the ranges of clay thickness are divided as presented in Figure 3. The first zone includes areas with the clay thickness of 17 m to 19 m. The thickness ranging from 17 m to 18 m is found in the north-western area bordering Nakhon Pathom, Nonthaburi, and Samut Sakhon. The second zone with the clay thickness of 19 - 21 m is found in the eastern area (bordering Chachoengsao Province), south-western area (bordering Samut Sakhon Province), and north-western area (bordering Nonthaburi Province). The zone with the soft clay layer thickness of 21–23 m dominates and is mainly found in the main plain of the Bangkok Metropolitan Area to the southern part of the Bangkok. The areas with clay layer thicknesses that vary from 23 m to 25 m are concentrated in small areas around Bangkok, especially in small areas in northern, southern, and south-western Bangkok.

The analysis shows that the clay layer in Bangkok is relatively thick. Surarak *et al.* (2012) reported that a thick clay layer had been identified in the Bangkok Metropolitan Area. Several studies conducted by Ashford *et al.* (2000), Likitlersuang *et al.* (2020), and Qodri *et al.* (2021) have demonstrated that the soft clay layer in Bangkok could play an important role in intense amplification effects during earthquakes.

Undrained Shear Strength of Clay Layer (s_u)

Given that another objective of this study is to observe the variation in the undrained shear strength of the clay layer, the interpretation of undrained shear strength is presented. Figure 4 presents the zonation map of the average undrained shear strength of the clay layer in the Bangkok Metropolitan Area. As observed in Figure 4, the undrained shear strength of the clay layer varies from 0 to 60 kPa. Similar to the values in Figure 3, the values of undrained shear strength are also grouped into several ranges. The first range, *i.e.* undrained shear strengths less than 10 kPa, is found

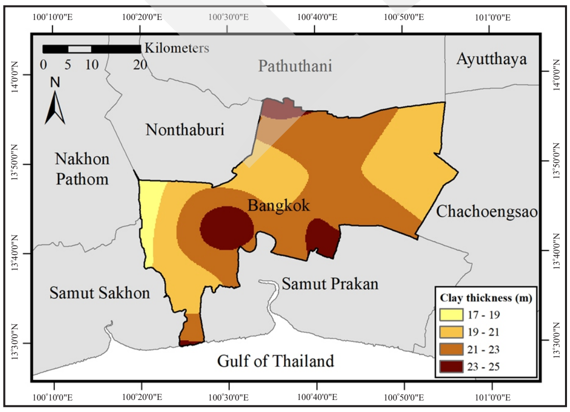

Figure 3. Averages of clay layer thickness in Bangkok Metropolitan Area.

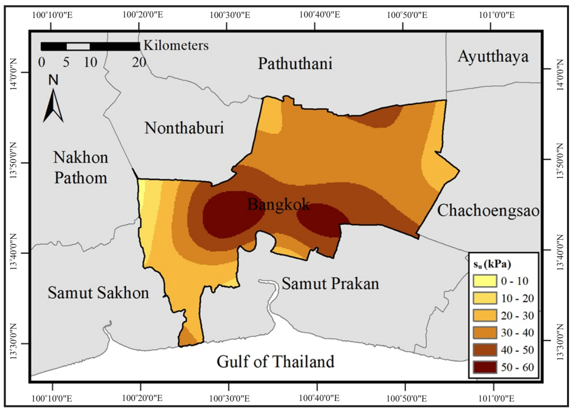

Figure 4. Variations in the undrained shear strength (s_u) of the clay layer in Bangkok Metropolitan Area.

in the western part of the Bangkok Metropolitan Area bordering Nakhon Pathom Province. Undrained shear strengths ranging from 10 - 20 kPa are generally distributed in the western area of Bangkok that borders Samut Sakhon and Nonthaburi. Areas with undrained shear strengths of 20-30 kPa are generally found in the western part of the Bangkok Metropolitan Area and the edge of the Bangkok Metrolopolitan Area bordering Nonthaburi, Pathumthani, and Chachoengsao Provinces.

In general, the Bangkok Metropolitan Area is dominated by undrained shear strengths ranging from 30 kPa to 40 kPa. The undrained shear strengths of the clay layer at the centre of the Bangkok Metropolitan Area range from 40–50 and 50–60 kPa. In general, the interpretation of undrained shear strength in the Bangkok Metropolitan Area is generally consistent with the observation by Jirasakjamroonsri *et al.* (2019). Surarak *et al.* (2012) and Likitlersuang *et al.* (2020) reported that the information on the undrained shear strength of the clay layer was important for supporting structural design in the Bangkok Metropolitan Area.

Unit Weight of Clay Layer (γ)

Figure 5 presents the average of the unit weight of the clay layer in the Bangkok Metropolitan Area. It shows the five zone ranges of the average unit weights of the clay layer in the Bangkok Metropolitan Area. The first zone, *i.e.* 15.0–15.5 kN/m^3, is generally found in the northern part of the Bangkok Metropolitan area that borders Nonthaburi and Pathumthani Provinces. The second zone, *i.e.* the area with values of 15.5 - 16.5 kN/m^3, generally occupies the edge areas of the Bangkok Metropolitan Area bordering Nakhom Pathom, Nonthaburi, Chachoengsao, Samut Prakan, Samut Sakhon, and the Gulf of Thailand. The third zone with the unit weight of 16.0-16.5 kN/m^3 mainly occurs in the Bangkok Metropolitan Area. The fourth zone, *i.e.* the area with unit weights ranging from 16.5 kN/m^3 to 17.0 kN/m^3, is generally recognized in the middle of the Bangkok Metropolitan Area and in the northern part of the Bangkok Metropolitan Area bordering Pathumthani Province. The last zone, the area with the unit weight of the clay layer ranging from 17.0 kN/m^3 to 17.5 kN/m^3, generally exists in the middle of the Bangkok Metropolitan Area. A small area with this range of clay layer weight also appears in the northern part of the Bangkok Metropolitan Area bordering Pathumthani. Due to Bangkok is one of megacities in Southeast Asia and the infrastructure development in this city is considerable, the information on the average unit weight of the clay layer could help provide information on structural design, especially for substructure construction.

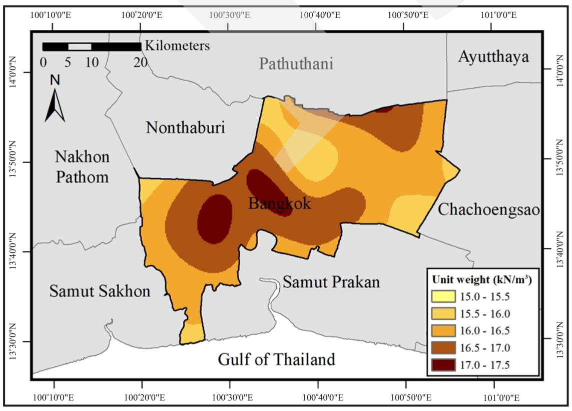

Figure 5. Average unit weight (γ) of the soft clay layer in Bangkok Metropolitan Area.

Contours of V_{s30}, V_{s100}, and V_{s500}

In this study, the geophysical parameters V_{s30}, V_{s100}, and V_{s500} are presented to depict the general overview of the site condition of the studied area. Figure 6 presents V_{s30} in the Bangkok Metropolitan Area. Generally, V_{s30} in the Bangkok Metropolitan Area varies from 100 m/s to 225 m/s. The National Earthquake Hazard Reduction Program (NEHRP, 2020) states that V_s values of 100 - 180 m/s and 180 - 360 m/s are indicative of site classes E and D, respectively. The figure shows that V_{s30} values of 100 - 125 m/s and 150 - 175 m/s are dominant in the studied area. In general, the dominant V_{s30} distribution in the studied area is generally consistent with studies conducted by Jirasakjamroonsri *et al.* (2019). Figure 6 also shows that V_{s30} increases northward and vice versa. Figure 7 exhibits the distribution of V_{s100} in the studied area. V_{s100} values in the studied

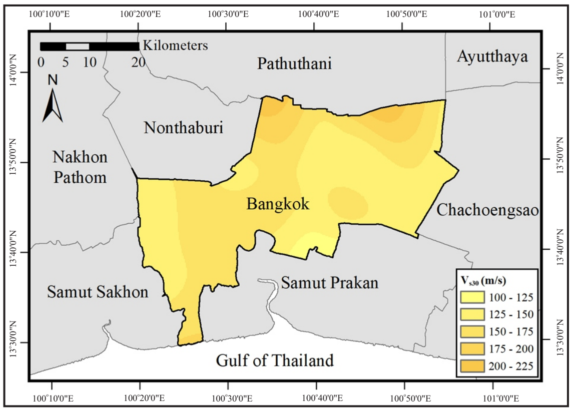

Figure 6. Variations in the V_{s30} of Bangkok subsoil.

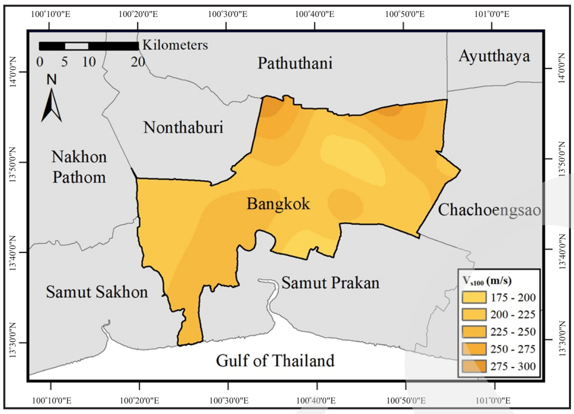

Figure 7. Variations in the V_{s100} of Bangkok subsoil.

area vary from 175 m/s to 300 m/s. In general, V_{s100} values ranging from 200 m/s to 225 m/s dominantly occur in the Bangkok Metropolitan Area. V_{s100} shows a similar tendency that its distribution tends to increase in northern areas. Figure 8 presents the distribution of V_{s500} in the Bangkok Metropolitan Area. As presented in Figure 8, V_{s500} values in the Bangkok Metropolitan Area vary from 325 m/s to 450 m/s. In general, V_{s500} values ranging from 375 m/s to 400 m/s are dominantly recognized in the studied area. Similar to V_{s30} and V_{s100}, V_{s500} increases in the northern part of the Bangkok Metropolitan Area and vice versa. Therefore, sites close to the Gulf of Thailand have low soil resistance and vice versa.

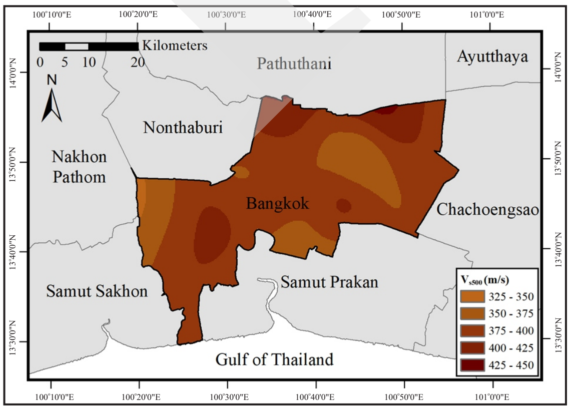

Figure 8. Variations in the V_{s500} of Bangkok subsoil.

Depth of Engineering Bedrock

This study also presents the depth of the engineering bedrock surface as shown in Figure 9. The figure illustrates that the Bangkok Metropolitan Area can be divided into five zones on the basis of the depth of the engineering bedrock surface. In this study, the depth of the engineering bedrock is indicated by layers with $V_s \geq 760$ m/s (Miller *et al.*, 1999; Mase *et al.*, 2022). The first zone, *i.e.* areas with the depths of the engineering bedrock surface of 375 - 425 m, is generally found in several small areas in Bangkok, such as areas in the southeast Bangkok Metropolitan area bordering Chachoengsao Province and the northern Bangkok Metropolitan Area bordering Pathumthani Province. The zone with the depths of engineering bedrock ranging from 425 m to 475 m occupies the Bangkok Metropolitan Area. Therefore, the engineering bedrock surface dominantly occurs at depths of 425 - 475 m. The third zone, *i.e.* areas wherein the depth of the engineering bedrock ranges from 475 m to 525 m, is found in the southern and northern

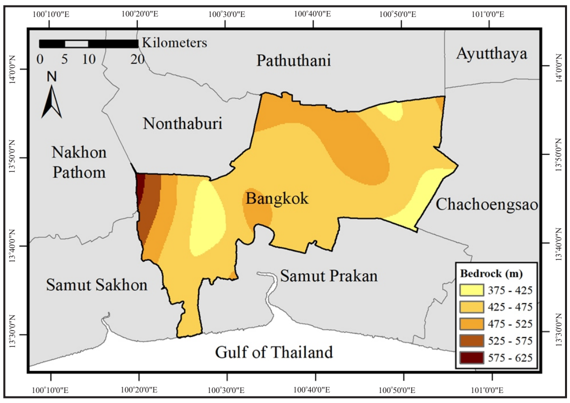

Figure 9. Depths of the engineering bedrock surface in the Bangkok Metropolitan Area.

areas bordering Samut Prakan, Pathumthani, and Chachoengsao Provinces. In the eastern part of the Bangkok Metropolitan Area bordering the Nonthaburi, Nakhon Pathom, and Samut Sakhon Provinces, the engineering bedrock surface can be recognized at the depths of 525 to 625 m.

Depth of Engineering Bedrock

This study also presents the depth of the engineering bedrock surface as shown in Figure 9, which illustrates that the Bangkok Metropolitan Area can be divided into five zones on the basis of the depth of the engineering bedrock surface. In this study, the depth of the engineering bedrock is indicated by layers with $V_s \geq 760$ m/s (Miller *et al*., 1999; Mase *et al*., 2022). The first zone, *i.e.* areas with the depths of the engineering bedrock surface of 375 - 425 m, is generally found in several small areas in Bangkok, such as areas in the southeast Bangkok Metropolitan Area bordering Chachoengsao Province and the northern Bangkok Metropolitan Area bordering Pathumthani Province. The zone with the depths of engineering bedrock ranging from 425 m to 475 m exists in the Bangkok Metropolitan Area. Therefore, the engineering bedrock surface dominantly occurs at depths of 425 - 475 m. The third zone, *i.e.* areas wherein the depth of the engineering bedrock ranges from 475 m to 525 m, is found in the southern and northern areas bordering Samut Prakan, Pathumthani, and Chachoengsao Provinces. In the eastern part of the Bangkok Metropolitan Area bordering the Nonthaburi, Nakhon Pathom, and Samut Sakhon Provinces, the engineering bedrock surface can be recognized at the depths of 525 - 625 m.

Information on engineering bedrock is crucial for seismic response analysis and earthquake engineering studies (Mase *et al*., 2018). The effects of remote earthquakes could influence high-raise buildings in the Bangkok Metropolitan Area (Likitlersuang *et al*., 2020; Qodri *et al*., 2021). Therefore, the information on engineering bedrock in the Bangkok Metropolitan Area is very useful for local engineers when considering the effects of earthquakes on the city development. Generally, the results of this study could contribute to strengthening seismic hazard mitigation in the studied area.

Conclusion

This study presents the variations in subsoil properties in the Bangkok Metropolitan Area, Thailand, on the basis of geophysical measurements. Ambient noise is measured from the twenty sites in the Bangkok Metropolitan Area with a seismometer. An inversion analysis was conducted to obtain the best model of the investigated sites. Several geotechnical and geophysical parameters, such as the thickness of the clay layer, the average of the undrained shear strength of the clay layer, the average of the unit weight of the clay layer, V_{s30}, V_{s100}, V_{s500}, and the depth of the engineering bedrock surface are illustrated using contour maps to observe subsoil variations. Several conclusions can be drawn as follows:

Researchers studying soil characteristics have known of the existence of a thick clay layer in the Bangkok Metropolitan Area. This study elaborated on the variabilities in the thickness of the clay layer, the undrained shear strength of the clay layer, and the unit weight of clayey soil. In the general, these parameters are important for substructure design. The results of this study could benefit preliminary investigations on the studied area. In addition, the information on the clay layer in Bangkok could help engineers to estimate possible effects, such as consolidation settlement and intense amplification that may occur during earthquakes.

This study also interprets geophysical parameters, such as V_{s30}, V_{s100}, and V_{s500}. Generally, the Bangkok Metropolitan Area has relatively low V_{s30}, V_{s100}, and V_{s500} values. The V_{s30} values show that the sites are dominated by site classes E and D. This result indicates that these areas are highly vulnerable to seismic impact as reflected by the existence of the soft clay layer at the sites. Generally, the sites with high soil resistances (V_{s30}, V_{s100}, and V_{s500}) are found in northern areas and vice versa. The variation of shear wave velocity pattern indicates that soft sediment may be generally found in areas close to the Gulf of Thailand and in southern areas. Detailed investigations could be conducted to confirm the predictions obtained in this study.

The engineering bedrock surface presented in this study reflects the sediment thickness in the studied area. The information on bedrock provided by this study could be used to develop recommendations for local engineers in estimating earthquake effects in the studied area. Calculations in seismic ground response analysis require information on engineering bedrock. Therefore, this information could improve the prediction of seismic response in the Bangkok Metropolitan Area.

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