Estimation of Subsurface Soil Layers using H/V Spectrum of Densely Measured Microtremor Observations

(Case Study: Yogyakarta City, Central Java-Indonesia)

Zaw Lin Kyaw^{a,b,*}, Subagyo Pramumijoyo^b, Salahuddin Husein^b, Teuku Faisal Fathani^c, Junji Kiyono^d and Rusnardi Rahmat Putra^d

^{a,b}Geology Department, Yangon University, Yangon, Myanmar

^bGeological Engineering Department, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta and 55281, Indonesia

^cCivil and Environmental Engineering Department, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta and 55281, Indonesia

^dDepartment of Urban Management, Graduate School of Engineering, Kyoto University, Katsura Campus, Nishikyo, Kyoto and 615-8540, Japan

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Abstract

Yogyakarta City was seriously damaged by the Yogyakarta earthquake which was an M_w 6.3 event that occurred on May 27, 2006 and caused more than 5,700 fatalities and over 37,000 injuries. Seismic damage is closely related to the ground structure. It is very important to clarify the geological bedrock of the region, when designing earthquake-resistance buildings and structures and in drawing up an earthquake disaster prevention plan for the region. Microtremor measurement is effective as a method for conveniently and cheaply understanding the ground properties. The single observations of microtremors were densely performed at 274 sites in Yogyakarta City. The predominant periods due to

horizontal vertical ratio are in the range of 0.15 to 4.00 sec. From the distribution of the short and long predominant periods (T_s and T_d) which reflect the information of relatively shallow and deep sedimentary layers. The depth of earthquake and the sediment thickness are also estimated from the predominant periods of H/V spectrum for microtremor. From the results of this study, it is apparent that the characteristics of microtremors are dependent on the type of soil deposits, therefore we can observe information of seismic response between the predominant periods, sediment thickness and S-wave velocity.

Keywords: Shallow and deep soil layers; H/V spectral ratio; Microtremor observations; Boreholes; Yogyakarta City

1. Introduction

Yogyakarta City, the capital of Yogyakarta Special Province, is situated in the southern part of the volcanic arc island of Java. Yogyakarta City is located in the so-called Yogyakarta Depression area, which is only about 30 km from the Merapi volcano which reaches the elevation of 2911 m above sea level; it is the most active volcano in Indonesia, and about 40 km from the coast of the Indian Ocean. Yogyakarta City is situated at the centre of the province, in the middle of the Yogyakarta basin. An earthquake with the magnitude M_w 6.3 occurred near the City of Yogyakarta, on May 27th, 2006 at 5:54 am local time. The earthquake directly affected the provinces of Yogyakarta and Central Java Island. This earthquake caused nearly 6,500 casualties and more than 36,000 were injured. More than 135,000 houses were damaged, and 600,000 people were made homeless. The Basin response in such cases depends on the site geometry, impedance contrast, soil properties and constitutive model, and on the complexity and strength of the input solicitation.

Yogyakarta city, the second most popular tourism area in Indonesia after Bali, is a rapidly growing population center, subject to significant seismic risk that occupies a basin (graben) with known young volcanic deposits of the Merapi volcano (Quaternary Succession). Based on the population census conducted in the year 2010, the population of the city has reached 388,088 with a growth rate of 0.39 % in the city. Population density for the same year was 12,206.5/km² at the city (www.pemda-diy.go.id). The geological characteristics and the high population of the city cause quite serious problems of geo-hazards and environmental degradations.

The prediction and mitigation of the damage due to natural disasters, especially seismic shaking, are urgent demands of human society. When looking into the damage, we often notice that the conditions of the landform and the

* Corresponding author. Tel.: +62-081-229-816-116
E-mail address: zlk yaw.geol@gmail.com

soil are strongly associated with it. This fact indicates that it is essential to know the shallow and deep soil layers when considering natural disaster mitigation as well as planning to construct facilities. The shallow and deep soil layers of the site represent the local site condition and can help to estimate the site response. They are the key factors in assessing seismic hazard and understanding ground motion characteristics. The subsurface geology and soil properties have significant influences on the intensity of earthquake ground motion. Understanding site conditions are of great importance in site effect evaluation.

2. Background geology

The geology around Yogyakarta City is controlled by active plate tectonic phenomena such as the active volcano and active subduction of the Indian-Australia oceanic plate below the Eurasia continental plate. To the west, highly faulted a dome of andesitic breccias and lava flows occurred. Meanwhile in the eastern part of the Yogyakarta City, steep mountains of carbonaceous-volcanic rocks as well as limestone with karst land scapes are exposed. The major structure is the north-eastern trending normal fault, known as the Opak fault, which defines the eastern limit of a trough extending from Yogyakarta to the coast.

There are two kinds of Successions around the research area which are the Yogyakarta Tertiary and the Quaternary Successions. The Yogyakarta Tertiary Succession includes Old Andesite Formation, Jonggrangan Formation, Kebo-Butak Formation, Semilir Formation, Nglanggran Formation, Sambipitu Formation, Sentolo Formation Wonosari Formation and Kepek Formation. Meanwhile, the Quaternary Succession is composed Old Merapi Volcanic Unit, Young Merapi Volcanic Unit, Sleman Unit, Yogyakarta Unit, Wates Unit and Alluvium. The Quaternary Succession is dominated by volcanic activities, largely attributable to Gunung Merapi. Other important deposits such as littoral clay deposits in the vicinity of Wates, minor valley and terrace alluvium in the main river valleys, deflation materials on limestone and sand dunes adjacent to the coast have also been encountered. The Yogyakarta unit forms the surface outcrop throughout the lowland area of Yogyakarta Basin from Merapi Middle Slope to the coast. The unit consists of an inter-bedded sequence of sand, gravels, silts and clay. The amount of clay increases southwards. However, layers of coarse materials have been encountered throughout the basin. The thickness of this unit is variable and up to 45 m in some places. This unit lies unconformable upon the Sleman unit.

Yogyakarta City sits in a broad valley between two groups of roughly north-running mountains with the Kulon Progo Mountains to the west and the southern mountains to the east. The towering Merapi volcano caps the northeast end of the valley. Behind it is the single peak of the Sundero

volcano and a cluster of small peaks in the Dieng volcano complex as shown in Figure 1.

Figure 1 Topography map in Yogyakarta area

3. Historical seismicity

Figure 2 Historical Seismicity in Indonesia ($M_w > 4.0$ and 1840-2013) (Source USGS, 2013 and Rusnardi, 2012)

The Java trench region shows low seismicity but destructive earthquakes have occurred there in the past and some of these generated tsunamis. The historical earthquake record in this area can be generally divided as the pre-historical period up to about 1840 with the epicentre locations and magnitudes based largely upon felt reports, and an instrumental period which is inferred from the USGS (NEIC) and ANSS earthquake catalogues as shown in Figures 2. According to the historical and instrumental records, most of the earthquakes which effected the

Yogyakarta special province occurred within the radius of 200 km as shown in Figure 3.

Apart from the latest May 27, 2006 event, historical records indicate that Yogyakarta has been struck several times by earthquakes and significant damage was reported. The Yogyakarta area therefore can be regarded as a seismic prone area and similar destructive earthquakes can be expected in future. The prevention and mitigation of seismic risk in this area is one of the major needs.

Figure 3 The epicenter distribution of the historical events around Yogyakarta in central Java (Source USGS, 2013)

4. Microtremor measurements

The earth surface is always in motion at different frequencies; even in the absence of active seismic sources. These constant vibrations are called microseisms or preferably microtremors whose amplitude is generally too small (10^{-4} - 10^{-2} mm) to be felt by human senses. Microtremors are considered as noise sources in seismological studies and a very convenient tool to estimate the effect of surface geology on seismic motion without other geological information. Moreover, observation methods have been developed as a simple and cost effective method to determine the characteristics of the ground properties [3&6].

The single microtremors observations of 274 sites in Yogyakarta City are shown in the Figure 4. The measurements were carried out during the daytime using a microtremor instrument which is model of Mitutoyo-GPL-6A3P and serial No. 0418707. It was composed of a short-period, three-component seismometer with natural period of one second, a 24-bit A/D converter with GPS time, sampling each channel at 100, and a laptop computer to control the system and store the data. At each sites microtremors were recorded with a sampling rate of 100 Hz for 5 minutes. During the measurements particular

attention was given to keep the recordings free from very local noise sources, like e.g. passing pedestrians, vehicles or operating machineries. Meteorological disturbances, e.g. rainfall or gusty wind, did not occur during the observation period. The site's topography and local peculiarities were also considered, e.g. artificial soil replenishments, floor coverings, paved or tarmac roads, and neighbouring elevated structures.

To provide a good coverage of the study area, the measurement sites were designed with a grid spacing of 500 meters to the main path of the north-south and east-west of the research area, so that the configuration soft rocks and contact hard rock could be known in detail.

Figure 4 Location of densely microtremor observations and existing boring sites

The results of microtremors observations were measured only for five minutes by using the sampling rate of 100 Hz with 3-components. Although they are results from five minutes measurements, it is still enough to get the first fundamental period of H/V ratio in most cases. The first fundamental frequency of the H/V ratio mostly reflects the S-wave velocity of sediments and it is therefore used for validation of S-wave velocity structures determined by a geotechnical approach.

4.1. Application of HVSr method

The microtremor H/V technique was first proposed by Nogoshi & Igarashi (1971) [9] and widespread by Nakamura (1989) [3]. It consists in estimating the ratio between the Fourier amplitude spectra of the horizontal and the vertical components of ambient noise vibrations. In this study, H/V ratios are calculated using the BIDO software. The objective is to assure the stationary microtremor

observations, and to avoid the transients often associated with specific urban sources (footsteps, close traffic). The final H/V ratio and the associated standard deviation are obtained by averaging the H/V ratios from all windows. The standard deviations on H/V ratio curves are estimated considering the arithmetic average for all individual logarithms of the H/V ratio computed for each time window [10].

In this approach, Eq. (1) was applied several times to calculate the HVSR for each window, and then average them to obtain the site response. Moreover, not only which peak of the average HVSR is highest, but also whether or not this peak appears stable in time in the FFT, was taken into account. The amplitude spectra of the three components was calculated using an FFT algorithm. This was then applied Eq. (1) to obtain the HVSR. All noise-free HVSRs representing stable dominant frequencies were selected and averaged to yield the average HVSR, whose peak determines the dominant frequency for the site as shown in Figures 5(a) and (b). Taking into account the response of instruments and the frequency content of microtremors recorded in Yogyakarta City, the possible dominant frequencies were restricted to the range 1-10 Hz. This condition is not too restrictive, since this is the range of frequencies usually obtained in this kind of studies.

The procedure generally used to calculate the HVSR consists in the application of Eq. (1) to the average amplitude spectra of the three components of motion. This HVSR method postulates the shape of the Fourier spectrum [4].

$$HVSR = \frac{\sqrt{F_{NSi}(\omega)^2 + F_{EWi}(\omega)^2}}{F_{UDi}(\omega)^2} \quad (1)$$

Where $F_{NSi}(\omega)$, $F_{EWi}(\omega)$ and $F_{UDi}(\omega)$ denote the Fourier amplitude of the NS, EW and UD components of each interval, respectively, and ω is the frequency.

Figure 5(a) Typical examples of three components of the H/V spectrum ratio (UD, NS and EW)

Figure 5(b) Typical examples of the Fourier spectra of the three components of the H/V spectrum ratio (UD, NS and EW)

4.2. Predominant period of H/V spectrum

Among various kinds of geological explorations using microtremor records, the horizontal to vertical spectrum ratio (H/V spectrum) is considered most effective [5]. The H/V spectrum only requires observation at a single point, which is much easier than the array observation for the F-K spectrum and the SPAC methods. In this study the potential effectiveness of the H/V spectrum for the investigation of shallow and deep soil layers on the volcanic sediments of low land sites is discussed with reference to microtremor observations at 274 sites in Yogyakarta City.

Based on the nature of the H/V spectrum mentioned above, the soil structure of Yogyakarta City was estimated. For deep soil, the predominant period is estimated from a peak in long period range of the H/V spectrum. On the other hand, the shapes of H/V spectrum are various in the short period range, showing the variety of shallow soil conditions. It is shown that the existence of the clearly contrasted soil layer is almost detected by the peak period of the H/V spectrum considering the microtremor as a Rayleigh wave.

The spectral ratio of horizontal and vertical motion obtained by microtremor observations is called the H/V spectrum. The predominant period of an H/V spectrum is thought to be equivalent to the predominant period of the ground directly beneath the site. H/V spectra at each site in the target area were calculated. The H/V spectrum was classified into three types according to the shape of the spectra [2].

- Type A: two distinct peaks (Figure 6(a))
- Type B: a single clear peak (Figure 6(b))
- Type C: without clear peaks (Figure 6(c))

The distinct peaks express the characteristic of the layers for which the shear wave velocity is quite different. According to this interpretation, the lower and higher periods in Type A represent the effects from deep and shallow soil layers, respectively. In Type B, the difference between the two layers is not marked, and the effect of one layer is absorbed into that of the other layer. Type C is an observation site that has hard soil. Thus, the data was established for both long and short predominant periods, T_d and T_s . In Yogyakarta City, T_d is between 0.15 and 4.00 sec in Figure 7(b) and T_s is between 0.1 and 1.00 sec in Figure 7(a). Although the predominant period does not always indicate the characteristics of an individual layer because typically the actual shaking mode of the ground is complex, it was assumed that the long and short periods reflected information from each layer. On the basis of these results, it would appear that it is possible to use the H/V spectral ratio to determine the fundamental periods and establish the seismic microzonation in terms of a predominant period's map of the studied region.

Figure 6 Typical examples of (a) the two distinct peaks (Location site (157) 7°51'56.3"S, 110°24'26.9"E)

Figure 6 Typical examples of (b) a single clear peak (Location site (167) 7°49'1.4"S, 110°24'29.3"E)

Figure 6 Typical examples of (c) without clear peaks of the H/V spectrum ratio (Location site (047) 7°48'1.2"S, 110°22'32.0"E)

Figure 7 Spatial distribution of (a) the short predominant period

when the clear layer boundary with high impedance ratio is existed.

As shown in Figure 7(b), the long predominant period in Yogyakarta City is ranging from 0.15 to 4.00 sec. From the long predominant periods, T_d , which expresses the information of relatively deep sedimentary layers, a deep layer with a period of greater than 1.8 sec is observed in the studied area. The highest predominant period (>1.8 sec) is observed at Gondokusuman, Terban, Kricak, Sinduadi, north part of Catur Tunggal, east of Depok, South-East of Muja Muju and Baturetno. The lowest predominant period (0.15 to 1.4 sec) is observed at Yogyakarta, Rejowinangun, Umbulharjo, Mantrijeron, Giwangan, Sewon, Prenggan and east of Baturetno. It is observed (as anticipated) that the area where thicker sediments are present show higher predominant periods. Figure 7(a) and 7(b) show the distribution of the site predominant periods especially short and long predominant periods were developed for the purpose of seismic microzonation. In conclusion, it is obviously showed that the maps of the short and long predominant periods indicate the shallow subsurface soil layer and the deep engineering bedrock layer in the research area.

5. Determination of layer thickness

It has been well-documented that the effect of local on ground shaking is an important factor in earthquake engineering. Particularly, soft sedimentary cover could strongly amplify the seismic motion. The peak period of the H/V spectrum plot shows the "predominant period" of the site. The H/V spectra were obtained for all the observation sites and the predominant periods of ground motion for all the sites were identified. The peak in the short and long periods (T_s and T_d) of the observed H/V spectrum could be explained by the estimated subsurface soil.

An investigation of the sediment thickness and seismic zones in addition to use of the H/V spectrum by microtremors enables the ground amplification properties to be understood. The first order peak seen in H/V spectrum is considered to be an accurate indication of the natural period of the ground. There is a good correlation between the sediment thickness and period. This allows the distribution of the sediment thickness in the Yogyakarta base in to be determined accurately with high density observations.

Several studies show the relationship between the velocity structure beneath the recording site and the dominant frequency obtained from $HVSR$ analysis [5]. As a first-order approximation, a simple formula can be applied that relates the fundamental frequency to the thickness and seismic velocity of a medium composed of a single layer over a half-space:

From the single microtremor observations, the short predominant periods, T_s , is obtained from 0.1 to 1.00 sec. The target area is less than 1.00 sec of the short predominant periods which reflects the information of the shallow soil layer. In this study area it is clearly verified that the shallow soil layers are generally the north-south alignment because it is assumed that the young volcanic soft sediment are derived from the Merapi volcano from the north of the research area as shown in Figure 7(a). It is understood that the relatively shallow soil layers can be detected from H/V spectrum of short period microtremor

Figure 7 (b) long predominant period, T_d

$$f_0 = V_s / 4H \quad (2)$$

where V_s is the average S -wave velocity and H is the thickness of the layer. When the sites are located over the same structure as in Yogyakarta City Area, it can be assumed that the S -wave velocity is approximately constant from site to site. This is usually the case in most sedimentary basins like the Yogyakarta basin. The former relation thus yields a map of sediment thickness from estimates of the resonant frequency [1]. Inversely, if it can be assumed that in a certain region the surface layers have approximately a constant thickness, the dominant frequency at each point would be then related to an S -wave velocity and a map of surface velocities could be obtained.

The thick and loose sediments are observed in the almost the whole area (>14 m) and high amplification and strong ground motion can occur in these areas (Figure 8-a). The east of Terban, between Catur Tunggal and Depok, south of Muja Muju, Umbulharjo, Baturetno and east of Baturetno area are included in very thick sediment zones (>32 m). The thickness of sediments in almost the whole City area especially Depok, Yogyakarta, Muja Muju, Rejowinangun and Prenggan are 14m to 32m and medium to high amplification can be expected. The shallow sediments (6m-14m) are investigated in Sindaudi, Kricak, Terban, Gondokusuman, north and south of Catur Tunggal, west and south of Yogyakarta City, south of Rejowinangun, Mantrijeron, Sewon, Giwangan and these areas can be regarded as low amplification zones.

Figure 8 (b) The three-dimensional shape of the estimated subsurface layers

Figure 8 (b) shows that the boundary depth between the subsurface ground and basement ground plotted in 3-dimensional form. Over 25 m thick layer of sediment uniformly accumulated in the yellow colour zone of Yogyakarta City. The sediments are generally trending for north-south alignment of the studied area. The boundary depth was around 50-60 m and appeared a little bit deep. Focusing on the observation sites, although the elevation of surrounding area is almost at the same level (about 150 m) a gentle change in sedimentary layers can be seen.

6. Conclusions

The microtremor observations and data analyses were performed to obtain useful and practical data for earthquake disaster mitigation in Yogyakarta City. In this research, the procedures and conclusions are employed as follows:

- 1) The 274 dense single-point microtremor observations which covered almost the whole city area were conducted to estimate the shallow and deep soil layers from the short and long predominant periods in Yogyakarta City.
- 2) The H/V spectra were calculated at all the single observations sites and a distribution of predominant periods was obtained. Basically the spectrum had two peaks, T_s and T_b , each of which reflects the information of a shallow and a deep soil layers.
- 3) It was confirmed that H/V spectrum for microtremor is horizontal to vertical amplitude ratio of Rayleigh wave including the first modes.
- 4) The depth of sediment thickness is estimated from predominant period range of H/V spectra for microtremor records and roughly average shear wave velocity for soil layer from the existing bore-holes data in research area.
- 5) In future work, it will be required to measure dense array investigations in Yogyakarta City, from which can be

Figure 8 (a) The spatial distribution of sediment thickness

concluded more detailed subsurface soil profiles and seismic shaking. By analysing the shallow and deep soil layers, the strong ground motion can be investigated and plans made to mitigate future damage.

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