Geotechnics for Catastrophic Flooding Events – Iai (Ed)

Bedrock elevation measurement using ambient vibrations and ultra-sonic pulse test

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ABSTRACT: One of the important steps in site specific analysis is finding the elevation of bedrock. Seismic waves in terms of acceleration time histories will be propagated from bedrock elevation to the earth surface. Invasive and non invasive are two methods commonly used for estimating the elevation of bedrock. Invasive methods required drilling into the ground. Non-invasive methods for estimating of bedrock elevation can be performed using ambient vibrations. Ambient vibrations are short period vibrations (0.02 to 50 Hz) result from environment activities such as traffic, wind interaction with vegetation, factory activities etc. A single feedback seismometer can be performed for measuring ambient vibration waves. A simple method by placing seismometer on the earth is required for ambient vibrations measurement.

This study presents result of bedrock measurements in south area of Semarang City, Indonesia using a single feedback seismometer. The Horizontal-to-Vertical Spectral Ratio (HVSR) analysis method from Nakamura (1989) was performed for estimating the depth of bedrock elevation. Bedrock elevation map was performed based on 196 locations of ambient vibration measurement. Drillings for finding rock sample for rock elevation less than 30 meter were also performed. To get the information of shear wave velocities of rock sample Ultrasonic Pulse Test of rock tests were performed.

Keywords: bedrock, ambient vibrations, HVSR, Ultrasonic Pulse Tests.

1 INTRODUCTION

Semarang is the capital city of Central Java Province and lies at the Northern part of Central Java Province. Semarang has an area of ±374 square kilometers. The city spans for 22 km long and 22 km wide and elongated in both North-South and East-West directions. Based on the geological formations, the northern part of Semarang (Light blue in Figure 1) lies on the alluvial sediments. They composed of soft clay, silt and sand and their thickness can reach more than 100 m (Thanden et al. 1996). The central part of Semarang lies on the Damar formation and composed by tuff sandstone conglomerate (orange in Figure 1). The other formation, a transition formation, is found in the southern part of Semarang and lies on Kaligetas and Kaligesik formations and composed of volcanic breccias, clay-stone, basalt and hornblende-augite-andesite (brown, red and pink in Figure 1). Based on the geology map and geology information there are no complete information concern with bedrock elevation in the city of Semarang. Whereas the overlying soil sediments are clearly important for the amplification prediction and for site response analysis.

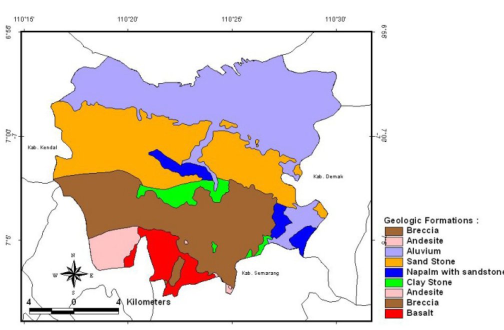

Figure 1. Geology map of Semarang city.

The Semarang city can be divided in two major landslopes, coastal plain area in the Northern part with max 5% slope and hilly part in the center and Southern part with max 33% slope.

Site response is an important part of geotechnical earthquake engineering studies. Amplification of seismic waves propagating up through a soil column depends on the depth of bedrock or the thickness of sediment layer. Investigation of bedrock elevation is an important part for developing seismic microzonation. Geology map of Semarang city (Figure 1) has no complete information about the elevation of bedrock elevation. The cost of deep boring down to the bedrock at all sites of the Semarang city is unrealistic approach. Due to this lack of bedrock elevation and unrealistic approach for deep boring for the whole city, introducing alternative cheaper method for predicting bedrock elevation is important. H/V (Horizontal to Vertical Spectral Ratio) analysis of ambient vibrations is a cheaper approach for predicting bedrock elevation.

This paper presents a geological map of bedrock elevation of Semarang city by performing site investigations using single station feedback seismometer. Extensive ambient noise measurements were performed in the whole sites of Semarang city and the H/V technique (Nakamura, 1989) for predicting bedrock elevation was conducted.

In order to better understand the use of feedback seismometer and H/V technique for estimating bedrock elevation, drilling investigations were performed. The purposed of these drilling investigations are to compare the elevation of bedrock calculated using ambient vibrations with real geological layers on site from drilling investigations. Laboratory geotechnical tests were conducted for all rock samples. The purpose of geotechnical test is to get the information of shear wave velocities (Vs) of all rock samples.

2 BACKGROUND THEORY

Estimating sediment thickness and the geometry of the bedrock is one of the important steps for site specific analysis in calculating surface hazard spectra. Estimating sediment thickness can be performed by using single station seismometer and H/V technique (Claudet et al. 2009, Johansson et al. 2008). The H/V method uses a single station broad-band three component seismometer to record ambient vibrations (North-South/NS, East-West/EW and Vertical/V). The horizontal-to-vertical (H/V) technique for ambient vibrations is a non-invasive technique that can be used to rapidly estimate the depth to bedrock. The H/V technique was first proposed by Nogoshi and Igarashi (1971) and then widespread by Nakamura (1989). The H/V technique consists of estimating the ratio between the Fourier amplitude spectra of the horizontal and the vertical components of ambient vibrations. The ratio of the averaged horizontal-to-vertical frequency spectrum is used to determine the fundamental site resonance frequency, which can be interpreted using regression equations to estimate sediment thickness or depth to bedrock.

The H/V method is a "passive" method that uses three-component measurements of ambient vibrations (vibrations induced by wind, ocean waves, anthropogenic activity, etc.) to determine and evaluate a site's fundamental seismic resonance frequency. Kramer (1996) described that soil response to the strong ground motion can be approximated by the transfer function of layered and damped soil on elastic rock. If Vs is the shear wave velocity of soil layer and H is the thickness of soil layer, the fundamental frequency of the soil (fo) can be predicted using Equation (1). Based on Equation (1) if Vs and fo can be defined, the depth or the thickness of soil layer can be easily calculated.

$$fo = \frac{Vs}{4H} \tag{1}$$

Nakamura (1989) showed that the fundamental resonance frequency of a site can be determined from the ratio of the horizontal Fourier amplitude spectra and the vertical Fourier amplitude spectra of ambient vibrations. If SNS and SEW are the horizontal Fourier amplitude spectra and SV is the vertical Fourier amplitude spectra of the ambient vibrations, Delgado et al. (2000) proposed a simple formulae for estimating the H/V spectral ratio as (Equation 2):

$$H/V = \sqrt{\frac{SNS^2 + SEW^2}{2SV^2}} \tag{2}$$

where SNS = North-South amplitude Fourier spectra; SEW = East-West amplitude Fourier spectra; SV = vertical amplitude Fourier spectra

Several equations can be used to establish the thickness of sediment layer. The equation which is used in this study was performed by Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002). They developed an empirical power law equation for predicting the thickness of sediment layer (Equation 3):

$$Z = a(fo)^b \tag{3}$$

where "a" and "b" are two fitting parameters determined from non-linear regressions of resonance frequencies and borings in Germany. The value of a (in meter) and b are given in Table 1. The advantage of this equation is that there is no Vs value required for calculating sediment thickness.

Table 1. H/V resonance Frequency Fitting Parameters.

a	b	Reference
96	−1.388	Ibs-von Seht and Wohlenberg (1999)
108	−1.551	Parolai et al. (2002)

3 METHODS AND RESULTS

3.1 *Ambient vibrations measurements*

Extensive ambient noise measurements, 196 locations, were performed in the city of Semarang during August to November 2012. The ambient noise vibrations were recorded using feedback seismometer. The type of seismometer used in this study is 100 Hz sampling rates three-component Feedback Short Period Seismometer model DS-4A. The signal has been recorded with 2 Hz velocity sensors for minimum 15 minutes.

Figure 2 shows setting up of equipments for ambient vibrations measurements. The seismometer is connected to computer laptop via digital portable data logger and GPS. The locations for which 196 ambient noise were recorded are shown in Figure 3. These locations were distributed randomly inside the study area (165 locations) and outside the study area (31 locations).

The H/V technique (Nakamura, 1989) in estimating the ratio between the Fourier amplitude spectra of the horizontal and the vertical components of ambient noise vibrations were calculated using Geopsy software. H/V ratios were calculated for the frequency range 0.2 Hz until 20 Hz. The average H/V curves were systematically analyzed and the application of the reliability criteria of peaked H/V curve frequencies was carried out using SESAME guidelines (SESAME, 2004). At the end, the H/V peak frequencies can then be used for estimating sediment thickness. Two simple empirically non-linear regression equations determined by Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) are used for predicting sediment thickness.

Based on the H/V peak frequencies calculation of all datas can be divided into four spatial distribution intervals: 0.5–2 Hz, 2–5 Hz, 5–10 Hz and 10–20 Hz. Figure 4 shows the spatial distribution of H/V peak frequencies. Data with peak frequency between 0.5–2 Hz are clearly located on the North and North-East area of Semarang (red area in Figure 4). Data with peak frequency between 2–5 Hz (green area in Figure 4) are located within three separated locations, middle, Southern and South-East part of the city. Data with peak frequency between 5–10 Hz (blue area in Figure 4) are located in the middle part and southern part. Data with peak frequency between 10–18 Hz (dark green in Figure 4) are scattered in small area in the City.

Using the value of peak frequency (fo), value of ‘a’ and ‘b’ from Table 1, the depth of bedrock can be estimated directly. Figure 5 shows the relation between the

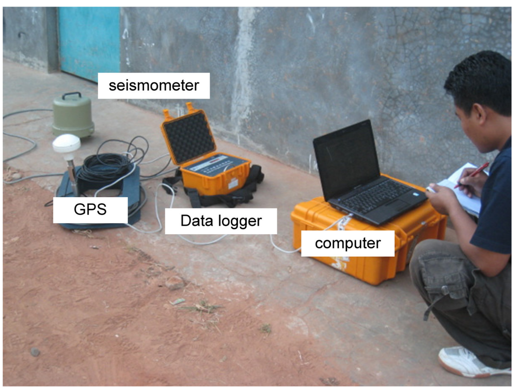

Figure 2. Feed-back seismometer connected to laptop via portable data logger for H/V ambient noise surveys.

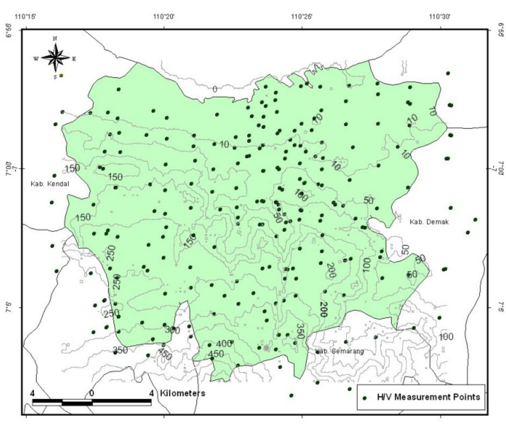

Figure 3. Ambient noise test locations.

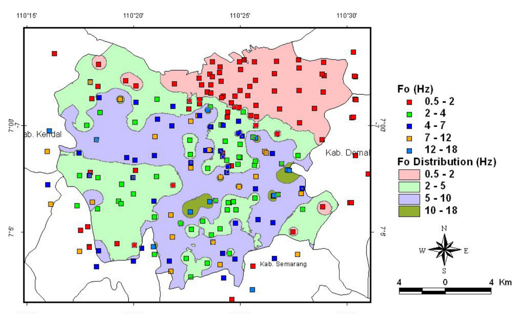

Figure 4. Distribution of peak frequencies (fo).

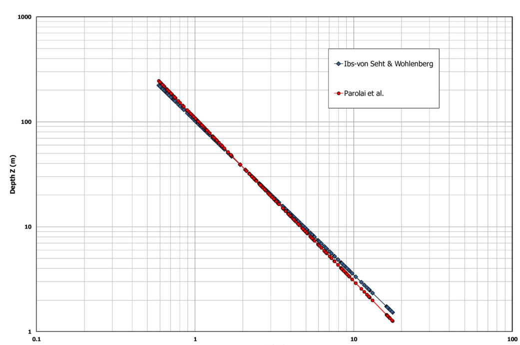

Figure 5. Relation of sediment thickness (z) and peak frequency (fo) developed from 196 data.

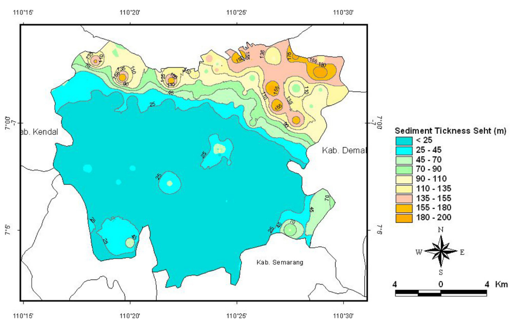

Figure 6. Sediment thickness spatial distributions based on Ibs-von Seht and Wohlenberg method.

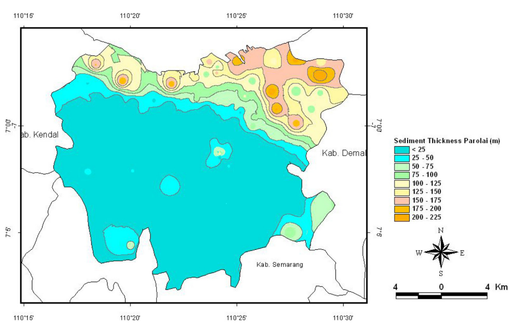

Figure 7. Sediment thickness spatial distributions based on Parolai et al. method.

thickness of sediment layer "z" and peak frequency "fo" developed from 196 data. Figure 5 shows the comparison of two graphical models developed using Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) approaches. As it can be seen in Figure 5, both graphs have no significant differences. For fo less than 2 Hz, Ibs-von Seht and Wohlenberg method gives the value of z less than Parolai et al. method. However for fo greater than 2 Hz, Parolai et al. method gives the value of z less than Ibs-von Seht and Wohlenberg method.

The result of sediment thickness distribution is presented in two contour maps. The first map (Figure 6) shows the contour of sediment thickness based on Ibs-von Seht and Wohlenberg (1999) approach. The second map (Figure 7) shows the contour of sediment thickness based on Parolai et al. (2002) approach. Both maps give almost the same information about the spatial distribution of sediment thickness layer. The depth of bedrock elevation gradually increases from south to north part of the city. The deepest elevation of bedrock lays on the north-east part of the city.

Area with sediment thickness less than 50 meter (blue and light blue area in Figure 6 and Figure 7) are clearly located on the south and middle part of the city. Area with sediment thickness between 50 meter and 100 meter (soft green and green area in Figure 6 and Figure 7) are located in the middle part of the study area. It can be seen in Figure 6 and Figure 7

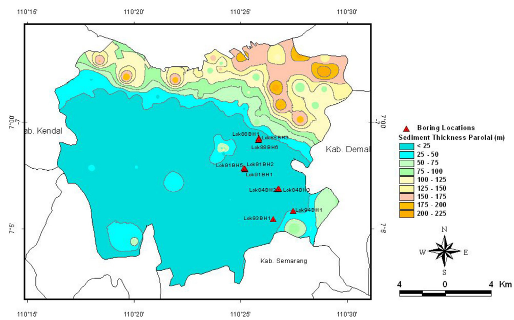

Figure 8. Drilling locations.

Figure 9. Ultrasonic Pulse Test and example output Using Sonic Viewer SX.

that the majority of the north part of the city area (yellow to orange area) has minimum 100 meter sediment thickness.

3.2 *Ultrasonic pulse test*

In order to better understand the use of feedback seismometer and H/V technique for estimating bedrock elevation, drilling investigations were performed during October 2012 until July 2013. Ten drilling locations with minimum 30 meters depth were performed. All the boreholes crossed the sediment layer and reached the geological bedrock within minimum 30 meter dept. Figure 8 shows ten drilling locations in the study area.

To get the real physical characteristics of all rock samples, laboratory geotechnical tests were conducted for all rock samples using ultrasonic pulse test (Sonic Viewer Type SX). The purpose of geotechnical test is to get the information of shear wave velocities (Vs) of all rock samples. Ultrasonic pulse test (Figure 9) was used for conducting the shear wave velocities of rock samples. Based on SNI 03-1276-2012, bedrock (SB) is a soft-rock with Vs greater than 760 m/s and less than 1500 m/s.

Table 2 shows the conclusion result of ultrasonic pulse test. As can be seen in Table 2 all rock samples have shear wave velocity Vs greater than 760 m/s.

Table 2. Bedrock elevation and Shear Wave Velocity Tests Result.

No	Location	Date	Bedrock Elevation (m)	Rock Types	VS (m/s)
1	Lok84BH2	Oct-12	−8	Breccia	2457
2	Lok84BH3	Oct-12	−5	Breccia	3461
3	Lok88BH1	Mar-13	−17	Sandstone	2265
4	Lok88BH3	Apr-13	−27	Sandstone	1947
5	Lok88BH6	Apr-13	−26	Sandstone	1848
6	Lok91BH1	Apr-13	−23	Sandstone	1631
7	Lok91BH2	Apr-13	−21.5	Sandstone	2554
8	Lok91BH5	Apr-13	−22	Sandstone	2150
9	Lok93BH1	Jul-13	−11	Sandstone	2012
10	Lok94BH1	Jul-13	−5	Claystone	2895

Figure 10. Sample sand stone from Lok93BH1 with minimum depth −15 meter.

Figure 11. Sample clay stone from Lok94BH1 with minimum depth −5 meter.

Based on the information get from Table 2 the elevation of bedrock are less than 30 meter. Figure 10 to Figure 12 show three examples of rock sample from drilling investigations.

Figure 12. Sample sand stone from Lok88BH3 with minimum depth −26 meter.

4 CONCLUSIONS

The use of ambient vibrations recorded by single station feedback seismometer can be an alternative method for investigating bedrock elevation. The ambient vibrations data produce peak resonance frequency which gives a good correlation with the geology map of Semarang. The depth of bedrock elevations were interpreted using two different regression equations and give a good estimates for predicting bedrock elevations. The detail analysis of ambient vibrations data and H/V method outlines two major areas of sediment thickness or bedrock elevations. The South and middle part of Semarang have bedrock elevation less than 50 meter. The North part of the City, the alluvial sediments area, has bedrock elevation more than 50 meter. The deepest elevation of bedrock lies on the North-East part of the City. The depth of bedrock elevation of this area is more than 200 meter.

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