Site Characteristics Based on Microtremors and Borehole Data in the Epicentral Area of the Central Java Earthquake of 2006

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ABSTRACT :

The Central Java earthquake of Ms6.3 occurred on May 27, 2006. Although the magnitude of this event was relatively small, the reported structural damage in the epicentral area was quite heavy, that is, more than 140,000 houses were totally collapsed or heavily damaged and about 5,700 people were killed. The purpose of the investigation performed by the collaborated survey team of Kyushu University in Japan and Gadjah Mada University in Indonesia is to understand the primary cause of this devastating damage. For the strong ground motions in the epicentral area we conducted microtremor measurements there. Not much geophysical exploration data was available before the earthquake and therefore we report the soil amplification characterization survey conducted in the region and consider effects of soil amplification on spatial damage distribution first. We found that the strength of ground shaking should not be so high, probably 7 to 8 in MMI seismic intensity scale and the observed local damage ratio variation from site to site should be primarily controlled by the local site conditions. We also use boring data to characterize the soil conditions at several sites inside the Yogyakarta basin. Based on the collected information we concluded that the devastating damage on the residential masonry houses should be attributed to their very low seismic resistance, even though soil amplification should be attributable for the observed spatial damage distribution.

KEYWORDS: Central JAVA earthquake, Microtremors, Site effects, Damage distribution, Boring

1. INTRODUCITON

The most noticeable feature of the disaster of the Central Java, Indonesia earthquake of 2006 is very heavy damage in epicentral areas considering its small magnitude of Mw6.3. It is important to investigate the cause of such heavy damage for preventing similar heavy damage by future destructive earthquakes in Indonesia. Unfortunately no strong motion data was available in the epicentral region so that we can only speculate the levels of strong motions in the epicentral region based on the structural damage investigation there. We first report briefly the damage survey conducted in the region and estimated strong motion levels based on that. We also calculate averaged epicentral strong motion levels derived from attenuation relationships established in Japan, where similar tectonic environment is expected.

The strong motion characteristics are determined by three important factors, namely source, path, and site. In the epicentral areas of inland (crustal) like the one investigated here source and site effects would play a major role so it is important to investigate the site characteristics in such areas for quantitative studies on the cause of structural damage. Not so much geophysical and geological information was available in the epicentral region at the time of investigation and therefore we conducted microtremor measurements in the epicentral region. Later Gadjah Mada University and other national teams organized a project funded by JICA and other agencies to collect geological and geophysical information such as boring log data with SPT values. We use here several boring data to characterize soil conditions. We report here the soil amplification characterization survey conducted in the region and consider effects of soil amplification on spatial damage distribution in the epicentral regions.

2. DAMAGE SURVEY

2.1. Survey Outline

The outline of our damage survey in the epicentral region is as follow:

1) Preliminary investigation

First we surveyed briefly the general condition of heavily damaged areas in the epicentral region, namely, Desa Pleret (Pleret village), Kecamatan Jetis (Jetis county), and Imogiri City. When we moved along a southbound highway from Jetis to Imogiri we found that the damage levels are changed strongly. This sudden change of damage levels corresponds to the difference of damage levels determined by UNOSAT from satellite photos (Fig.1). Therefore, the UNOSAT figure shows more or less precise damage distribution in the epicentral region.

2) Line-1 investigation

Then we started detailed investigation along a east-west line of about 10km, Line-1, which is crossing the Opak fault through Pleret (See Fig.2). We investigated the damage of each village using an elementary school or a local village office which is usually located in the center of each village. We also conducted questionnaire survey to evaluate the levels of strong ground motions in each village.

3) Line-2 investigation

In the same way we continued to investigate damage at 7 sites along the east-west line across the Opak fault through Imogiri City center, Line-2 as shown in Fig.2. The averaged damage ratios are not as high as those in Line-1.

4) Klaten sites

In addition to these measuring lines we investigated damage levels at six sites in Klaten area., too In the southern part of Klaten severe structural damage as well as other types of damage on geological and civil engineering structures can be observed.

2.2. Results of Damage Investigation

We summarize the essence of our structural damage survey mainly along the Pleret line (Line-1). As shown in the following photographs the most popular way of construction of houses in the damaged area is a one-storied no-reinforced, no-confined masonry structure with a tiled roof on top of the wooden roof truss. Old houses do not have any reinforced concrete (RC) frames, while relatively new houses should have such

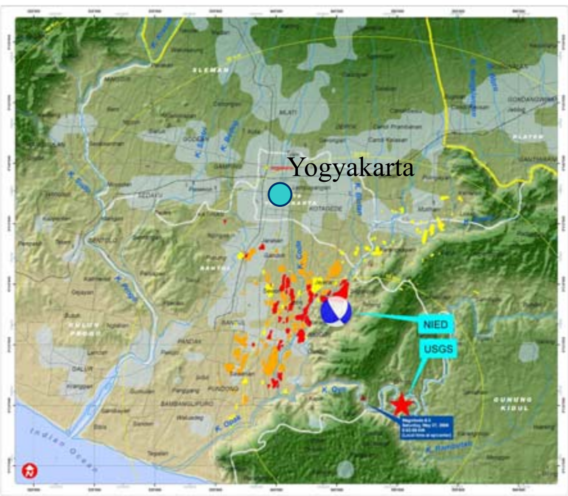

Fig.1 Damage distribution obtained by UNOSAT and the location of the epicenter (star) by USGS and the mechanism and location of the moment centroid by Nakano et al. (2007).

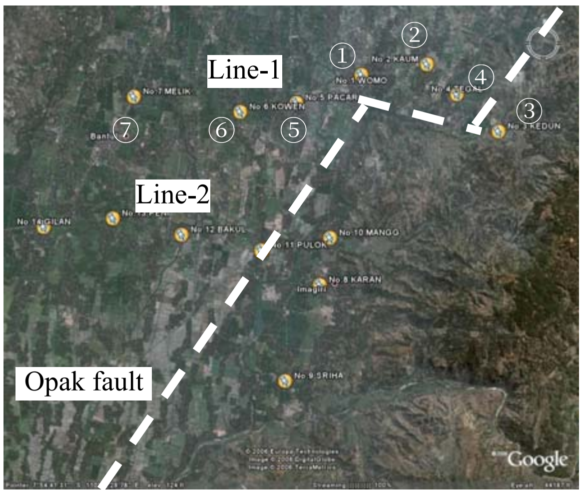

Fig.2 Two survey lines and the Opak fault in the heavily damaged areas.

frames for most of the cases. However, such RC frames do not either have large sections nor strong steel bars. We can see almost no RC structures as residential homes in the heavily damaged areas. We will show examples of the damaged structures here that relate to the estimation of the strong motion levels.

1) No.1 site: MAN Wonokromo high school at Ketonggo/Wonokromo/Pleret/Bantul
This high school building does not have so severe damage as a structure; only one beam in the second floor shows severe damage. It looks like a RC structure with bricks infill visually, although we cannot guarantee. The damage in residential houses of this village is quite high, about 71% of the total.

2) No.2 site: Kauman village elementary school at Kauman/Pleret/Pleret/Bantul
The main building of the elementary school was totally collapsed during the earthquake (Photo 1), while the other classroom has only walls stand still. A library building and a stockyard building had survived as well as two adjacent mosques (as shown in this photo) and a one-storied building of the local government office. Statistical data obtained from this local office yields damage ratio of about 75%. However, there existed several houses completely survived in this village as shown in Photo 2.

3) No.3 site: Kedungpring village elementary school at Kedungpring/Bauran/Pleret/Bantul
This village lies in the area not mentioned in a damage distribution map of UNOSAT (Fig.1), considerably far in the eastern side from the center of Pleret. However, damage in this village is as severe as the others; school buildings as well as a mosque are totally destroyed. Probably more than 60% of houses are heavily damaged. Since this site is close to the hill zone, we should not expect high amplification due to soft soil, and therefore strong ground motions at this site may reflect strength of the earthquake source. It is guessed that strong ground acceleration produced at this site may not exceed 200 Gals (20% of g) because a store building survived with only a slight damage and a small steel tower in the village center do not suffer any damage.

Photo 1 Debris of a totally collapsed elementary school and a survived mosque at No.2 survey site, Kauman in Pleret.

Photo 2 A beautifully survived house near No.2 survey site, Kauman in Pleret.

4) No.4 site: Tegalrejo elementary school at Tegalrejo/Bauran/Pleret/Bantul
This site is in between No.2 and No.3 and close to the river so some site amplification must be expected. Our impression of the damage in this village is very severe, very close to 100%. The newly constructed school building with RC beam was totally collapsed. In Japan we can use tomb stone to estimate strength of the ground motions, however, in Indonesia tomb stone does not show systematic damage pattern since the aspect ratio is not high. We saw a lot of water storage tank as shown in Photo 3 without any cracks, which suggests that the level of strong motion was not so high even in this area with soil amplification.

5) No.5 site: Pacar elementary school at Pacar/Timbulharjo/Sewon/Bantul
Most of the school buildings seem to have been destroyed completely, and the site was already cleared up

neatly. This village is close to the long furniture factory building which was damaged heavily. Destruction ratio of buildings in this village was considerably high, however, we still found an almost intact elegant house in this village with a colorful wall. This is a concrete piece of evidence that proves strong resistance capacity of houses constructed with a high quality material.

Photo 3 A beautifully survived water tank near No.3 survey site, Tegalrejo in Pleret.

6) No.6 site: Kowen/Timbulharjo/Sewon/Bantul
At this western site the damage ratio of houses seems to decrease to 40% to 50%.

7) No.7 site: Melikan SMP2 at Melikan/Bantal City/Bantul
At this westernmost site the damage ratio of houses is quite small, should be less than 20%.

These are brief description of the survey results along the line-1. It is not easy to estimate strong motion levels in the epicentral region from observation of the above- mentioned damage. However, it is not considered to be the case that the shaking level in terms of the JMA seismic intensity exceeds 6-, which corresponds to VIII for MMI intensity scale, in terms of peak ground acceleration (PGA) level, 400Gals, or peak ground velocity (PGV) level, 20 ~ 40cm/s, because at least we see a few examples of survived structures such as water tanks or steel towers which does not seem to have enough earthquake resistance.

On the other hand, basic earthquake resistance capability of brick houses in this area of Indonesia seems considerably low, because severe damage ratios are observed in the southern part of Klaten prefecture 30km away from the epicenter, where it is unlikely to have severe strong motion levels there, even if we consider high soil amplification.

3. MICROTREMOR SURVEY

3.1. Outline

As mentioned in the introduction, the strong motion characteristics can be separated into three important factors, that is, source, path, and site. In the epicentral areas source and site effects would play a major role so it is important to investigate the site characteristics in such areas for quantitative studies on the cause of structural damage. Unfortunately not so much geological and geophysical information was available in the epicentral region before the earthquake and therefore we conducted microtremor measurements in the epicentral region. We report here the soil amplification characterization survey conducted in the region and consider effects of soil amplification on spatial damage distribution. The outline of our microtremor survey in the epicentral region is as follow:

1) Line-1 investigation
We started microtremor measurement along a east-west line of about 10km, Line-1, which is crossing the Opak fault through Pleret (See Fig.2). We measured microtremors in each village using a playground or courtyard of an elementary school or a local village office which is usually located in the center of each village. In total seven sites are investigated. We also conducted. We also measured microtremors in the two school structures with two stories.

2) Line-2 investigation
In the same way we continued to perform microtremor measurements at 7 sites along the east-west line across the Opak fault through Imogiri City center, Line-2 as shown in Fig.2.

3) Klaten sites
In addition to these measuring lines we investigated microtremor survey at six sites in Klaten area. In the southern part of Klaten severe structural damage as well as other types of damage on geological and civil engineering structures can be observed.

3.2. Results of Microtremor Survey

3.2.1. Method of measurement and analysis
We measured microtremors on the ground of each sites, normally in the center of the playground, by using handy accelerometer system SMAR-6A3P with three accelerometers and 24 bits A/D converters. Amplification ratio was set to 500, sampling frequency to 100 Hz, and high-cut filter of 50 Hz. We measured all three components at the same time and calculated spectral ratios between horizontal component and vertical one. The peak frequency of H/V spectral ratio usually corresponds to the peak frequency of S-wave soil amplification (Nakamura, 1988; Satoh et al., 2001). Peak amplitude may reflect impedance contrast between the bedrock and the shallow sediments. When we measured microtremors of structures, we measured two locations simultaneously, namely on the highest floor and on the basement (ground) floor. Measurement lasted for 15 minutes and we cut them into a lot of 40.96 second samples with 50% overlapping and calculated Fourier spectra as an ensemble average. We also used Parzen window of 0.25 Hz for smoothing.

3.2.2. Line-1 investigation
In Fig.3 we show H/V spectral ratios at No.3 site, KEDUN, the easternmost site. This figure suggests that the thickness of the surface sediments must be very small (shallow) because the peak frequency is as high as 6Hz. If we assume the averaged S-wave velocity of surface sediment to be 250m/sec and if we assume the peak frequency of H/V ratio may close to the S-wave amplification peak frequency, then the thickness at this site is estimated to be 10m. However, peak frequencies for different time segments show different values and their amplification level is not so high that the S-wave at this site may be increasing as we go downward.

Fig.4 shows H/V ratios at No.4 site TEGAL. The peak frequency becomes lower to 2.5Hz and its amplitude becomes higher, close to 10 times. This suggests high impedance contrast between bedrock and shallow Quaternary sediments. Peak frequencies for different time windows do not change much, which also suggests high impedance contrast. If the average S-wave velocity of sediments is assumed to be 200m/sec, then their thickness may be 20m and the S-wave velocity below may be 1,000m/sec.

When we look at next station, No.2 site KAUM in Fig.5, the peak frequency of the H/V ratio is lowest, 1.5 Hz, which suggests the thickest sediments at this site along the Pleret line. However, its peak level is only two so we cannot expect high impedance contrast here. At the next western station No.1 site Wonokromo, the peak frequency becomes 3.0Hz as seen in Fig.6. This means after KAUM the thickness of the sediments tend to be larger as we go to the west. If we assume the S-wave velocity of sediments to be 200m/sec, the peak frequency of 1.5Hz suggests the thickness of 33m, while it is 3.0Hz, the thickness of 17m. If we assume 300m/sec of S-wave velocity, then thickness could be 50m and 25m, respectively.

At No.5 PACAR and No.6 KOWEN both H/V ratios have similar peak frequencies around 2.5Hz to 3Hz to No.1 Wonokromo. However, at No.7 site MELIK we cannot see any clear peaks, which suggests no soft shallow layers with high impedance contrast.

In Fig.7 we show results of detailed investigation from No.3 site (KEDUN) to No.1 site (WONOKROMO), peak frequency distribution of H/V spectral ratios. As we move from the east bank of Opak river to the west peak frequency is varying from 6Hz to 1.5Hz. This suggests that the Opak fault may be running near the Opak river.

3.2.3. Line-2 Investigation
We have seen quite similar characteristics of H/V spectral ratios along the Imogiri line, Line-2, so it may be the common structure in the epicentral region. If this is the case, then the spatially complicated pattern of the

damage concentrated areas as seen in Fig.1 may be the results of both source rupture pattern along the fault as well as the local soil conditions, which may strongly amplify ground motions impinged from the source to the surface.

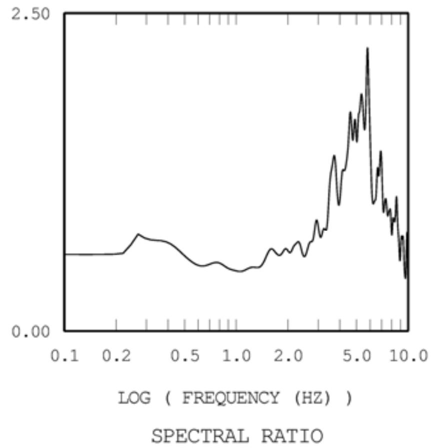

Figure 3 H/V spectral ratios at No.3 site in line-1（KEDUN）.

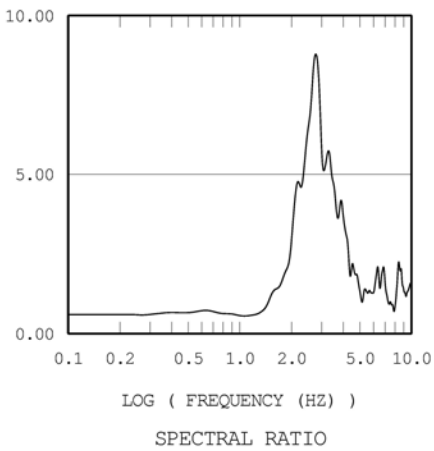

Figure 4 H/V spectral ratios at No.4 site in line-1（TEGAL）.

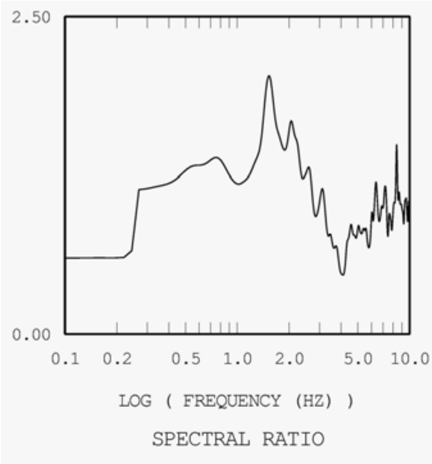

Figure 5 H/V spectral ratios at No.2 site in line-1（KAUMAN）.

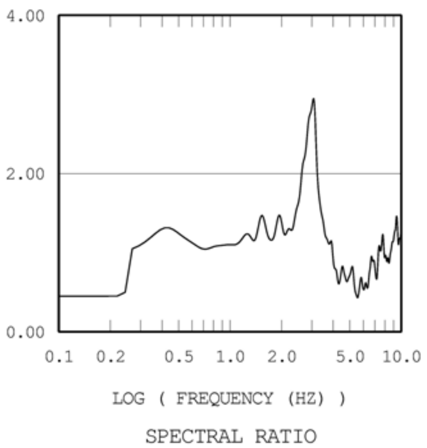

Figure 6 H/V spectral ratios at No.1 site in line-1（WONOKROMO）.

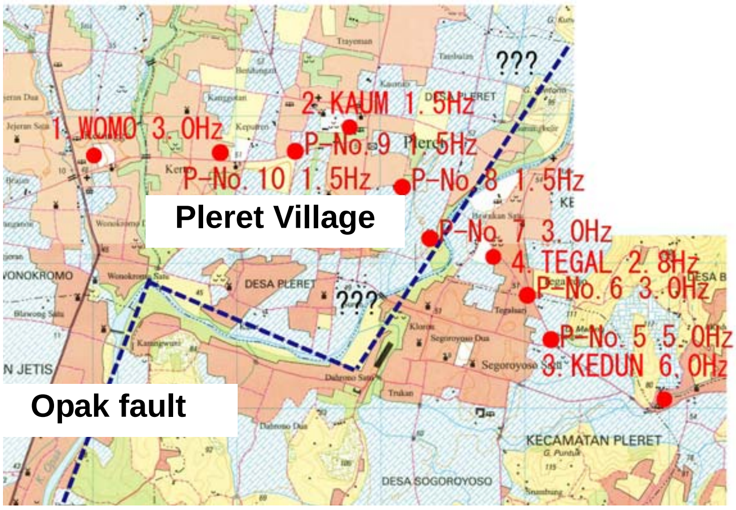

Figure 7 Peak frequency distribution in Pleret district based on microtremor H/V spectral ratios.

4. BORING SURVEY

4.1. Outline

The local geologic and soil condition have a great influence on the intensity of ground motion and earthquake damage. Local site conditions can profoundly dominate on amplitude characteristic (peak acceleration, velocity and displacement), frequency content, and duration of strong ground motion. The extent of their influence depends on geometry and properties of subsurface material. However, as we mentioned before, not so much subsurface geological information was available in epicentral region and so boring survey was conducted to characterize subsurface soil condition.

The detailed boring survey had been performed at nine selected sites in Yogyakarta Basin, especially in Bantul, the most severely damaged area, for subsurface investigation. The boreholes were generally drilled up to bedrock and varying 20 m to 50 m in depths. The SPT tests were performed at every 2 m interval during boring and soil and rock samples were collected for laboratory testing.

The outline of our boring survey in Yogyakarta Basin, especially in epicentral area is as follows:

Line – I: Boring was firstly carried out in the southern part of Yogyakarta basin as Line – I, passing through Opak fault as shown in Figure 8. It consists of Wijirejo, Bambang Lipuro, Pranti, Watu, and Tampuran sites. The depths of boreholes are varying from 26 m to 50 m.

Line – II: Four boreholes were drilled in Line – II, starting from BPKP-1 which is located in Jl. Parangtritis, Yogyakarta City and then BPKP-2, Krajan. It finally crossed Opak fault and ended at Karang Semut site as shown in Figure 8.

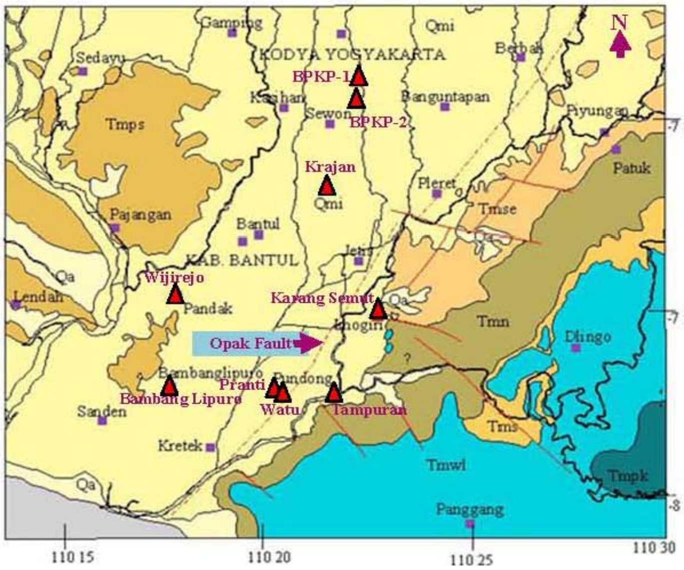

Figure 8 Borehole locations in the Yogyakarta Basin

4.2. Results of the Boring Survey

In this study, the subsurface soil profiles and soil types are determined according to the Unified State Soil Classification (Craig, 1991), based on grained size analysis, Atterberg's Limits Test and borehole logs. The shear strength parameters are obtained from direct shear test and tri-axial test. The water content, void ratio and specific gravity for each layer also determined. These subsurface profiles and properties are fundamental input parameters for ground response analyses.

4.2.1. Line – I Investigation

The subsurface soil profile and geotechnical parameters of each soil layer at Tampuran site are shown in Figure 9(a). That borehole is located near Opak River. It was drilled just up to 26 m since bedrock had been encountered starting at 13 m. The water table in this area is very shallow and observed at 2.5 m depth. Fine to medium uniform sand had been observed up to 12 m. This zone is very loose (N≤18) and so the high amplification can be expected in this zone. This zone is underlain by 1 m thick clay layer. The bedrock, breccia, was encountered starting from 13 m.

Figure 9(b) shows the soil condition and related properties of Watu site, up to 35 m depth. The water table was at surface. Medium to gravelly coarse sand are mainly observed in upper 1 m and silt to fine sand are dominant from 1 m to 20 m depth. This portion (N≤18) will be a major zone for the consideration of ground motion and amplification. This zone is underlain by 1 m thick clay layer. The bedrock, breccia, is encountered starting from 22 m to 30 m. Blackish brown, fine-grained, hard sandstone is observed after 30 m depth.

In Figure 9(c), the subsurface soil condition of Pranti site is shown. It was drilled up to 40 m depth and the water table was encountered at the depth of 14.6 m. It is an area of thick sand deposit. Bedrock is encountered after 30 m depth and which is overlain by sand deposit of different layers. This is an area of thick unconsolidated sediment (N≤19), and so high amplification and strong ground motion during an earthquake can be expected in this area. Although Watu and Pranti sites are very close to each other, their soil conditions are quite difference. This can be due to the proximity of the Opak river and the Opak fault. It is quite clear that we need to consider nonlinear behavior at these sites in their dynamic response analyses.

4.2.2. Line – II Investigation

We show the soil condition and geotechnical information of Karang Semut site in Figure 9(d). It was in Imogiri, Bantul and drilled up to only 20 m depth as bedrock, where sandstone is emerged at 14 m. The water table was observed at 8.5 m depth. The upper 4 m is mainly composed of fine to medium sand and two sandstone layers are observed at depth 4.5 m and 7.5 m. A thin clay layer is found at 12 m depth, which is overlying on sandstone bedrock. The different impedance ratio between sandstone and soft soil layers will cause trapping most of seismic waves in soil layers and more cycles of dynamic loading can be expected.

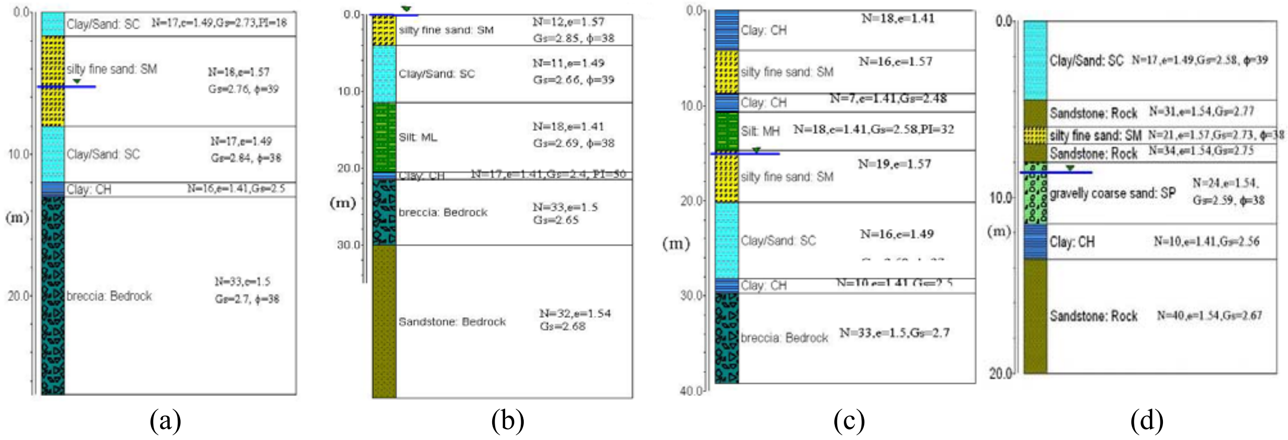

Figure 9 Subsurface soil profiles and geotechnical parameters of (a) Tampuran, (b) Watu, (c) Pranti, and (d) Karang Semut Sites

5. CONCLUSIONS

To understand the effects of local soil conditions on the strong ground motions in the epicentral area of the Central Java earthquake of 2006 we have conducted microtremor measurements there. We also collected several boring survey data conducted after the earthquake to correlate the effects of soil amplification on spatial damage distribution.

We found that the strength of ground shaking should not be so high, probably 5+ to 6- in the JMA intensity scale, that is, 7 to 8 in MMI seismic intensity scale, and the observed local damage ratio variation from site to site should be primarily controlled by the local site conditions. Boring data suggest that there may be a strong impedance contrast at 12 to 25 meters below the surface where we will see a systematic existence of sedimentary rock formation. However, the devastating damage on the residential masonry houses should be mainly attributed to their very low seismic resistance considering several concrete pieces of evidence for not so high ground motion input. The boreholes data we used here were kindly provided by Prof. Drikorita Karnawati and Prof. Subagyo Pramumijoya of Graduate School of Engineering, University of Gadjah Mada, Indonesia.

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