

THE ESTIMATED PGA MAP OF THE $M_w6.4$ 2006 YOGYAKARTA INDONESIA EARTHQUAKE, CONSTRUCTED FROM THE MODIFIED MERCALLI INTENSITY I_{MM}

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(Submitted June 2017; Reviewed September 2017; Accepted March 2018)

ABSTRACT

Many moderate and strong earthquakes have occurred in Indonesia. However, since ground motion records are unavailable, a concise earthquake peak ground acceleration (PGA) map has never before been constructed. Several efforts have been made to construct PGA maps after the $M_w6.4$ 2006 Yogyakarta earthquake, i.e. earthquake PGA maps by researchers [1–4]. However, due to their use of completely different earthquake sources, methods of analysis and by using exclusion criteria of ground motion prediction equations (GMPE), the maps differed greatly and did not match the actual structural damage found in the field. Estimation of a 2006 Yogyakarta earthquake PGA map became possible after field surveying of the I_{mm} conducted by Wijaya [5]. The estimated PGA map was constructed based on the isoseismic lines, intensity prediction equation (IPE) by Wijaya [5] and peak ground acceleration at YOGI and BJI station control points, as published by Elnashai et al [6]. A set of most recent GMPEs were chosen, as they closely predicted the PGA at two control points. An Extrapolation Method was developed in which the PGA between YOGI and BJI stations would be extrapolated to all data points in the field to yield the 2006 Yogyakarta seismic PGA map. Result of the investigation indicated that the pattern of the new PGA map does not form a circle with radius R , but occurs longitudinally following the direction of the Opak River fault trace and closely follows the pattern of I_{mm} map and damage to buildings in the field. It was found that the maximum upperbound PGA reached ± 0.50 - $0.51g$ and it did not occur at the epicenter area but instead took place in relatively deep soil deposit approximately ± 2 km west of the Opak River fault.

INTRODUCTION

Earthquake ground motion parameters, such as horizontal and vertical accelerations, provide very important information about the impact of earthquakes. Ground acceleration is very important and necessary for structural dynamics, design, and evaluation of building structures as well as for the purpose of natural hazard risk assessment. In particular areas where recording networks of strong motion have been installed, ground motions in spatial form can be easily determined [7]. However, in regions not so equipped, such as in the Yogyakarta region, the availability of spatial peak PGA turned out to be a potential problem and became scientifically recognized as an emergency condition.

Tectonically, the Yogyakarta region is strongly affected by the activity of oceanic Indian-Australian subduction (300 km south of Yogyakarta City) and by the activity of the Opak River fault, as shown in Fig.1. On Saturday May 27 2006, the $M_w6.4$ Yogyakarta earthquake occurred at 5:53AM local time; i.e. on Friday 26 May at 22:53:58PM UTC. The earthquake epicentre was reported by several sources, each differing from the other. However, as reported by USGS, the coordinates of the epicenter were 7.96S, 110.46E; putting it only ± 20 km from Yogyakarta city. It was also found that not only was the earthquake close to the city, but the hypocenter lay at a depth of only ± 12 km [8]. Although the earthquake magnitude was considered relatively moderate; it caused more than 5,700 fatalities and the collapse of more than 130,000 unreinforced masonry houses. The predominant causes of damage to unreinforced housing were: building age, inappropriate construction and use of poor quality building materials. Another influential factor was soil condition. The earthquake occurred in a densely populated area,

making its effects devastating.

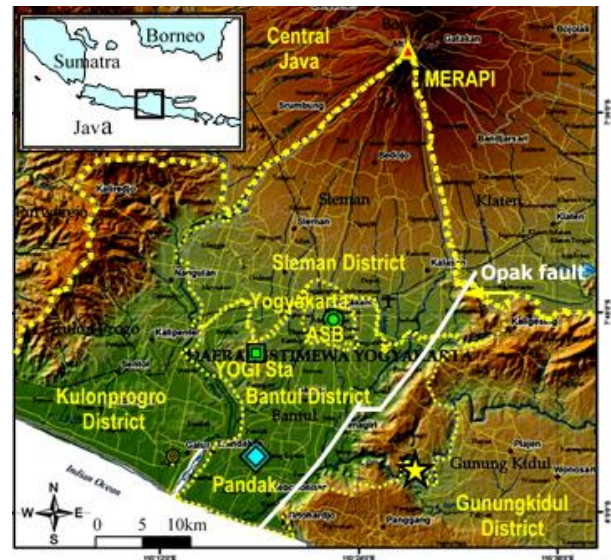


Figure 1: Topographical map of Yogyakarta special Province.

In the absence of a PGA map, several engineering tasks, such as a natural hazard risk assessment, assessment of the existing buildings and structural dynamics analysis could not be properly done. Fortunately, [9] stated that in the absence of ground motion records, an estimation of the ground acceleration could be made by other methods. For this reason, an attempt to develop a method for solving the problem became essential.

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Estimation of the spatial PGA and I_{mm} by using quadratic expression derived from New Zealand Data had also been done by [10]. In this investigation, exponential expression has been used to estimate the spatial ground acceleration.

A PGA map of the 2006 Yogyakarta earthquake had been proposed by several past studies [1–4]. However, the GMPEs used in determining PGA are included in the exclusion criteria as presented in [11–14] and the maps did not correspond to the observed housing damage in the field.

The main aim of this investigation was to refine the existing 2006 Yogyakarta PGA map, based on the I_{mm} as proposed by [5,15]. This paper does not attempt to demonstrate the application of sophisticated method, but it emphasizes more on how real problem in the field can be solved by availability of very limited data. A specific research method needed to be developed in which the PGA map would match the distribution of housing damage in the field and thus be used in the dynamic analysis of structures and risk assessment.

SITE CONDITION AND THE Mw6.4 MAY 27 2006 YOGYAKARTA EARTHQUAKE

A topographical map of Yogyakarta Special Province (YSP) is presented in Fig.1. North of YSP is the Central Java province while to the south, lies the Indian Ocean. The YSP consists of four districts i.e Sleman (north), Bantul (south), Gunungkidul (south-east), Kulonprogo (west) plus the Yogyakarta municipality. As shown in the figure, the Opak River-fault, which is about 54 km long, is located approximately 10 km east of Yogyakarta city. As previously noted, no strong motion station record was found in the area with the exception of the YOGI station. The characteristics of the ground acceleration

time series cause directivity effects as clearly presented in [16,17], but these characteristics were not available in the 2006 Yogyakarta earthquake. Thus the directivity effects during the 2006 Yogyakarta earthquake could be neither described nor discussed.

According to Kyaw et al [18], the formation of the rocks and soils in YSP were initiated during the Tertiary and Quarternary periods. The western part of Kulonprogo (Menoreh) and Gunungkidul districts are mountain ranges where the rocks were formed during the Tertiary period. In the northern part, i.e the Sleman regency (the closest to the slopes of active volcano Mount Merapi), the soil profile consists mainly of coarse sand and gravel, formed by successive sedimentation from Mt. Merapi eruptions. Meanwhile the southeastern parts, Kulonprogo and most of the Bantul district, are the valley areas where soils were formed during the Quarternary period. Their soil deposits are made up of fine sand, clay and silt as a result of Tertiary sedimentary rock weathering [19]. The soil in these areas consists of relatively thick and young soil deposits, which have a high potential seismic vulnerability index [2].

Fig.2 presents an isoseismic or I_{mm} map of the 2006 Yogyakarta earthquake where the higher I_{mm} are located in the deeper soil deposits [5]. The star shown in the figure is the epicenter as reported by USGS. The figure also shows the Yogyakarta (YOGI) and Banjarnegara (BJI) Geophysics stations with their corresponding ground acceleration time histories as reported by [6], a report which stated that the middle value of the PGA was 0.262g for the east-west component and 0.270g for the north-south component, while only the north-south component was reported at the BJI station, where the PGA was 0.028g.

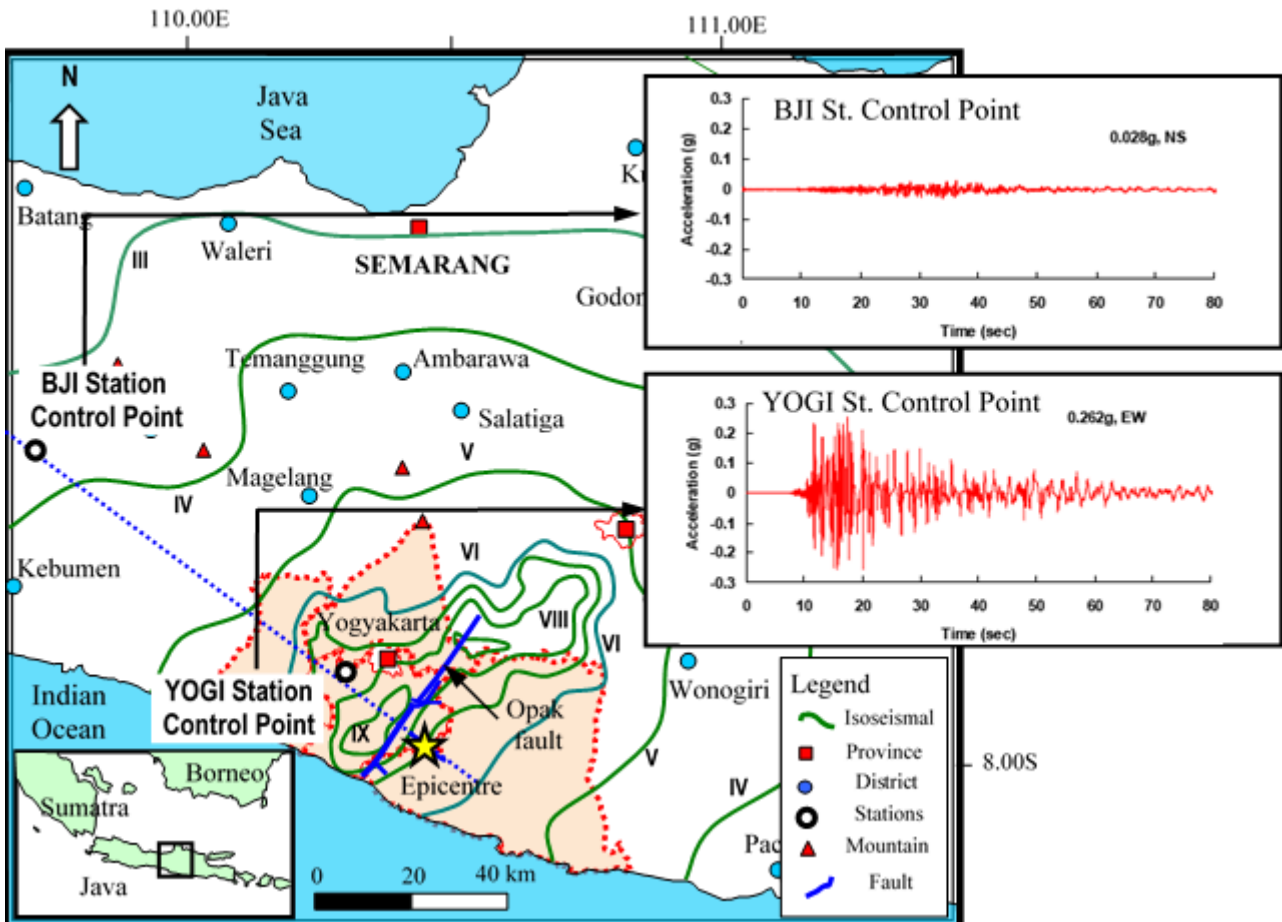
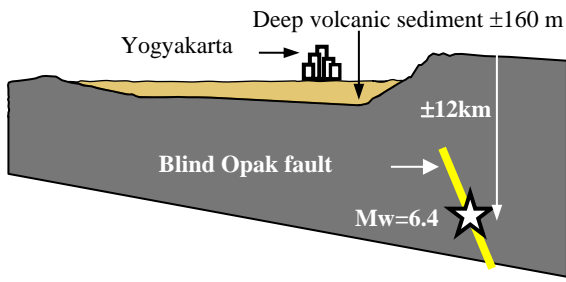
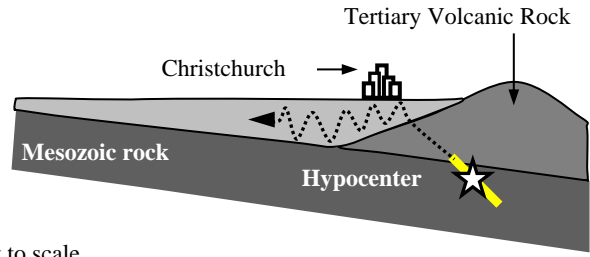


Figure 2. The YOGI, BJI station control points and I_{mm} map of the 2006 Yogyakarta earthquake [5].



a) Yogyakarta volcanic sedimentary basin [8].



Not to scale

b) Christchurch sediment [17].

Figure 3: Similarities in the sedimentary basins of Yogyakarta and Christchurch.

A cross section of the Yogyakarta sedimentary basin is presented in Fig.3a [8], whereas Fig.3b is of the Christchurch (NZ) sedimentary basin as presented by [20]. It is clearly shown in the figures that both Yogyakarta and Christchurch are located in deep sedimentary basins. The case of the 2011 Christchurch earthquake is also taken into account in this paper, since both locations exhibited similar severity of ground acceleration intensity following moderate magnitude earthquake.

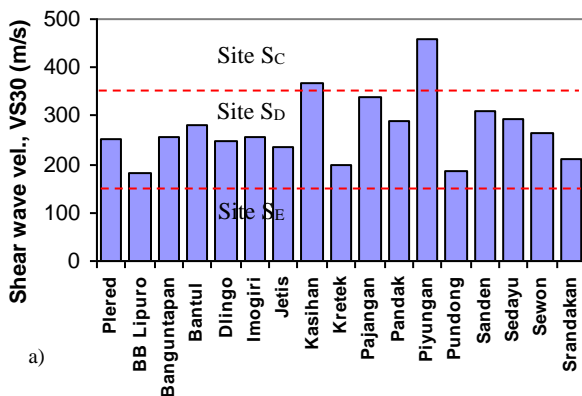
Some aspects such as soil types, soil variability, non-linearity soil characteristics, water table, depth of soil deposit, as well as shear wave velocity are among the characteristics for which discussion is important. Based on the field investigation as reported in [2], soil types at the valley regions (southeastern parts, Kulonprogo and Bantul districts) mainly consist of deep/thick fine sand, silty sand, sand and clay sand. As reported in [21], the depth/thickness of the clay deposit in Turkey was a contributing factor in the heavy structural damage incurred there.

Based on the field research reported by [2], ground water levels in the Bantul valley are very shallow, between 0–4.0 m. According to Yang and Yan [22], the depth of the water table plays an important role in PGA amplification. Thus, the shallow ground water table in deep/thick soil deposits in the study area contributed to the soil response and to housing damage. In the soil classification, one important factor for consideration is the shear wave velocity at 30m upper layer or V_{S30} [23]. The V_{S30} in the Bantul and Sleman districts are presented in Figs.4a and 4b [24]. As shown in Fig.4, most of the Bantul and Sleman regencies possess $V_{S30} = 150\text{--}350$ m/s. According to Muzli et al [24], V_{S30} at YOGI station and Amongrogo Sport Building (ASB) are ± 240 m/s and ± 230 m/s respectively. Hence, those

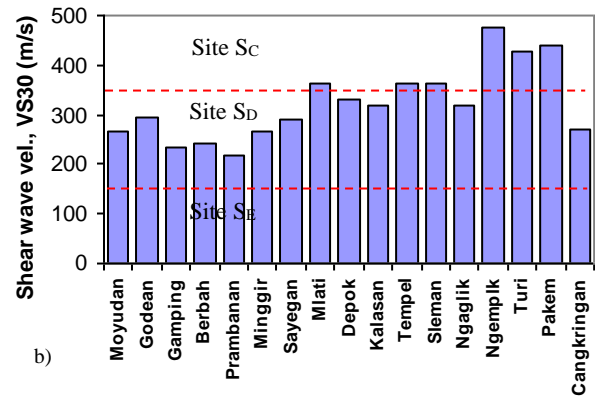
sites and including most of the Bantul area fall into the same soil category i.e firm soil S_D [25]. However, in the Kasihan and Piyungan sub-districts, as depicted in Fig.4a, and Sayegan as shown in Fig.4b, the sites fall into the ‘very dense/stiff soil’ S_c category, since the sites are located in rocky mountainous terrain. Similar site category (S_c) examples were found at Tempel, Ngaglik, Turi and Pakem as presented in Fig 4b, as those sites are located closer to the summit of Mt. Merapi.

Aside from the possibility of PGA amplification, the study area is also vulnerable to susceptibility of soil liquefaction. Widespread soil liquefaction under the 2006 earthquake was investigated by [26] and found to have a tendency to occur along the Opak river. Research on the steady state and state parameters for evaluating potential liquefaction of Yogyakarta volcanic soil was also conducted by [27]. The research found that the ground most susceptible to soil liquefaction is located in the area along the Opak river, where the shear wave velocity was only $156\text{--}250$ ms^{-1} . The sedimentary deposit consists mainly of sandy silt, silty sand, and partly of clay sand. Grain-size analysis indicated that the soil is dominated by fine sand with fine content varying from 8-21%. Since by its nature, silty-sand tends to be deposited in a looser state, the region is undoubtedly susceptible to exhibiting soil liquefaction.

From the above description, there is a clear indication that the Merapi plain area is very vulnerable to natural hazards, particularly volcano eruptions, earthquake events and their respective effects. The lack of availability of an appropriate PGA map indicates an urgent and important need for a study such as this to provide an estimate of spatial PGA in the area for assistance in disaster reduction.



a)



b)

Figure 4: Shear wave velocity at upper 30 m, V_{S30} : a) Bantul sub-district; b) Sleman sub-district.

THE 2006 EARTHQUAKE PGA MAPS FROM PREVIOUS RESEARCH

PGA maps for the 2006 Yogyakarta earthquake have been proposed by several studies [1–4]. However, the results differed significantly from one another and did not match the structural damage distribution found in the field as reported by Wijaya [5]. Some of the corresponding PGA maps are described below.

A 2006 Yogyakarta base-rock map was proposed by Daryono [2] as part of his dissertation and is presented in Fig.5. The base-rock map was determined by simply using the Fukushima and Tanaka (1990) GMPE. The earthquake source was modelled as a line source and accordingly, as shown in Fig.5, the distributions of the base-rock map were parallel to the Opak River fault-trace, with a maximum base-rock acceleration of about 0.44g. On the other hand, Khalfan [3] used USGS PGA maps, i.e. near real-time maps of ground motion caused by the earthquake and earthquake intensity, the result of which is presented in Fig.6. As shown in the figure, the maximum

ground acceleration was around 0.60g, which occurred at the epicenter area.

PGA maps of the May 27, 2006 Yogyakarta earthquake were also presented by Thant [1] and Hartanyo et al [4], which are shown respectively in Fig.7 and Fig.8. Both of these investigations used the fault rupture defined by Tsuji et al [28]. As mentioned earlier, the location of the earthquake fault rupture was assumed to be ±10 km east of and parallel to the Opak fault trace. The maximum ground acceleration was estimated to have occurred at the fault rupture, and the ground accelerations were attenuated parallel to the earthquake fault rupture. The PGA according to [1] was ± 0.33g and according to [4] the PGA at the fault rupture was ± 0.35g. The pattern of these PGA maps is similar to the I_{mm} map as reported by Dowrick and Rhoades [10]. By comparing Figs.5, 6, 7 and 8 it can be seen that the patterns of the PGA maps are different from each other.

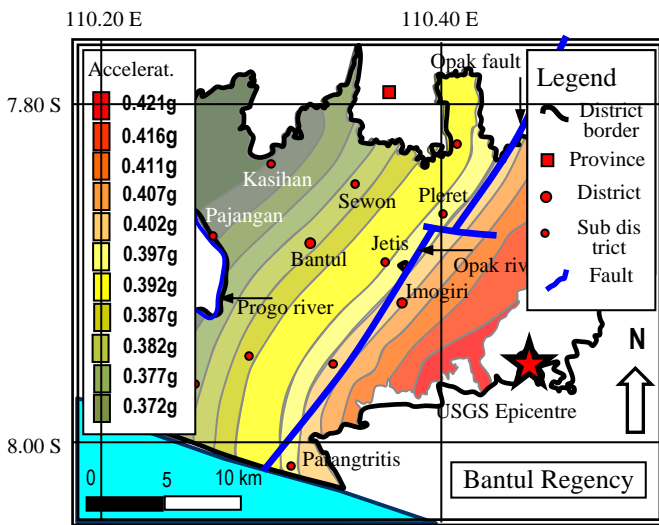


Figure 5: The 2006 Yogyakarta earthquake PGA map [2].

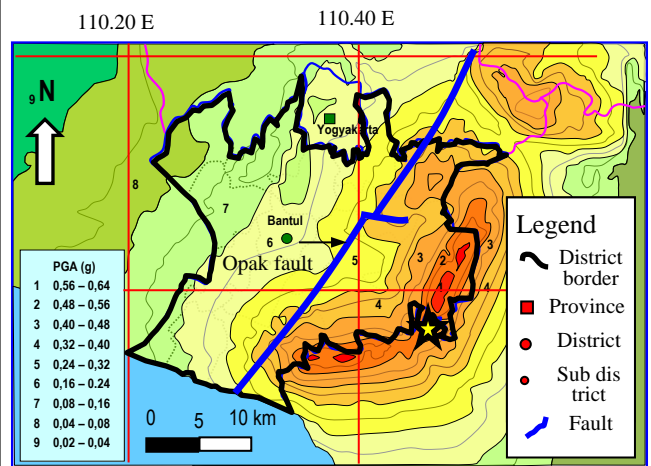


Figure 6: The 2006 Yogyakarta earthquake PGA map [3].

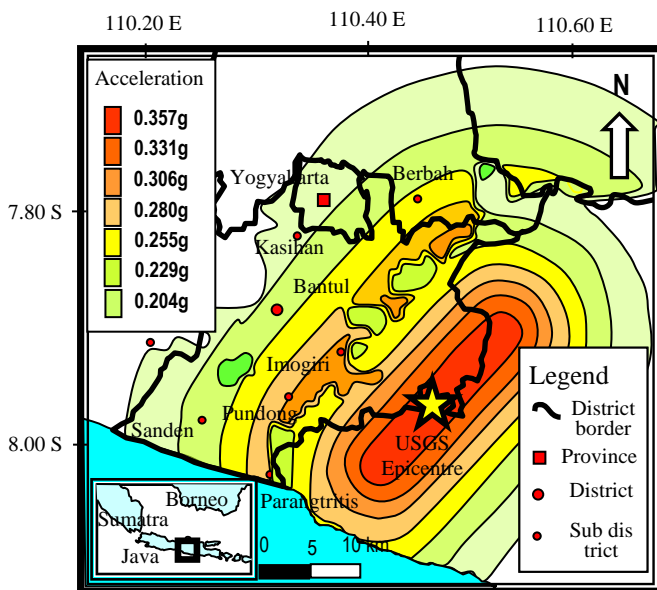


Figure 7: The 2006 Yogyakarta earthquake PGA Map [1].

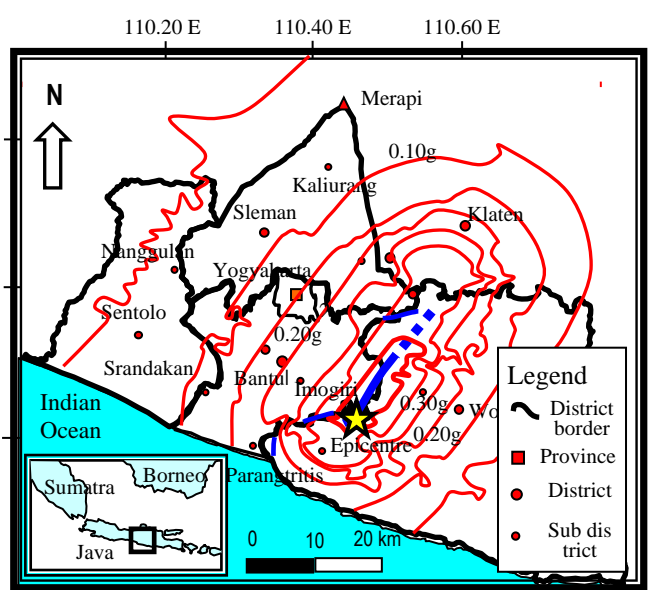


Figure 8: The 2006 Yogyakarta earthquake PGA Map [4].

THE ACCELERATION CONTROL POINTS AND INTENSITY PREDICTION EQUATION (IPE)

Field reconnaissance of the May 27, 2006 Yogyakarta earthquake was carried out by Elnashai et al [6]. During this field investigation, the ground velocity records, i.e the north-south, east-west, and vertical direction records, were retrieved at Yogyakarta Geophysics Station (YOGI). The YOGI station is located in the Gamping Sub-District and is constructed on soil with a shear wave velocity of 235 ms^{-1} [24]. According to UBC 1997, the soil is categorised as stiff soil or S_D soil. Based on the available information, it was found that the PGA was only $0.03g$, which was unrealistic, especially considering the distance from the epicenter and the observed levels of building damage in Yogyakarta City.

By considering the above result, another approach was necessary to determine a more realistic PGA [6]. The case of the collapsed 2-storey Amongrogo Sport Building (ASB) was selected to determine a realistic PGA value. The distance from epicenter to YOGI and to ASB sites is approximately same (see Fig.1) and according to research conducted by Muzli et al [24], both sites have the same soil category that is S_D soil. Calibration of the PGA at the YOGI station was carried out by structural back-analysis of the collapsed beams of the 2-storey Amongrogo sport building by considering the concrete compressive strength $f'_c = 17.1$ to 27.6 MPa , steel yield strength $f_y = 310$ to 520 MPa , and finally back-analysis, which yielded a peak ground acceleration of $0.197g - 0.336g$ for the horizontal and $0.183g - 0.303g$ for the vertical direction. The high level of vertical ground acceleration indicated that the instrument was installed relatively close to the earthquake source. As presented in [6], the PSA fundamental period $T = 0.24s$ was found, thus it was evident that due to resonance frequency, collapse of the 2-storey ASB would inevitably occur. The middle value of the ground acceleration time history at the YOGI and BJI stations is presented in Fig. 2.

Estimated PGA at YOGI are classified into three levels, namely the upper bound ($0.336g$), the middle value ($0.262g$) and the lower bound ($0.197g$). Meanwhile, the ground accelerations at the BJI station were $0.028g$ for the north-south component and $0.020g$ for the vertical component. The BJI station is located in medium stiff soil similar to that of the YOGI station. Calibration of the peak ground acceleration was made due to the fact that the ground shaking was relatively small and no housing damage was found.

Every data point in the field investigation conducted by Wijaya [5] and further developed by Widodo et al [15] contains: 1) field earthquake intensity denoted by $I_{mm,E}$; 2) coordinates (x,y) and 3) distance $R(\text{km})$ to the epicentre. Those field data will be used to develop the PGA map of the May 27, 2006 Yogyakarta earthquake. The research undertaken by Wijaya [5] leads to the proposed Intensity Prediction Equation (IPE) which is presented in the equation,

$$I_{mm,E} = 8.889 \cdot e^{-0.0088 \cdot R} \quad (1)$$

where $I_{mm,E}$ is calculated earthquake intensity based on Eq.(1) and R is the distance in kilometres from the epicentre.

The I_{mm} map was developed based on an intensive field investigation involving 294 field data, and is therefore referred to as global IPE. By comparing Fig.1 and Fig.2, it seems that besides being affected by distance, I_{mm} is also affected by soil condition, the stiffer the soil the smaller the I_{mm} . Thus, the effect of the soil condition is already included in the I_{mm} - R relationship. The distribution of field data point is presented similarly to that in Fig.15. The data include the coordinates of the respondents' houses, results of field observations and interviews. The interview instrument was prepared according to the XII-scales Modified Mercalli Intensity, I_{mm} . The data

obtained were based on: 1) people's response during earthquake; 2) response of any objects; 3) environmental damage and 4) damage to housing. The data was then analysed, developed and finally presented in terms of the I_{mm} map of the 2006 Yogyakarta earthquake as shown in Fig.2.

SELECTION OF THE GROUND MOTION PREDICTION EQUATIONS (GMPE)

Ground motion prediction equation (GMPE) is a model for predicting ground motion characteristics at a particular site [11]. GMPEs are used because the earthquake records are not always available in all places particularly in the earthquake prone area. The prediction is commonly presented in terms of median spectral amplitudes including its intrinsic uncertainties. The uncertainties are commonly referred by epistemic and aleatory uncertainty [29-31]. The epistemic uncertainty can be caused by incomplete knowledge which can consist of several things i.e. inexact model selection, error in statistics, error in measurements and errors in data base. In probabilistic seismic hazard analysis (PSHA) the presence of epistemic uncertainty can be treated by applying the logic tree model [32]. Meanwhile, aleatory uncertainty in other side may be caused by the natural variability of the soil site, the soil non-linearity or site amplification [29,33], which usually consist of intra and inter-events [34] and presented by standard deviation or sigma [11].

Selection of the GMPE is the most critical step in the seismic hazard analysis as well as in this investigation. The general and detailed criteria for selecting and adjusting the GMPE models have been presented briefly by [11,13]. Among of the general criteria, important ones are those related to consideration of global earthquake models and exclusion criteria. According to [11,12,14], the exclusion criteria in selection of the GMPE can be categorized as:

1. **Tectonic regimes:** GMPE is proposed based on inappropriate tectonic regimes consisting of a stable continent region (SCR), an interface or in-slab subduction zone (SZ) and an active shallow crustal region (ASCR). In addition, the hinging and footing walls mechanism may also have not been included.
2. **Earthquake mechanisms:** GMPE is developed by applying inappropriate earthquake mechanisms including the megathrust, intermediate intra-slab, deep intra-slab, reverse, strike slip and the oblique faults.
3. **Data:** GMPE is constructed based on insufficient, inaccessible, not reviewed and unpublished data.
4. **Functional form:** GMPE is developed by using inappropriate functional form includes source, source-site path, site effect or site amplification.
5. **GMPE model:**
 - a. has been superseded by a more recent model,
 - b. published with inappropriate explanation variables, M_L , R , V_{s30} , etc.,
 - c. constructed by inappropriate process in determination of coefficients,
 - d. derived by not considering non-linear magnitude or magnitude-dependence decay with distance,
 - e. derived with inadequate range of spectral period, and
 - f. is not widely/internationally published.

However, it was strongly suggested by Cotton et al [11] that the criteria of GMPE selection should not be excessively specific, tied to time at writing and thus remaining static, both rather should be sufficiently flexible and adaptable. Since Indonesia does not have its own GMPE then utilization of GMPEs from regional/world-wide data, such as applied in Vietnam [35], is therefore required. The selected GMPEs as presented in the

following sections have been scrutinised. In addition, the selected GMPEs should be able to predict or match with the PGA at YOGI and BJI station control points. It was suggested [11] that to accommodate the ground motion uncertainty more than one GMPE must be used. In this investigation four GMPEs have been selected as follows:

1. The Campbell and Bozorgnia, C-B (2007): Next Generation Attenuation [36] in which a number of definitions and provided coefficients can be found in [37],
2. Akkar and Bommer, A-B (2010): GMPE with definitions and its coefficients can be found in [38],
3. Laurendeau (2013): GMPE with definitions and its coefficients can be found in [38] as well,
4. Akkar, Sandikkaya, Bommer, A-S-B (2014): GMPE in which the PGA reference at rock site or PGA_{REF} initially was proposed by [39].

A number of data are required in the implementation of the four selected GMPEs above. According to Walter et al [8], the source mechanism data for the 2006 Yogyakarta earthquake are: a) dip angle of 87° ; b) rake angle of 177° (right lateral strike-slip) and c) the upper edge of the fault (Z_{TOR}) at 6 km.

METHOD OF INVESTIGATION

The I_{mm} defined in Eq.1 is used as a basis for solving the problem in this study. The PGA at YOGI and BJI are used as references for PGA interpolation between two-stations. The distance between the epicenter and the YOGI station is about 24 km, and between the YOGI and BJI stations, about 77 km. The interpolation point is determined at distance R equal to 1, 5, 10, 14, 28, 40, 53, 67, 80 and 92 km respectively from the centre of isoseismal line Io , thus the distance from epicentre to Io is about 9km. To solve the problem an Extrapolation Method has been proposed and schematically is presented in Fig. 9.

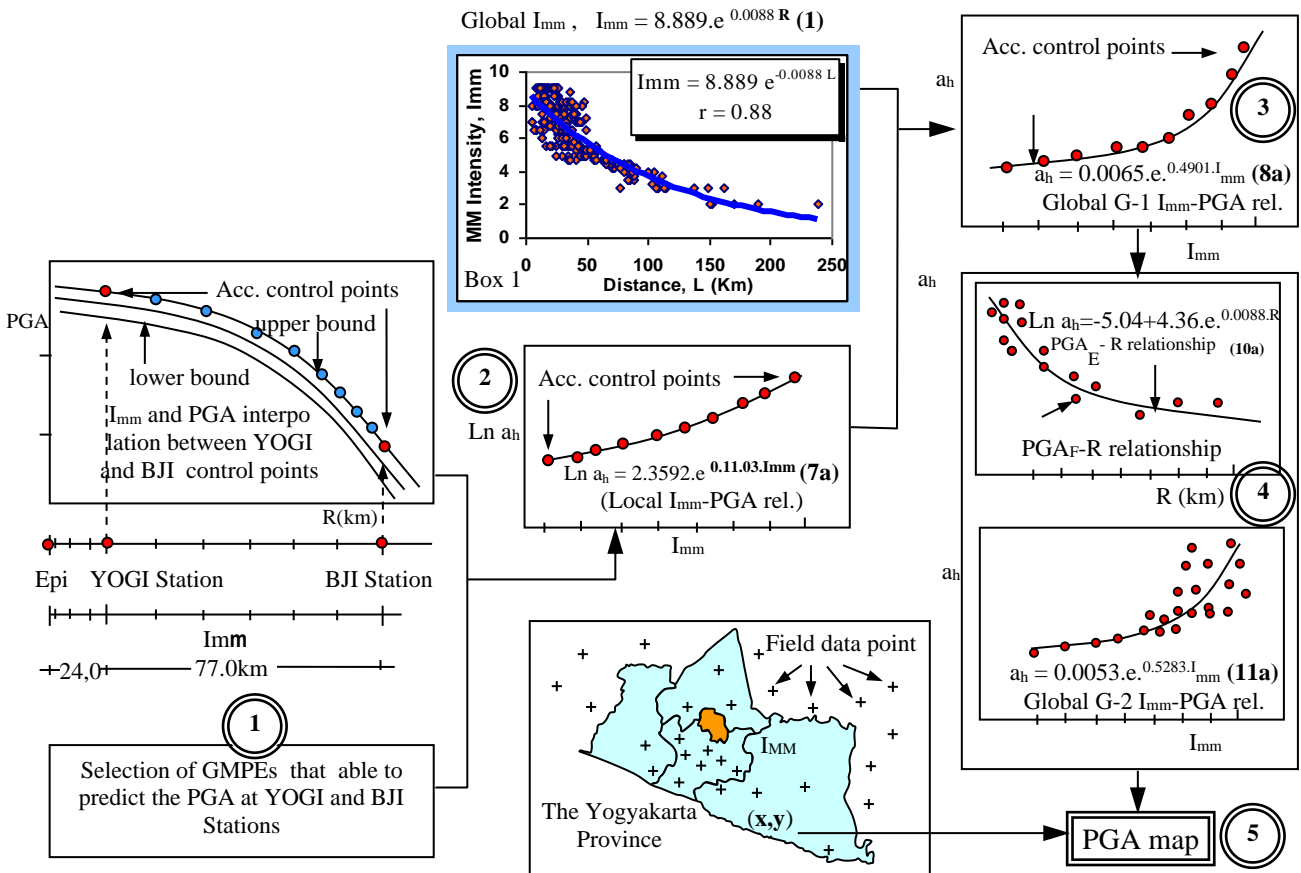


Figure 9: The flow of investigation in the Extrapolation Method.

There are several steps of this method, which in detailed are presented as follows:

1. The first step was to choose four GMPEs that were not included in the exclusion criteria as mentioned before,
2. The second step was to determine $I_{mm,E}$ at each interpolation point between YOGI and BJI stations by using Eq.(1) and PGA or a_h by using the selected GMPEs with particular values of σ and V_{S30} . Theoretically PGA should be calculated based on V_{S30} on each interpolation point. However, due to insufficient data, a rough assumption has been made in which all interpolation points are assumed to have similar soil types with V_{S30} same as at YOGI station. The assumption was made solely for the purpose of solving the existing problem. The local PGA- I_{mm} mathematical relationship at every interpolation point between two

control points could be developed. The result is called local relationship because the PGA is just calculated by using selected GMPE and has not been determined based on the global IPE as presented in Eq.(1),

3. The third step was to compute the global PGA_E at interpolation point by substituting global IPE or $I_{mm,E}$ from Eq.(1) to local PGA- I_{mm} relationship from the 2nd step. It should be noted that I_{mm} at every interpolation point from 2nd step has been computed. Thus, a global G-1 PGA- I_{mm} relationship could then be constructed. The term global is used because even though the computed PGAs are still in two control points, but the global IPE or $I_{mm,E}$ defined in Eq.(1) has been inserted/used in the calculation of PGA,
4. The first stage of the 4th step is matching between PGA_F-R and PGA_E-R relationships. The maximum ground

acceleration at every field data point denoted by PGA_F is determined by substituting the field earthquake intensity $I_{mm,F}$ to the G-1 Global PGA- I_{mm} equation from the 3th step. Meanwhile the PGA_E is the maximum ground acceleration calculated based on global IPE or $I_{mm,E}$ as presented in Eq.(1). Therefore, matching between PGA_F - I_{mm} and PGA_E - I_{mm} relationships can be done. The next stage of the 4th step is to develop relationship between PGA_F and $I_{mm,E}$ and then is called the Global G-2 PGA- I_{mm} relationship,

- The fifth or the final step was to draw the PGA map, since PGA_F has been computed and every field data point possesses coordinates (x,y). Finally a PGA map of the 2006 Yogyakarta earthquake could be drawn. This approach is called an Extrapolation Method, since the interpolated PGAs from two control points then to be extrapolated throughout the field data points in whole research area.

RESULTS AND DISCUSSION

The selected Ground Motion Prediction Equation (GMPEs)

The first step of this investigation was to choose GMPEs that were able to predict the PGA at YOGI and BJI stations. The values of PGA at YOGI and BJI stations (control points) computed based on the selected GMPEs are presented in Table 1. As shown in Fig.2, the horizontal PGAs at the YOGI and BJI stations were 0.262g and 0.028g for middle value and 0.336g and 0.035g for upper bound value [6]. As shown in Table 1, the four selected GMPEs predicted well the upper bound of PGA targets.

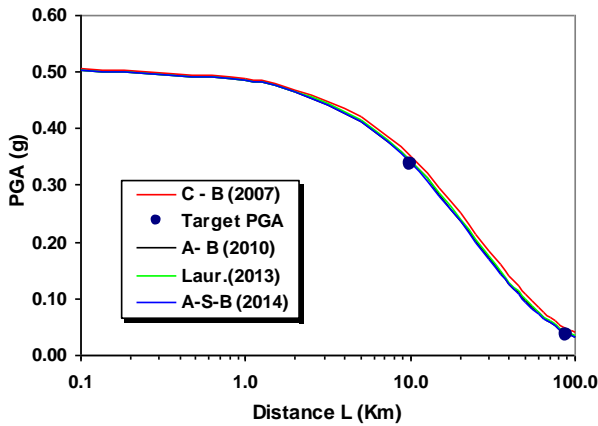


Figure 10: The selected GMPEs for predicting upper bound PGA targets.

As shown in Table 1, the predicted PGAs were calculated based on aleatory uncertainty as represented by sigma which was equal to 0.24, 0.20, -0.15 and 0.39 respectively for C-B (2007), A-B (2010), Laurendeau (2013) and A-S-B (2014) GMPE. The median value of GMPEs used has been adjusted to site conditions by applying the value of V_{S30} at the site. The used sigma for each GMPE is still smaller than the total value (sigma-t). The YOGI and BJI stations are ± 10 km and ± 90 km respectively from the centre of maximum isoseismal line Io.

The performance of four-GMPEs in predicting the PGA at YOGI and BJI control points is shown in Table 1 or in Fig.10.

Fig.10 is the performance of the selected GMPEs to predict the upper bound of PGA at YOGI and BJI stations. It shown in Fig. 10 that C-B (2007) GMPE predicts slightly higher PGA, meanwhile A-K (2010), Laurendeau (2013) and A-S-B (2014) GMPEs are very close and predict PGA well.

I_{mm} and PGA Interpolation between two Control Points and Local I_{mm} - PGA Relationship

As shown in Table 1 and Fig.10, the C-B (2007) and A-S-B (2014) GMPEs were chosen as examples for interpolating the PGA from the YOGI and BJI stations. By using those GMPEs, the result of the first step is the PGA_E at every interpolation point represented by filled-dots in Fig.11. As shown in the figure, the peak ground acceleration a_h was connected to the $I_{mm,E}$ by exponential instead of linear function as conducted by [5,15]. The relationship could then be plotted to yield the following equations:

$$\ln a_h = 2.3592.e^{0.1103.I_{mm}} \quad (2a)$$

$$\ln a_h = 2.1171.e^{0.1227.I_{mm}} \quad (2b)$$

Eqs.(2a) and (2b) are based on the C-B (2007) and A-S-B (2014) GMPEs respectively. As previously stated, Eqs.(2a) and (2b) are called local relationships since the global IPE or $I_{mm,E}$ as presented in Eq.(1) has not been used in calculating PGA. It is clearly shown in the Fig.11 that all data are well fitted, which yields high correlation coefficient presented in exponential function. Fig.11 is the result of the 2nd step of the investigation.

Fig.12 is the result of the 3rd step i.e by substituting global IPE or Eq.(1) to Eq.(2). The relationship in Fig.12 is called the global PGA- I_{mm} relationship since eventhough the computed PGAs are still illustrated at each interpolation point between the YOGI and BJI stations but the global $I_{mm,E}$ from Eq.(1) already included in the PGA calculation. Plotting the relationship between PGA and I_{mm} as shown in Fig.12 can be denoted as the global G-1 PGA- I_{mm} equations and presented as,

$$a_h = 0.0065.e^{0.4901.I_{mm}} \quad (3a)$$

$$a_h = 0.0045.e^{0.5313.I_{mm}} \quad (3b)$$

It should be reminded that term I_{mm} refers to variable of earthquake intensity. As a variable, the I_{mm} can be replaced by field earthquake intensity $I_{mm,F}$ or replaced by computed earthquake intensity $I_{mm,E}$ based on global IPE as presented in Eq.(1). The relationships presented in Fig.11 differs from Fig.12. In the former, PGA at every interpolation point is calculated by using selected GMPEs whereas the latter, PGA is calculated based on global IPE as presented in Eq.(1). Mathematical relationship between PGA- I_{mm} is presented in Eq.(3). Eqs.(3a) and (3b) are already in the global relationship then it can be used to determine the field peak ground acceleration or PGA_F at every field data point based on the available field $I_{mm,F}$.

Table 1: Initial predicted of Upper bound PGA computed based on the selected GMPEs.

Control Points	Upper bound PGA targets	Ground Motion Prediction Equation, GMPE			
		Campbell & Bozorgnia (2007) (sigma = 0.24)	Akkar & Bommer (2010) (sigma = 0.20)	Laurendeau (2013) (sigma = -0.15)	Akkar, Sandikkaya, Bommer (2014) (sigma = 0.39)
YOGI Station	0.336g	0.327g	0.339g	0.323g	0.323g
BJI Station	0.035g	0.044g	0.037g	0.034g	0.034g

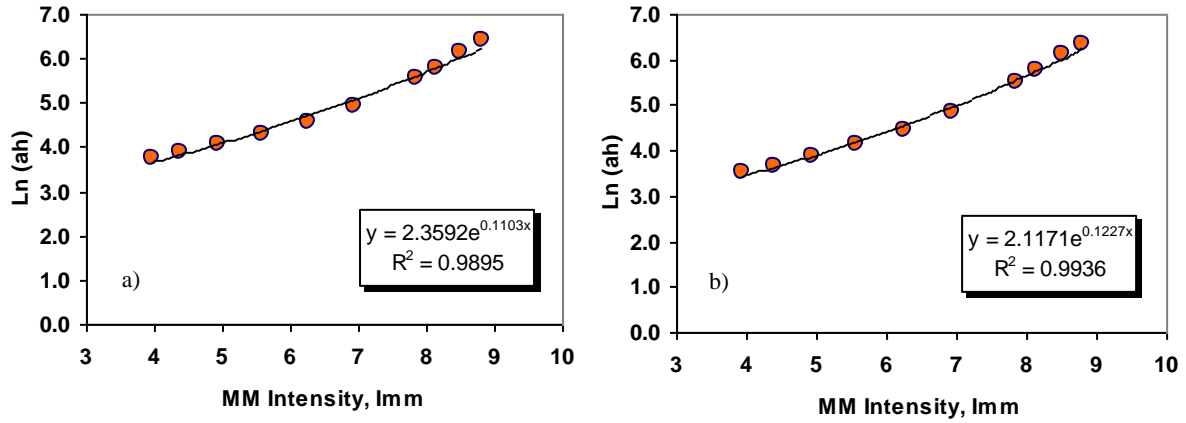


Figure 11: Local $\ln a_h$ - I_{mm} relationship based on: a) C-B (2007); b) A-S-B (2014) GMPE.

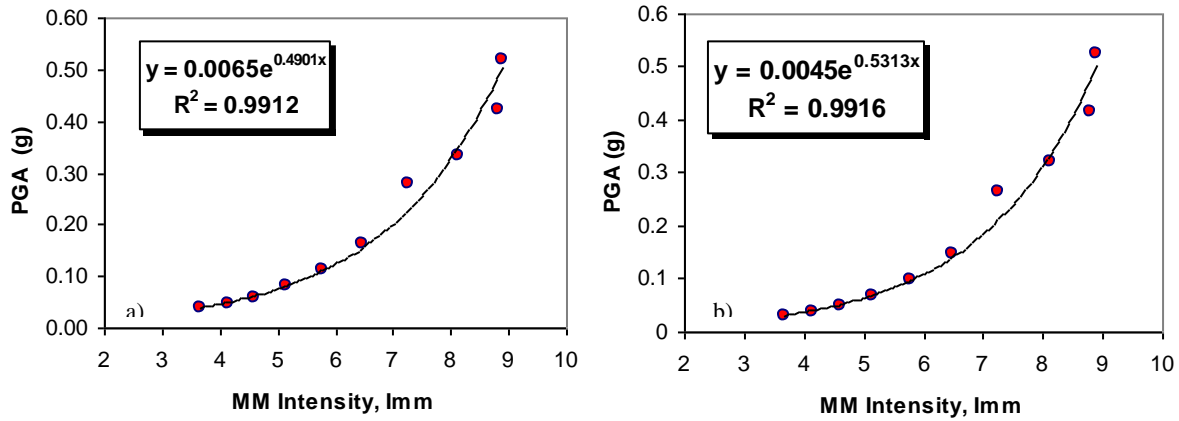


Figure 12: Global G-1 PGA- I_{mm} relationship based on: a) C-B (2007); b) A-S-B (2014) GMPE.

The PGA-R and PGA_F - $I_{mm,E}$ Relationships

The first stage of the 4th step is to construct PGA-R relationship. The computed peak ground acceleration or $a_{h,E}$ at any distance R can be determined by substituting the global IPE in Eq.(1) into Eqs.(3a) and (3b). The result is denoted by PGA_E since it computed based on IPE as presented in Eq.(1). The PGA_E -R relationship yields the following global equations,

$$a_{h,E} = 0.0065.e^{0.4901.(8.889.e^{-0.0088.R})} \quad (4a)$$

$$a_{h,E} = 0.0045.e^{0.5313.(8.889.e^{-0.0088.R})} \quad (4b)$$

Eqs.(4a). and (4b) can be simplified to,

$$\ln a_{h,E} = -5.04 + 4.36.e^{-0.0088.R} \quad (5a)$$

$$\ln a_{h,E} = -5.40 + 4.72.e^{-0.0088.R} \quad (5b)$$

Eqs.(4a) and (5a) refer to C-B (2007) GMPE and Eqs.(4b) and (5b) refer to A-S-B (2014) GMPE. The final predicted of upper bound PGA according to the four selected GMPEs is presented in Table 2. It clearly shown in Table 2 that even though all final predicted PGA are higher than the initial one, but in general four selected GMPEs closely predicted the PGA targets. It is also appears that the PGA targets are best/closest predicted by the A-S-B (2014) GMPE.

Table 2. Final predicted upper bound PGA computed by $a_h = \alpha e^{\beta I_{mm}}$.

Stations	PGA targets	Ground Motion Prediction Equation (GMPE)							
		C-B (2007)		A-B (2010)		Laurendeau(2013)		A-S-B (2014)	
		α	β	α	β	α	β	α	β
		0.0065	0.4901	0.0048	0.5239	0.0052	0.5147	0.0045	0.5313
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
YOGI Station	0.336g	0.327g	0.351g	0.339g	0.341g	0.323g	0.342g	0.323g	0.340g
BJI Station	0.035g	0.044g	0.046g	0.037g	0.039g	0.034g	0.041g	0.034g	0.038g

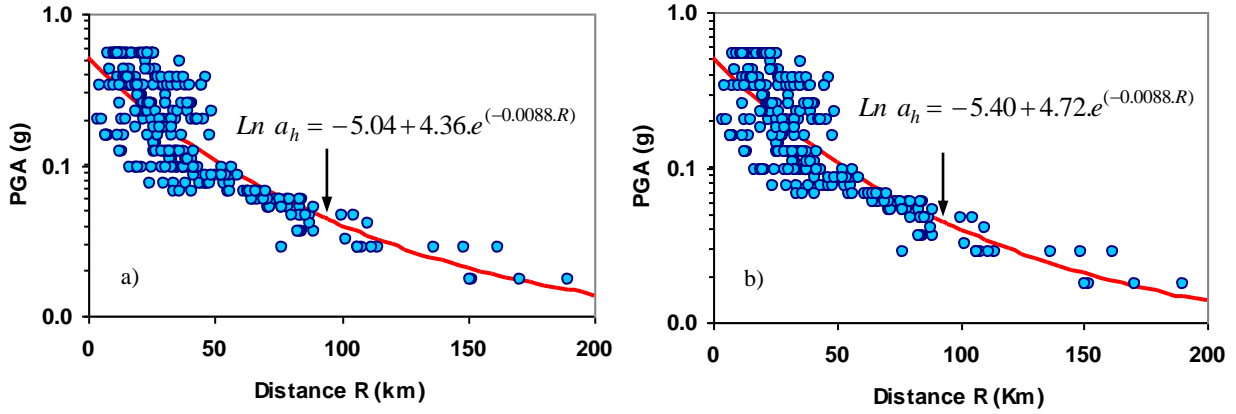


Figure 13: Matching between PGA_F -R and PGA_E -R relationships based on: a) C-B (2007); b) A-S-B (2014).

Meanwhile, substituting the field earthquake intensity $I_{mm,F}$ into Eqs.(3a) and (3b) will provide the field peak ground acceleration PGA_F at every data point. The filled dots as presented in Fig.13 are plotting between PGA_F with R or PGA_F -R relationship. Therefore, Fig.13 is matching between PGA_F -R and PGA_E -R relationships. It is clearly shown in the figure that the PGA_F distributions are scattered over a short distance. The huge scatter in I_{mm} near the source originally was taken from the field research result as reported by Wijaya [5] (see blue box in Fig. 9). The scatter in I_{mm} may be caused by the high variability of the building construction quality, the people’s reaction during earthquake and the response of objects in the field when the information was collected by Wijaya [5]. Thus, scatter of I_{mm} in this investigation could not be avoided. Figs.13a and Fig.13b respectively refer to the C-B. (2007) and the A-S-B (2014) GMPEs. It is clearly shown in the figures that Eqs.(5a) and (5b) are matching well the PGA_F -R relationship. However, these results are valid only for the M_w 6.4 May 27, 2006 Yogyakarta earthquake. Thus, for other earthquake magnitudes, the specific GMPE as presented in Eqs.(5a) and (5b) should be re-evaluated.

The next stage in the 4th step is to construct the Global G-2 PGA - I_{mm} relationship. It has been mentioned before that there are field maximum ground acceleration PGA_F computed based on $I_{mm,F}$ and PGA_E computed based on $I_{mm,E}$. Plotting the relationship between PGA_F - $I_{mm,F}$ will be back to Eq.(3), meanwhile plotting between PGA_F - $I_{mm,E}$ is presented by filled dots as depicted in Fig.14. The result as presented in Fig.14 is called the Global G-2 PGA - I_{mm} relationship. Plotting the global

G-2 PGA - I_{mm} relationships with regard to C-B (2007) and the A-S-B (2014) GMPEs yields the following global equations:

$$a_h = 0.0053.e^{0.5283.I_{mm}} \tag{6a}$$

$$a_h = 0.0036.e^{0.5727.I_{mm}} \tag{6b}$$

It is important to note that Eq.(3) differs from Eq.(6). In this case PGA or a_h in Eq.(3) was derived based on field earthquake intensity $I_{mm,F}$ collected from the field survey, while a_h in Eq.(6) was derived based on $I_{mm,E}$ computed from Eq.1. Fig.14 and Eq.(6) are the result of the 4th step of this investigation.

As clearly shown in Fig.14 that the increase of PGA is well fitted for an $I_{mm} < VI$. This result is supported by the fact that according to the I_{mm} description, when $I_{mm} < VI$, no structural damage had taken place. However when $I_{mm} \geq VI$, the condition fell to moderate severity, in which sporadic cracking of plastered brick walls and slight damage to buildings began to occur [40]. It is also apparent from the figure that when $I_{mm} > VI$, increases in PGA and I_{mm} appeared to spread. As shown in Box 1, Fig.9, variations in housing quality and people’s response during the earthquake caused large spreads of higher I_{mm} at short distances. This result greatly affects the scattering relationship between PGA and I_{mm} as shown in Fig.14. If can be seen in Fig.14 that PGA_F - $I_{mm,F}$ is very close to the PGA_F - $I_{mm,E}$ relationship.

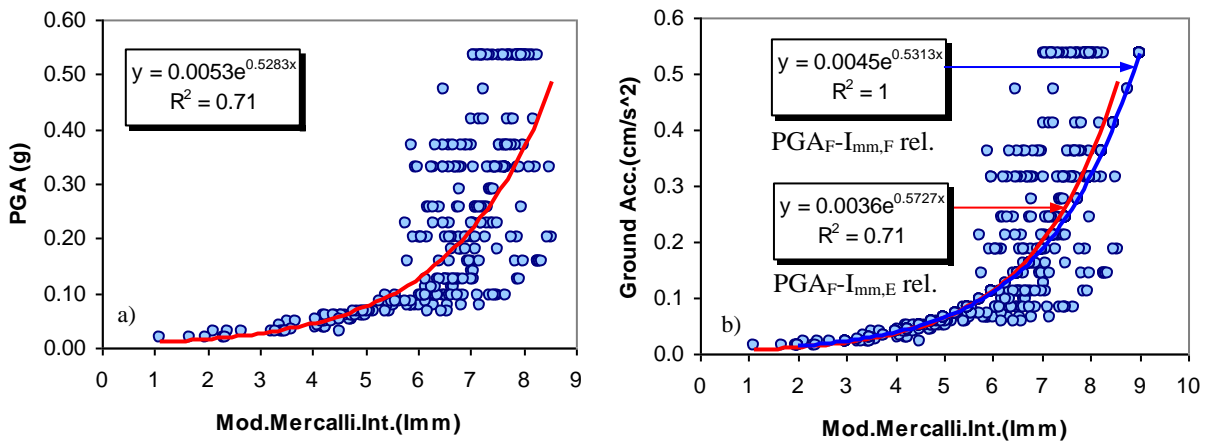


Figure 14: Global G-2 I_{mm} -PGA relationship based on: a) C-B (2007); b) A-S-B (2014) GMPE.

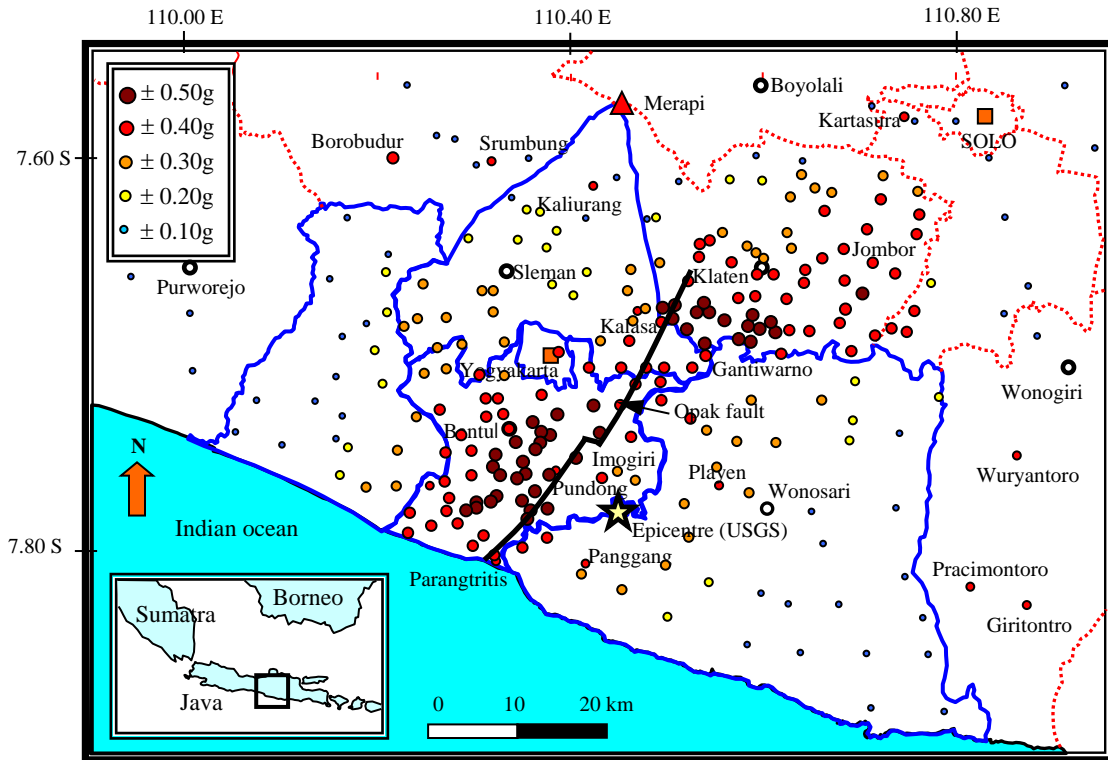


Figure 15: Distribution of the computed PGA at every data point.

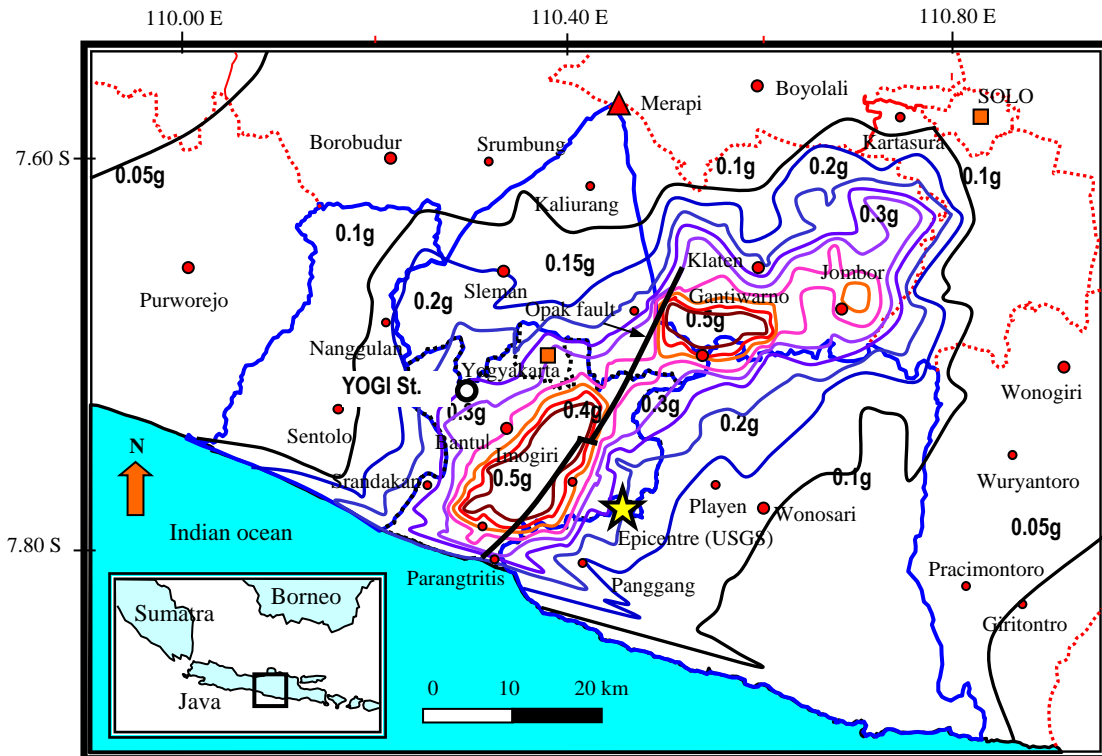


Figure 16: The estimated PGA map of the May 27, 2006 Yogyakarta earthquake (upper bound).

The PGA Map of the May 27, 2006 Yogyakarta Earthquake

A result of the 5th step of this investigation is the PGA_F at each data point as presented in Fig.15. It is clearly shown in Fig.15 that the higher ground accelerations were mostly situated in locations with deeper soil deposits and higher I_{mm} , as presented in Figs.1 and 2. The highest PGAs occurred most notably in two separate places, Imogiri (Bantul Regency) and Gantiwarno (Klaten Regency) as represented by the dark-filled circles. According to the research results presented by [24,41] the soil shear wave velocity V_s in the Imogiri sub-district was relatively

low at $V_s = 125.4 - 263 \text{ ms}^{-1}$, while according to [27] the shear wave velocity in the same region was $V_s = 248 \text{ ms}^{-1}$. Based on [25], the site is categorized as soft-medium soil type. Thus, it was not surprising that in the May 27, 2006 earthquake in soft-medium soil media, deep soil sedimentation with high ground water level caused soil-amplification, and more than 130,000 houses were either heavily damaged or collapsed completely. This result implies that the soil types, soil conditions and soil response had a direct and significant affect on structural damage.

Based on the calculated PGA at every data point found in Fig.15, an estimated earthquake PGA map can be drawn. An estimated upper bound PGA map of the May 27, 2006 Yogyakarta earthquake is illustrated in Fig.16. The spatial PGA as presented in the figure is the upper bound value, where the maximum horizontal ground acceleration reaches 0.50-0.51g, whilst 0.45g is the middle value. As shown in Fig.15, the maximum value of PGA occurs at Pundong and Imogiri sub-districts, the area where the deep soil deposits were reported in [2]. The numbers 0.1; 0.2; 0.3 etc. as shown in Fig.16 are the estimated PGA in g. By comparing Figs.1, 2 and 16, it can be clearly seen that the I_{mm} and PGA at rocky site are smaller than in deep soil deposits. Thus, it can be concluded that the effects of site condition have been inclusively included in the determination of I_{mm} . The figure shows that the increasing distance from the centre of maximum PGA, the ground acceleration will decrease, the damage to building also decreases as clearly shown in Fig.17.

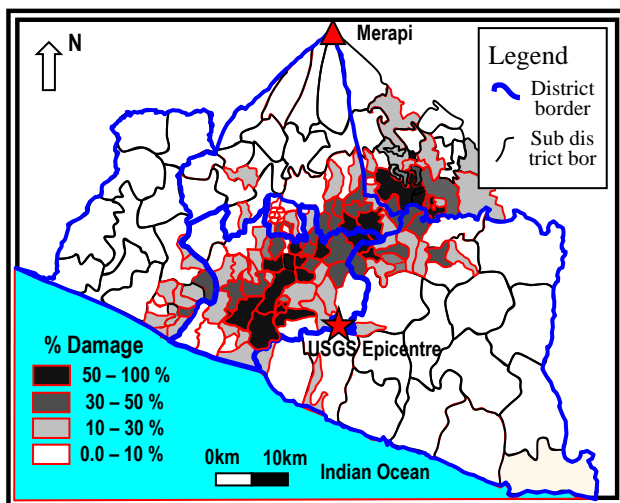


Figure 17. Distribution damage to building [42]

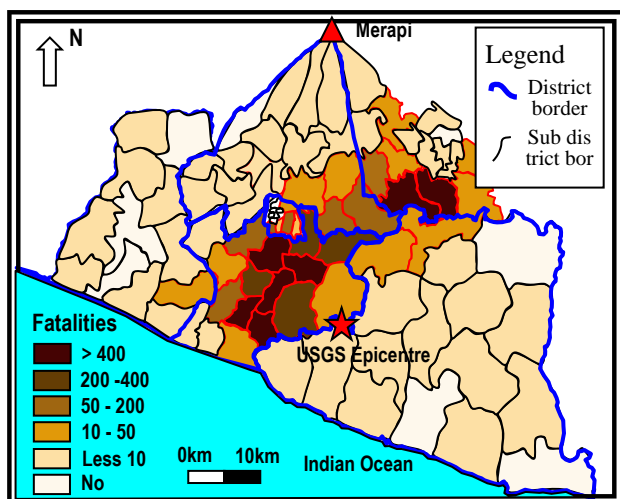


Figure 18: Distribution of fatalities [43].

The earthquake PGA map shown in Fig.16 is quite different when compared with Fig.5 by [2], Fig.6 by [3], Fig.7 by [1] and Fig.8 by [4]. The pattern of the PGA map in Fig.16 closely follows that of the I_{mm} map presented by [5,15]. It is also shown in the figure that the patterns of the PGA lines tend not to be circular in shape, but occur longitudinally following the direction of the Opak River fault trace. The appearance of three PGA closed-lines in the map (Imogiri, Gantiwarno and Jombor area) are the maximum PGA caused by the types, depths and water tables of the soil deposits. The maximum PGA did not

occur in the epicentre area and did not exactly coincide with the fault trace, but instead took place approximately ± 2 km west of the Opak River fault. The ground acceleration at the YOGI station was about 0.28g, as high as reported by [6].

The distribution of building damage according to Miura et al [42] is presented in Fig.17, meanwhile the distribution of fatalities is depicted in Fig.18 [43]. Again, the results of previous studies presented in Figs.5, 6, 7, and 8 are quite different compared to Figs. 17 and 18.

Meanwhile, the pattern of PGA presented in Fig.16 fits well with pattern of building damage distribution in Fig.17 and fatalities distribution in Fig.18. It may be concluded that the new PGA map is able to model well the distribution of building damage in the field. Thus the new PGA map is an improvement over the maps proposed by previous research results.

As stated before or as presented in Fig.15 maximum PGA occurs at deep soil deposits. Meanwhile, in Fig.17 also appears that in the same area there has been severe damage to the buildings. Thus, there is a strong relationship between PGA, deep soil deposits and severe building damage and commonly referred to as site effects. Resonance frequency response is the critical condition where frequency vibration of structure is close to the excited loading which is affected by the nature of soil deposits. Site effects and building damage have been reported by researchers [21,44,45].

It was realized that soil conditions in the study area were not the same. However, when I_{mm} field research was conducted [5] as described before, the effect of soil conditions was already considered. On the rock/hard soil near the epicenter area for example the building damage was even smaller than the longer distance on soft-moderate soil. Given that the PGA map is developed from the I_{mm} maps it means that the effect of soil conditions on PGA has been inclusively taken into account. For that reason, and assuming that the building typology is uniform the PGA map can be made in which the effect of the different soil condition is accounted for.

The PGA map presented in Fig.16 is of great importance, serves a significant purpose and is urgently needed. Disaster mitigation programs need to carry out natural hazard assessments including the effects of earthquake events. There are two important parameters in a seismic hazard assessment; these are the PGA and its probability of occurrence, where the probability can be determined by the Conditional Probability principle [46]. Therefore, due to the availability of a PGA map, as presented in Fig.16, the hazard level at any desired location can be assessed. In the process of natural hazard risk reduction, the disaster risk can be assessed by the availability of an earthquake PGA map, facilitating further efforts to save lives. In structural dynamics, the value of the maximum PGA, as well as its time history, are also important and are required for assessing the structural response.

CONCLUDING REMARKS

The development of a PGA map for the May 27, 2006 Yogyakarta earthquake was completed. Previous research results were also reviewed. Previous research results differed greatly from one another and the incompatibility between the distribution of ground accelerations and distribution of housing damage in the field supported the necessity for conducting this research to seek a solution.

A PGA map of the 2006 Yogyakarta earthquake was constructed, despite the limitation of ground motion records and soil data in the region. It was demonstrated that the Extrapolating Method had been successfully developed and implemented in the construction of a new PGA map. Although the PGA map was only applicable to a particular earthquake, it will however, be significantly useful for seismic hazard

assessment and natural hazard risk assessment, as well as loading in structural dynamics.

This new PGA map of the 2006 Yogyakarta earthquake is a refinement of existing PGA maps. The pattern of the new PGA map does not form a circle with radius R and does not follow the pattern for previous PGA maps proposed by [1-4] but rather follows the pattern of the I_{mm} in the field. Because the I_{mm} map was formulated based on damage to dwellings, the resulting PGA map also matched the distribution of building damage and distribution of fatalities in the field.

The upper-bound PGAs did not occur in the epicentre area, but occur around Pundong, Imogiri and Gantiwarno sub-district area and reached 0.50-0.51g. The common assumption that the maximum PGA always occurs at the epicentre area did not occur. Even though the geotechnical aspects were only briefly elaborated in this paper, it can be concluded that the nature of soil deposits play important role in the ground seismic response as well as the damage to buildings. Some assumptions have been made regarding the application of this approach/method solely for solving actual problem in the field based on very limited data so that in the future the quality improvement of this approach is still needed by improving the quality of the data.

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