GMPE based Shakemap Generation of Peak Ground Motion and Intensity Maps for Pidie Jaya Earthquake

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Abstract. An algorithm based on GMPE (Ground Motion Prediction Equation) is used for generating standard and officially Shakemap as early information for disaster mitigation quick respond. We investigate the method developed by USGS (US Geological Survey) namely ShakeMap for generating Peak Ground Motion and Intensity Maps. The 2016 Mw 6.5 Pidie Jaya Earthquake which strike-slip mechanism was selected for the scenario earthquake. The appropriate GMPE (i.e. Zhao06\textsubscript{06} crustal) was selected for this earthquake, which is located at the crust with focal depth of 13km and strike-slip mechanism. Strong ground motion on bedrock, without sediment amplification, generate PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity) spherically uniform. The algorithm able to consider the site effect only for thin sedimentary layer Vs30 without considering deeper structural layer. The amplification effect is calculated based on Vs30 without considering the nonlinear effect and independently each site-class. Because of unavailable spatial distribution Vs30 measurement, the Vs30 was estimated from the topographic gradient and the method is commonly used. Strong ground motion on sediment layer will be amplified following the Vs30 distribution. The intensity map, which is easier to read, shown in MMI (Modified Mercalli Intensity) and SIG-BMKG (Indonesia Earthquake Intensity Scale). The GMPE based shakemap has bias error because of the general equation has not considering complete structural model and radiation pattern of a focal mechanism. An advance method for the future development will be much more realistic with the shakemap based on synthetics seismogram calculation.

Keywords: Shakemap, GMPE, Pidie Jaya Earthquake

1. Introduction
Indonesia is an earthquake disaster prone area because geographically located at margin tectonic plate. Aceh province is an area suffering with earthquake and required rapid disasters mitigation respond based on adequate information. The quick available information is the preliminary magnitude and location. However, the information have not provided the strong ground-motion which affected to buildings. Therefore, when earthquake with significant magnitude happens one of the important disaster management processes is providing strong ground motion distribution for located rapid emergency and monitoring respond. The information is called shakemap which important for decision maker before getting real condition in field.
Shakemap is a very essential information to be able to quickly respond to areas where heavy damage occurs. Therefore institution who monitoring earthquake immediately release shakemap for the public. For example, USGS (US Geological Survey) provide shakemap which contains information such as PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity) as shown in figure 1. USGS provides the shakemap for the worldwide area immediately after a significant earthquake based on a preliminary magnitude and focal location. Usually, the information not accurate and updated magnitude and the location is releases and the shakemap not update. Therefore, we have the knowledge to generate shakemap based on updated information. This paper explains about shakemap algorithm developed by USGS and applying for Pidie Jaya Earthquake 7 December 2016 M6.5 which strike-slip mechanism.

Figure 1. Shakemap generated by USGS with a given magnitude and focal mechanism without any modification and using MMI scale. The maps have a wide coverage area and cannot provide detailed information about the affected area. Therefore, we need produce shakemap with customizing coverage area and recalculated updated magnitude and focal relocation.

2. Methodology
Producing shakemap is starting from source definition such as magnitude, focal location, and mechanism. Next step, strong ground motion on bedrock is calculated based on GMPE (or called attenuation equation) for surrounding area. The actual strong ground motion has to include the amplification effect of the sedimentary layer. All the steps including fancy map plotting and for web preparation are combined into the ShakeMap software.

2.1 Ground Motion Prediction Equation
The propagation of the seismic wave is complicated because the wave propagates in 3 dimension direction and involving stress tensor in 9 component. Therefore, obtaining the strong ground motion from the simulation of seismic wave propagation is computationally expensive. The practical solution is empowering statistical approach to produce empirical equation based on seismogram recoding data. The empirical equation will predict the strong ground motion, thus the equation is called GMPE.
The bias of strong ground motion prediction arises from applying generic GMPE without considering the structural model of the side, except for thin layer (Vs30) not deeper than 30m.

The empirical equation of GMPE has a limitation in range magnitude, depth, and focal mechanism. In this calculation, we provide a series of GMPE as shown in following piece part of the code (grind.conf)

```
gmpe: BA08 0.0 5.3 0 22
gmpe: Zhao06_crustal 5.3 9.9 0 22
gmpe: Zhao06_intraslab 0.0 7.2 22 50
gmpe: Zhao06_interface 7.2 9.9 22 50
gmpe: Zhao06_intraslab 0.0 9.9 50 9999
```

The GMPE of BA08 and Zhao06 which used in this calculation were derived from another area. The GMPE of BA08 is derived by empirical regression of an extensive strong-motion database compiled by the “PEER NGA” (Pacific Earthquake Engineering Research Center’s Next Generation Attenuation)[1]. GMPE of Zhao06 were derived from a very large number of strong ground-motion records up to 2003 Off Tokach main and aftershocks mainly in Japan[3]. The GMPE of Zhao06 classified by three tectonic environment Zhao06_(crustal | interface | intraslab) with certain coefficient.

The specific GMPE will be selected from the top of the code for particular magnitude and depth. The magnitude of Pidie Jaya earthquake is M6.5 is not including in the range of the first line with range magnitude from 0.0 to 5.3 thus go to the second line. The Zhao06_crustal has range magnitude from 5.3 to 9.9 and the Pidie Jaya earthquake in the range. The focal depth of the earthquake is 13 km is in the rage of 0km to 22 km. Therefore, the program will use GMPE from Zhao06_crustal without checking for next line of GMPE[4].

The GMPE of Zhao06 adopted from Abrahamson and Youngs (1992). The GMPE has feature not only predict PGA but also spectral acceleration by controlling parameter as explain in table 4 of their paper[3]. Other feature of the GMPE embedding amplification Coefficients for Site Class Terms in table 5 of their paper[3]. Following simple form of the GMPE as function of attenuation equation.

\[
\log_{e}(y_{i,j}) = aM_{wi} + bx_{i,j} - \log_{e}(r_{i,j})
+ e(h - h_{c}) \delta_{h} + F_{R} + S_{I} + S_{S}
+ S_{SL} \log_{e}(x_{i,j}) + C_{k} + \xi_{i,j} + \eta_{i},
\]

\[
r_{i,j} = x_{i,j} + c \exp(dM_{wi}),
\]

The result of PGA describe by symbol \(y_{i,j}\) (in centimeters per second 2 ) or 5% damped acceleration response spectrum (the geometric mean of two horizontal components in centimeters per second 2 ) for a certain spectral, \(M_{w}\) is the moment magnitude, \(x\) is the source distance in kilometers, and \(h\) is the focal depth in kilometers. The reverse-fault parameter \(F_{R}\) applies only to crustal events with a reverse-faulting mechanism and is zero for strike-slip events. The tectonic source-type parameter \(S_{I}\) applies to interface events and is 0 for strike-slip events, and \(S_{S}\) applies to subduction slab events only and zero strike-slip event. Source distance \(x\) is the shortest distance to the rupture zone for earthquakes with available fault models, and hypocentral distance for the other events. \(C_{k}\) is the site-class term for a given site class When \(h\) is larger than \(h_{c}\), the depth term \(e(h < h_{c})\) takes effect, with \(\delta_{h}\) being a dummy variable that equals 0 for \(h > h_{c}\), and 1 for \(h = h_{c}\)[3]. Coefficients \(a, b, c, d, e, \) and \(r_{i,j}\), site class term \(C_{k}\), reverse-fault term \(F_{R}\), and source-type terms \(S_{I}, S_{S}\), and \(S_{SL}\) are determined by regression analysis for each period, detail see Table 4 of their paper[3].
In order to verify the value of PGA produce by shakemap calculation for Pidie Jay earthquake with magnitude M 6.5, we compare the plotting PGA respect to distance with the PGA respect to distance plotting by their paper[3] for the magnitude 5,6,7,8 as shown in figure 2.

(a) PGA respect to distance from Zhao06 [3] paper for magnitude 5,6,7, and 8
(b) PGA respect to distance from shakemap for magnitude 6.5 (file gmpeVSdist.txt)

Figure 2. The plotting (b) from shakemap calculation for magnitude 6.5 show the value of PGA between the value PGA of magnitude 6 and 7 (between line 2 and 3 from top).

2.2 Amplification of Site Effect
Providing shakemap without site amplification effect will be not accurate because some of the damaged building is located at flat basin above the sedimentary layer. The amplification effect is compensation from decreasing velocity of the seismic wave will increase density energy which increases the amplitude of ground shaking. However, the seismic wave propagation is complicated mechanics and even propagation in sedimentary wave more complicated. However simple and practical approach is using assuming the amplification only depend on seismic shear wave velocity Vs30 at thin layer 30m.

Due to poor Vs30 data collection for covering the area of investigation, an alternative method has been developed for evaluating regional seismic site conditions, or the average shear velocity to 30 m depth (Vs30), from topographic data. The Vs30 is estimated of from the topographic gradient developed for active tectonic and stable continental regions[6], see table 1.

| NEHRP Site Class | Vs30 Range (m/sec) | 9 arcsec Gradient Range (m/m) (Active Tectonic) | 9 arcsec Gradient Range (m/m) (Stable Continent) | Modified 30 arcsec Gradient Range (m/m) (Active Tectonic) |
|------------------|-------------------|-----------------------------------------------|-----------------------------------------------|----------------------------------------------------------|
| E                | < 180             | < 3 x 10^{-4}                                  | < 1 x 10^{-4}                                  | < 3 x 10^{-4}                                            |
|                  | 180–240          | 3 x 10^{-4}–3.5 x 10^{-3}                      | 1 x 10^{-4}–8.5 x 10^{-3}                      | 3 x 10^{-4}–3.5 x 10^{-3}                                |
| D                | 240–300          | 3.5 x 10^{-2}–0.010                            | 4.5 x 10^{-2}–8.5 x 10^{-3}                    | 3.5 x 10^{-3}–0.010                                     |
|                  | 300–360          | 0.010–0.024                                   | 8.5 x 10^{-3}–0.013                            | 0.010–0.018                                             |
|                  | 360–490          | 0.024–0.08                                    | 0.013–0.022                                   | 0.018–0.05                                              |
| C                | 490–620          | 0.08–0.14                                     | 0.022–0.03                                   | 0.05–0.10                                               |
|                  | 620–760          | 0.14–0.20                                     | 0.03–0.04                                    | 0.10–0.14                                               |
| B                | > 760            | > 0.20                                        | > 0.04                                       | > 0.14                                                  |
Table 2. Site Class Definitions Used in the Present Study and the Approximately Corresponding NEHRP Site Classes[3]

| Site Class | Description     | Natural Period | $V_{30}$ Calculated from Site Period | NEHRP Site Classes |
|------------|-----------------|----------------|--------------------------------------|--------------------|
| Hard rock  | Rock            | $T < 0.2$ sec  | $V_{30} > 1100$                      | A                  |
| SC I       | Hard soil       | $0.2 < T < 0.4$| $V_{30} > 600$                       | A + B              |
| SC II      | Medium soil     | $0.4 < T < 0.6$| $200 < V_{30} = 300$                | C                  |
| SC III     | Soft soil       | $T = 0.6$ sec  | $V_{30} = 200$                       | D                  |

Five site classes are used in the present study, Hr, SC I, II, III and IV, approximately corresponding to the hard rock, rock, hard soil, medium soil, and soft soil[7]. The Table 2, which shows the approximately corresponding site classes defined by the Building Seismic Safety Council (2000)[8]. Figure 4b. shows the site class classification based on VS30 estimation. According to the site classification, the coefficients for site class term $C_k$ determine by table 5 from Zhao06 paper[3].

2.3 ShakeMap Software Package

ShakeMap software from USGS[4] will combine and manage each small piece of commands into a suit and comfortable packages. The program running on Ubuntu 16.04 with perl, GMT4, MySQL and others supporting program. The global configuration file located in folder config/*.conf and the main configuration input file for specific event save in data folder with subdirectories events name, for instance data/pijay65/event.xml.

ShakeMap become complex program because the software synchronize data with MySQL databased, web server, and sending email. ShakeMap processing sequence might go some thing like this[4]: retrieve → pending → grind → tag → mapping → genex → shakemail → transfer →setversion

However, the important step for computation the shake map in the program grind and mapping. The program grind will process input ground motion parameters and estimate ground motions in map area based on GMPE and site amplification factor will be computed if option flag -qtm is applied. The program mapping will generate the fancy map with shaded topography and caption label.

```
grind -event pijay65 -rcg -qtm
mapping -event pijay65 -gsm -itopo -bounds 95/97/4/6
```

3. Results and Discussion

The ShakeMap 3.5 features not only considering point source earthquake but also finite fault plane source earthquake. In this paper we only discuses about point source earthquake and applying site amplification effect.

GMPE based shaking map without involving the site amplification effect of sediment will generate spherically symmetry PGA and PGV as shows in figure 3. That mean, the GMPE which use in the calculation, see equation 1, did not take into account the radiation pattern of focal mechanics[9].

Involving the site amplification effect based the GMPE require Vs30. In this study we derive the Vs30 as shown in figure 4b which derived from DEM as shown in figure 4a. Based on the Vs30 the GMPE from Zhao06[3] has capability for calculating site amplification effect as shown in figure 6 and the distribution for PGA and PGV follow topography effect and not spherically symmetry any more.
Figure 3. Shakemap for PGA and PGV map without site amplification effect

Figure 4. The Vs30 estimate from gradient of topographic data using table 1. The resolution Vs30 map reduce to resolution which required by shakemap.
Figure 5. Shakemap for PGA and PGV map without site amplification effect

Figure 6. Shakemap for intensity, (a) MMI scale is official intensity map used by USGS (b) SIG-BMKG scale is officially used by Indonesia Agency for earthquake monitoring (BMKG)
For more general public consumption, the use of PGA and PGV less understandable, so it needs to be made more easily understood maps in the form of a map of the intensity of the earthquake. In Figure 6a, the intensity map in the MMI scale is automatically generated by the Shakemap program. The MMI scale has 10 levels so that it provides a more detailed classification and is very suitable for scientific purposes. Because of the scale is quite complex so that it is easier to understand, a simpler division is made with 5 levels called the SIG-BMKG scale and the results are shown in figure 6b.

4. Conclusions and Suggestion
We have successfully used the ShakeMap software on the Ubuntu 16.04 operating system for the calculation of the Pidie Jaya earthquake shakemap. The GMPE equation from Zhao06_crustal will be selected for an earthquake with a magnitude of M6.5 and a focal depth of 13km. The equation has involved site amplification factor. Shakemap are spherically symmetry pattern is formed when not involving the effect of site amplification, and the pattern will be lost when it involves the calculation of the amplification effect.

The use of GMPE which does not involve the radiation pattern of the focal mechanism will have an error bias. It is recommended that strong ground motion is calculated from synthetics seismograms that can use the mode summation method. Shakmap is a hazard factor and the magnitude of damage needs to be multiplied by the vulnerability so that it is well known that the damage map estimates the damage to buildings so that it is more appropriate in the decision making for emergency response.

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