SEISMIC HAZARD AND MICROZONATION FOR A DISTRICT IN BANDA ACEH CITY POST 2004 GREAT SUMATRA EARTHQUAKE

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ABSTRACT:

Sumatra 2004 earthquake (Mw=9.3) has caused many building and infrastructure collapsed in the city of Banda Aceh and the surrounding areas. Reconstruction and long-term development of the city requires seismic design criteria that consider potential earthquake sources surrounding the city. Probabilistic seismic hazard analysis (PSHA) that considers both subduction and shallow crustal faults has been conducted herein. The PSHA through de-aggregation analysis indicates that Aceh and Seumeulem faults, that is relatively very close to the city, is the potential source that could generate a big earthquake in the future, since the potential of subduction require long time to accumulate energy for potential another big earthquake. The PSHA indicates that the peak ground acceleration at baserock for 10% and 2% probability of exceedance in 50 years is 0.3g and 0.55g, respectively. The analysis also provides spectral values at short (T=0.2 sec) and long period (T=1.0 sec) motions. Site response analyses for some sites have been conducted for seismic microzonation mapping for Meuraxa District within the city of Banda Aceh. Some spectral analyses of surface wave tests have been conducted for the microzonation mapping. Results of the PSHA, design response spectra for several site-class, and microzonation map are recommended for reconstruction and long-term development of the district after 2004 Great Sumatra earthquake disaster.

KEYWORDS: Microzonation, probabilistic, seismic-hazard, response-spectra, site-class, Sumatra

1. INTRODUCTION

Thousands of people had killed and many buildings, infrastructures, and lifelines have been completely collapsed due to the Aceh earthquake (Mw=9.3) December 26th, 2004 earthquake. Observations has indicated some buildings completely collapse, some buildings experience major structural damages, some slightly damage and some without structural damages. In addition, many roads and embankments were identified to have collapsed and damaged due to liquefaction and lateral spread. Moreover, there has been a spatial distribution of damage observed and this is considered due to combination of both distribution of ground shaking contributed by variation in local soil condition and also could be due to the vulnerability of different buildings under different types and building construction qualities.

Efforts toward seismic disaster risk reduction in the early stage of reconstruction and development of buildings and infrastructures of the city shall consist of providing seismic design criteria. This paper presents seismic hazard and microzonation mapping of Meuraxa District in city of Banda Aceh, Meuraxa District is one of the area that destroyed the worst during earthquake and tsunami disaster of December 2004. The mapping is developed from a probabilistic seismic hazard analysis (PSHA). The PSHA presented in this paper is an update of previous preliminary PSHA conducted by Sengara et al., 2005 and Sengara and Hendarto, 2006.

There are some variations in local ground condition within the district spatially. Therefore, a set of geotechnical investigation have been conducted for microzonation mapping of the district. Site-response analysis (SRA) for various site class represented by shear wave velocity profiles had been conducted. Finally, microzonation map of the district and seismic design criteria is presented in terms of recommendation of design response-spectra representing each site-class.

2. PROBABILISTIC SEISMIC HAZARD ANALYSIS

PSHA for city of Banda Aceh post Great Sumatra 2004 is conducted to recommend the level of peak ground acceleration (PGA) at base-rock for probability hazard level of 475 and 2475 years earthquake return period. The PSHA would also resulted in the associated uniform hazard spectra at the reference base-rock or site-class S_B representing geotechnical profile with shear wave velocity of a value higher than 720 m/s. The PSHA conducted herein is based on the all seismic source zones within 500km radius from the site of interest. The PSHA methodology considers 3-dimensional seismic source zones. Total probability theorem assuming earthquake magnitudes (M), hypocenter distances (r) as continuous independent random variables that affected the intensity (I), in this case PGA, is adopted in this PSHA. The total probability theorem expresses annual frequency of earthquakes that produce peak acceleration A higher than a, H(a) as

$$H(a) = \sum_i v_i \iint P[A > a \mid m, r]\, f_{Mi}(m)\, f_{Ri\mid Mi}(r,m)\,dr\,dm$$

where v_i is annual rate of earthquakes (with magnitude higher than some threshold value of M_{oi}) in source I, and f_{Mi} (m) and $f_{Ri\mid Mi}$(r,m) are probability density functions on magnitude and distance, respectively. P[A > a| m, r is the probability that an earthquake of magnitude m at distance r produces a peak acceleration A at the site that is greater than a. This theorem is implicitly implemented in EZ-FRISK computer program [Risk Engineering, 2004] used in the PSHA. The essential components of the PSHA conducted in this study consist of seismic source zoning, earthquake recurrence, attenuation functions, and logic tree formulation.

2.1. Tectonic Setting and Earthquake History

City of Banda Aceh is surrounded by earthquake sources originated from subduction at the west side and shallow crustal Aceh and Seumeulem faults, which are relatively very close to the city. Indo-Australia oceanic plate move south-eastward with slip rate of approximately 60mm/year subduct beneath the Sumatra Island along the Sumatra-Java basin. In-perpendicular movement direction of Indo-Australian plate to the basin structure causes Sumatra Fault Zone (SFZ) to be formed along the Sumatra Island and this SFZ consists of several segments (Sieh and Natawidjaja, 2000). Aceh and Seumeleum shallow crustal faults are part of the segment of SFZ.

Many earthquakes had occurred along interface of the subduction zone and the rate of this subduction is estimated about 60 mm/year. Following the Great Sumatra (Mw=9.3) 2004 earthquake, later Nias earthquake occurred on March 28, 2005 with M_w=8.7 and then Padang earthquake occurred in April 2005 with Mw=6.8. Whereas, SFZ activities were indicated by occurrence of earthquakes at shallow depths (< 60 km). The SFZ activities triggered relatively smaller earthquakes. However, the earthquake hypocenters from this SFZ were shallower (less than 30 km).

2.2. Seismic Source Modeling

Seismic source model has been developed considering both subduction and Aceh+Seumeulem faults based on the seismo-tectonic setting from geological and seismological input. The potential of seismic sources within radius of 500km is considered in this model. The subduction earthquakes are modeled by area sources in accordance with segmentation in conjunction with the geological input. Likewise, the Aceh+Seumeulem earthquake are modeled by thin area sources with segments also in conjunction with the geological input (Sieh and Natawidjaja, 2000). Figure 1 presents seismic source model for the PSHA covering of seismic sources within radius of 500 km from city of Banda Aceh. Each seismic source zone is assigned seismic parameters representing seismic characteristics of the source.

2.3 Earthquake Recurrence Model

Prediction of PBA to occur in the future requires use of recurrence model to be assigned as seismic parameters for each seismic source zone. An earthquake recurrence model provides a description of potential future

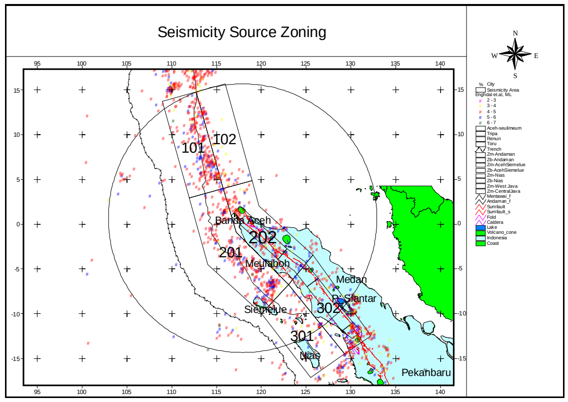

Figure 1 Seismic source zoning representing both of subduction and shallow crustals

earthquake in terms of their spatial variation, rupture size and frequency of occurrence. Seismic parameters resulted from use of this model for a seismic source zone describes earthquake characteristics within the earth crust at that particular zone. The seismic parameters from use of the recurrence model for each source zone are obtained from both instrumental and historical data, as well as information on its maximum moment magnitude (M_w). Maximum magnitude for each source zone is assigned based on both historical and potential magnitude estimated magnitude from geometry and slip rate of the plates or faults. Maximum magnitude assigned for subduction zone is 9.3. Meanwhile, SFZ that is Aceh and Seumeleum faults, are assigned a value from its potential to generate maximum magnitude (M_{max}) of 7.7 and 7.5, respectively (Sieh and Natawidjaja, 2000).

Maximum magnitude (M_{max}) assigned for subduction zone is 9.3. Meanwhile, Aceh and Seumeleum faults are assigned a value from its potential to generate maximum magnitude of 7.7 and 7.5, respectively (Natawidjaja, 2002). In this PSHA, earthquake recurrence model parameters have been calculated based on seismicity and slip data to be used in exponential and characteristic recurrence models. There has been limited information and study conducted on two faults (Aceh and Seumeulem faults) that is relatively very close to the city of Banda Aceh. Available information on slip rate of Aceh fault is 5mm/year that was based on GPS monitoring (Genrich et al., 2000 in Natawidjaja, 2002) and southern segments of SFZ which has slip rate of 27mm/year (Bellier and Sabrie, 1995, in Natawidjaja, 2002). With some of the information that has been collected on the slip-rate, there is a tendency of reduced slip-rate to the north to be approximately in the order of 5-11mm/year. There is actually no specific information on slip-rate of the Seumeulem fault.

In this PSHA, earthquake recurrence model parameters have been calculated based on seismicity data that has been analyzed considering epicenter re-location, completeness data, and excluding dependent events. The seismic parameters also consider engineering judgment as well as parameters obtained from some references assigned by others for similar analysis and source zones. Both exponential and characteristics recurrence model is applied in the PSHA. Three exponential recurrence models are used, that is least square (weighted a factor of 0.2), Weichert (weighted 0.3), and Kijko & Sellevol models (weighted 0.5). For characteristics model, the main input is maximum magnitude and slip rate. Combination of both exponential and characteristics models as formulated by Schwartz and Coppersmith (1984, in McGuire, 2004) is applied in the PSHA where the characteristic model is adopted to represent high magnitude recurrence, meanwhile the exponential model is applied to represent to the low magnitude recurrence. The seismic parameters also consider engineering judgment as well as parameters obtained from some references assigned by others for similar analysis and source zones such as use of b-value of 1.0 from regional evaluation of the subduction segments.

2.4. Ground Acceleration Attenuation Functions

Young's et al. (1997) attenuation function has been adopted to represent the subduction earthquake source. While, Sadigh et al. (1997) and Idriss (2004) attenuation functions have been adopted for shallow crustal seismic sources. Attenuation functions of Sadigh et al. (1997), and Idriss (2004) are assigned a relative likelihood of 0.5, respectively.

3. RESULTS OF PSHA

The PSHA that has been conducted herein has resulted in hazard curve that provides the level of PBA with various probability levels. Results of PSHA provide PBA of 0.18, 0.30, 0.4, and 0.55g , for 200, 475, 1000, and 2475 years earthquake return period, respectively. More complete results showing the spectral values at T=PGA, T=0.2 sec, and T=1sec, for 10% and 2% probability of exceedance (PE) in 50 years, respectively, is summarized in Table 1. Hazard level recommended is probability hazard level of 475 years earthquake return period, which corresponds to 10% PE in 50 years, as commonly adopted in many building codes and currently still adopted in Indonesian seismic building codes (SNI-03-1726-2002). Therefore, PBA recommended for city of Banda Aceh is 0.3g. UHS resulted from the PSHA for 10% PE (475 years RP) and 2% PE (2475 years RP) in 50 years is presented in Figure 2. This UHS is adopted as target spectra for scaling input ground motion for subduction or shallow crustal earthquake in site-response analysis.

Table 1 Summary on spectral values resulted from PSHA for city of Banda Aceh

Hazard Level	T=PGA (g)	T=0.2 second (g)	T=1.0 second (g)
10 % PE in 50 years	0.30	0.75	0.31
2% PE in 50 years	0.55	1.26	0.60

It is essential to identify the potential controlling earthquake hazed in the PSHA, therefore de-aggregation analysis has been conducted. The de-aggregation analysis determines the dominant earthquake magnitudes and distances. It is indicated in the analysis that for 10% PE in 50 years, the dominant event is originated from shallow crustal (Aceh and Seumeulem faults), and also from subduction megathrust segment, as presented in Figure 3. There has been sensitivity analysis conducted for the Aceh and Seumeulem shallow crustal faults, providing different slip rates adopted in the PSHA. For this current analysis result, slip rate of 5mm/year for Aceh fault and 11mm/year for Seumeulem fault have been adopted. It is identified that result of PSHA is sensitive to the slip rate adopted in the analysis. Since there are some uncertainties in seismic parameters, particularly for Aceh and Seumeulem fault segments that are still need to be verified, characteristics of these segments still need further detail investigation. Currently, further PSHA using other attenuation functions derived from global database that is use of new generation attenuation (NGA) functions is undergoing.

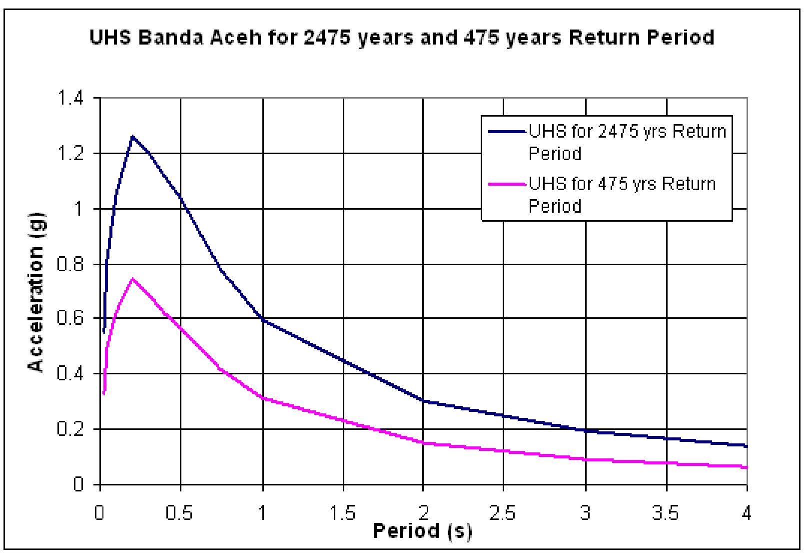

Figure 2 Uniform Hazard Spectra for 10% and 2% PE in 50 years

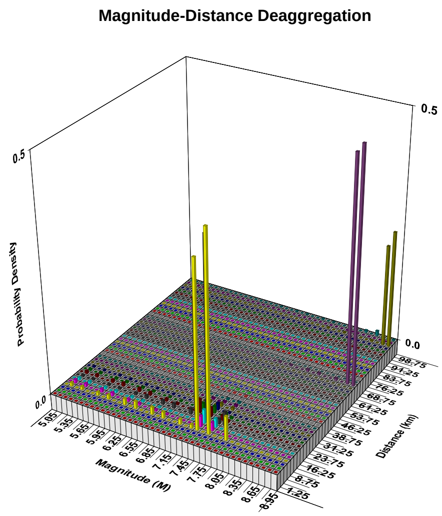

Figure 3 De-aggregation curve indicating dominant earthquake that contribute to the seismic hazard for T=PGA

4. SITE-RESPONSE AND DESIGN SPECTRA

Site-response analysis (SRA) to estimate peak ground surface acceleration and response spectra needs to be performed by considering appropriate input motions and dynamic soil properties of the site. In the case no strong motion data were available; the simplest and conventional method to generate input motions is by scaling available strong motion records from other sites. Strong motion records are commonly scaled to match target PBA of the site of interest. Another method is development of synthetic time histories to match target spectral acceleration through generation of synthetic input motion or through spectral-matching techniques proposed by Abrahamson that is adopted and built in the EZ-FRISK Computer Program. In this case, spectral-matching techniques to the target spectra are adopted to generate earthquake input motions for the wave propagation analysis from referenced base-rock to the ground surface. The spectral matching was conducted for both subduction and shallow crustal earthquakes scenario that is scaled to short (T=0.2 sec) and long period (T=1.0 sec) motions. Figure 4 shows one of the spectral curve to match Aceh+Seumeulem shallow crustal earthquake scaled to T=0.2 sec UHS, using Loma Prieta available input motion. Other input motions considered to have similar characteristics have also been used to match the subduction earthquake scaled to T=0.2 sec and T=1.0 sec UHS.

4.1 Seismic Wave Propagation Analysis

Local site condition (*site-class*) within the district is classified into 3 (three) classifications that is Soft, Medium, and Hard. Each site-class is represented using a soil profile having a value of average shear wave velocity (Vs) in accordance with Indonesian Building Codes or International Building Codes (IBC2006). Seismic wave propagation analysis was conducted using NERA computer program (Bardet and Tobita, 2001). This program applies time-domain approach of non-linear soil properties where its shear modulus decreases as a function of increasing strain, while damping increases as a function of increasing strain. The wave propagation analysis using NERA computer program indicated that the peak acceleration is amplified from 0.3g at the base-rock to values that vary from 0.325g to 0.4g at ground surface, depending upon the site class. The PGA is considered to be influenced by the shear wave velocity profile and frequency content of input motions that have resulted in variations in the PGA. Results of typical SRA for Soft site-class is presented in Figure 5(a), and recommended design response spectra for three site classes is presented in Figure 5 (b).

4.2 Geotechnical Investigation

A set of geotechnical investigation has been conducted to identify variations in local ground condition covering the Meuraxa District. Approximately 50 points of investigation points consisting of cone penetration tests, hand

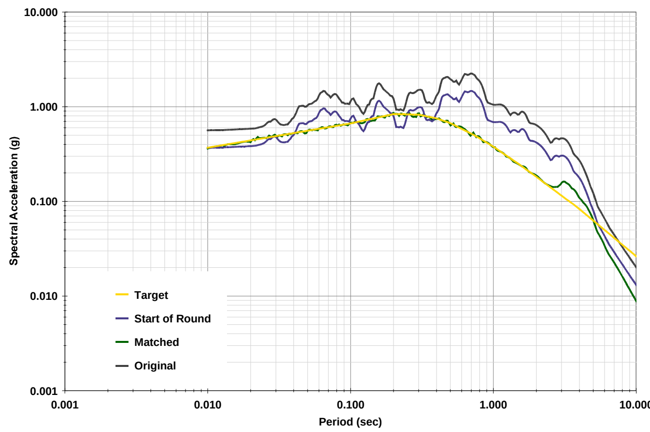

Figure 4 Spectral matching of available input motions to the target spectra of shallow crustal earthquake for T=0.2 sec UHS.

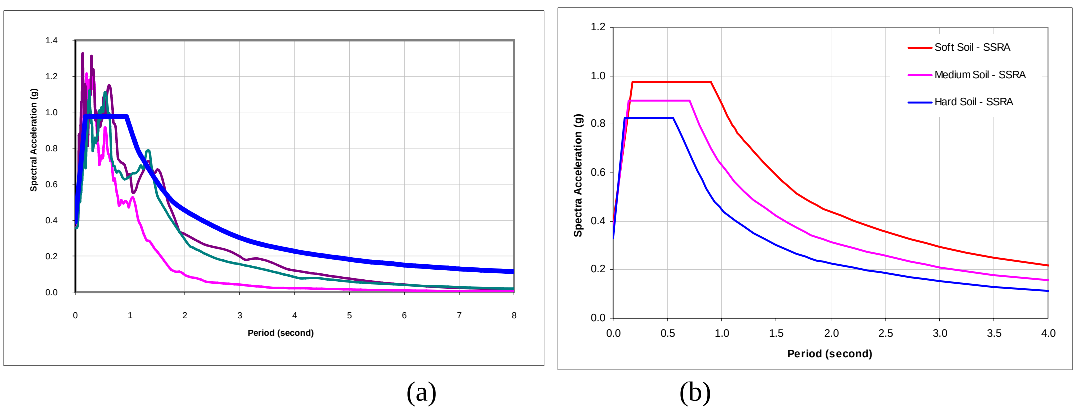

Figure 5 Result of SRA for Soft site-class (a), and recommended design response spectra for three site-classes, 10 % PE in 50 years (b)

auger boring, and spectral analysis of surface wave (SASW) seismic test were conducted. Figure 5 shows location distribution of the investigation points within the district

Results of CPT and SASW tests indicated that the area shows different local ground conditions. The area could be divided into several zones that have different soil condition and average shear wave velocity profiles. In general, the geotechnical conditions of the district along the shorelines consist of gravel alluvium formation, sand and mud. Site-classification analysis shows variations from Soft to Hard site-class with average shear wave velocity varies from as low as 93 m/s to as high as 508m/s. Available soil boring close to the harbor area indicated that 0-3m consists of silty sand, 3-6.5m consists of silty fine sand (N=27); 6.5 – 10m consists of silty fine sand (N=43); 10-12m consists of silty sand fine to course, very dense (N=56); 12-20m consists of silty fine sand and sandy clayey silt (N=39). Groundwater level is about 1 m from the ground surface. It is considered and observed that many liquefaction occurred in the area, particularly along the shorelines. Geological condition of the city provide information that baserock is estimated to consist of calcareous sandstone, conglomerate, very deep from the ground surface.

4.3 Seismic Microzonation Mapping

The geotechnical investigation consisting of CPT and SASW has provided average shear wave velocity profile distribution within the Meuraxa District. Several site response analyses have been conducted representing various shear wave velocity profiles. Results of the SRA are used as basis for seismic microzonation mapping of the district. The microzonation mapping is developed also in accordance with the site-classification mapping. Figure 6 presents site classification and seismic microzonation map of Meuraxa District.

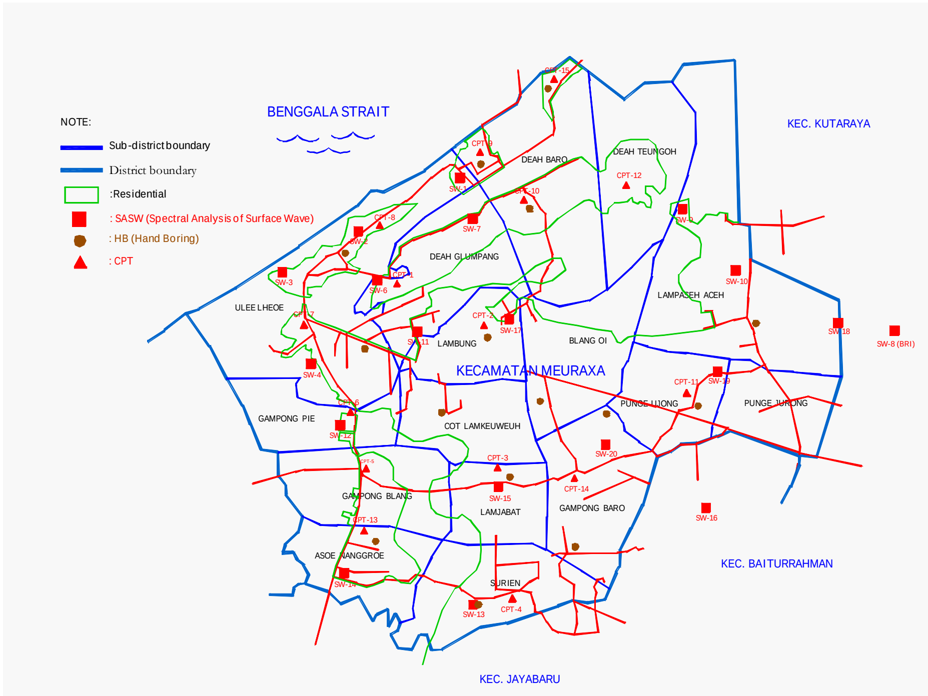

Figure 5 Location of geotechnical investigation points within the district

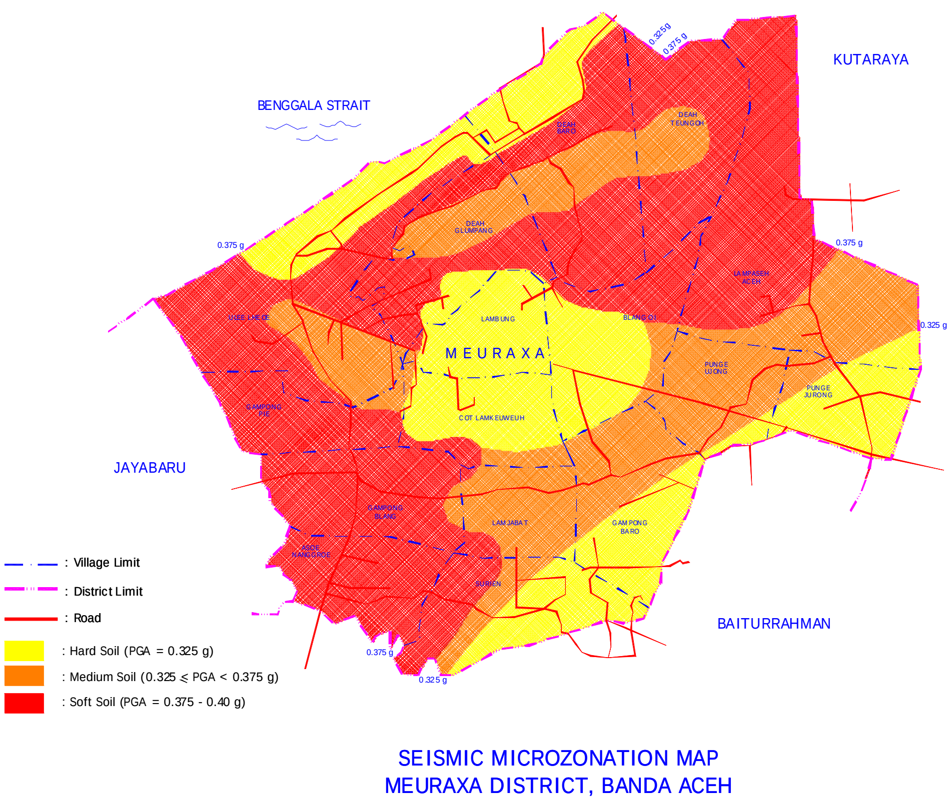

Figure 6 Site-classification and seismic microzonation map of Meuraxa District for 10% PE in 50 years

5. CONCLUSIONS AND RECOMMENDATIONS

Probabilistic seismic hazard analysis (PSHA) considering both subduction and Aceh and Seumeulem shallow crustal earthquake sources has been conducted. The PSHA indicated that peak acceleration at baserock of approximately 0.30 to 0.55g is potential to occur in Banda Aceh. These level of peak accelerations correspond to 10% and 2% PE in 50 years, respectively. De-agregation analysis shows that the peak acceleration is dominant to be originated from Aceh and Seumeulem faults which are of relatively very close distance from the city. The PSHA also provides target spectra that further adopted to develop ground motions for site-response analyses, for hard, medium, and soft site-class. Site classification and seismic microzonation map developed from a set of geotechnical investigation consisting of SASW tests and from results of the site-response analyses has developed. The analysis has provided design response spectra for various site-classes. The values of the peak ground accelerations resulted from this study are recommended as seismic design criteria for reconstruction and long-term development of buildings and infrastructures for Meuraxa District in particular and for city of Banda Aceh in general. Since there is limited information and study of the Aceh and Seumeulem faults and there are some uncertainties associated with the seismic parameters to the corresponding hazards, then in long-term, further detailed investigation on this faults need to be conducted to be analyzed further using attenuation functions derived from global database. The methodology adopted in this paper could be used to develop seismic design criteria for other cities and areas as an input to seismic building codes.

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