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SEISMIC MICROZONATION FOR BANDA ACEH CITY – A GIS APPROACH

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ABSTRACT

Banda Aceh which lies about 100 km from Sumatra Subduction Zone and 10 km close to the Sumatran Transform Faults makes this place extremely vulnerable to earthquake hazards. Learning from the earthquake and tsunami on December 26th 2004 which caused many deaths, property loss and devastation of the city, urban planning and development in the future should consider these earthquake potential hazards. Based on this purpose, seismic microzonation maps which identify and map different earthquake hazard potentials can be used as reference or tool in the initial phase of earthquake risk mitigation. The main objective of this study is how to create seismic microzonation maps using Geographic Information Systems (GIS) and in turn can be used as guidance in urban planning and development. The maps incorporate various seismic hazard maps including ground shaking hazard map, liquefaction hazard map, landslide hazard map, surface faulting hazard map and tsunami hazard map.

KEY WORDS: Earthquake, Hazard, Seismic Microzonation, GIS.

INTRODUCTION

Earthquake is one of the most devastating natural phenomena. These natural events can cause severe impact to human life like death or injury, loss of valuable goods and cause massive damage to structures such as buildings, transportation systems, communication systems, and lead to total devastation of cities. There are a lot of past and current earthquakes that are well popular, not just for their extent but also for the casualties they came along with. A compendium report on the significant worldwide earthquakes, right from the past to the most current ones, shows that the loss in the lives of inhabitants and property damage are caused by earthquakes (Chen and Scawthorn, 2003).

The damage caused in an incidence earthquake is not only on the volume of its magnitude, but also the development of socio-economic activities in the settlement. The amount of incidences of large earthquakes has stayed fairly stable but the loss in property and human lives in the recent periods of the earthquakes has augmented in multiples because of the increase in human population and the urbanization where populace and activities that are economic-based tends to concentrate in larger urban areas, most of which are situated in susceptible coastal regions. Another factor related to the increasing impact of earthquake is level of development of the country. In the developed countries, where warning-systems are more sophisticated, the application of building codes, restrictive zoning and the new constructions have better earthquake resistance also claims for a lesser the amount of casualties than in those countries that are underdeveloped (Westen, 2002; Walling and Mohanty, 2009).

Although every country has adopted seismic zonation for estimating the seismic hazard at national level (seismic macrozonation), it is not adequate in urban and regional planning, where is needed seismic microzonation map especially for those cities that are populated or townships that industrial-based comes under high hazard areas and like wise those places that are liable to earthquake hazard. Seismic microzonation map will be use identifying and mapping the difference in earthquake hazards within a confined region – mainly a city or municipality – as a result of difference in ground motion or conditions and local site conditions (Coburn and Spence, 2002). It makes it possible to select relatively safer sites for the allocation of appropriate land resources when mapping the variation in earthquake hazards at the municipal level. The patterns of urban development can be oriented toward relatively safer areas. This reduces losses (DRM/GDDA, 2004).

Banda Aceh has experienced catastrophic damages due to large magnitude earthquake (Mw = 9.3) and tsunami of December 2004. More than seventy thousands resident of this city experienced lost in lives and lot of buildings, lifelines and infrastructures are damage or collapsed. Most

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of the residential around the coastal regions were as well destroyed by tsunami, likewise many roads and embankments were identified to have collapsed and destroyed as a result of liquefaction and lateral spread (Koshimura *et al*., 2005). Based on the experienced and the location of Banda Aceh, it is important that the development of Banda Aceh in the future should consider the hazard caused by an earthquake. For this purpose, seismic microzonation map can be used as an effort to reduce the impact of the hazards. Seismic microzonation map can be used in regional or urban planning in determining appropriate land use, zoning restrictions, building codes and improved structures (Ansal *et al*, 2009).

In producing seismic microzonation map, Geographic Information Systems (GIS) can be used. GIS is defined as a computer based information system that enables capturing/collecting, storing, retrieving, modeling, analysis, and displaying/presenting of geographically referenced data for particular set of data. The capability of GIS in integrating of several data types (spatial and non spatial data) or parameters such as seismology, geology, lithology, hydrology, topography, and analysis of the integration of data types can be used to produce the seismic microzonation map. In this study, Geographic Information Systems (GIS) together with Multi Criteria Decision Analysis (MCDA) such as Analytical Hierarchy Process (AHP) is used to produce seismic microzonation maps.

THEORY OF SEISMIC MICROZONATION

Seismic waves generated at the earthquake source propagate through different geological formations until they reach the surface at a specific site. The travel paths of these seismic waves in the uppermost geological layers strongly affect their characteristics, producing different effects on the earthquake motion at the ground surface. In general, thicker layers of soft, unconsolidated deposits tend to amplify selectively different wave frequencies. These complex physical phenomena are known as soil effects. On the other hand, the local topography can also modify the characteristics of the incoming waves, leading to the so called topographic effects. Soil and topographic effects are considered under the general denomination of local site effects. Beyond these effects and under certain circumstances, induced effects may occur for large amplitude incoming waves, among which are slope instabilities (landslides) in mountainous area and liquefaction in recently deposited sands and silts area.

Within a more generalized scope, active faulting should also be considered as, in case of fault ruptures. In addition, permanent differential displacements and near fault effects are other important issues to be recognized. Earthquake induced tsunami is also considered in the coastal area, especially the site near to the fault rupture in sea bed. In many past and recent earthquakes, it has been observed that the local site conditions - soil and topographic effects, as well as induced effects - have a great influence on the damage distribution. It is therefore, very important to take into account and predict these possible local site effects when assessing the earthquake hazard at regional and local scale.

Seismic microzonation is the subdivision of a region into smaller zone that have relatively similar exposures to various earthquake effects. The underlying concept arises from the fact that the effects of surface geology on seismic motion could be considerably large. Several studies on devastating earthquakes have demonstrated a large concentration of damage in specific areas due to site-dependent factors related to surface geologic conditions and local soils altering seismic motions (Nath *et al*, 2008).

The general concept of zoning refers to the process of subdividing a region into sectors with similar behavior under seismic action with respect to a given set of parameters. Zoning always relates to a specific application, and, in most cases, is linked to engineering design or land-use planning purposes. Seismic zonation and microzonation refer to the working scale, regional and local, respectively. They are the basic tools for earthquake damage mitigation on the side of ground shaking and ground induced effects (Oliveira *et al*., 2006).

Mapping of earthquake hazard at the regional or urban level makes it feasible in the selection of the relatively less affected sites for the distribution of suitable land uses. Patterns of urban development can be oriented toward these relatively less affected regions to reduce likely earthquake damages. Seismic microzonation is as well fundamental for the structural designer and builder to enable them to expect predicaments related to amplification of ground shaking, liquefaction and landslide susceptibilities (Ansal *et al.*, 2009)

Various approaches are currently applied for microzonation studies. Experimental techniques, together with theoretical approaches involving ground motion modelling under different hypotheses, are used to classify urban areas in various zones of different earthquake response characteristics. According to Technical Committee No. 4 for Earthquake Geotechnical Engineering under the auspices of International Society for Soil Mechanics and Geotechnical Engineering (TC4-ISSMGE) (1999), the practice of microzonation is classified into three grade groups:

1) First grade (Level 1), map can be prepared with scale of 1:1,000,000 – 1:50,000 and the seismic hazards are assessed based on the historical earthquakes and existing information of geological and geo-morphological maps.
2) Second grade (Level II), the scale of the mapping is 1:100,000-1:10,000 and seismic hazards are assessed

based on the micro-tremor and simplified geotechnical studies.
3) Third grade (Level III), map seismic hazards has been assessed based on the complete geotechnical investigations and ground response analysis with a scale of 1:25,000-1:5,000.

The three levels are calibrated with respect to their specific use and relevant objectives. For vast area land planning the first level is sufficient, while level 2 or level 3 are usually needed for accurate urban and emergency planning and for structural design (Dolce, 2002).

The key issue affecting the applicability and the feasibility of any microzonation study is the usability and reliability of the parameters selected for microzonation. These parameters need to be meaningful for city planners as well as for public officials and should not lead to controversial arguments among the property owners and city administrators. According to ‘Primer on Natural Hazard Management in Integrated Regional Development Planning’ (OAS/DRDE, 1991) and Seismic ‘Microzonation for Municipalities: Manual’ (DRM/GDDA, 2004), the parameters that have to be consider in derivation and creation of seismic microzonation maps by using Geographic Information Systems (GIS) are:

a. Ground Shaking Map

Two types of data or sources that have to be prepared in assessing the ground shaking effects:
1) Seismological (earthquake source and path characteristics): shear wave velocity, predominant period/frequency, peak ground acceleration/velocity (PGA/PGV).
2) Site characteristics (local geological and geotechnical site condition): depth of engineering bedrock, soil layer (stratification) and type (classification), groundwater depth and topography.

b. Surface Faulting Map

This is relatively easy to do, since surface faulting is associated with fault zones. According to this, a geological map of the investigated area and its surroundings should be provided, indicating faults with documented activity, potentially active faults and type of fault movement (normal, reverse or slip). If earthquakes surface faulting was observed in the past, the tracks of the observed faults should be mapped, based on the available documents.

c. Liquefaction Susceptibility Map

Two factors influence liquefactions susceptibility:
1) Soil type, liquefaction usually happened in the area with recently deposited sand and silts such as Holocene deltas, river channels, areas of floodplain deposits, and poorly compacted fills.
2) High ground water level, where water table is at depth of less than ten meters.

d. Landslide and Rock Fall Hazard Map

To get the landslide and rock fall hazard, the following input data are needed:
1) Geology: weak, incompetent rock or soil is more likely to fall than strong, competent rock or soil.
2) Topography or slope inclination: generally, steeper slopes have a greater change to landslide or rock fall.
3) Hydrology due to moisture contains.

e. Earthquake-related Flooding Map

Estimates of the risk of future tsunamis are based primarily on two types of information: the past history of tsunamis and the prediction of tsunamigenic earthquakes, such as fault zone, terrestrial topography (bathymetry) and local conditions of near-shore marine. The most readily available sources of information on historic tsunamis, including current activities in tsunami research.

THE STUDY AREA

Banda Aceh City is a large city and the capital of Aceh province in western Indonesia, located in the north western point on Sumatra Island, lies between the latitude 05° 16' 15" - 05° 36' 16" North and longitude 95° 16' 15" - 95° 22' 15" East. It is the principal administrative, commercial, educational and cultural centre of the province. The area of this study covers about 1160 sq km including the city of Banda Aceh (Banda Aceh Municipality) which is an area of 60 sq km, and half area of Great Aceh Regency which is an area of 1100 sq km (Figure 1).

Fig. 1: Location and the study area (insert)

Geologically, Banda Aceh is located on deltaic plain of Aceh River (Krueng Aceh). The city stands astride the Aceh River which flows in a broad valley between low Tertiary and Quaternary volcanic hills to the east and Cretaceous limestone hills to the west (Figure 2). The valley itself is filled with relatively recent alluvial and marine sediments to depths in excess of 179 metres. These were deposited in a graben structure formed between the main Sumatran Fault System (SFS). The oldest rocks in the Banda Aceh area are the limestone, slates and phyllites that outcrop on the west side of the Aceh River valley. These are of Cretaceous age and form generally steep mountains at the northern end of the Barisan Mountains (Bukit Barisan) range that runs the length of Sumatra Island. The limestones are fairly massive but moderately weathered. The east side of the valley is flanked by extensive deposits of andesitic tufts and subsidiary flows, some probably water lain. These deposits and their parent volcano, Seulawah Agam, lie on the line of the eastern Sumatran Fault, a splay off the main fault system (Culshaw *et al.*, 1979).

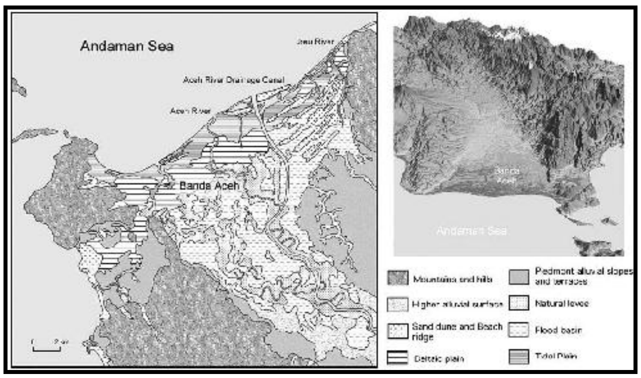

Figure 2: Topography of the study area

Seismically, Banda Aceh is located on the area that very hazardous to the earthquake. It is located near to Sumatra Subduction Zone about 100 km on the west-southern of the city and very close about 10 km to Sumatran strike-slip Fault or Sumatran Transform Fault (STF) that runs through the entire length of Sumatra Island. Generally, tectonic features that affected Banda Aceh city are caused by two these seismic source zones (Figure 3). The Sumatra Subduction zone is formed by subduction of the India-Australian plate beneath the Eurasian plate at a rate of about 50 - 67mm per year (Sun and Pan, 1995). Most of the earthquakes generated in this zone are shallow to intermediate with very unusual deep events. As the subducted slab moves at a shallow angle, the overriding and the subducting plates are strongly coupled in this zone and hence strong earthquakes could occur (Sun and Pan, 1995). On the other side, The transform zone of Sumatra is formed due to the oblique convergence of Indo-Australia with Eurasia plates. This mechanism results in lateral displacement across the Sumatran fault The slip rates along the fault vary from 6 to 27mm/year with the slip rate accelerating to the west (Sieh and Natawidjaja, 2000). All of these earthquakes occurred due to strike slip movement along clearly defined faults in the frontal arc area of Sumatra Fault classified as Sumatra transform zone (STZ). The seismic activities of the STZ zone also indicated the occurrence of earthquakes at shallow depths < 60 km along the faults (Sengara et.al., 2008). Compared to Sumatran subduction zone, the energy released from this fault is at a relatively lower stress level, but because the earthquake hypocenters from this fault were shallower (usually less than 30 km) and close to the urban areas, earthquakes of the STZ can cause large damage to urban environment. The study of the Sumatran fault that is given by Sieh & Natawidjaja (2000), the location of Banda Aceh is very close to the Aceh and Sileumeum fault segments that are only a few kilometres distance from city of Banda Aceh. In the future this fault is considered potential to generate large earthquakes, since the subduction earthquake would need much longer time to accumulate its energy post 2004 earthquake for another large earthquake (Sengara *et al.*, 2008).

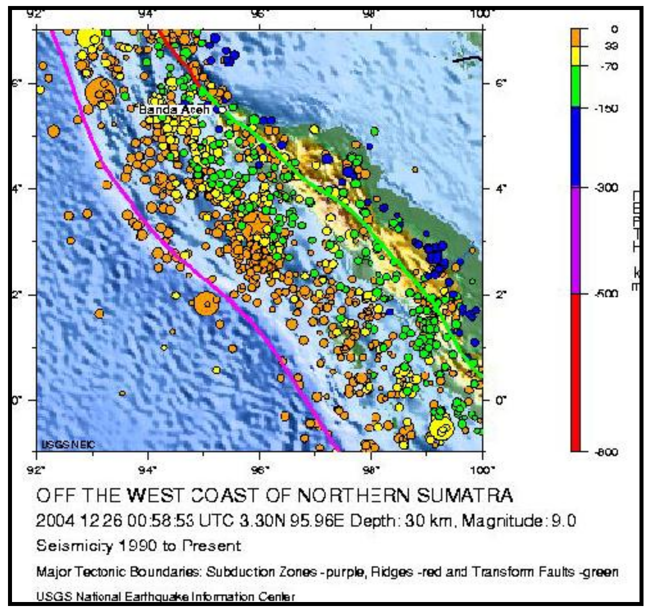

Fig. 3: Seismicity of the region affected by Sumatra Subduction Fault (purple) and Sumatran Transform Fault (green)

GIS DATABASE

For the study on Banda Aceh, the seismic microzonation maps which have been developed on a scale of 1:225,000 using ArcGIS ver. 9.3 can be classified as seismic microzonation level 1 (TC4-ISSMGE, 1999) which is suitable for vast area planning (Dolce, 2002). The data, mainly for the maps were obtained from Aceh Province's Energy and Mineral Resources Department and Development Planning Agency of Aceh Province, which they carried out the seismological, geological and geotechnical studies. The data were categorized into two main theme; seismological data, which include Peak

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Ground Acceleration (PGA), faults, and tsunami inundation maps; and site characteristics data, which include geology (soil and rock formation), lithology (soil type and classification), hydrology (groundwater quantity and distribution) and topography (contour map). All collected data are combined in a geo-spatial database on the ArcGIS platform.

Peak Ground Acceleration (PGA)

Peak Ground Acceleration (PGA) is a measure of earthquake acceleration on the ground. It represents a short period ground motion parameter signifying damage potential to the buildings and an important input parameter for earthquake engineering. The PGA values depend on the tectonic regime and seismicity of the area and extrapolated on the basis of similar soil types and the basement rock depth. According to the Intensity map of the area produced by Energy and Mineral Resources Department of Aceh Province, the expected PGA value in the region varies from 0.05 g to 0.15 g. The highest value is on the alluvial sediments especially on the coastal region in the northern part of the area which is thick clay deposits. The PGA value decrease towards the eastern part which is andesitic deposits, the western part which is limestone deposits, and the southern part which is underlying bedrock relatively shallow. The objective of PGA coverage in the study is to identify the effect of ground shaking of the area. The higher PGA value will cause more severe damage than the lower PGA value. The PGA value is shown in Figure 4.

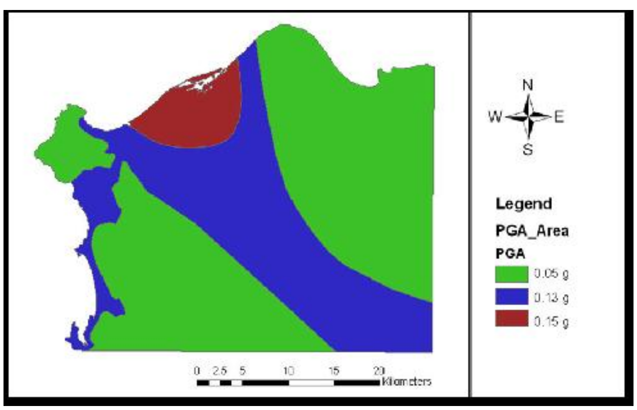

Fig. 4: Peak Ground Acceleration (PGA) data layer

Faults

Identification of the faults in this study is important to determine the region that will be affected by surface faulting during an earthquake. Surface faulting is the offset or tearing of the ground surface by differential movement along a fault during an earthquake. There are two segments of the Sumatran transform faults located very closed to the city: Aceh segment in the west part of the city and Seulimum segments in the east part of the city (Figure 5).

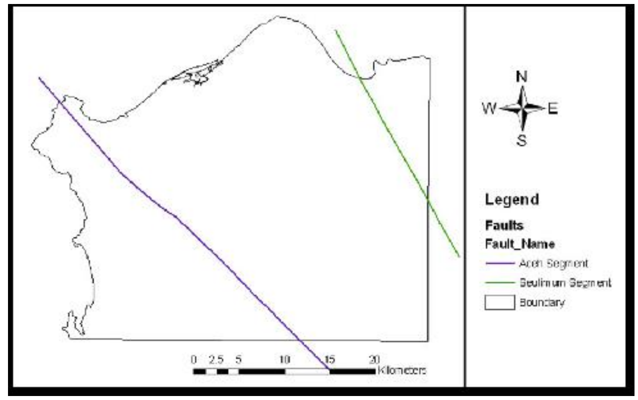

Fig. 5: Fault data layer

Tsunami

Coastal areas of City of Banda Aceh has experienced catastrophic damages due to earthquake (Mw = 9.3) and tsunami of December 2004.

The tsunami inundation map was made based on the historic tsunami occurrence. There are many studies that have been done to investigate the inland propagation and impact of tsunami in the coastal area of Banda Aceh and its vicinity (JICA, 2005; Borrero, 2005; Umitsu et al, 2007; Takahashi et al, 2008; Lavigne et al, 2008). Based on inundation depth and the impact to building damage of the region, the tsunami map is classified into 4 zones: high, moderate, less and no vulnerability to tsunami. The zones that indicated high vulnerability to tsunami are the areas that got inundation depth of 7 – 10 m and totally destroyed to heavy damage of buildings (75 - 100%). The zones that indicated moderate vulnerability to tsunami are the areas that got inundation depth of 3 – 6 m and major to moderate damage of buildings (25 - 75%). The zones that indicated less vulnerability to tsunami are the areas that got inundation depth of 0 – 2 m and slightly to no damage of buildings (0 - 25%) and last, the zones that were free from vulnerability to tsunami are those areas that got no inundation depth (Figure 6).

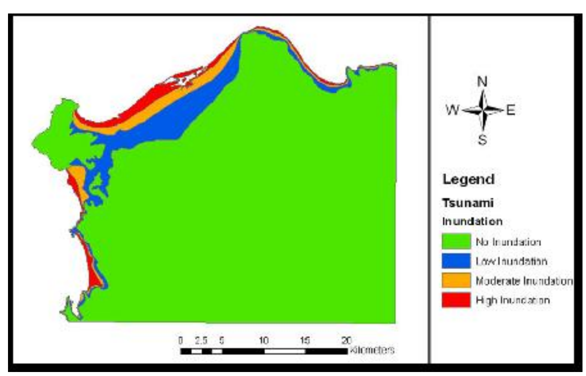

Fig. 6: Tsunami inundation data layer

Geology

Identification of the geology characteristics in this study is important to determine the effect of ground shaking and to identify landslide potential in the area. According to the geology structure and deposits, the geology of the study region consists of younger alluvium plain, old alluvium plain, massive limestone and andesitic tuffs of volcanic. The highest seismic hazard in this region is younger alluvium plain with thick deposits of sediments, followed by old alluvium plain, andesitic volcanic and limestone plain (Figure 7).

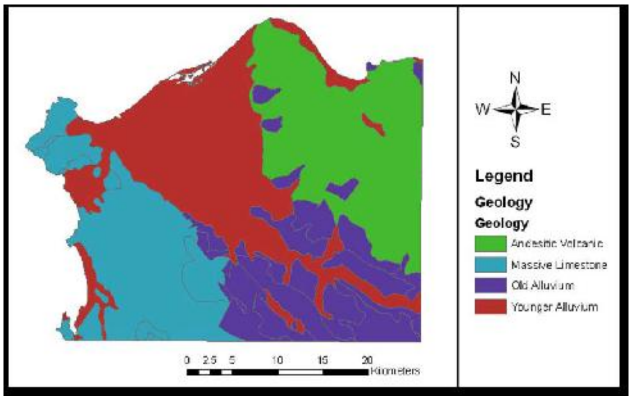

Fig. 7: Geology data layer

Lithology (Soil Layer Type and Classification)

It is well known that unconsolidated soil amplifies ground motion that may cause considerable damage to man-made structures, while on hard rock exposures; the amplification of ground motion is not observed. For a given magnitude of earthquake, it will have different effects on an area depending on its local soil condition.

The soil layer of the study area was taken from the geotechnical map produced by Energy and Mineral Resources Department of Aceh Province. The map was produced based on reviewing and evaluating of standard penetration test (SPT) of the boreholes data that have been taken around Banda Aceh. The result is soil type based on Unified Soil Classification System (USCS). USCS classify the soil based on unifying texture, grain size, the liquid limit and plasticity index of the soil. Based on USCS classified, the soil type of the area can be defined as: SM (silty sands), MH/ML (Silt), CL/ML (Mixture of Clay), CH/CL (Clay), SC (Clayey sands) and Rock, where SM (silty sands) has bearing capacity very low (<0,1 kg/m2) and Rock has bearing capacity very high (>1 kg/m2). The soil type of the region can be seen in Figure 8. Soil type is used to estimate the potential of liquifaction on this area.

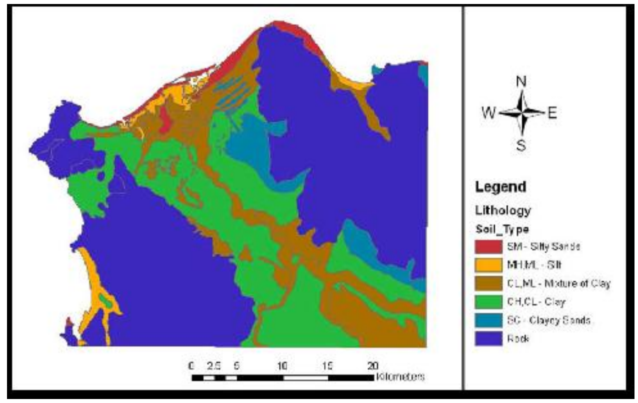

Fig. 8: Soil type data layer based on Unified Soil Classification System (USCS).

Another classification of Lithology is based on the International Building Code (International Code Council, 2009). The classes are defined by the average shear wave velocity of the upper 30 metres of soil ($VSav_{30}$), by improved descriptions of the stratigraphy, and by ranges of values of geotechnical parameters shear wave velocity of the ground. The soil class based on IBC classified in this area can be defined as A (hardrock), B (rock), C (very dense soil), D (stiff soils), E (soft soils) and F (very soft soils), where A (hard rock) has $VSav_{30} > 1500$ m/sec and E (soft soils) has $VSav_{30} < 180$ m/sec (Figure 9). Soil class is used to estimate the potential ground shaking on this area.

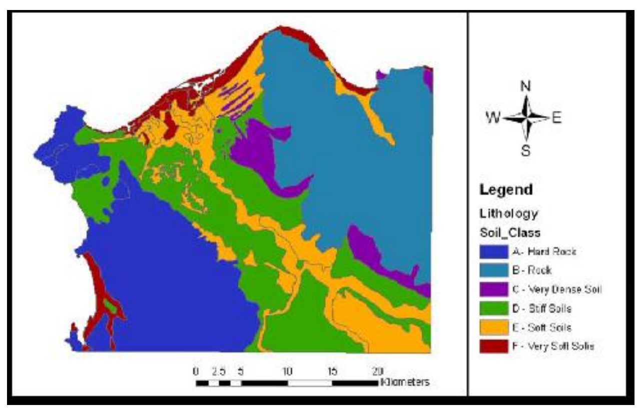

Fig. 9: Soil class data layer based on International Building Code (IBC 2009)

Groundwater

The groundwater depth and distribution is one of the main factors to check the liquefaction potential of different parts of the city, since liquefaction is a factor of water saturated soil. Together with the soil condition such as sands and silts sediments (silty sands, sand-silt mixes), it will contribute to liquefaction phenomena. The ground water also has contribution to amplify ground motion and the occurrence of landslide. Distribution of groundwater can

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be seen in Figure 10.

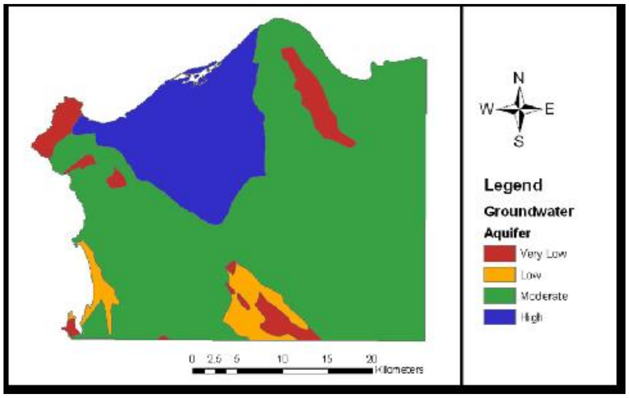

Fig. 10: Groundwater data layer

Topography (Contour Lines)

Topography is an important factor to consider landslide susceptibility in terms of slopes. The topography map of the study area was taken from topography map provided by Development Planning Agency of Aceh Province. For the purpose of this study, the contour lines were used to generate the Digital Elevation Model (DEM) by using 3D analyst tools of ArcGIS and the slope layer was produced from DEM by using surface analysis function in Spatial Analyst tools or 3D analyst tools of ArcGIS. The topography map in terms of DEM is illustrated in Figure 11. Since the landslide covers in an area, the slope map that derived from DEM was digitized into vector data structure. The slope map was prepared in degrees and subdivided into four main classes according to the guidelines from The Organization of American States, Department of Regional Development and Environment (OAS/DRDE, 1991). The slope classes are 0-12 degrees, 12 – 25 degrees, 25 – 50 degrees and above 50 degrees (Figure 12).

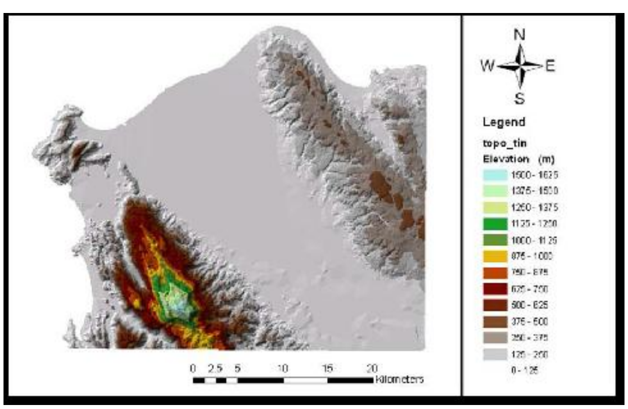

Fig. 11: Topography in term of Digital Elevation Model (DEM)

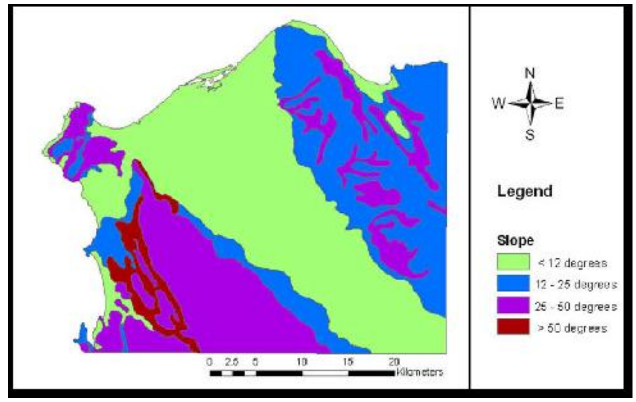

Fig. 12: Slope data layer after digitized from DEM

METHODOLOGY

The seismic microzonation maps are developed by identifying the hazard caused affected by an earthquake in the area which are ground shaking, liquefaction, landslide, surface faulting and tsunami. Each hazard has parameters or criteria, that are the parameters of ground shaking hazard maps are peak ground acceleration (PGA), soil class, geology and groundwater; the parameters of liquefaction are soil type and groundwater depth; the parameters of landslide are slope steepness, geology and hydrology (see theory of seismic microzonation).

Ground shaking hazard map

Ground shaking hazard map created by using *weighted overlays* of parameters that influence the level of hazard, which are peak ground acceleration (PGA), soil class, geology and ground water. In this process Saaty's Analytical Hierarchy Process (AHP) theory is used to help in making the right decision or producing a good result. Following the AHP theory, the parameters are assigned weights on a scale of 1–4 depending on their contribution to seismic hazard. The higher weight is assigned to the theme that contributes more to the hazard and in this case the highest weight is given to the PGA and followed by Soil Class, Geology and Groundwater respectively (Nath *et al.* 2004). Calculating the principal Eigen vector and averaging the values of each row matrix, the weights obtained for each theme are: PGA (0.4), Soil Class (0.3), Geology (0.2), and Groundwater (0.1). These values are used in weighted overlay analysis of ArcGIS (Table 1).

Table 1: Assigned weight of parameters for ground shaking analysis using AHP.

Parameters	PGA	SC	Geo	Gw	Weightage
PGA	4/4	4/3	4/2	4/1	0,4

e-ISSN 2656-7520

Soil Class (SC)	3/4	3/3	3/2	3/1	0,3
Geology (Geo)	2/4	2/3	2/2	2/1	0,2
Groundwater (Gw)	1/4	1/3	1/2	1/1	0,1

Providing rating (rank value) for each sub-criterion (feature) of the parameters is based on the contribution of each feature on the level of hazard. The method used adopts the approach of Nath *et al.* (2004), Mohanty *et al.* (2007) and Anbazhagan *et al.* (2010). This is done by making a ranking of 1 - ‘n’ (n=number of feature) for each feature, where ‘1’ shows the smallest contribution, while ‘n’ indicates the highest contribution on hazard level of ground shaking.

Since the values within each thematic map/layer or parameter vary significantly, they are classified into various ranges or types, in assigning rank or rating, these features have to be normalized to ensure that no layer exerts an influence beyond its determined weight. Therefore, a raw rating for each feature of every layer is allocated initially on a standard scale from ‘1’ to ‘n’ (number of features) and then normalized between range 0-1 using the relation: (Nath *et al.*, 2004; Mohanty *et al.*, 2007; Anbazhagan *et al.*, 2010)

$$X_i = \frac{R_i - R_{min}}{R_{max} - R_{min}} \quad \text{.. (Eq. 1)}$$

Where, X_i = normalized rank score; R_i is the raw score, R_{min} and R_{max} are minimum and maximum scores of a particular layer.

The normalized rank should have been used as a rank value for feature of parameters, but because the weighted overlay analysis embedded in ArcGIS 9.3 works only on integer (not floating point), the normalized rank resulted have to be standardized into integer value in rank scale 1-3. The scale in rank 1-3 indicates 3 levels of hazards (low, medium and high hazard). Obtaining new standardized rank value is carried out by calculating ‘range’ using relation: (Wan Ibrahim, W. Y., 2008)

$$Range = \frac{Rn_{max} - Rn_{min}}{N} \quad \text{... (Eq.2)}$$

Where, Rn_{max} and Rn_{min} are maximum and minimum scores after normalized, in this case Rn_{max} = 1 and Rn_{min} = 0; N is number of rank scale, in this case N = 3 (levels of hazards). So,

$$\text{Range} = \frac{1 - 0}{0} = 0.33$$

It means the range 0 – 0,33 = 1; 0,34 – 0,66 = 2; and 0,67 – 1 = 3.
A new standardized rank value of each feature of parameters for creating ground shaking hazard map can be seen in Table 2.

Table 2: Assigning rank value for feature class of each ground shaking parameters.

Parameters	Feature	Ranking (Sort 1 – n)	Normal-ized Rank	Standar-dized Rank
PGA	0,05 g 0,13 g 0,15 g	1 2 3	0,00 0,50 1,00	1 2 3
Soil Class (SC)	A-Hard rock B-Rock C-Dense soil D-Stiff soil E-Soft soil F-Very soft soil	1 2 3 4 5 6	0,00 0,20 0,40 0,60 0,80 1,00	1 1 2 2 3 3
Geology (Geo)	Limestone Andesitic tuff Old Alluvium Young Alluvium	1 2 3 4	0,00 0,33 0,66 1,00	1 1 2 3
Groundwater (Gw)	Very low Low Moderate High	1 2 3 4	0,00 0,33 0,66 1,00	1 1 2 3

After obtaining the weight and rank value, the next step is to perform the analysis using these weight and rank value as input in weighted overlay analysis of ArcGIS 9.3. Automatically, ArcGIS compute the data inputted for each pixel of the output microzonation map using the equation: (Malczewski, 1999)

$$M_i = \Sigma_j w_j r_{ij} \quad \text{.......................…………………....…. (Eq.3)}$$

Where, M_i = each pixel of the output microzonation map, wj = standardized weight of the jth layer (parameter), and r_{ij} = rank value of the ith class (feature) with respect to the jth layer.

In the case of ground shaking hazard (GSH) map, ArcGIS compute the data for each pixel of the output ground shaking hazard map:

$$GSH = PGA_w PGA_r + SC_w SC_r + Geo_w Geo_r + GW_w GW_r$$

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Where, PGA = peak ground acceleration, SC = soil class, Geo = geology, GW = groundwater, w = weight value of the layer, and r = rank value of each feature class.

The result is ground shaking hazard map showing 3 (three) level of hazards in the area that can be used in urban/regional planning (DRM/GDDA, 2004); 1 means low hazard, 2 means medium hazard, and 3 means high hazard, can be seen in Figure 13.

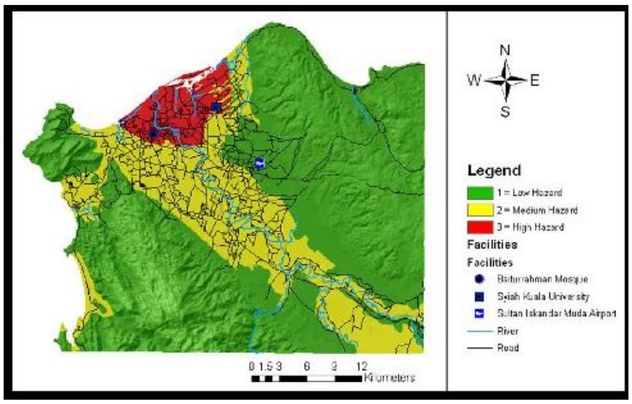

Fig. 13: Ground shaking hazard map shows 3 level of hazard (low, medium and high hazard zones).

Liquefaction Hazard Map

Similar to the creation of ground shaking hazard map, liquefaction hazard map was developed by using weighted overlay of spatial analyst function of ArcGIS and AHP method in analysis of weight value of parameters. The parameters are assigned weights on a scale of 1–2, where the highest weight is given to the soil type and followed by groundwater (OAS/DRDE, 1991). Calculating the principal Eigen vector and averaging the values of each row matrix, the weights obtained for each theme are: Soil Type (0.67) and Groundwater (0.33). These values are used as a weight of parameters in weighted overlay analysis of ArcGIS (Table 3).

Table 3: Assigned weight of parameters for liquefaction analysis using AHP.

Parameters	ST	Gw	Weightage
Soil Type (ST)	2/2	2/1	0,67
Groundwater (Gw)	1/2	1/1	0,33

Table 4: Assigning rank value for feature class of liquefaction parameters.

Parameters	Feature	Ranking (Sort 1 – n)	Normal-ized Rank	Standar-dized Rank
Soil Type (ST)	Rock	1	0,00	1
	Clayey sand	2	0,20	1
	Clay	3	0,40	2
	Clayey silt	4	0,60	2
	Silt	5	0,80	3
	Slity sand	6	1,00	3
Groundwater (Gw)	Very low	1	0,00	1
	Low	2	0,33	1
	Moderate	3	0,66	2
	High	4	1,00	3

Similarly, determining the rating (rank value) for each sub-criterion (feature) of the liquefaction parameters adopts the approach of Nath *et al.* (2004), Mohanty *et al.* (2007) and Anbazhagan *et al.* (2010) by making a ranking of 1 - 'n' (n=number of features) for each feature, where '1' shows the smallest contribution, while 'n' indicates the highest contribution on hazard level of liquefaction. Then, by using equation 1 to determine normalized rank value and using range of equation 2 to determine standardized rank value (Table 4).

The liquefaction hazard map was produced by using weighted overlay analysis of ArcGIS and input data of weight and rank value as shown in Table 3 and 4. Automatically, ArcGIS compute the data inputted for each pixel of the output microzonation map. In the case of liquefaction hazard (LQH) map, ArcGIS compute the data for each pixel of the output of liquefaction hazard map:

$$LQH = ST_wST_r + GW_wGW_r$$

Where, ST = soil type/classification, GW = groundwater, w = weight value of the layer, and r = rank value of each feature class.
The liquefaction hazard map for the area can be seen in Figure 14.

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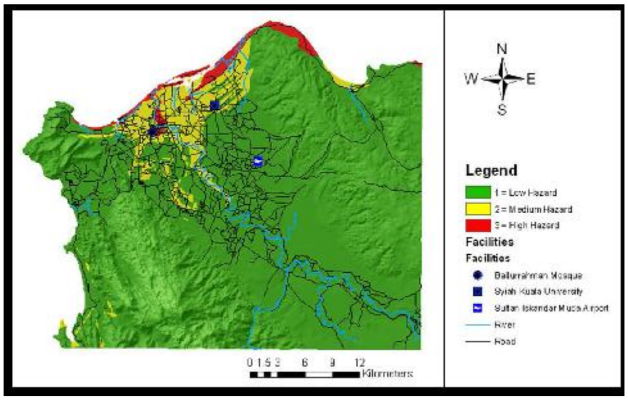

Fig. 14: Liquefaction hazard map shows 3 level of hazard (low, medium and high hazard zones).

Landslide Hazard Map

Similar to the creation of ground shaking hazard map and liquefaction hazard map, landslide hazard map was developed by using weighted overlay of spatial analyst function of ArcGIS and AHP method in analysis of weight value of parameters. The parameters are assigned weights on a scale of 1–3, where the highest weight is given to the slope steepness, geology and followed by groundwater (OAS/DRDE, 1991). Calculating the principal Eigen vector and averaging the values of each row matrix, the weights obtained for each theme are: Slope Steepness (0.5), Geology (0.33) and Groundwater (0.17). These values are used as a weight of parameters in weighted overlay analysis of ArcGIS (Table 5).

Similarly, determining the rating (rank value) for each sub-criterion (feature) of the landslide parameters adopts the approach of Nath *et al.* (2004), Mohanty *et al.* (2007) and Anbazhagan *et al.* (2010) by making a ranking of 1 - 'n' (n=number of features) for each feature, where '1' shows the smallest contribution, while 'n' indicates the highest contribution on hazard level of landslide. Then, by using equation 1 to determine normalized rank value and using range of equation 2 to determine standardized rank value (Table 6).

Table 5: Assigned weight of parameters for landslide analysis using AHP.

Parameters	SS	Geo	Gw	Weightage
Slope steepness (SS)	3/3	3/2	3/1	0,5
Geology (Geo)	2/3	2/2	2/1	0,33
Groundwater (Gw)	1/3	1/2	1/1	0,17

Table 6: Assigning rank value for feature class of each landslide parameters.

Parameters	Feature	Ranking (Sort 1 – n)	Normal-ized Rank	Standar-dized Rank
Slope steepness (SS)	< 12 degree 12 – 25 degree 25 – 50 degree >50 degree	1 2 3 4	0,00 0,33 0,66 1,00	1 1 2 3
Geology (Geo)	Limestone Andesitic tuff Old Alluvium Young Alluvium	1 2 3 4	0,00 0,33 0,66 1,00	1 1 2 3
Groundwater (Gw)	Very low Low Moderate High	1 2 3 4	0,00 0,33 0,66 1,00	1 1 2 3

The landslide hazard map was produced by using weighted overlay analysis of ArcGIS and input data of weight and rank value as shown in Table 5 and 6. Automatically, ArcGIS compute the data inputted for each pixel of the output microzonation map. In the case of landslide hazard (LSH) map, ArcGIS compute the data for each pixel of the output of landslide hazard map:

$$LSH = SS_w SS_r + Geo_w Geo_r + GW_w GW_r$$

Where, SS = Slope steepness, Geo = geology, GW = groundwater, w = weight value of the layer, and r = rank value of each feature class.

The landslide hazard map for the area can be seen in Figure 15.

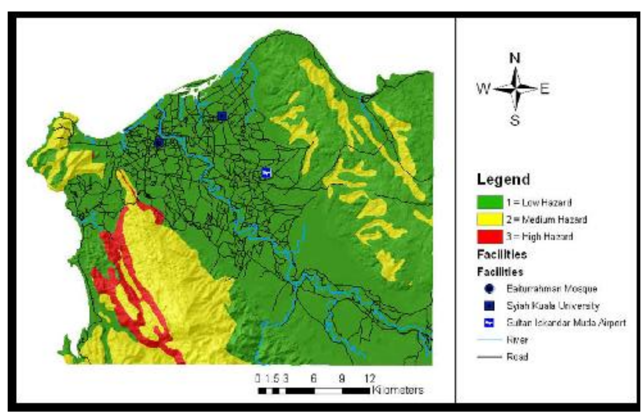

Fig. 15: Landslide hazard map shows 3 level of hazard (low, medium and high hazard zones).

Surface Faulting Hazard Map

Surface Faulting map is made based on faults map on the area. According to the data, surface faulting susceptibility can occurred with significant damage up to 300 meters wide along the fault, and subsidiary ruptures may occur three to four kilometers wide along the main fault (OAS/DRDE, 1991). In this study, surface faulting susceptibility map was created by calculating distance and reclassifying into two hazard zones areas (DRM/GDDA, 2004): low hazard (>2000 meters from faults), and high hazard (<2000 meters around the faults). Surface faulting map can be seen in Figure 16.

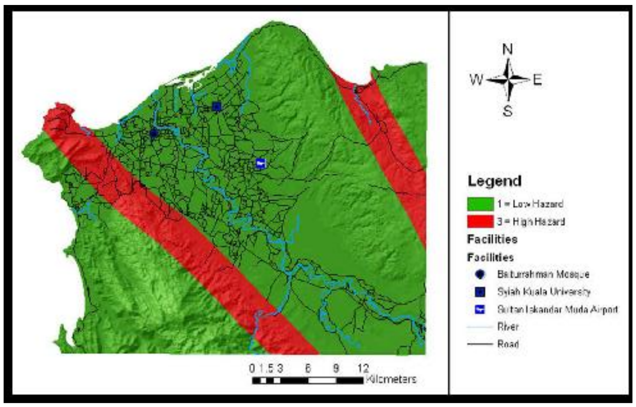

Fig. 16: Surface faulting hazard map shows 2 level of hazard (low and high hazard zones).

Tsunami Hazard Map

Tsunami hazard map is developed based on the historic tsunami occurrence that happened on 26th December 2004. The tsunami hazard map was classified into three zones: low, medium, and high hazard zones (DRM/GDDA, 2004). Low hazard zone shows no tsunami affected, medium hazard zone shows the area that got flooding but none to slightly damage of buildings with inundation 0 – 2 meters, and high hazard zones shows the area that got medium damage to total damage of buildings with inundation > 3 meters. The tsunami hazard map after reclassification can be seen in Figure 17.

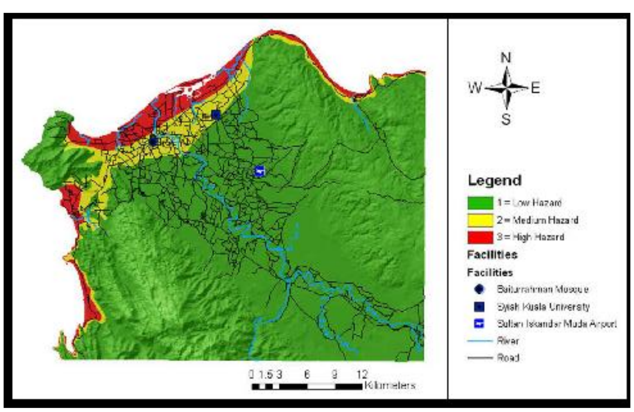

Fig. 17: Tsunami hazard map shows 3 level of hazard (low, medium and high hazard zones).

The Final Seismic Microzonation Map

The final seismic microzonation map is the composite of all the thematic maps such as ground shaking hazard map, liquefaction hazard map, landslide hazard map, surface faulting hazard map and tsunami hazard map. The final seismic microzonation map was created by using *local function* of spatial analyst tool of ArcGIS. Local function compute an output raster dataset where the output value at each location is a function of the value associated with that location on one or more raster datasets. In this case, maximum values of cells are used; it means that the maximum value of cells from multiple raster datasets are chosen as output raster datasets. The final seismic microzonation map can be seen in Figure 18.

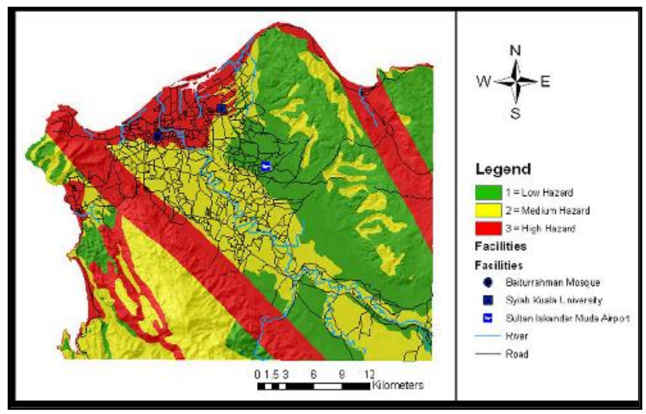

Fig. 18: The final map showing different level of hazard.

RESULTS AND DISCUSSIONS

The results of this study are ground shaking hazard map (Figure 13), liquefaction hazard map (Figure 14), landslide hazard map (Figure 15), surface faulting hazard map (Figure 16), tsunami hazard map (Figure 17) and the final seismic microzonation map (Figure 18).

Table 7: Hazard areas generated by various hazards maps.

	High Hazard		Medium Hazard		Low Hazard	
	Hactares	%	Hectares	%	Hectares	%
Ground shaking map	6,055.58	5,0	30,455.52	25.8	81,737.47	69,2
Liquefac-tion map	2,451.82	2,0	8,567.05	7.3	107,229.70	90.7
Landslide map	4,142,73	3.5	24,644.01	20.8	89,461.83	75.7

Surface faulting map	20,710.09	17.5	-	-	97,538.48	82.5
Tsunami inundation	6,534.69	5.5	8,002.41	6.8	103,711.47	87.7
Final map	33,897.00	28.7	44,935.29	38.0	39,416.28	33.3

Tabel 7 shows the total areas in term of hazard level generated by various thematic maps. According to the ground shaking hazard map, approximately 5% of the whole area can be identified as high hazard zone especially located around city centre which is located on recent alluvial plain and has high PGA value; while 25.8% is identified as medium hazard zone which is located on the valley along the river on old alluvial plain; and 69.2% is identified as low hazard zone which is located on the hilly and mountain, suggesting a dense soil or rock. The liquefaction hazard map on the other hand shows only 2% identified as high hazard zone, which is the beach area that is located on silty sand with high groundwater depth; while approximately 7.3% is identified as medium hazard zone which is located on silt, mixture of silt and clay with high groundwater depth; and approximately 90.7% of areas is identified as low hazard which is located on clay, clayey sand and rock. The high hazard zone in term of landslide effect is an area that lies on massive limestone with slope >50 degrees, that is approximately only 3.5% of the whole area; while the medium hazard zone is also located on massive limestone and andesitic tuffs but with the slope 25-50 degrees, that is approximately 20.8%; and the low hazard zone is located on old and recent alluvial plain, that is approximately 20.8% of the whole area. Surface faulting map, approximately 17.5% can be identified as high hazard zone which is around 4000 meters wide along the main fault; while approximately 82.5% is identified as low hazard zone. The tsunami map shows approximately 5.53% of area can be identified as high hazard zone which is especially located on 0 – 2.5 km inland from the coastline; approximately 6.77% is identified as medium hazard zone which is located on 1 – 5 km inland from the coastline depend on characteristics of the land; and 87.71% is identified as low hazard zone. The final seismic microzonation map shows approximately 28.7% of the whole area can be identified as high hazard zone; approximately 38.00% are identified as medium hazard zone and 33.3% identified as low hazard.

In terms of land-use management or city/urban and regional planning, seimic microzonation map can be regarded as an appropriate tool to minimize the impact of earthquakes. Seismic microzonation maps provide a more detailed evaluation of potential earthquake effects, which can provide valuable guidance in urban planning and development. The two principal considerations in earthquake loss reduction are '*sitting*' and '*design*'.

1) *Sitting* means by identification of various levels of hazard and risk potential of areas, it is possible to select relatively safer sites for the allocation of appropriate land resources where urban development patterns can be oriented toward relatively safe zones and avoid high hazard zones for development.
2) *Design* means by knowledge of the variation of earthquake hazards at the microzonation level, the structural designer and builder enable to anticipate problems related to the amplification of ground shaking, liquefaction, landslides, surface faulting, or tsunami, although detailed site information for specific building design may still require site-specific investigation.

CONCLUSION

Development of seismic microzanation map for Banda Aceh city has been carried out through series of analysis of parameters (data layers) that influences hazard on the area. The parameters included seismic data (PGA, Fault, and Tsunami) and site characteristics data (Soil Type, Soil Class, Geology, Groundwater, and Slope Steepness). Some maps such as ground shaking hazard map, liquefaction hazard map and landslide hazard map were created through weighted overlay analysis. Weights of the parameters were obtained through a series of analysis using the AHP method. Other maps such as surface faulting hazard map and tsunami hazard map were created through calculating distance and reclassify. Then, each hazard map was combined into one map by using cell statistics analysis. The final map is multi seismic hazard map that shows various levels of hazard on the area. In terms of urban/regional planning, these maps can be used as guidance for urban development such as determining appropriate land use, zoning restrictions, building regulation, etc.

According to Technical Committee No. 4 for Earthquake Geotechnical Engineering under the auspices of International Society for Soil Mechanics and Geotechnical Engineering (TC4-ISSMGE, 1999), this study can be classified into seismic microzonation grade/level I, in which the seismic hazards are assessed based on the historical earthquakes and existing information of geological and geo-morphological maps. This kind of grade/level is sufficient for vast area land planning or regional planning (Dolce, 2002). For urban planning or getting more quality and accurate result, this seismic microzonation needs to be increased into grade 2 or grade 3, in which can further generate a better level quality and accurate assessment. This type of grade with a scale of 1:100,000 - 1:5,000 requires complete geotechnical investigations and ground response analysis and involving geological and geotechnical experts.

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