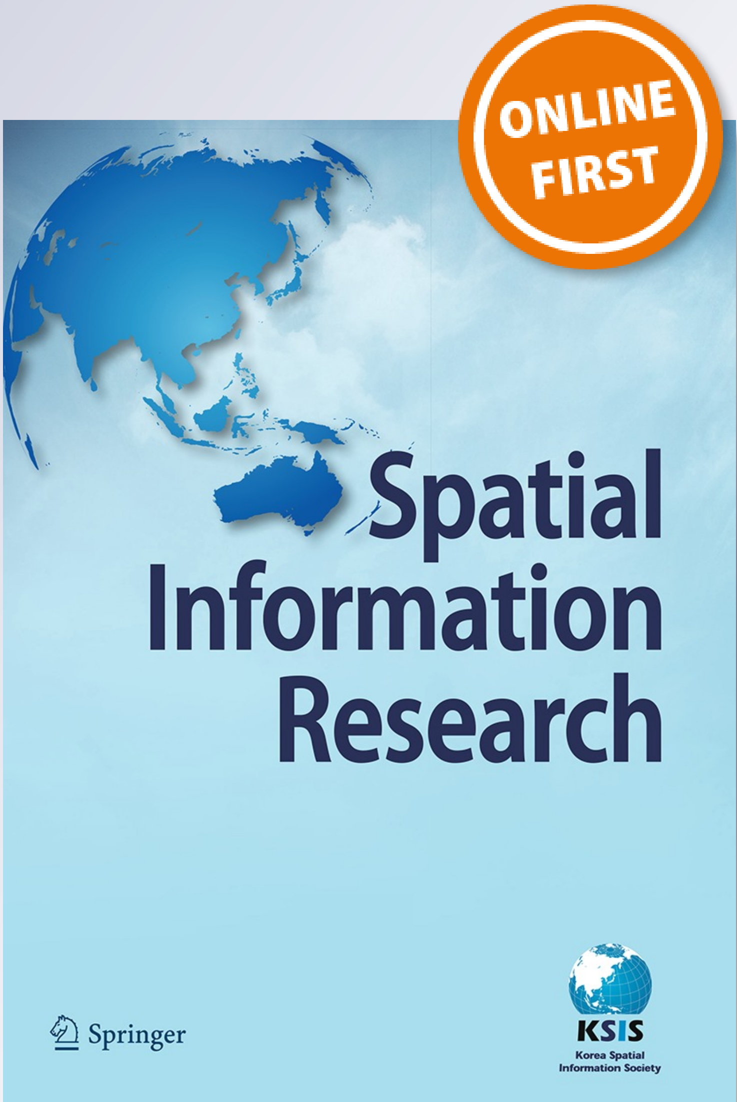
Earthquake hazard assessment in the Momase region of Papua New Guinea

Tingneyuc Sekac, Sujoy Kumar Jana, Indrajit Pal & Dilip Kumar Pal

Spatial Information Research

ISSN 2366-3286

Spat. Inf. Res.
DOI 10.1007/s41324-016-0058-2



Springer

Spat. Inf. Res.
DOI 10.1007/s41324-016-0058-2

Earthquake hazard assessment in the Momase region of Papua New Guinea

Tingneyuc Sekac[1] · Sujoy Kumar Jana[1] · Indrajit Pal[2] · Dilip Kumar Pal[1]

Received: 17 September 2016 / Revised: 6 October 2016 / Accepted: 8 October 2016

Abstract Tectonism induced Tsunami, fire, landslide along with the tremor-triggered-liquefaction are the common hazards experienced worldwide. Such hazards often lead to collapse of built-up infrastructures like roads, bridges, buildings apart from inflicting heavy toll on human life and properties. Momase region of Papua New Guinea is one such vulnerable stretch where the appropriate planning is paramount in safeguarding the life and infrastructures. The study sought evaluation and assessments of the level of vulnerability to earthquakes in Momase region. The output can be used as a tool to assist in appropriate site selection that will minimize the earthquake damage risk and also to assist in better and appropriate future construction design or planning at a site. For the present study, application potentials of GIS and remote sensing are utilized to evaluate and assess possible earthquake hazard in the study region. The influence of soil and geology as the media responsible for aggravating or mollifying earthquake waves are underlined as input. These are the media that influence ferocity of shaking intensity leading to the destructions during an earthquake episode. Therefore, the site-soil geology and geomorphology are assessed and integrated within GIS environment coupled with seismicity data layers to evaluate and prepare liquefaction potential zones, followed by earthquake hazard zonation of the study area. Multi-criteria evaluation with analytical hierarchy process are adopted for this study. The technology involves preparing and assessing several contributing factors (thematic layers) that are assigned weightage and rankings, and finally normalizing the assigned weights and ranking. The spatial analysis tool in ArcGIS 10, the raster calculator, reclassify and weightage overlay tools were mainly employed in the study. The final output of LPZ and earthquake hazard zones were reclassified to 'very high', 'high', 'moderate', 'low' and 'very low' to indicate levels of hazard within a study region.

Keywords GIS · Tectonism · Liquefaction · Hazard zonation · Multi-criteria evaluation

✉ Sujoy Kumar Jana
sujoy2007@gmail.com

Tingneyuc Sekac
tingneyucsekac@gmail.com

Indrajit Pal
indrajit.pal@gmail.com

Dilip Kumar Pal
dkpal200090@gmail.com

[1] Department of Surveying and Land Studies, Papua New Guinea University of Technology, Lae, Papua New Guinea

[2] Disaster Preparedness, Mitigation and Management (DPMM), Asian Institute of Technology, P.O. Box 4, Klong Luang, Pathumthani 12120, Thailand

1 Introduction

Assessment and monitoring of any natural hazards like cyclone, flood, earthquake, landslide, etc. in a region are of vital importance for the enterprises responsible for disaster risk reduction (DRR) and disaster risk management (DRM). Such studies provide fixed tools that help in better infrastructure development planning, mitigation measures and also foster in developing early warning system. The paper here essentially deals with the hazards emanating from earthquakes, the contributing factors to earthquake hazard, and the source and cause of earthquake hazard within the study region.

The earthquake is one of the natural disasters around the world causing wide spread damage and death. According to Gupta [1], earthquake damage within a region may perhaps differ locally, since it depends on the types of infrastructures, subsurface ground conditions, nearness to faults and fractures, bed rock structures and the unconsolidated substrate saturated with water. Earthquakes normally occur due to tectonic plate motions acting on the geological settings of the site. In 1998 a magnitude 7.0 earthquake event at 10 km depth struck at the north coast region near Aitape, PNG triggering a large undersea landslide that caused a destructive tsunami resulting in 2202 deaths with 50 million USD economic losses [2].

Papua New Guinea is one of the countries in the Pacific region that lies within the Pacific ring of fire—an arc of active seismic belt. According to Stanaway [3], PNG is located on the rim of colliding Pacific and Indo-Australian Plate that makes PNG tectonically active. Within this collision zone there are several micro plates that have formed adding to the complexity of the tectonic setting. It is anticipated that earthquakes of varying magnitude are most likely to happen in an area that do have multiple of plate boundaries in the vicinity moving in various directions at differential speed.

During any earthquake events, the seismic wave which is the source of shaking intensity is generated and propagates from the earthquake focus (hypocenter) to the surface. The shaking hazard which is the first common hazard during earthquake, depends on factors such as the magnitude, properties of fault zones, the distance from the fault and site-soil-geologic setting [4].

In the present study, the application of geographic information science (GIS) and remote sensing (RS) is utilized to investigate and assess earthquake hazard for a significant stretch of the country PNG based on existing data and materials. GIS and remote sensing technologies are now a day's widely used for decision support system and natural resources and disaster management [5]. Application of GIS based knowledge for seismic observation in PNG, was also carried out by another researcher [6]. He discussed the categorization of earthquake events within the environment of GIS, where the output maps or graphic format information could be more useful. Furthermore as explained [7], in any seismic study the investigation of soil, lithological structure and identification of parameters like fracture zones, lineament, fault etc. are done with relative ease through remote sensing and GIS techniques. For the present study, the geological, geomorphological and seismicity data layers were mostly used and integrated in GIS environment to achieve the main aim of the study.

According to Upsis [8], the first main earthquake hazard (danger) is the damage caused to buildings or infrastructures owing to ground shaking. The follow up of the shaking hazard during earthquake, can be liquefaction, landslide, flood, Tsunami and fire. These are all hazards related to earthquake and are termed earthquake hazards. According to Pal et al. [9] the earthquake hazard zonation (EHZ) in Sikim Himalaya was prepared from analyzing 8 thematic layers within the GIS platform. They have integrated several environmental and seismic data layers namely: geology (GE), soil site class (SO), slope (SL), landslide (LS), rock outcrop (RO), frequency wave number (F-K) simulated peak ground acceleration (PGA), predominant frequency (PF), and site response (SR) at predominant frequencies using geographic information system (GIS). The study was carried through assigning ranking and weightage to each factors and then normalizing the weightage and rankings using Satty's analytical hierarchy process. The final output was a geohazards and a seismic hazard zones of Sikim Himalaya. The related study on seismic hazard micro-zonation was also carried out by other researchers [10]. They integrated five (5) thematic layers in GIS environment to delineate seismic hazard zones of Delhi (India). This was done through investigation and analysis of site soil geology along with historical earthquake databases.

Liquefaction is a collateral hazard linked to earthquake and it is common in any earthquake event of greater magnitude leading to intense shaking. The severe shaking is the main cause of any liquefaction episode. Thus liquefaction is the process in which water is combined with soft and saturated sediments or soils, normally from the actions of shaking intensity and the pressure it implies, which causes the soils to behave like quick-sands [11]. It is obvious that investigation and assessment of sub and site surface relating to geology and geomorphological structure is of paramount importance in terms of delineating liquefaction potential zones of a site [12]. Liquefaction potential zonation is a scientific and technical approach for estimating and understanding the types of soil and or sediment structures that are under earthquake excitation and hence GIS is possibly the best approach to carry out this task [13]. The main idea behind identifying each site for liquefaction potential, is to identify and assess several geological, seismological and geomorphological factors in a GIS environment, each to be weighted and ranked in accordance with its potential for causing liquefaction [12]. The soil attributes/properties such as; soil texture, drainage and depth, the geological rocks or sediment types (quaternary deposits) in terms of consolidated and unconsolidated, the seismicity of and area, topography are the key factors in a GIS and remote sensing environment that are utilized or integrated toward delineating liquefaction potential zones [12, 14–16].

PNG is a developing country with immense potential for industrialisation; while population, the cheap source of workforce is increasing at a high rate. Constructions of roads, bridges and multi-storeyed buildings are booming of late. Thus it is important to carry out such earthquake related study, where the outcome of the study can be a proper tool for channelizing investment for development. On the other hand the study can let the stake-holders be aware of parameters that are accompanied with earthquake hazards.

Significance of the study owes to a multitude of active fault lines emanating from the existence of several micro plates in the vicinity. These faults pass through the region making it remarkably prone for earthquake events, which can be corroborated from the historical data. It is also obvious that the study region plays an important role in the economic wellbeing of the country. Lae city, the second largest and most industrialized city in PNG is also located within the study region. Hence this makes the study all the more important to be carried out. According to World Bank [17], out of twenty-six (26) Asian Pacific countries, PNG is ranked amongst the top six (6) countries having the highest percentage of people exposed to earthquake hazard. This figure gives a glimpse of the relevance of this study being paramount for the resident communities' socioeconomic wellbeing in the study region, where the earthquakes of various magnitudes are felt very frequently.

2 Study area and research methodology

The country Papua New Guinea (PNG) is one of the major island countries in the Pacific Region, which is located on the active seismic belt 'Pacific Ring of fire'. The country is made up of 22 provinces and is divided into 3 regions namely; Highlands, Momase and Island region. The country is made up of a majestic diversity of tropical plants and animals and is also rich with natural/mineral resources such as gold, copper, silver, natural gas, timber and fisheries and it is home to various agro-horticultural activities. More importantly the country is the seat of the boundary of seven (7) tectonic plates, that is the two major ones; pacific plate and Australian plate and five other small ones that manifest PNG as a region of active seismicity (Fig. 1c). With the total of 22 provinces of country PNG, the study attempts to do earthquake hazard assessment and monitoring in the province of Madang, Morobe, East and West Sepik—the Part of Momase region of PNG. The region is located between 141°E and 148°E longitude, 2°S and 8°S latitude. The second largest and most industrialised city of PNG; Lae city is located within the Study region. The study region covers the total area of 144, 840 km^2 and according to 2011 census, the total population of the study region is 1,795,474. The study region is a combination of four provinces with total of 26 districts. Figure 1a illustrates the general view of the study region.

Since millions of years the tectonic plate movements within a region have created landforms by pushing up mountains and hills accompanied with the erosion by water and wind that have denuded and created landforms as discussed [18]. Within the study region, there were about 30 landform types identified and mapped using the PNGRIS metadata in ArcGIS 10. The low lying areas of the study region are mostly the formations of quaternary deposits from the past events of tectonism, erosion and weathering. The types of landforms are basically alluvial, colluvial, swamp, mudflow leading to floodplains and fans. The classifications of landforms were done as adopted in [19]. Figure 1b illustrates the types of landform found in a study region.

Within the country PNG there are several micro-plates boundaries (major fault lines) with their specific characteristics of differential velocity. These are: Ramu Markham Fault Zone—a subduction zone which is a convergent boundary that separates/borders South Bismarck plate and New Guinea highlands deformation zone, highlands fault and trust belt—a subduction zone that borders/separate Indo-Australian plate from New Guinea Highlands deformation zone, Owen Stanley Fault Zone—transformation zone which is strike slip fault line, that separates/borders Woodlark plate from New Guinea highlands deformation zone and Papuan Peninsula, Bismarck Sea Seismic Lineation—a transformation zone that separates/borders South Bismarck plates from North Bismarck Plate, New Guinea Trench—subduction zone, New Britain Trench—subduction zone and woodlark spreading centre [3, 20–23].

According to several researchers as stated here, there have been different base maps about PNG tectonic structure distributions were prepared based on types of research, data, instruments and knowledge they have. That is; According to [3], the tectonic distribution of PNG was prepared through GPS monitoring of Plate tectonics, according to [23], tectonic distribution of PNG was prepared through topographical and bathymetric analysis of SRTM DEM and from East and South East Asia (CCOP) 1: 2000, 000 Geological map and according to [22], tectonic distribution of PNG was prepared with the knowledge of Bird eye view image (2003). From the literature, the tectonic distribution or structure by different authors as discussed are convergent to the tune of about 90 %, where slight differences are approximated as updated and modified for the present study. The base maps prepared by different researchers or authors as discussed above, where updated and modified with the help of 2014 Landsat 8 satellite images, PNG SRTM DEM and knowledge of seismicity distribution. The modified and updated tectonic

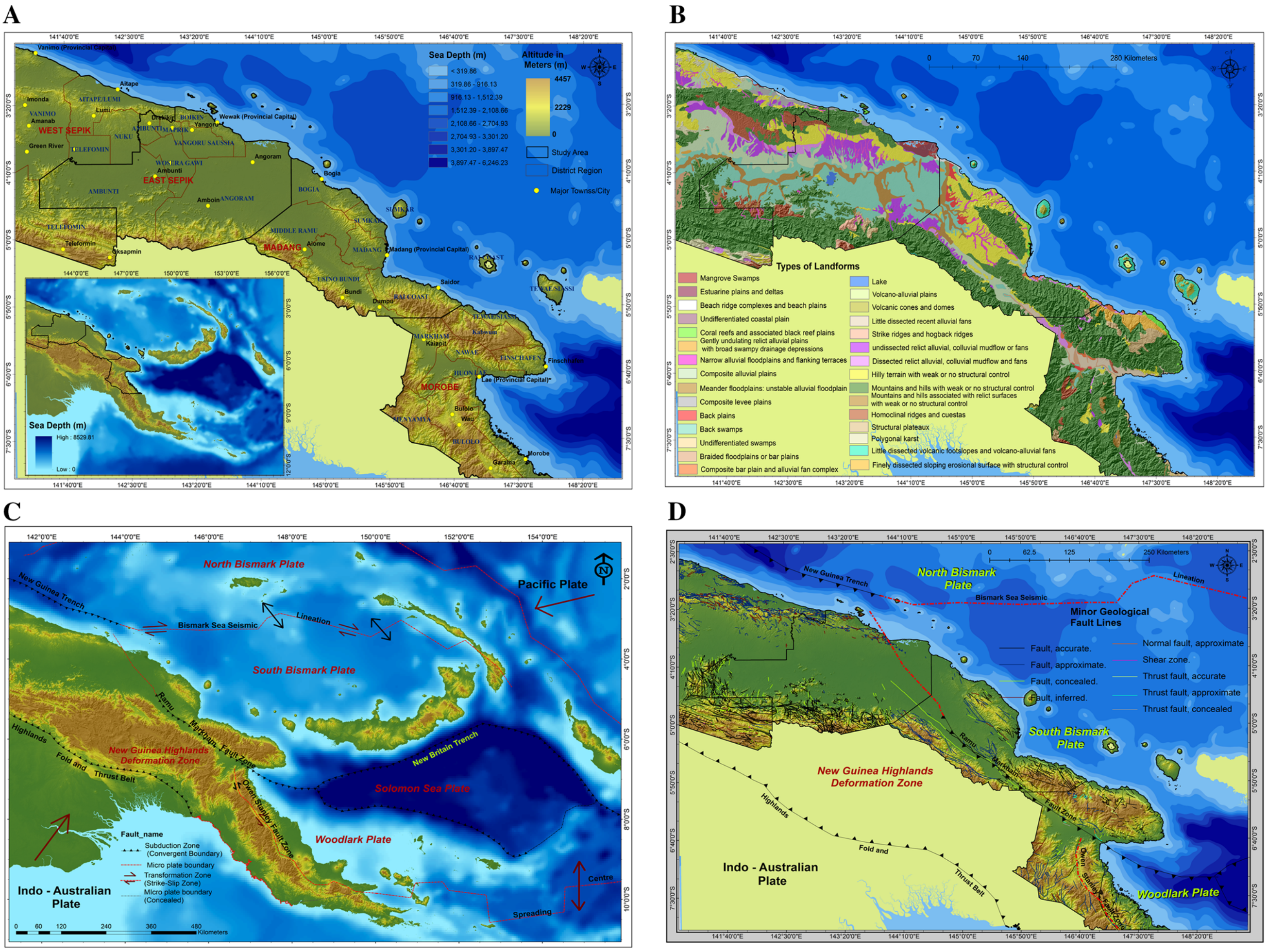


Fig. 1 Study area information. **a** general view of study region, **b** Landform, **c** PNG tectonic distribution [modified from; Stanaway [3], Koulali et al. [23], Ghasemi et al. [22], Wallace et al. [21], **d** study area tectonic distribution

distribution prepared are illustrated in Fig. 1c for country PNG as a whole and Fig. 1d for the study region. There also exist minor geological fault lines which do contributes to earthquake and it is illustrated in Fig. 1d.

Based on assessments carried out, the three micro-plates that are Highlands's deformation zone, Woodlark plate and South Bismarck plate constitute the study region. The Boundaries of these plates form three major fault lines within the study region, that is, Ramu Markham Fault zone, Owen Stanley Fault Zone and New Guinea Trench (Refer to Fig. 1d.

The number and extent of micro-plates and major fault lines that have evolved within the larger Australian and Pacific plate boundary zone are controversial [24] and remain open to interpretation [22]. In addition there is a great uncertainty [25] that geology and tectonic evolution of Papua New Guinea must necessarily be somewhat speculative.

2.1 Data collection and pre-processing

The seismicity data for PNG are recorded real time and updated at the United States Geological Survey (USGS Earthquake Catalogue) after every event of earthquake. For the present study, all necessary historical earthquake data i.e., date or year of particular earthquake event, magnitude and depth of earthquake are all acquired in an excel (csv) format from USGS earthquake catalogue centre. The collected seismicity data are from year 2000 up to 2016, the 16 years time period. The total number of earthquake events recorded from year 2000 up to 2016 especially for the study region and the surrounding was 3129. Figure 2a illustrates the earthquake events (depth) distribution for PNG as a whole and Fig. 2b illustrates the earthquake distribution (magnitude) of study region. The charts and graphs below in Figs. 3 and 4 explain all necessary information of each earthquake event between year 2000 and

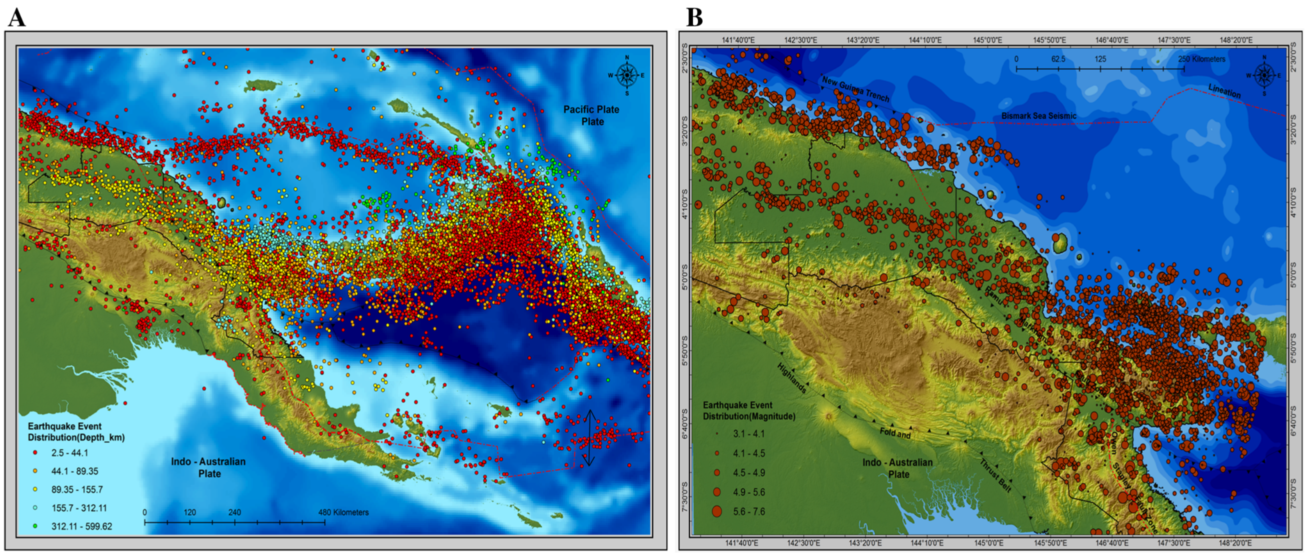


Fig. 2 **a** Earthquake event (depth) distribution of PNG, **b** earthquake event (magnitude) distribution of study region

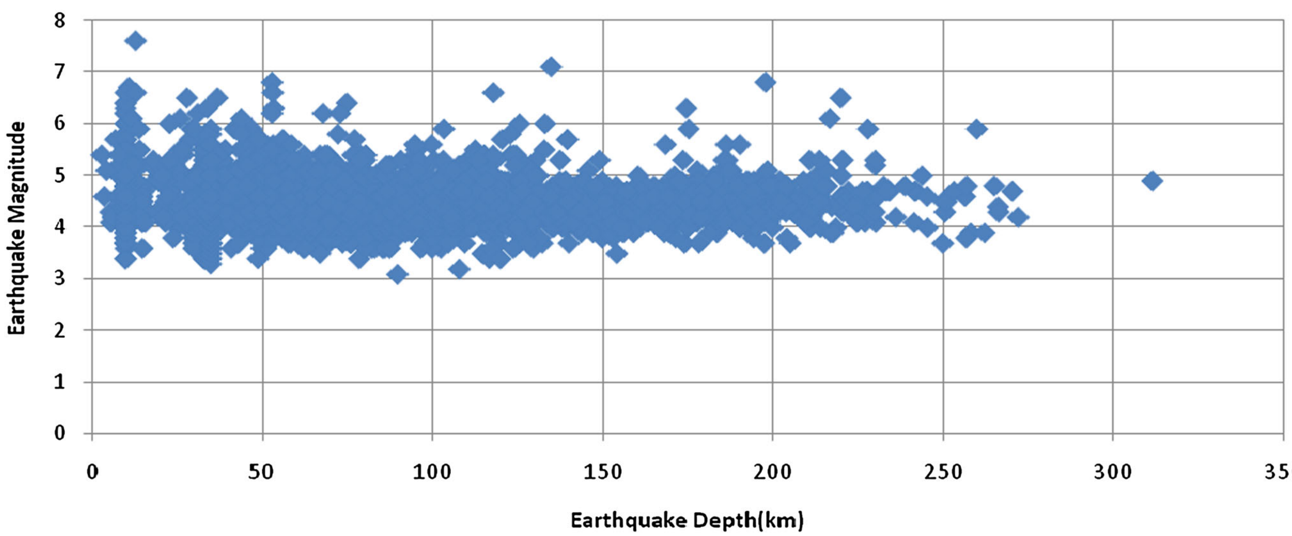


Fig. 3 Earthquake magnitude against earthquake depth

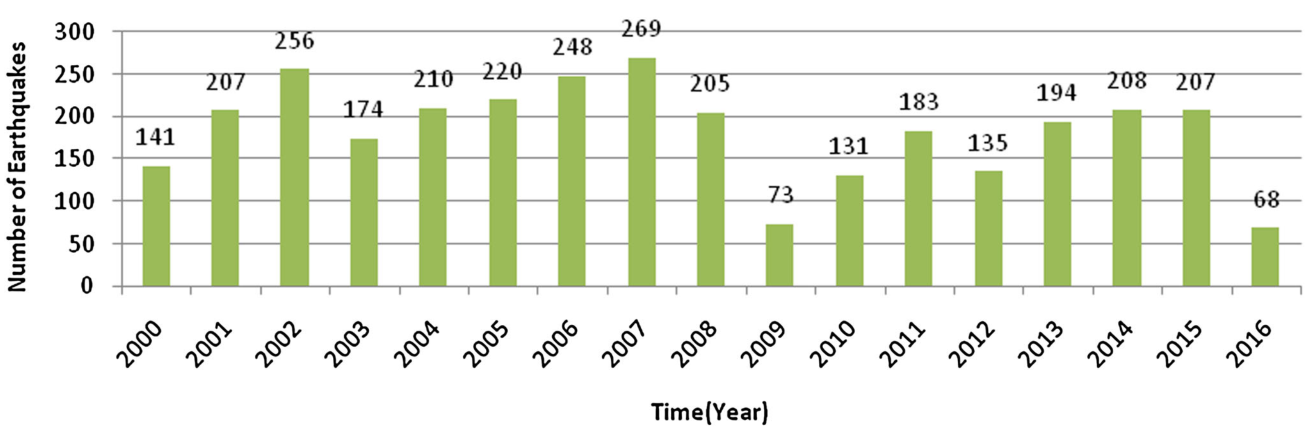


Fig. 4 Number of earthquake events per year from year 2000 up to 2016

2016. Hence these are the general view and information of necessary historical earthquake event data that were collected and used for the analysis. The entire databases were further edited and exported using ArcGIS 10 software to point features in shape file (shp) format for further analysis. Furthermore the other historical earthquake data that was needed apart from earthquake depth, time and magnitude was shaking intensity data layers (earthquake ground motion) that is PGA which are measured and recorded in percent gal (%g) right after the event of any earthquake. The data was collected from USGS earthquake archive centre in txt file format and later imported via excel to csv format. It was again exported to shape file using ArcGIS 10 software to point features where interpolation was done to assess levels of shaking in a particular sites. Generally all these data collected are clipped and limited to the study area and the surrounding and hence after the interpolation technique to create its raster surface, it was subset to indicate only for the study region excluding the surroundings.

In order to accomplish an earthquake related study for a particular region, the fault line data are very important. This is because fault lines are the common source of earthquakes. If the region that have multiple fault lines then the region are more prone to earthquakes. For the present study, several base maps as discussed above were collected and rectified. After the rectification process the tectonic structure (major fault lines) for the study region were digitized and extracted. It was then verified and modified using PNG shutter radar topographical mission (SRTM) digital elevation model (DEM), Landsat 8 OLI data with the knowledge of seismicity distribution. Figure 1d illustrates the tectonic distribution of the study region that was prepared, where major fault lines were taken into consideration for doing further analysis explained below.

For the present study, remote sensing data sets were also needed i.e., DEM data and Landsat images. Thus Landsat 8 imagery for year 2014 for the study region was downloaded band by band up to eleven bands at particular web site. After downloading, all the bands were georeferenced, followed by mosaicing and finally sub-setting using ERDAS Imagine 8.5 software, thus readied for analysis. The terrain dataset was collected from Surveying and Lands department, PNG Unitech. From the terrain datasets, the slope and altitude data was extracted as the necessary layer for analysis. DEM data and Landsat data were also used for verifying, updating and delineation of major fault lines and or plate boundaries with respect to base maps and charts downloaded and digitized.

In case of doing seismic hazard assessment and monitoring, two of the main factors to be considered are geological and geomorphological features and attributes. The geological data sets comprise rock structures (geological faults, fractures, lineaments) and the lithology info about mineral/sediment composition extracted from PNG resource information system (PNGRIS) and PNG Geology metadata which were collected from Surveying and Lands department. For the geomorphological data for the present study, mostly soil attributes were considered. Thus soil attributes consisting of soil texture, soil drainage and soil available water holding capacity (Soil AWC) are all extracted from PNGRIS Meta data and [26] which was collected from Surveying and Lands Department and further verified and updated with Landsat 8 OLI. Furthermore the Geobook data was also used for municipal and administrative analysis purpose. Those mentioned data collected formed the main data bases or data layers that were used or needed for analysis and processing to achieve the final output based on stated aims and objective. All the data collected was processed and analyzed in the GIS environment.

2.2 Analysis of data layers

There were certain and specific procedures followed to analyse and process the pre-processed data. The analysis was carried out in order to achieve or satisfy the stated two (2) main objectives that is; (a) delineating liquefaction potential zones of study region, (b) Earthquake hazard micro-zonation for the study region. After delineation of liquefaction potential zones, the analysis was furthered to evaluate and to do seismic hazard micro-zonation through assessing and analysing liquefaction potential zones with seismicity or historical earthquake events data layers as were discussed above. The explanation and analysis procedures are followed.

In order to assess liquefaction potential zonation (LPZ), different types of data related to terrain, geomorphological (according to soil attributes) and geology (according to rock types available in geologic formation) were integrated within GIS environment. In view of data availability, literature and scientific relevance with respect to liquefaction potential, six (6) layers were selected, prepared and integrated through MCE techniques [27]. MCA techniques happen to be a significant decision support tools for dealing with complex decision constellations where technological, economical, ecological and social aspects are included [27]. From the Geobook and PNGRIS datasets (geomorphology), the thematic layers of soil attribute were prepared using ArcGIS 10 software. The soil attributes considered here are Soil AWC, Soil drainage and Soil texture layer. It was then corroborated and updated using Landsat 8 OLI through Normalised Differential Vegetation Index (NDVI) and Normalised Differential Water Index (NDWI) calculation in ArcGIS 10 and ERDAS Imagine 8.5. From the PNG Geological data sets coupling with

PNGRIS Metadata, the thematic layer of rock structure (lithology) was prepared based on consolidation status using ArcGIS 10 software. From the DEM datasets the slope layer was prepared using slope tool in ArcGIS 10 spatial analysis. Finally for the fault lines that were prepared and mapped earlier, its buffer zones were created followed by thematic layer preparation. A total of six thematic layers were integrated for liquefaction potential zone mapping. As regards fault data, the buffer zone was created with specific distance interval in kilometres (km) according to the precept that earthquakes most frequently occur along fault zones that tend to concede the central tendency of epicentre of earthquake episodes in a tectonically active region [28]. According to consolidation status by [19], the classification of rock types of study region for the present study was extracted, reclassified and assessed. Unconsolidated sediments of rock types are more prone to liquefaction and have the potential to amplify seismic waves where liquefaction can easily occur; whereas the consolidated sediments or rock types mitigate seismic wave propagation [29]. For the three factors related to soil, it was reclassified based on saturation status keeping in mind that saturated and soft soils are more prone to liquefaction and can amplify seismic waves resulting in liquefaction [28]. Each factor as prepared was ranked according to its potentiality in contribution to liquefaction. Also the class of each factor was assigned weightage according to its potentiality in liquefaction hazard. The assigned weight or rank for each factor or class is based on different experts' opinions. However, pair-wise comparison, as introduced by Saaty [30–33] for weights assigned was carried out essentially to normalise the weights and to calculate the consistency ratio in order to be consistent of the weights and ranks assigned [34]. All the normalized weights for both factors with their classes are then integrated in GIS environment using raster calculator in ArcGIS 10. Thus the method used to calculate final output for liquefaction potential zones was adopted from [9] and is discussed in the next chapter. Figure 5 illustrates the general methodological flowchart pursued in the study (Table 1).

The liquefaction potential zone was used as one of the thematic layers into preparing earthquake hazard microzonation, with seismicity or historical earthquake data sets. After the editing, conversion and exporting the seismicity datasets that is magnitude, depth and PGA to ArcGIS format, the thematic layer or factor was prepared. The seismicity datasets once exported to ArcGIS format are all in point features. Mainly for this analysis, interpolation technique that is inverse distance weighting (IDW), a ArcGIS 10 spatial analysed tool was employed to prepare the factors. This is simply to interpolate raster surface from points since all seismicity data are in point format once opened in ArcGIS 10. The three factors (thematic layers) prepared through interpolation techniques are earthquake depth distribution, earthquake magnitude distribution and PGA which are all raster surface that were prepared from points. The earthquake depth distribution was prepared based on how deep down or shallow the particular earthquake was. It was then reclassified according to the idea that, shallower the earthquake depth, greater will be the hazard while deeper the earthquake depth lesser will be the hazard. The other raster surface prepared from interpolation technique was earthquake magnitude distribution. It was reclassified based on how big or small the earthquake magnitude was, i.e.; smaller the magnitude, lesser the hazard while bigger the magnitude, greater the hazard. Finally the raster surface for levels of shaking intensity (PGA) within a study region was prepared. Purposely for the preparation of PGA raster surface, only the shaking intensity level for major earthquake event was considered. It was reclassified based on how big or small the shaking hazard, i.e., smaller the shaking lesser the hazard while greater the shaking more the hazard will be. After preparation of four thematic layers, MCE technique was employed to generated levels of earthquake hazard in a study region. As was discussed earlier, the same procedure of assigning weightage and ranking was used, that is according to its potentiality in contribution to earthquake hazard. The summary of methodology applied to generate each thematic layer and produce earthquake hazard zones are shown in the flowchart in Fig. 5.

The other phase of the task or study was to process and assign weightage to each factor and their classes based on different experts' opinions where it is to be normalized using the Saaty's AHP. The AHP was developed by Saaty [31–33], specifically to assess or synthesize judgments or decisions made by the experts to achieve their set goal and to evaluate and check the consistency of judgment made. It is one of the best known and most widely used MCE approaches. It allows users to assess the relative weights of multiple criteria or multiple options against given criteria in an intuitive manner. It allows efficient group decision-making, where group members can use their experience, values and knowledge to break down a problem into a hierarchy and solve it by AHP steps. For the present study, the AHP technique was adopted as a decision aiding method to finalize the weights and ranks assigned to different thematic layers with their classes that were employed to do LPZ and Earthquake hazard micro-zonation. After preparing all the factors as discussed above, their individual classes were reclassified using "reclassify" tool in ArcGIS 10. In case of LPZ, the weight scale range of '1'–'4' was employed and for the case of earthquake hazard microzonation, the weight scale range of '1'–'5' was employed. For the case of Liquefaction potential

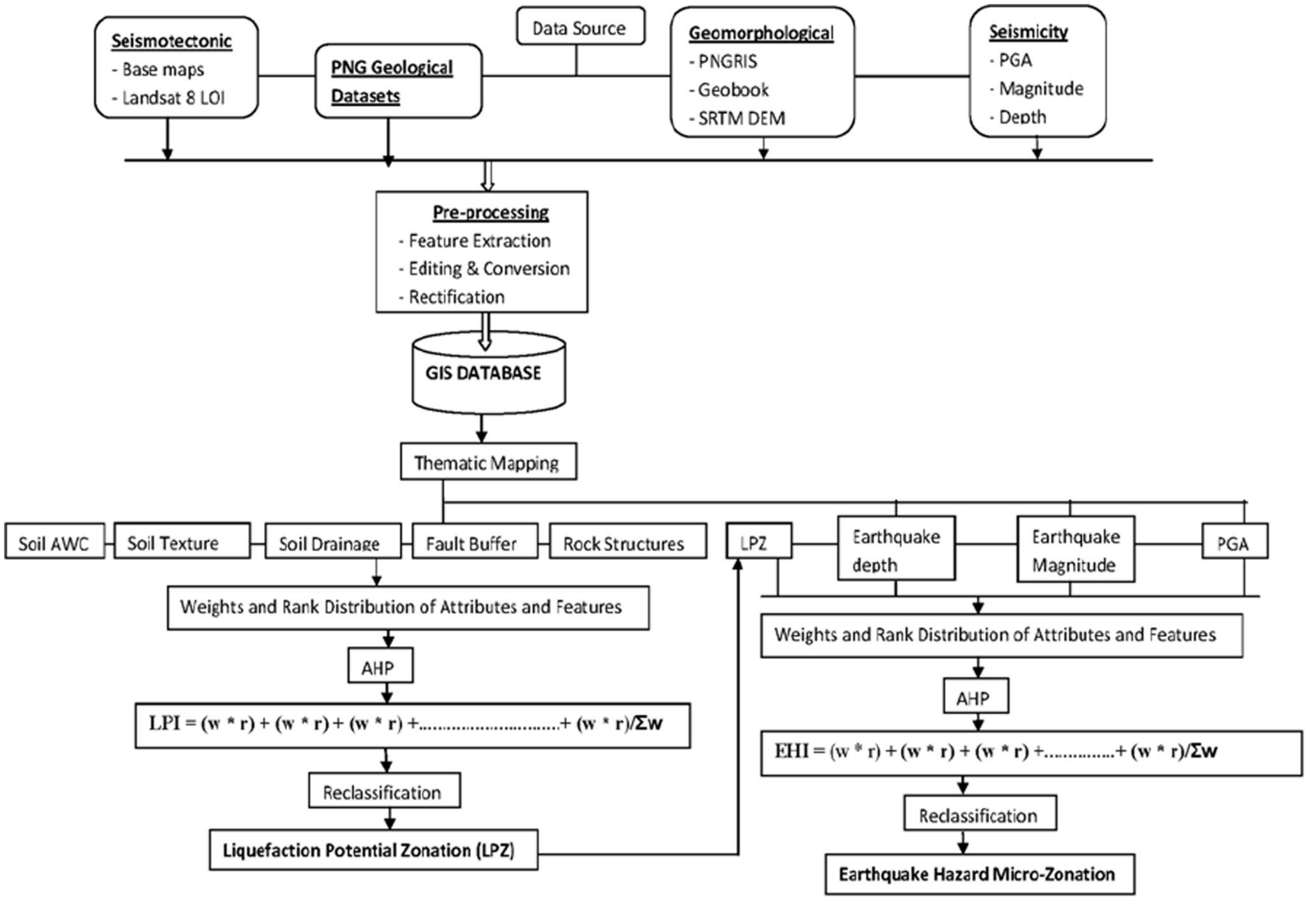


Fig. 5 Methodological flow chart

Table 1 Data used for the processing and analysis

Data layers/data base	Description	Source
Earthquake magnitude	Downloaded from USGS websites	USGS earthquake catalogue centre https://earthquake.usgs.gov/earthquakes/search/
Earthquake depth	Downloaded from USGS websites	USGS earthquake catalogue centre https://earthquake.usgs.gov/earthquakes/search/
PGA (%gal)	Downloaded from USGS websites	ShakeMap Archive-USGS Eartquake Hazards Program http://earthquake.usgs.gov/earthquakes/shakemap/list.php
Landsat 8 ETM + satellite image (30 m spatial resolution-2014)	Verifying and updating of tectonic structure and soil attributes	https://libra.developmentseed.org/
SRTM DEM(30 m spatial resolution-2003)	Preparation of terrain features and for verification and updating	Department of Surveying and L/S, PNG Unitech
Slope factor	Extracted from PNG SRTM DEM	PNG University of Technology
Soil attributes	Derived from geobook and PNGRIS meta data	PNG University of Technology
Geology (according to rock types available in geologic formation)	Derived from PNGRIS metadata and PNM geological metadata	PNG University of Technology
Fault line buffer zones	Derived from PNM Geological metadata and from Downloaded base maps	PNG University of Technology

contribution, the weight ‘1’ indicates “low” whereas weight ‘4’ indicates “high”. For example, the class ‘D’ in the factor Soil texture was given the weight of value ‘1’ because this class corresponds to minimal contribution to liquefaction, that is, the soil group ‘D’ the infiltration rate is minimum that reflects soils are a bit compact and not loose, and thus this can indicate low vulnerability to liquefaction. On the other hand, the class ‘A’ is given the weight of ‘4’ which is the highest value because it is the factor that can decide for more liquefaction because the soils with the highest infiltration rates are loose enough to becomes saturated very fast and thus becomes highly susceptible to liquefaction. For the case of earthquake hazard microzonation, the weight '1' indicates "low" whereas weight '5' indicates "high". For example, the higher magnitude level in the surface raster of earthquake magnitude distribution was given the higher weightage of '5' because the higher earthquake magnitude contributes for worse damage or hazard. On the other hand, the classes of lower magnitude zones were given the value of '1' because lower earthquake magnitude contributes less to earthquake hazard. Thus same principle was applied to other factors as well. The weightage assigned for each factor or class was decided based on lessons gleaned from literature, formal discussion and interview process. The weightage assigned for each class and its factors are normalised by Saaty's Analytical Hierarchical Process. One of the strengths of AHP is that it allows for inconsistent relationships while, at the same time, providing a consistency ratio (CR) as an indicator of the degree of consistency or inconsistency [35]. In order to be consistent about the weightage assignment, the consistency ratio (CR) value should be less that 0.10 [30–33]. If the consistency ratio is greater than 0.10 then the weight assignment is to be re-evaluated to avoid inconsistency. Also the CR denotes the possibility that the matrix ratings were randomly generated. The normalised weights and assigned weights for 6 factors that were used to generate LPZ are shown in Table 3, while the normalized weights and assigned weights for 4 factors that were used to prepare earthquake hazard zonation are shown in Table 5. With respect to liquefaction contribution, it indicates that the lithological factor (based on consolidation statues) was ranked the highest with a normalised weight of 0.383 while Slope factor was considered as the least with a normalised weight of 0.044. With respect to earthquake hazard level zonation, it indicates that the liquefaction factor was ranked the highest with a normalized weight of 0466 while earthquake depth distribution raster surface was considered as least with a normalized weight of 0.096. The assigned weights were normalised and consistency ratio was calculated. Pair- wise comparison matrix for 6 factors assessed for the delineation of LPZs is shown in Table 2 while pair-wise comparison matrix for 4 factors assessed for the delineation of EHZs is shown in Table 4. After normalising and being consistent about the weight assigned for each factor and class, the spatial analyse tool; raster calculator in ArcGIS 10 was employed to derive the final thematic map for LPZs and EHZs for the study region through employing the formula adopted from [10].

3 Results and discussion

The liquefaction zones were prepared through analysing and assessing six (6) geological and geomorphological factors. LPZs were then used as one of the 4 factors that were used in preparing earthquake hazard micro-zones (EHZs). The other three factors which were integrated with LPZs are mainly historical earthquake data. MCE and AHP are the common technique used within the GIS environment to prepare LPZs and EHZs. MCE technique is applied in different categories of field, like flood hazard assessment, ground water potential investigation, malaria hazard risk investigation, and so forth. The technique consists of processing and overlaying several environmental factors in the GIS environment. MCE works well with AHP to synthesise and normalise the decision made. The spatial analyse tool; weighted overlay, weighted sum, raster calculator and reclassify tool in ArcGIS 10 were mainly used for these types of analysis. For the present study, all these techniques as discussed were involved and the results were generated. The necessary thematic layers assessed and integrated are all discussed and illustrate below.

3.1 Assessments for liquefaction potential zonation (LPZ)

According to Green [36], during any shaking hazard at the time of earthquake events the sediments that are saturated and soft that is; clay-free (bereft of cementing agent)

Table 2 Pair-wise comparison matrix of factors used for the delineation of LPZs

Themes	Themes					
	Lithology	Soil texture	Soil AWC	Fault zone	Soil drainage	Slope
Lithology	1					
Soil texture	1/2	1				
Soil AWC	1/3	1	1			
Fault zone	1/4	1/3	1/2	1		
Soil drainage	1/5	1/4	1/3	1/2	1	
Slope	1/6	1/5	1/4	1/3	1/2	1

Table 3 Assigned and normalised weights of factors used for the delineation of LPZs

Factors	Assigned weights	Normalised weights
Lithology(geology)	6	0.382826354
Soil texture	5	0.225101209
Soil AWC	4	0.17968953
Fault zone	3	0.103019351
Soil drainage	2	0.065766675
Slope	1	0.043596882
Total		1
CR		0.02

deposits of sand and silts are more vulnerable to lose strength and behave as a fluid on severe shaking, thus this is simply a process of liquefaction. He further discussed that the seismic waves that passes through saturated granular layers during earthquake events are the main actions taking place in the soil that leads to liquefaction. At this time of action, the granular structures are distorted, and cause loosely packed groups of particles to collapse where any infrastructures that are built on top are also more likely to collapse. With that in mind several geomorphological and geological factors were assessed within the GIS environment with the aid of MCE and AHP to identify and delineate LPZs. The six (6) factors assessed and prepared are; Geology (according to rock types), Soil attributes that is; Soil AWC, Soil Drainage, Soil Texture, the Slope factor and major Fault line buffer zones. Thus their effectiveness or importance in contributing to Liquefaction is discussed below. The weightage and normalized weightage assigned including area calculation of each class of each factors are all tabulated in Table 7 while the final output generated are illustrated in Fig. 7. The six (6) factors selected to do liquefaction potential zone mapping, are all related to each other in contributing to liquefaction.

Table 4 Pair-wise comparison matrix of factors used for the delineation of EHZs

Themes	Themes			
	LPZ	PGA	Depth	Magnitude
LPZ	1			
PGA	1/2	1		
Magnitude	1/3	1/2	1	
Depth	1/4	1/3	1/2	1

Firstly base on classification and discussion of rock type by [19] for the country PNG, the analysis was done to evaluate rock types of the study region based on consolidation status. To evaluate earthquake event leading to Liquefactions within a study region, the consolidation status of the sediment type or rock types were considered and evaluated coupling with other factors. As the seismic wave propagates from the earthquake focus to the surface, the consolidation status of the materials determine the level of amplification. If the sediments are defined as unconsolidated then the seismic wave are more likely to be amplified and hence might lead to liquefaction and concomitant collapse of overlying infrastructure. If the sediments or rock types are defined as consolidated culminating in the attenuation of seismic waves, and thus liquefaction possibility is negated. Based on this understanding the rock types were assessed and thematic layer was prepared (Fig. 6a) with weightage and rankings assigned (Table 7).

Soil textures was one of the factor that was considered base on its infiltration capacity. The hydrological Soil groupings in Soil Conservation service (SCS, USDA) consist of four classes based on infiltration rate and that is group; A, B, C and D. All the soil textures after extraction

Table 5 Assigned and normalised weights of factors used for the delineation of EHZs

Factors	Assigned weights	Normalised weights
Liquefaction factor	4	0.4658194
PGA	3	0.27714047
Magnitude	2	0.16107023
Depth	1	0.0959699
Total		1
CR		0.01

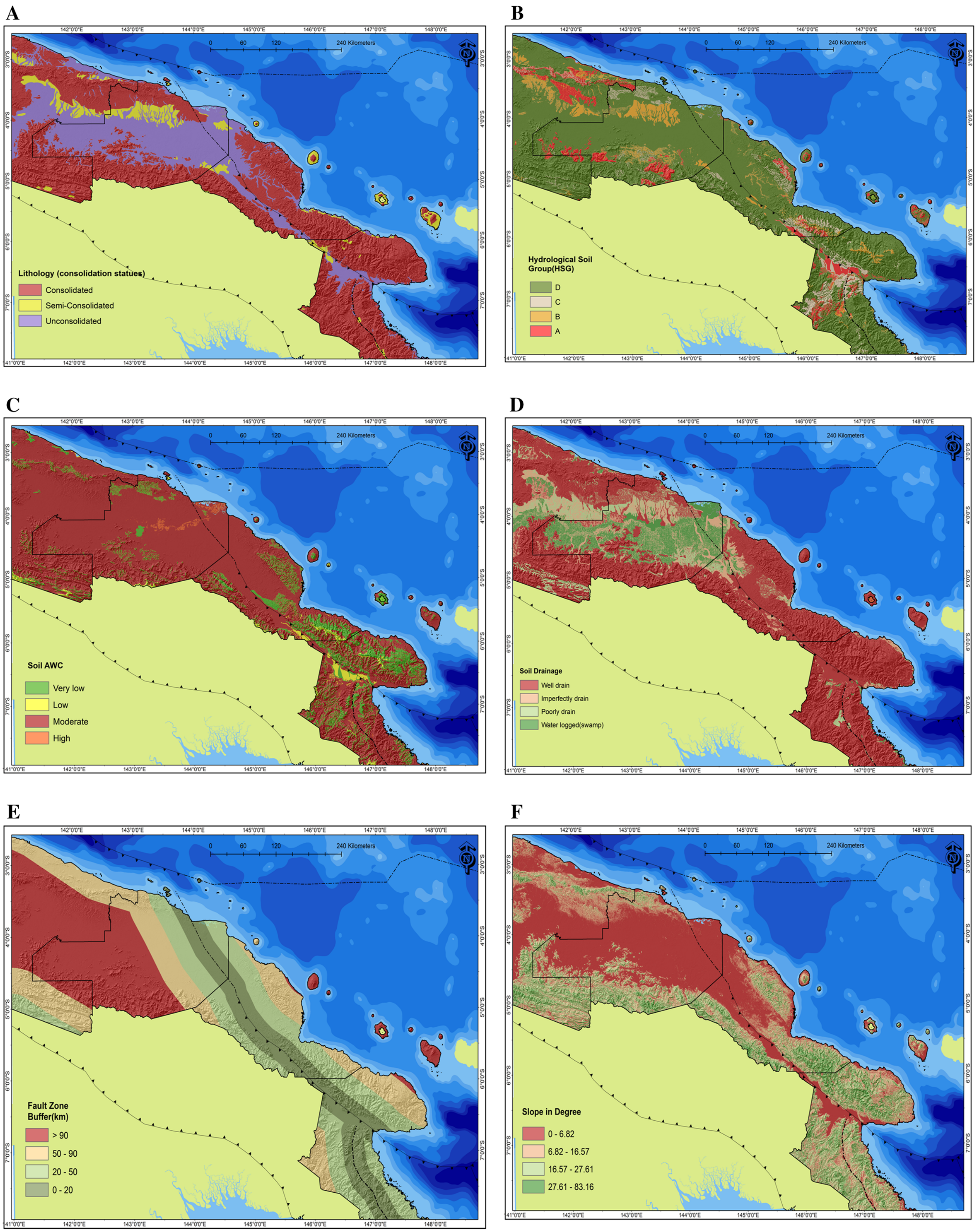


Fig. 6 Factors assessed for LPZ, **a** Rock types in the form of consolidation statues, **b** soil texture, **c** soil AWC, **d** soil drainage, **e** fault buffer zones, **f** slope factor

Table 6 Classes of HSG

HSG	A	B	C	D
Soil texture	Sand Loamy sand/sandy loam	Silt loam/loamy soil	Sandy clay loam	Silty clay loam Sandy clay Silty clay, clayey Peat

Table 7 Weightage and rankings of each factor assessed for LPZs

Theme	Weight	Classes	Ratings	Normalize rate	Area (km^2)	Area (%)
Geology (according to rock types) (GE)	0.383	Consolidated	1	0.11	91,711.29	64.45
		Semi-consolidated	3	0.19	8418.51	5.91
		Unconsolidated	4	0.7	42,169.57	29.63
Soil texture (ST)	0.225	D	1	0.02	114,913.68	80.66
		C	2	0.10	8050.80	5.65
		B	3	0.28	9134.06	6.41
		A	4	0.6	10,359.86	7.27
Soil AWC (SA)	0.18	Very low	1	0.10	17,588.03	12.35
		Low	2	0.14	2516.71	1.77
		Moderate	3	0.16	121,621.80	85.37
		High	4	0.6	733.01	0.51
Fault buffer (km) (FB)	0.103	>90	1	0.02	46,633.65	32.69
		50–90	2	0.07	36,080.03	25.29
		20–50	3	0.30	34,373.43	24.09
		0–20	4	0.61	25,568.29	17.92
Soil drainage (SD)	0.066	Well drain	1	0.09	100,380.46	70.46
		Imperfectly drain	2	0.1	15,469.54	10.86
		Poorly drain	3	0.3	9446.62	6.63
		Water logged	4	0.5	17,168.49	12.05
Slope (degree) (SP)	0.044	0–6.82	1	0.09	65,459.39	45.97
		6.82–16.57	2	0.13	33,385.18	23.45
		16.57–27.61	3	0.28	30,192.55	21.20
		28.61–83.16	4	0.49	13,356.53	9.38

were regrouped into each class of hydrological soil group (Table 6). The infiltration rate of soil group "A" is highest while infiltration rate of soil group "D" is the lowest. Thus according to [37], the rate or capacity of infiltration of surface water into soils has the potential to cause adverse geotechnical or geohazards conditions such as potential for liquefaction during earthquakes, expansion of clay soils, or compression of fill or alluvium under certain circumstances. If the infiltration rate is high it leads to increased of volume of water in the subsurface zone or on the other hand if the infiltration rate is high, it can be concluded that the soils with high infiltration rate are loose with lots of void air spaces. Thus during any earthquake events liquefaction can easily occur. According to these ideas, thematic layer was prepared (Fig. 6b) with weightage and rankings assigned (Table 7).

The soil AWC was one of the soil attributes that were assessed to evaluate liquefaction potential. Soil AWC is the amount of water held in a soil. From the Geobook and PNGRIS metadata the data was extracted and evaluated, and the soil AWC factor of the study region was prepared based on the idea of soil AWC classification by [38]. Thus it was then verified and updated using Landsat 8 OLI and Landsat 7 ETM+. According to seismic hazard analysis due to liquefaction, the soil region that has high rank of AWC can be termed as saturated soils and are more prone to liquefaction. According to [39], if there is very low available water holding capacity in the soil, then there's no chance of liquefaction however liquefaction during earthquake is possible if the amount of water capacity is more in the soil. Based on this knowledge the thematic layer was prepared (Fig. 6c) with weightage and rankings assigned (Table 7).

Soil drainage has been one of the soil attributes that was assessed to evaluate LPZs. Based on drainage capability due to soil, it was discovered that the poorly drained soils are more susceptible to liquefaction because they have high water table and have saturated subsoil, while well drained soils are not quite susceptible to liquefaction because they have a low water table. The soil drainage factor for the study region which was extracted and prepared from PNGRIS and Geobook database was verified and updated with Landsat 8 OLI and Landsat 7ETM+. Based on the knowledge of drainage potential towards liquefaction as was discussed; the factor was reclassified from well drained to poorly drained soil or water logged. Higher weightage was assigned to poorly drained soil because they are more susceptible to liquefaction and low weightage were assigned to well drained soil. Figure 6d illustrates the soil drainage distribution of study region and Table 7 tabulates the weightage and ranking assigned.

The major fault lines within the study region which were extracted and buffered were used as one of the thematic layers to be integrated with other factors to delineate LPZs. It is obvious that fault lines are the very source of earthquakes and earthquakes do frequently occur within or near fault lines. Thus areas closer to fault lines are more prone to face greater hazard and frequent earthquakes then areas further away. Keeping in mind the relationship of fault lines with the earthquake, the buffer zones of specific distance in kilometre were created to highlight the levels of effects related to earthquake at each zones. Fault lines are the source and targets are the surrounding sites. Hence total of four zones were created. The zones created close to the fault lines were assigned higher weightage and zones that are further apart were assigned lesser weightage. Figure 6e highlights the fault zones created and Table 7 tabulates the weightage and ranking assigned.

Finally, Slope was one of the important factors that was considered and was used to integrate with other factors to delineate LPZs of the study region. In any seismic active region, most importantly the terrain factor must be considered because it is the factor that contributes more to any earthquake related hazard like liquefaction and or landslide. Within the study region, vulnerable public residences and other infrastructures do exist. Considering the terrain factors with site soil-geology is more important and can assist in identifying vulnerable areas of liquefaction due to earthquakes. It is obvious that during any earthquake events and shaking, the steeper slopes are more likely to liquefy if the site soil-geology can't resist the shaking hazard during earthquake. Based on these understanding of relationship between earthquakes and terrain, the thematic layer was prepared (Fig. 6f) with weightage and rankings assigned (Table 7).

Table 8 Liquefaction potential index re-classification

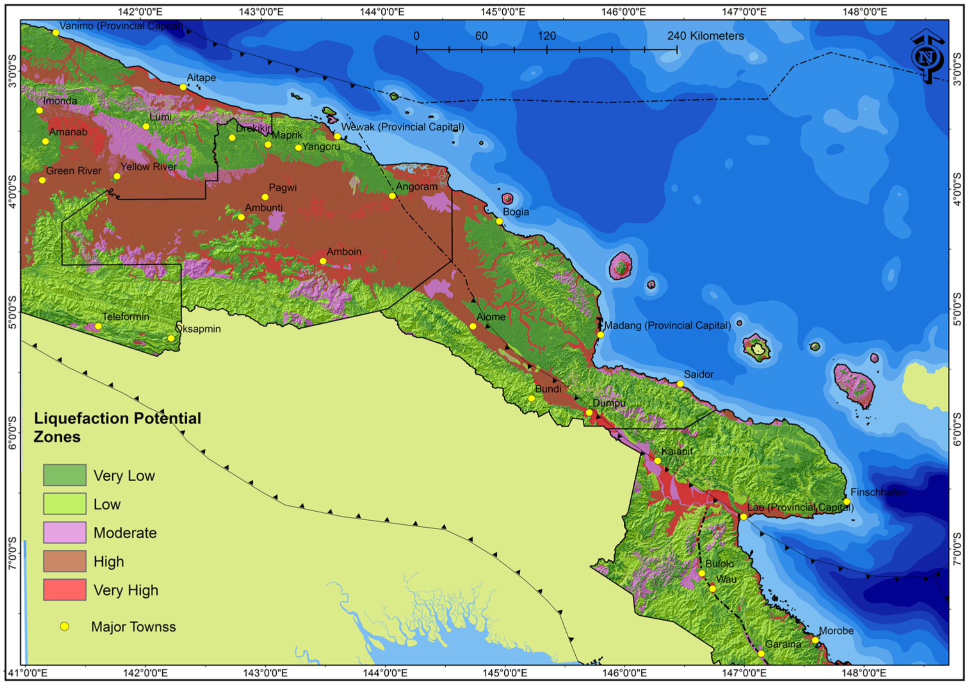
LPI	LPZ	Area (km^2)	Area (%)
0.95–1.43	Very low potential zone	48,814.83	34.40
1.43–1.83	Low potential zone	33,905.42	23.89
1.83–2.33	Moderate potential zone	13,125.44	9.25
2.33–2.78	High potential zone	40,186.05	28.32
2.78–3.56	Very high potential zone	5882.18	4.14

Table 7 tabulates the weightage and ratings assigned for each theme with their classes for the delineation of LPZs. The normalized weights were calculated using AHP techniques and were assigned for each theme. For the theme that contributes more to liquefaction was assigned high weightage and low weightage was assigned to theme that contributes less. As regards for each class of each factor the ratings were assigned and again were normalized using AHP techniques. From the Table 7 it can be seen that, value 1 was assigned to classes that contribute the least, up to value 4 to classes that contribute the most. The table also shows the area in kilometre square (km^2) and percentages (%) for each classes of each team.

After reclassifying and assigning all the weightage and ratings as tabulated and mapped, the spatial analyse tool; Raster Calculator in ArcGIS 10 was employed in calculating and producing the final LPZs map. The final map derived was based on reclassification done and the weightage and ratings assigned. The formula highlighted by Pal et al. [9] was adopted and modified to calculate and prepare LPZ. The formula employed was: $LPI = [(GEw.\ GEr) + (STw.\ STr) + (SAw.\ SAr) + (FBw.\ EBr) + (SDw.\ SDr) + (SPw.\ SPr)]/\Sigma w$, where LPI = Liquefaction potential Index which also means Geohazard Index (GHI), w = weight and r = rank/ratings. Through integration and calculation, the LPI values were generated and then were assessed and reclassified in order to delineate LPZs. Table 8 highlights the LPI value that was generated and was reclassified into each potential zones of liquefaction from very low to very high.

Table 8 presents the LPZs re-classification according to LPI numbers that was generated during integration of 6 thematic layers In ArcGIS 10. The standard deviation technique of classification in ArcGIS 10 was employed. The tables also show areas in square km (km^2) and percentage (%) for each level of potential zones. The very low and low zones indicates that there is little risk of liquefaction; the moderate potential zones indicates liquefaction might be a possibility in case of a tremor of very high ferocity in the vicinity; however high to very high potential zone indicates genuine possibilities of liquefaction potential within the study area. It was found out that 'very low' potential zone has 34.40 % of area coverage, 'low'

Fig. 7 Liquefaction potential zones of the Momase region



potential zone has 23.89 % of area coverage, 'moderate' potential zone has 9.25 % of area coverage, 'high potential' zone has 28.32 % of area coverage and 'very high' potential zone has 4.14 % of area coverage. Figure 7 illustrates the final output of LPZ of the study region after necessary assessments.

3.2 Assessments for earthquake hazard micro zonation

As was discussed by [10], earthquake hazard micro-zonation is a way forward to identifying or demarcating vulnerable zones of earthquake hazard or risk where this can assist in adopting safety measures during an earthquake event. Earthquake hazard zonation is the way of sectoring or dividing seismic zones through assessment and analysis into smaller zones that have somewhat similar exposures to various earthquake effects. Thus the importance of EHZ is that it can be used both for engineering structures design, mitigation of disaster and of insurance purpose. For the present study, EHZ was done after delineation of LPZs, because LPZs was one of the common factors associate with geological and geomorphological background where it was assessed and integrated with seismicity data layers. The seismicity data layers are mainly PGA raster surface, Magnitude Raster surface and Depth raster surface. Al these where prepared through interpolation techniques in ArcGIS 10. Four (4) factors were integrated with the MCE and AHP technique in GIS environment and the earthquake hazard zones/levels were delineated. Thus their effectiveness or importance in contributing to earthquake hazard are discussed here. The weightage along with normalized weightage assigned including area calculation of each class of each factor are all tabulated in Table 9 while final output is illustrated in Fig. 9.

The combination or the integration of all geological and geomorphological parameters that is; rock types, soil attributes, terrain and fault structure have resulted in delineation of LPZs. According to [40], possibility of liquefaction is simply a geohazards within a region related to earthquake. Integration of liquefaction with other factors into delineation of EHZs has been emphasized here. Combination and integration of LPZs with seismicity data layers were resulted in EHZ of the study region. The LPZs were reclassified into five (5) classes as was discussed above that are very high potential zones, high, moderate, low and very low potential zones. These potential zones were assigned weightage and rankings in order of influence of contribution to earthquake hazard. Very high potential zone was assigned higher weightage based on idea that during any earthquake events, the areas that are more prone to liquefaction can leads to higher earthquake hazard. The areas with low potential zones were assigned lower weightage. From the analysis, it was found out that the very high LPZ are the indication of the areas of soft, saturated and unconsolidated sediments, soil or rock and the areas of low LPZs are the indication of hard and consolidated sediments, rock or soil. The thematic layer prepared is shown in Fig. 8 while Table 9 tabulates the weightage and ranking assigned.

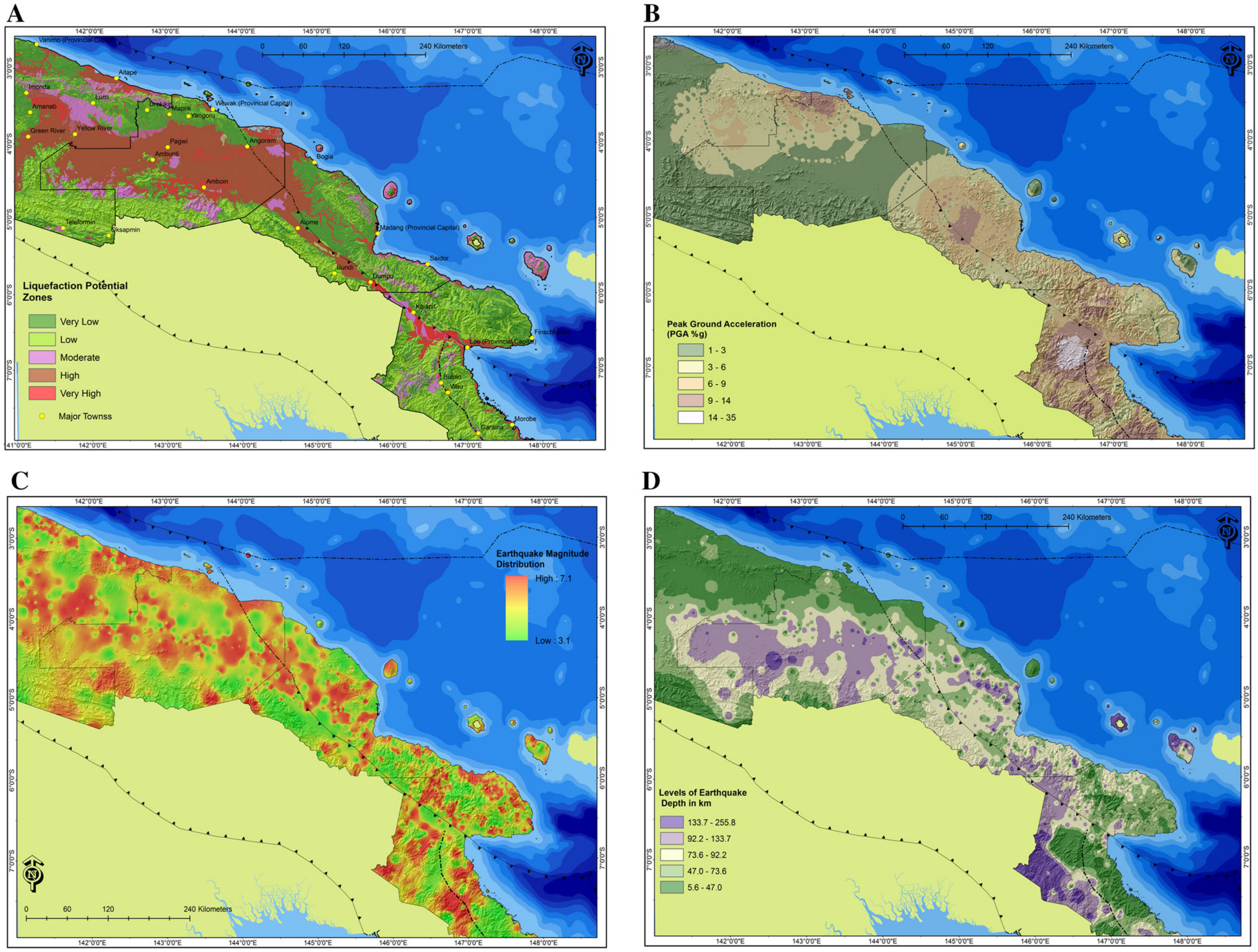


Fig. 8 Factors assessed for EHZ, **a** Liquefaction potential zones (LPZs), **b** peak ground acceleration (PGA %gal), **c** earthquake magnitude, **d** earthquake depth

Peak Ground Acceleration (PGA) raster surface was one of the factors that were employed into preparation of EHZs or levels of the study region. PGA can be also term Peak horizontal acceleration which is contoured in units of percent- g, g being the acceleration due to the force of gravity. The peak value of the horizontal acceleration was used to construct a PGA raster surface thematic layer. Once the earthquake strikes at the focus, the wave is generated and propagates to the surface. The intensity of shaking felt at each sites are measured in %gal at nearby recording stations. For the case of present study, the recorded PGA of higher earthquake magnitude of 5 and above from year 2000 up to 2016 was used in preparing PGA raster surface. Actually for all recorded PGA for each major earthquake events were acquired in point format and then were interpolated to prepare one single raster surface of PGA. From the integration of all recorded PGA values, it was found out that the highest shaking intensity experience within the study region was 35 %gal and the lowest was 1 %gal. After the preparation of PGA raster surface, it was reclassified into 5 classes, based on its intensity values/ levels. The higher PGA values were given higher weightage based on the fact that higher the intensity of ground shaking, more the damage will be. The effects of PGA intensity at each site are determined or controlled by size of the earthquake; that is greater the earthquake magnitude more the shaking intensity. Furthermore the depth of earthquake is very important; shallower the earthquake depth, shaking intensity it will more vigorous. However the fact remains that the levels of shaking intensity are highly controlled by sub and site surface conditions. As the wave propagates from the earthquake focus, it is the side and sub surface geology and geomorphological factors that determine whether the waves will be amplified or reduced. Thus according to Andrew [29] that once the waves propagates towards soft, saturated unconsolidated sediments, soil or

Table 9 Weightage and rankings of each factor assessed for earthquake hazard zonations

Theme	Weight	Classes	Ratings	Normalize rate	Area (km^2)	Area (%)
LPZ	0.466	Very low	1	0.04	48,814.83	34.40
		Low	2	0.09	33,905.42	23.89
		Moderate	3	0.16	13,125.44	9.25
		High	4	0.26	40,186.05	28.32
		Very high	5	0.45	5882.18	4.14
PGA (%gal)	0.277	1–3	1	0.04	51,748.73	36.56
		3–6	2	0.09	43,509.64	30.74
		6–9	3	0.15	30,751.31	21.73
		9–14	4	0.31	13,880.03	9.81
		14–35	5	0.41	1648.60	1.16
Earthquake magnitude (EM)	0.161	3.1–4.2	1	0.04	21,159.45	14.83
		4.2–4.4	2	0.09	50,476.98	35.38
		4.4–4.7	3	0.16	53,221.86	37.31
		4.7–5.1	4	0.26	16,019.3	11.23
		5.1–7.1	5	0.45	1784.78	1.25
Earthquake depth (km) (ED)	0.096	133.7–255.8	1	0.01	5473.17	3.84
		98.2–133.7	2	0.1	26,720.66	18.73
		73.6–98.2	3	0.20	37,523.54	26.30
		47.0–73.6	4	0.25	34,960.04	24.51
		5.6–47.0	5	0.44	37,981.58	26.62

rock, the seismic waves amplifies and hence cause more damage with the high shaking intensity. Base on these findings thematic layer was prepared (Fig. 8b) with weightage and rankings assigned (Table 9).

Magnitude raster surface that was prepared through interpolation techniques was used as one of the 4 factors into delineation of EHZs. As was discussed earlier, all the historical earthquake magnitudes from year 2000 up to 2016 were acquired in the point format and the interpolation technique in ArcGIS 10 was used to generate the raster surface of magnitude distribution for the study region. The raster surface was then reclassified to five (5) classes based on its levels or the magnitude. Thus Higher earthquake magnitude pose greater damage to the surrounding environment and lower magnitude pose minimum damage. By having in mind the damage related to magnitude, the thematic layer was prepared (Fig. 8c) with weightage and rankings assigned (Table 9). The higher weightage was assigned to ranges of higher magnitude and lower weightage was assigned to ranges of lower magnitude.

Earthquake depth distribution was one of the common factors that was also considered and integrated with 3 other factors into delineation of EHZs. The raster surface of earthquake depth distribution was prepared from interpolation techniques using ArcGIS 10. It is obvious that shallower the earthquake event, there's more possibility in any earthquake damage to occur, however it will be determined by site and sub surface features. Deeper the earthquake events, there is less possibility in any earthquake damage due to the fact that the wave from the earthquake focus travels long distance and has to negotiate different mediums where strength of waves can be greatly attenuated. However on the other hand the strength of the waves can be amplified if it comes to areas of soft, saturated and unconsolidated sediments or rocks, thus will be again reduced when it comes to consolidated sediments or rocks. Hence all depends on how deep or shallow the earthquake occurs. According to these ideas, the raster surface was reclassified into five (5) classes. Higher weightage was assigned to classes of shallower earthquake depth and low weightage was assigned to classes of deeper earthquake. Figure 8d highlights the raster surface of

Table 10 Earthquake hazard levels re-classification

EHI	Levels of earthquake hazard	Area (km^2)	Area (%)
0.86–1.72	Very low	29,020.37	20.60
1.72–2.14	Low	39,529.52	28.06
2.14–2.53	Moderate	33,218.96	23.58
2.53–2.99	High	29,747.61	21.12
2.99–4.30	Very high	9336.79	6.63

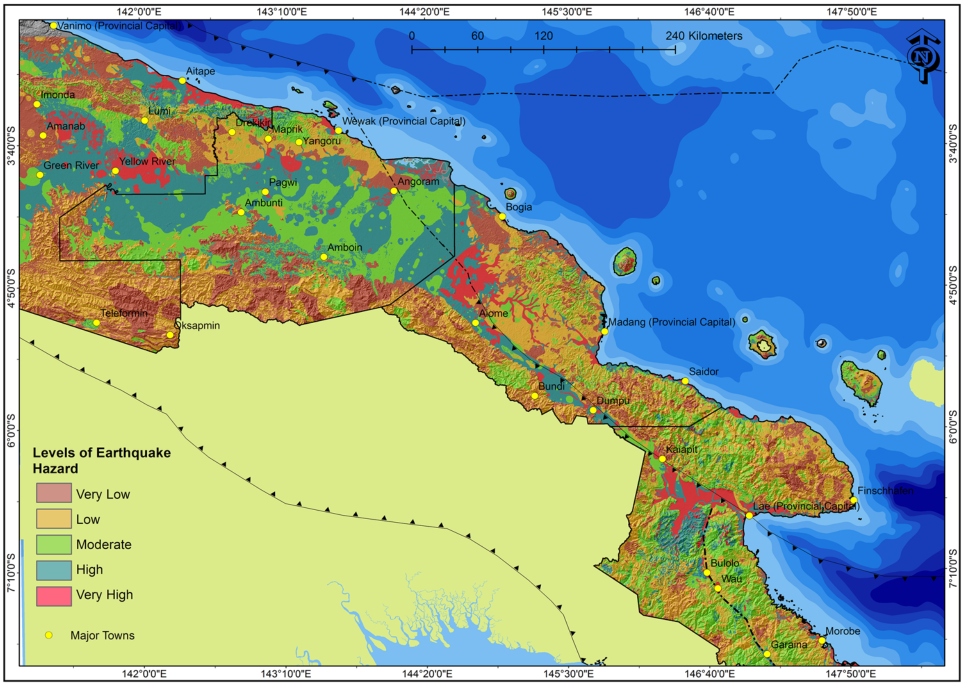


Fig. 9 Micro-zonation of each levels of earthquake hazard of Momase region

earthquake depth distribution and Table 9 tabulates the weightage and ranking assigned.

Table 9 shows the weightage and ratings assigned for each theme with their classes for the delineation of EHZs or levels. The normalized weights were calculated using AHP techniques and were finally assigned for each theme. For the theme that contributes more to earthquake hazard were assigned high weightage and low weightage was assigned to theme that contributes less. As regards for each class of the factors the ratings were assigned and again were normalized using AHP techniques. It can be seen from the Table 9 that value 1 was assigned to classes that contribute least, and up to value 5 to class that contributes the most. The tables also show the area in kilometre square (km^2) and percentages (%) for each class of the themes.

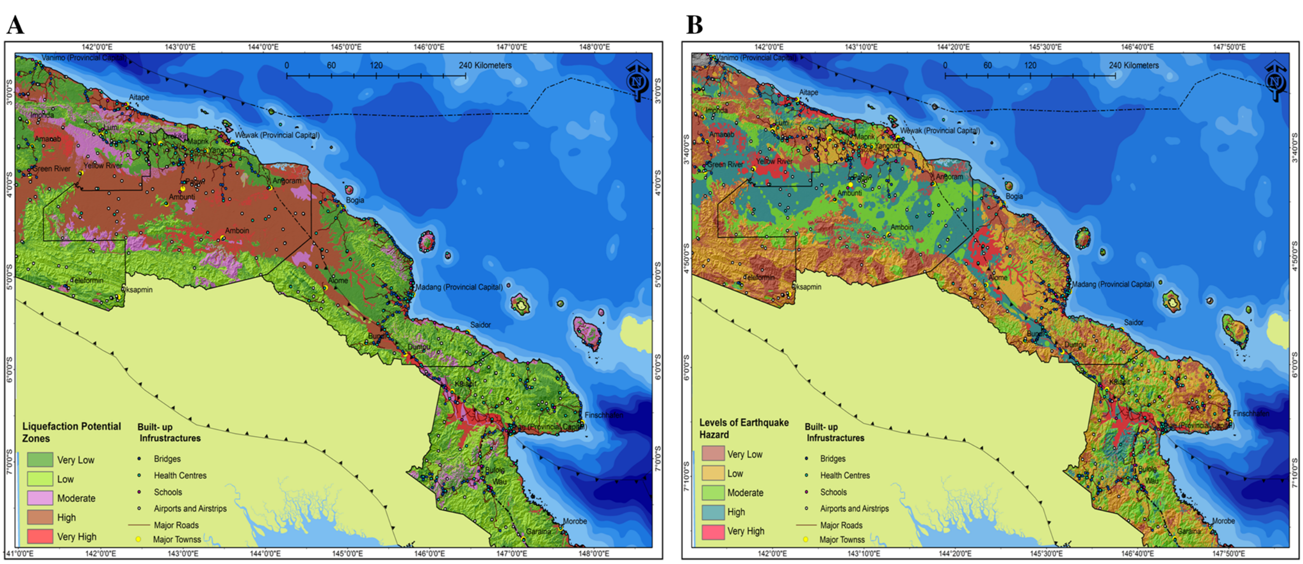


Fig. 10 Features assessed under each; **a** Liquefaction potential zones and **b** earthquake hazard zones

Table 11 Built-up infrastructure assessed under each liquefaction potential zones (LPZs)

Built-up infrustractures	Levels of liquefaction potential zones				
	Very high	High	Moderate	Low	Very low
Morobe province					
Major towns (counts)	1	1	2	1	2
Schools (counts)	4	9	2	5	4
Health centres (counts)	6	7	7	7	16
Road (distance in km)	384.42	238.66	456.60	507.91	745.83
Air ports and Air strips	5	5	8	11	34
Bridges	14	13	47	22	44
Madang province					
Major towns (counts)	1	4	0	0	1
Schools (counts)	1	5	1	0	3
Health centre	2	14	6	0	18
Road (distance in km)	159.77	616.01	161.93	156.65	751.67
Air ports and Air strips	0	9	4	4	18
Bridges	15	69	12	4	34
East Sepik province					
Major towns (counts)	2	2	0	1	3
Schools (counts)	0	10	0	0	11
Health centres	5	15	1	0	17
Road (distance in km)	26.91	377.91	26.01	75.69	985.26
Air ports and Air strips	4	32	0	3	8
Bridges	2	20	0	1	22
West Sepik province					
Major Towns (counts)	0	1	2	1	4
Schools (counts)	2	5	3	1	12
Health centres (counts)	3	9	3	2	19
Road (distance in km)	135.86	464.68	117.75	61.53	700.39
Air ports and Air strips	5	16	9	9	22
Bridges(counts)	18	37	11	4	22

After assigning all the weightage and ratings as tabulated in Table 9, the spatial analyse tool; Raster Calculator in ArcGIS 10 was employed in calculating and producing the final output of Levels of EHZs for the study region. The final map derived was based on reclassification done with weightage and ratings assigned. The formula highlighted by Pal et al. [9] was adopted and modified to calculate and prepare levels of EHZs for a study region. After the preparation of LPZs, it was used as one of the contributing factors as was discussed above with the other seismicity data layers to calculate and derive EHZs. The formula employed was: EHI = [(LPZw. LPZr) + (PGAw. PGAr) + (EMw. EMr) + (EDw. EDr)]/Σw, where EHI = Earthquake Hazard Index. From the calculation and integration, the EHI values were generated and then were assessed and reclassified in order to delineate EHZs. Table 10 highlights the EHI value that was generated and was reclassified into each zone of levels of earthquake hazard from very low to very high.

Table 10 presents the re-classification of earthquake hazard levels derived during integration of four (4) thematic layers. The standard deviation technique of classification in ArcGIS 10 was employed. The tables also show areas in square km (km^2) and percentage (%) for each level of hazard zones. The very low and low zones indicate that there is no risk of earthquake hazard at all; the moderate potential zones indicates earthquake hazard may or may not take place; however high to very high zone indicates actual possibilities of Earthquake hazard in the study area. It was found out that 'Very low' potential zone has 20.60 % of area coverage, Low potential zone has 28.06 % of area coverage, moderate potential zone has 23.58 % of area coverage, high potential zone has 21.12 % of area coverage and very high potential zone has 6.63 % of area coverage. Figure 10 illustrates the final output map of Earthquake Hazard Micro-Zonation of the study region.

Table 12 Built-up infrastructure assessed under each levels of earthquake hazard zones (EHZs)

Built-up infrustractures	Levels of earthquake hazard zones				
	Very high	High	Moderate	Low	very low
Morobe province					
Major towns (counts)	2	2	2	2	1
Schools (counts)	13	3	6	1	2
Health centres (counts)	9	6	8	10	8
Road (distance in km)	515.72	247.65	665.59	622.43	278.31
Airstrip and Airports(counts)	6	9	14	20	13
Bridges(counts)	20	13	53	44	13
Madang province					
Major towns (counts)	2	3	0	0	1
Schools (counts)	4	5	0	1	2
Health centre (count)	8	10	6	7	10
Road (distance in km)	262.41	517.12	193.50	519.54	349.89
Airstrip and Airports(counts)	6	3	5	6	15
Bridges (counts)	20	63	14	21	16
East Sepik province					
Major towns (counts)	1	2	3	1	1
Schools (counts)	6	3	3	5	4
Health centres	7	10	9	9	5
Road (distance in km)	160.18	199.1	251.81	678.23	202.86
Airstrip and Airports (counts)	1	21	14	5	5
Bridges (counts)	4	12	9	13	7
West Sepik province					
Major towns (counts)	1	0	1	1	3
Schools (counts)	3	4	2	5	6
Health centres (counts)	5	5	3	4	15
Road (distance in km)	218.87	310.81	175.99	203.42	468.42
Airstrip and Airports (counts)	9	13	9	11	20
Bridges (counts)	22	24	17	7	14

3.3 Evaluation of infrastructures with hazard zones

After the completion of delineation of LPZs and EHZs, several known and available public institutions and or built up infrastructure like roads, schools, health and major towns for the study region were overlaid on both the hazard zones, that is; liquefaction and earthquake hazard zones of a study region to evaluate and consider its possible susceptibility. Assessment of these features with hazard zones are of importance as it can contribute to the understanding of effects it might pose in the later events of earthquakes. These analyses are to let governing bodies and general public as a whole to figure out the possible locations of each built-up infrastructure, where this can assist in proper development planning and awareness. Also it can assist in proper and better future development planning. Table 11 tabulates the features assessed under each LPZ while Table 12 highlights the features assessed under each zone of earthquake hazard level. The features were only assessed under very high, high and moderate zones by having in mind that the possible damage owing to liquefaction and earthquake hazard is likely to be experienced. The table 'columns' indicates the hazard levels from very high to moderate and the 'rows' indicates each built-up infrastructure and or public institution assessed under each hazard levels or zones. Total length of roads with respect to each potential zone was measured in kilometres through spatial analysis techniques in GIS environment and the value was noted. The features like; major towns, health centres and schools that are found on each hazard zones were counted. Figure 10a illustrates the overall map of LPZs with its overlaid features while Fig. 10b illustrates the overall map of EHZs with its overlaid features.

4 Conclusions and recommendations

Earthquake Hazard assessment and monitoring in PNG is paramount because PNG is a seismically very active zone located within the Pacific Ring of Fire. Earthquakes and volcanic eruption do occur due to plate motion and hence any hazards to take place are decided upon sub and site surface geology and geomorphology and the shaking intensity emanating from the size of earthquakes.

There is always a possibility that if the particular sites that have experienced earthquake events in the past, the sites are always vulnerable for greater earthquake magnitude in the future. However there might be changes of magnitude either to be greater or smaller due to physical changes of sub and site surface geology and geomorphology over the time. If the greater magnitude earthquake triggered at shallow depth at a sites where the sediments, rock or soil are unconsolidated and saturated, then there is greater possibility of experiencing greater damage due to intense shaking.

Thorough analyses of seismicity, geology and geomorphological data layers were carried out keeping in mind that these factors are the most influencing ones that contribute to any hazard related to earthquake and hence they are the most useful criteria for assessment and monitoring of earthquake hazard. Generally six (6) thematic layers such as geology (according to rock types), soil AWC, soil texture, soil drainage, slope factor and fault buffer were integrated in GIS environment with AHP techniques in order to delineate LPZs. LPZs were then used as one of the thematic layers integrated with earthquake depth, magnitude and PGA raster surface in order to delineate EHZs or levels within the study region. Such studies are crucial in earthquake vulnerable areas such as PNG, where in any single devastating event, the country economy might collapse. As the country continues to develop, the earthquake risk will be high; hence hazard and risk mitigation must be a vital element through such a study. From the study, the levels of LPZ and EHZs from very high to very low were highlighted. From the analysis of infrastructure with hazard zones, it was found out that there were several key infrastructures located on the very high and high hazard zones, thus early mitigation and planning must be taken based on output results that were prepared to avoid any further loss or destruction. Furthermore for any further development to the near future, the prepared output results are to be consulted and the future development planning are to be properly done to minimise the risk of collapse emanating from earthquake hazard. Thus the liquefaction potential zonation mapping and earthquake hazard microzonation are important tools that can be used as an important tool for land use planning in terms of infrastructure development and mitigation measures. It creates easily—read, rapidly accessible charts and maps that facilitate decision making processes by Governing bodies. Armed with the scientific knowledge of each potential zone of liquefactions and earthquake hazard levels, future development planning can be done effectively towards site selection for investment decision of major infrastructures.

All in all, through the research and from the analysis, it was found out that within the study region there were no greater earthquake magnitude of 8 and above were experienced, and so far the study areas haven't faced any major damage or destruction due to earthquake related hazard. However from the analysis it was found out that some of the sites within the study region have a high and very high chance of experiencing liquefaction that might ensue in the aftermath a tremor. Thus according to research done, if the study region is to face earthquake event of 8 and above magnitude in Richter scale at shallower depth in the near future, the sites that are under high and very high hazard zones can possibly experience severe destruction. This piece of information is to be taken into account and amalgamated in the mid-term and long-term strategic planning the country has undertaken, as an immunity, as we don't know the actual date of such events lurking.

References

1. Gupta, R. P. (2003). *Remote sensing in geology*. Berlin: Springer.
2. Hugh, D. (1998). Tsunami PNG 1998, National Library of Papua New Guinea, ISBN 9980-85-262-3, Graphos Art Limited, Port Moresby, Retrieve form http://www.pacificdisaster.net/pdnadmin/data/original/JB_DM464_PNG_1998_Tsunami.pd.
3. Stanaway, R. (2008). A dynamic datum for PNG—improving PNG94. 42nd association of surveyors PNG congress, Port Moresby, 9th–12th July 2008.
4. Willige, T. B., & Wenzel, H. (2012). *Remote sensing and GIS contribution to earthquake disaster preparedness in Hungary* (Vol. 13355). Berlin: Berlin University of Technology (TU Berlin), Institute of Applied Geosciences.
5. Trinh, T. P. (2009). *Remote sensing and GIS for the study of natural hazards in Vietnam*. Nghiado: Institute of Geological Sciences, National Centre for Natural Sciences and Technology of Vietnam Vien Dia Chat.
6. Buri, E. (2013) Application of GIS for seismic observation in PNG, Portmorseby Geophysical Observation Geohazard Division, Department of mineral policy and and geohazard management. Retrieve from: http://www.pacificdisaster.net/pdnadmin/data/original/Pacific_GIS_RS_20131119_Eric_Fiji.pdf.
7. Willige, T. B. (2010). *Detection of local site conditions influencing earthquake shaking and secondary effects in Southwest—Haiti Usingremote sensing and GIS method*. Berlin: TU Berlin. Institute of Applied Geosciences.
8. UPSeis. (2016). *What are earthquake hazard? An educational site for budding seismologist*. http://www.geo.mtu.edu/UPSeis/.
9. Pal, I., Nath, S. K., Shukla, K., Pal, D. K., Raj, A., Thingbaijam, K. K. S., Bansal, B. K. (2007). Earthquake hazard zonation of

Sikkim Himalaya using a GIS platform. Springer Science+Business Media B.V. 2007. Retrieve through mail from Indrajit Pal. Pdf format.

10. Mohanty, W., Walling, M. Y., Nath, S. K., Pal, I. (2006). First order seismic microzonation of Delhi, India using geographical information system (GIS), Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur 721 302, India.
11. City of Rancho Cordova. (2006). Rancho Cordova Interim General Plan. Draft environment impact report, soil and geology Revised March 4, 2006, California.
12. Sharma, M. H., & Solaki, C. H. (2013). Liquefaction susceptibility criteria for zonation, international journal of engineering and technical research, *1*(7). Retrieve from https://www.erpublication.org/admin/vol_issue1/upload%20Image/IJETR011737.pdf.
13. Habibullah, B., Pokhrel, R., Kuwano, M. J., & Tachibana, S. (2012). *GIS-based soil liquefaction hazard zonation due to earthquake using geotechnical data*. Saitama: Geosphere Research Institute, Department of Civil and Environmental Engineering, Saitama University, Japan.
14. Bachhuber, J. L, Hengesh, J. V, & Sundermann, S. T. (2008). Liquefaction susceptibility of the bayamon and san juan quadrangles, puerto rico. U.S. Geological Survey National Earthquake Hazards Reduction Program Award 03HQGR0107.
15. Heidari, S. A., Sakhi, M. A., Mohammadi, M., & Soltani, Z. (2014). *Zonation for soil liquefaction potential assesment in Babol city, Iran* (Vol. 19). University of academic-applied Iran Frinco.
16. Pearce, J. T., & Baldwin, J. N. (2008). Liquefaction susceptibility and probabilistic liquefaction potential hazard mapping, st. Louis, Missouri and Illinois. William Lettis & Associates, Inc., 1777 Botelho Drive, Suite 262, Walnut Creek CA 94596. Url: www.lettis.com.
17. The World Bank. (2016). Reducing the risk of disasters and climate variability in the Pacific Islands. The Papua New Guinea Country Assessment, East Asia and Pacific Region, the world bank, 1818 H St. NW, Washington, DC. 20433. Retrieve from http://documents.worldbank.org/curated/en/318001468099588504/pdf/532060WP0P11201BLIC10PNG1ASSESSMENT.pdf.
18. National Geography Society. (2016). Landforms. Retrieve from http://nationalgeographic.org/encyclopedia/landform/.
19. Loffler, E. (1974). Geomorphological map of Papua New Guinea, scale 1:1000000, CSIRO Land research series, no 33.
20. Hamilton, W. (1979). *Tectonics of the Indonesian Region* (p. 345). Washington, DC: US Gov. Print. Off.
21. Wallace, L. M., Stevens, C., Silver, E., McCaffrey, R., Loratung, W., Hasiata, S., Stanaway, R., Curley, R., Rosa, R., & Taugaloidi, J. (2004). GPS and seismological constraints on active tectonics and arc-continent collision in Papua New Guinea: Implications for mechanics of microplate rotations in a plate boundary zone. *Journal of Geophysical Research, 109*, B05404. doi:10.1029/2003JB002481.
22. Ghasemi, H., McKee, C., Leonard, M., et al. (2016). Probabilistic seismic hazard map of Papua New Guinea. *Natural Hazards, 81*, 1003–1025. doi:10.1007/s11069-015-2117-8.
23. Koulali, A., Tregoning, P., McClusky, S., Stanaway, R., Wallace, L., & Lister, G. (2015). New Insights into the present-day kinematics of the central and western Papua New Guinea from GPS. Geographical Journal International. Retrieve from http://rses.anu.edu.au/geodynamics/tregoning/57.pdf.
24. Baldwin, S. L., Fitzgerald, P. G., & Webb, L. E. (2012). Tectonic of The New Guinea Region. Department of earth science, Syracuse University, Syracuse, New York 13244. Retrieve from http://www.uvm.edu/~lewebb/papers/Baldwin%20et%20al%202012%20New%20Guinea.pdf.
25. Sheppard, S., & Cranfield, L. C. (2012). Geological framework and mineralization of Papua New Guinea—an update: Mineral Resources Authority, Papua New Guinea, p. 65.
26. Geobook. (2009). *The UPNG geobook set—an interactive mapping atlas for each Province of PNG, Remote Sensing Centre, PO Box 320*. Papua New Guinea: Universityof PNG, NCD.
27. Sekac, T., Jana, S. K., Pal, I., & Pal, D. K. (2016). GIS based multi-criteria evaluation in earthquake hazard micro-zonation—a case study of Madang and Morobe Province, Papua New Guinea, International Journal of advanced Engineering Research and Science. ISSN 2349-6495 (P) 2456-1908 (O) (Vol. 3(8), pp. 95–104) .https://dx.doi.org/10.22161/ijaers.3.8.2.
28. Sekac, T., Jana, S. K., Pal, I., & Pal, D. K. (2016). A GIS based approach into delineating liquefaction susceptible zones through assessment of site-soil-geology—a case study of Madang and Morobe Province in Papua New Guinea, International Journal of Innovative Research in Science, Engineering and Technology, ISSN (Online): 2319–8753 (Vol. *5*(5), May 2016).
29. Andrew, M. (2005). *Estimating the influence of sediments on ground shaking*. Geosciences Australia. http://www.ga.gov.au/ausgeonews/ausgeonews200606/sediments.jsp.
30. Saaty, T. L. (1977). *The analytic hierarchy process: Planning, priority setting, and resource allocation* (1st ed., Vol. 17). New York: McGraw-Hill.
31. Saaty, T. L. (1980). *The analytic hierarchy process: Planning, priority setting, and resource allocation* (2nd ed., Vol. 18). New York: McGraw-Hill.
32. Saaty, T. L. (1992). *Decision making for leaders* (p. 19). Pittsburgh: RWS Publications.
33. Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences, 1*(1), 83–98.
34. Machiwal, D., Jha, M. K., & Mal, B. C. (2011). Assessment of groundwater potential in a semi-arid region of India using remote sensing. *GIS and MCDM Techniques, Water Resources Management, 25*(5), 1359–1386.
35. Forman, E. H., & Selly, M. A. (2001). *Decision by objective and how to convince others that you are right*. Singapore: World Scientific.
36. Green, R. A., Maurer, B. W., Bradley, B. A., Wotherspoon, L. W., & Cubrinovski, M. (2013). Implications from liquefaction observations in New Zealand for interpreting paleoliquefaction data in the central eastern united states (ceus). U.S. Geological Society Final Technical ReportCounty of San Diego low impact development handbook (2009). Geotechnical consideration.
37. Country of San Diego Low Impact Development Handbook (2009). Geotechnical Consideration.
38. United States Department of Agriculture (USDA). (1975). *Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys*. Washington, DC: US Govt. Printer.
39. U.S Army Corps of Engineers. (1992). *Draft environmental impact staement. Superconducting magnetic energy storage-engineering test model*. Chicago: Northwestern University.
40. Organization of American State. (1991). Primer on Natural Hazard Management in Integrated Regional Development Planning. Department of Regional Development and Environment Executive Secretariat for Economic and Social Affairs Organization of American States With support from the Office of Foreign Disaster Assistance United States Agency for International Development Washington, DC.