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RESULTS OF SITE-SPECIFIC GROUND RESPONSE ANALYSIS

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ABSTRACT: The city of Banda Aceh-Indonesia is extremely exposed to a significant seismic hazard. There are three main seismic sources around the city which are the tectonic subduction, the great Sumatran fault, and the West Andaman fault. Thus, seismic microzonation study of the Banda Aceh city is urgently required for any mitigation efforts. Site-specific ground response analysis was carried out at eleven sites in the city of Banda Aceh. An analytical model of the equivalent-linear model was used to perform ground response analysis. This analytical model of the equivalent-linear approach has demonstrated that it can simulate, reasonably well, the alteration of seismic motions at the ground surface. Three actual historical time histories recorded at rock sites nearby the city of Banda Aceh, and eleven developed sub-surface models in the city of Banda Aceh, were used to estimate the seismic characteristics, namely the peak ground acceleration, peak ground velocity, fundamental frequency, and estimated site amplification of the investigated sites. The results of the site-specific ground response analysis suggest that: (1) all the eleven sites have been classified as seismic site class D as per the provisions of SNI 1726-2012; (2) the site fundamental frequency in the city of Banda Aceh varies between 0.2 and 1.1 Hz; and (3) the amplification factor of the soils in the city of Banda Aceh can be up to 4.7. The largest spectral velocity and acceleration of the investigated sites were found to be 0.26 cm/s and 0.29 g, respectively.

Keywords: Seismic, Peak ground acceleration, Fundamental frequency, Site amplification, Banda Aceh

1. INTRODUCTION

The city of Banda Aceh-Indonesia is a coastal capital city of the Province of Aceh located in the Northern tip of Sumatra. It is a moderately sized city with an area of 59 km^2 and a population of 300,000. The city is located on the delta of the Krueng Aceh River. It is surrounded by the district of Aceh Besar to the North-East and South-West, and the Malacca Strait to the North-West. The city is relatively close to three seismic source zones, namely the tectonic subduction of the Indo-Australian and Eurasian Plates, the great Sumatran fault, and the West Andaman fault. Recently, the tectonic subduction seismic source zone has produced several strong seismic events, such as the 2004 Aceh earthquake (9.2 Mw), 2005 Nias earthquake (8.7 Mw), 2007 Bengkulu earthquake (8.5 Mw), and 2010 Mentawai earthquake (7.8 Mw). The 2004 Aceh earthquake has been suggested by National Geographic as the second-worst earthquake of all the time [1]. This event affected 14 countries, resulted in more than 220,000 casualties, displacement of more than 1.5 million people, and caused economic losses of $US10 billion [1]. The subduction of the Indo-Australian plate under the Eurasian plate to the west of Sumatra has produced 19 main fault segments with a length of 60 ~ 200 km on the shore of Sumatra [2], which are collectively known as the great Sumatran fault (GSF) [3]. This fault is identified as a dextral-lateral fault with an estimated length of ±1,900 km and stretches from Banda Aceh to the Sunda Strait. Several earthquakes that have occurred along the GSF include the 1906 Kerinci earthquake, the 1932 earthquake around Liwa and the 1952 earthquake around the Ketaun and Seblat valleys. The displacement of each of the GSF's segment has been measured and calculated using GPS geodetic surveying. A rough estimation of the displacement of the segments near the city of Banda Aceh, i.e. the Seulimeum-Aceh-Tripa segments, varies between about 16 and 20 mm/year [1].

The tectonic setting of the Andaman Islands and the surrounding area is very complex and is the subject of active research [4, 5, 6]. The West Andaman Fault was interpreted as a lateral fault by [7] but proposed as a thrust fault by [8]. This West Andaman fault can be correlated with the Deligent fault to the north and the Mentawai fault to the south [9, 10]. Thus, these three faults form a fault zone along the Andaman Islands and west, offshore of Sumatra.

The city of Banda Aceh is founded on thick Holocene Alluvium [11] and is classified as being in an area of high seismic hazard risk [1]. In a recent study on Indonesian seismic hazard assessment [1], the city of Banda Aceh can experience high peak ground accelerations during an earthquake. Furthermore, based on deterministic seismic hazard analysis studies, the city of Banda Aceh is exposed to an extreme onshore seismic hazard, with a potential magnitude of 7.5 [12]. Therefore, a detailed estimation of the local site effects is required for the city of Banda Aceh. To this end, microtremor measurements were carried out at 11 locations across the city of Banda Aceh. Subsurface and geotechnical data collected from various agencies were collated. These data were used to develop the sub-surface profiles used in the present study.

Commonly, the local ground response effect is examined using a one dimensional (1D) model to investigate the sub-surface local characteristics during an earthquake. The basic assumption of this 1D model is the propagation of seismic waves in the vertical direction through the horizontal layers of the soil, which can be solved using equivalent-linear or nonlinear analyses. In practice, equivalent-linear ground response analysis is widely used to simulate true nonlinear soil behavior because the model requires modest computational effort and few input parameters [13]. The computational process of this equivalent-linear analysis is outlined in [14]. In this study, the effects of local soil conditions on earthquake ground motions have been estimated by carrying out detailed 1D equivalent-linear wave propagation analysis using the EERA software [13]. The results are useful for structural engineers, town planners, and the government in any mitigation strategy. The results also can be used for carrying out more advanced soil-structure dynamic analysis. The significance of this study is a quantification of several dynamic parameters, such as the site's fundamental frequency, amplification factor, and response spectra within the study area.

2. REVIEW OF PREVIOUS STUDIES

Polom Arsyad, and Kumpel [15] carried out shallow shear wave reflection seismic measurements in the Krueng Aceh River basin within the Management of Georisk (MANGEONAD) project of the Federal Institute for Geosciences and Natural Resources (BGR), Hanover, Germany. Several near-surface shear wave velocity profiles of the city of Banda Aceh were produced. Setiawan and Kusuma [16] enhanced the results of [15] to estimate the local ground response during the 2004 Aceh earthquake. A detailed study of the near-surface shear wave velocity of the city of Banda Aceh was carried out by [17] using the multichannel analysis of surface waves (MASW) method at 49 locations. Seismic site classification, based on the Indonesian standard SNI 1726-2012, for the city of Banda Aceh was carried out. Most of the sites in the city of Banda Aceh are classified as having a seismic site class between E and D in accordance to SNI 1726-2012, which suggests class D for $V_{s,30}$ less than 175 m/s, and D for $V_{s,30}$ from 175 to 350 m/s.

In 2018 Saidi, Aulia, Setiawan, Abdullah, and Hasan [18] simulated typical retail buildings in the city Banda Aceh using a response spectra curve. Yunita, Setiawan, Saidi, and Abdullah [19] investigated the seismic site amplification of the city of Banda Aceh's soft soil. This investigation suggested a ground motion amplification of Banda Aceh's soils of up to 4.3.

3. METHODOLOGY

In its most elemental form, the methodology of this study can be summarized in the following four main steps: (1) collect the secondary and primary data, (2) develop the sub-surface profile models for the computer programs, (3) execute the computer program, and (4) deduce and interpret the results. The overall methodology is outlined in Fig. 1. Several main input data are required in the ground response analysis. In this study, these inputs are classified into three categories, as outlined in the following sections.

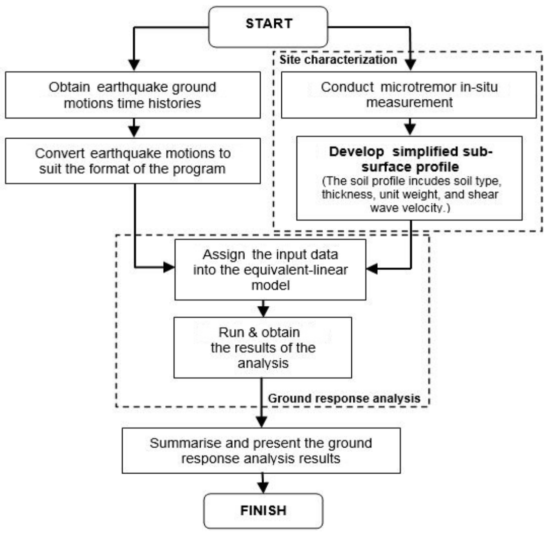

Fig. 1 The methodology of site response analysis.

3.1 Sub-surface Model Development

Site sub-surface model development includes the soil type, thickness, unit weight, shear wave velocity, and water level. In this study a one-dimensional (1D) sub-surface model is developed for the site response analysis at 11 locations in the city of Banda Aceh. Field ambient noise measurements were obtained at the 11 sites (Table 1) from which the sub-surface profiles at the measured sites were deduced (Fig. 2). The adopted field measurement process was consistent with the procedure outlined in [20]. These microtremor measurements were used to develop a shear wave velocity model at the measured sites using the horizontal vertical spectral ratio (HVSR) method. The method of applying the HVSR method to obtain the shear wave velocity is outlined by Setiawan, Jaksa, Griffith, and Love [21].

Table 1 Microtremor Measurement Locations of the Present Study

Site name	Latitude	Longitude
#1-Tib	5.582985	95.346500
#2-Jaw	5.573705	95.320037
#3-Smk	5.567211	95.340452
#4-Uns	5.570277	95.366409
#5-Lam	5.55046	95.359635
#6-Ill	5.543393	95.350411
#7-Bat	5.539967	95.331244
#8-Pad	5.549396	95.312956
#9-Inie	5.529166	95.301668
#10-Lon	5.520503	95.321865
#11-Pie	5.553098	95.285921

3.2 Sub-surface Dynamic Properties

Dynamic soil type characterization includes the assessment of dynamic soil properties, either by laboratory tests of soil samples taken from the investigated site or by standard curves and correlations. Modulus reduction and damping ratio curves have been selected based on the different types of soil properties. In the absence of the development of the site-specific modulus reduction and damping ratio curves, standard curves proposed within the EERA software were applied.

Fig. 2 Microtremor field measurement campaign in the city of Banda Aceh.

3.3 Seismic Time Histories

The compilation of earthquake ground motion time histories involves the selection of acceleration time histories based on either factual time histories or the generation of the synthetic ones. Generally, the selected time histories are consistent with the expected earthquake hazard in the study area. The selection of the factual earthquake ground motion, or the generation of synthetic seismic ground motion, is the final step in ground response analysis. This generation or selection of an acceleration time history must be compatible with the expected maximum dynamic loading at the site of interest. The selection of the suitable acceleration time histories can be based on the expected peak ground acceleration (PGA) value, maximum earthquake magnitude, the distance to the expected most significant seismic hazard or the seismic site class. This study is based on factual acceleration time history data without the selection of the suitable acceleration time history process for the investigated study site. Three factual historical seismic events, recorded at rock sites near the city of Banda Aceh, were collected from BMKG (Indonesian Meteorology, Climatology, and Geophysical Agency) earthquake data repository [22]. The selected data included acceleration time histories of the 2012 Simeulue earthquake, the 2013 Mane-Geumpang earthquake, and the 2013 Bener Meriah earthquake, as summarized in Table 2. The distance of these seismic events from the city of Banda Aceh are 613, 45 and 181 km, respectively.

Table 2 Three Historical Seismic Events Used in Site Response Analysis

Event name	Epicenter coordinates	Magnitude	Depth (km)
09:00:53.551 UTC on 11-04 2012 Simeulue	N 2.67 & 95.69 E	6.0	10
22:22:54.222 UTC on 22-01-2013 Mane-Geumpang	N 4.77 & 95.99 E	5.9	10
07:37:05.839 UTC on 02-07-2013 Bener Meriah	N 4.59 & 96.66 E	6.1	15

4. RESULTS

The results presented in the following sections are obtained from the ambient noise data and seismic ground response analyses.

4.1 Seismic Site Classification

In general, in seismic site classification, it is recommended to use the actual near-surface shear wave velocity. Usually, the average shear wave velocity of the top 30 m of the soil profile, $V_{s,30}$, is adopted. The average $V_{s,30}$, $\bar{V}_{s,30}$, for the top 30 m soil profile can be calculated using the following equation:

$$\bar{V}_{s,30} = \sum V_{s_i} \times \left(\frac{d_i}{30}\right) \qquad (1)$$

where V_{s_i} is the shear wave velocity of the ith layer and d_i is the thickness of the ith layer.

As aforementioned, the near-surface shear wave velocity is inverted using joint inversion of HVSR curve and site fundamental frequency. From the inverted shear wave velocity profile of the investigated sites and using Eq. (1), it has been observed in this study that all the investigated sites are associated with site class D based on SNI-1726-2012 with the average $V_{s,30}$ value for the profiles ranging from 203 to 235 m/s. These seismic site classification outputs were compared with the results of a study by Muzli, Rudyanto, Sakti, Rahmatullah, Dewi, Santoso, Muhajirin, Pramono, Mahesworo, Jihad, Ardiyansyah, Satria, Akbar, and Madijono [17] who carried out seismic site classification for the city of Banda Aceh using the MASW method. In comparison, the seismic site classes obtained from the present study are slightly higher than those suggested by [17]. This study classifies seismic site class D for all the investigated sites, but [17] suggested seismic site class E for sites #2-Jaw, #3-Smk, #5-Lam, #08-Pad, and #10-Lon. The detailed comparison is presented in Table 3.

Table 3 Average the top 30 m shear wave velocity and seismic site classification

Site name	Present study		[17]	
#1-Tib	205	(D)	196 or 142	(D/E)
#2-Jaw	218	(D)	173	(E)
#3-Smk	235	(D)	148	(E)
#4-Uns	203	(D)	-	-
#5-Lam	213	(D)	151	(E)
#6-Ill	217	(D)	175	(D)
#7-Bat	219	(D)	201	(D)
#8-Pad	210	(D)	148	(E)
#9-Inie	227	(D)	238 or 220	(D)
#10-Lon	205	(D)	151	(E)
#11-Pie	227	(D)	-	-

Note: The seismic site classification is based on SNI 1726-2016.

4.2 Seismic Ground Response Analysis

Seismic ground response analysis was carried out for 11 sites in the city of Banda Aceh. The main results of the site-specific ground response analysis, using the EERA model, are presented in Tables 4 to 6. The highest peak ground velocity (PGV) of 0.5 m/s is estimated at Site #08-Pad. The greatest peak ground acceleration (PGA) of 0.07g is predicted at two sites (#03-Smk and #10-Lon). The site fundamental frequency for the city of Banda Aceh is estimated to be between 0.2 to 1.1 Hz. The highest maximum spectral velocity and maximum spectral acceleration are estimated at Site #03-Smk of 0.0026 m/s and Site #10-Lon of 0.29g, respectively. In the present study, the seismic motion acceleration at the ground surface was compared with the acceleration at the expected basements of the sites. The objective is to deduce the site amplification, which is suggested to lie between 3.5 and 4.9 for the city of Banda Aceh. The spatial distribution of the site-specific ground response analysis results for the city of Banda Aceh are presented in Figs. 3 to 8.

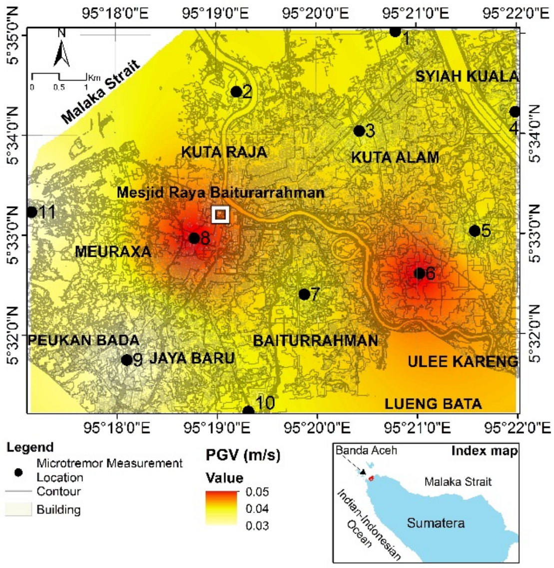

Fig. 3 Estimated maximum peak ground velocities in the city of Banda Aceh.

Table 4 Calculated peak ground velocities and peak ground accelerations

Site name	PGV Soil (m/s)	PGA Soil (g)
#1-Tib	0.04-0.08	0.03-0.06
#2-Jaw	0.03-0.04	0.03-0.06
#3-Smk	0.03-0.04	0.03-0.07
#4-Uns	0.4	0.03-0.06
#5-Lam	0.3-0.4	0.02-0.06
#6-Ill	0.3-0.5	0.03-0.06
#7-Bat	0.3-0.4	0.03-0.06
#8-Pad	0.4-0.5	0.03-0.06
#9-Inie	0.3	0.03-0.06
#10-Lon	0.3-0.4	0.04-0.07
#11-Pie	0.3	0.03-0.06

Table 5 Calculated maximum spectral velocities and accelerations

Site name	Max. spectral velocity (m/s)	Max. spectral acceleration (g)
#1-Tib	0.0018	0.22
#2-Jaw	0.0015	0.22
#3-Smk	0.0026	0.23
#4-Uns	0.0025	0.23
#5-Lam	0.0022	0.22
#6-Ill	0.0024	0.25
#7-Bat	0.0017	0.24
#8-Pad	0.0022	0.21
#9-Inie	0.0015	0.27
#10-Lon	0.0023	0.29
#11-Pie	0.0015	0.20

Table 6 Calculated site fundamental frequencies and maximum amplification factors (AFs)

Site name	Fund. Frequency (Hz) Theoretical	Exp.	Max AF
#1-Tib	0.4	0.3	4.2
#2-Jaw	0.4	0.4	3.9
#3-Smk	0.4	0.4	4.0
#4-Uns	0.4	1.1	3.6
#5-Lam	0.4	0.6	3.6
#6-Ill	0.4	0.4	3.5
#7-Bat	0.4	0.4	4.1
#8-Pad	0.4	0.2	4.6
#9-Inie	0.4	0.4	4.0
#10-Lon	0.4	0.6	4.7
#11-Pie	0.4	0.4	3.5

5. CONCLUSIONS

Local site effects associated with earthquake ground motions have been investigated for sites in the city of Banda Aceh, Indonesia, by conducting detailed 1D equivalent-linear ground response analyses. Actual acceleration time histories from the Simeulue (2012), Mane-Geumpang (2013), and Bener Meriah (2013) earthquakes were adopted as input ground motions. From the results obtained in this study, the following conclusions are drawn:

- Using the provisions SNI 1726-2012, all 11 sites have been classified as seismic site class D.
- The site fundamental frequency has been observed to be between 0.2 and 1.1 Hz.
- The amplification factors of the soils in the city of Banda Aceh have been observed to be in the range of 3.5 and 4.7.

The site fundamental frequency and amplification factor developed in this study can be used for the dynamic analyses of important structures in the city of Banda Aceh.

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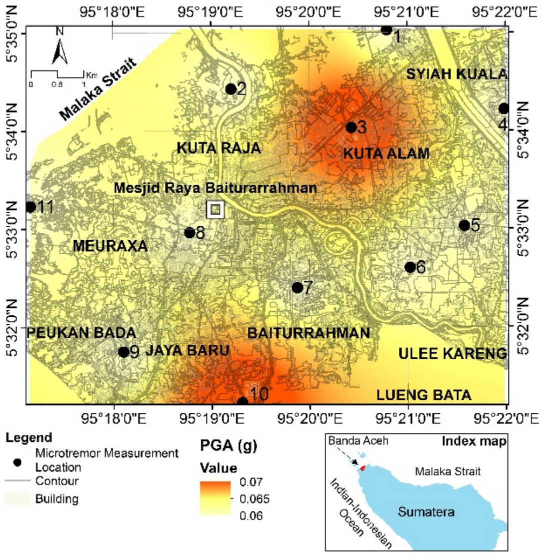

Fig. 4 Estimated maximum peak ground accelerations in the city of Banda Aceh.

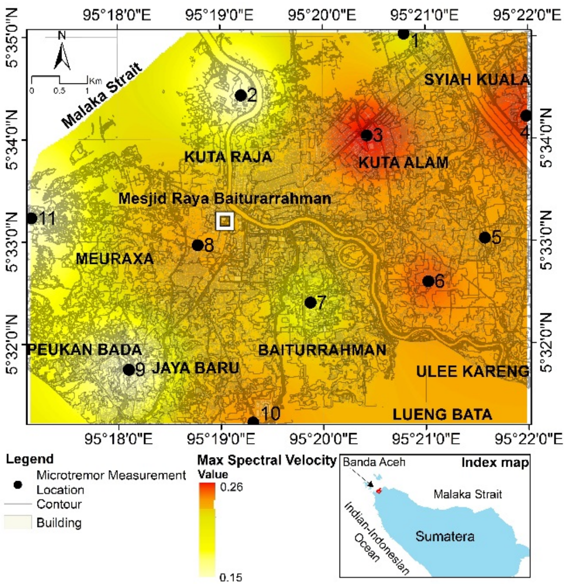

Fig. 5 Estimated maximum spectral velocity in the city of Banda Aceh.

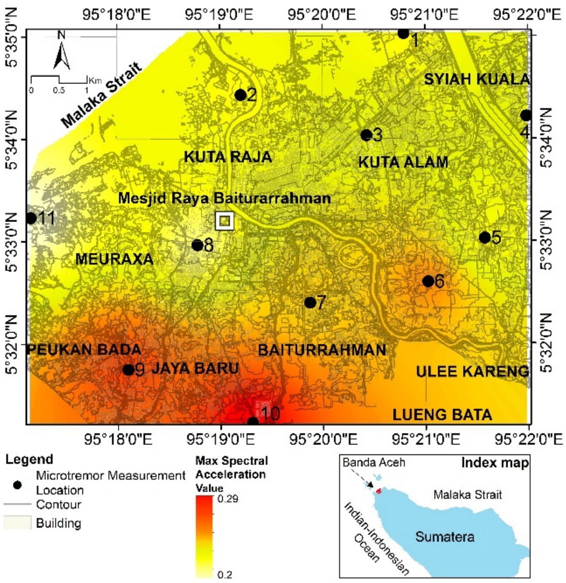

Fig. 6 Estimated maximum spectral acceleration at the city of Banda Aceh.

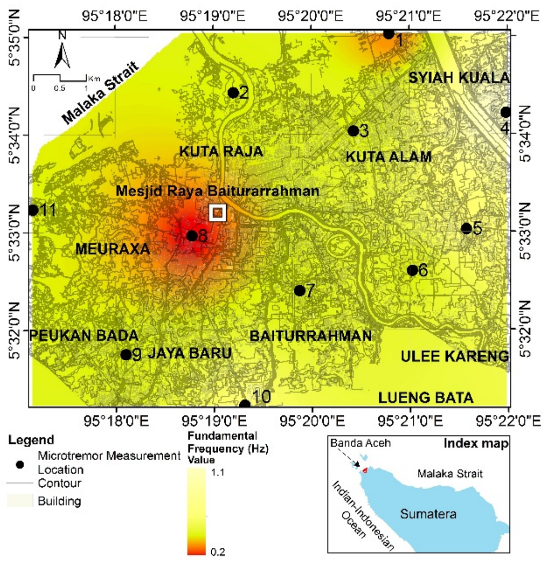

Fig. 7 Estimated site fundamental frequency at the city of Banda Aceh.

7. REFERENCES

[1] Irsyam M., S. Widiyantoro, D. Natawidjaja, I. Meilano, A. Rudyanto, S. Hidayati, W. Triyoso, N. Hanifa, D. Djarwadi, L. Faizal, S. Sunarjito, Peta Sumber & Bahaya Gempa Indonesia Tahun 2017 (Indonesian seismic source & hazard map of the year 2017). Pusat Penelitian & Pengembangan Perumahan dan Permukiman, Badan Penelitian & Pengembangan, Kementerian Pekerjaan Umum & Perumahan Rakyat (Centre of Research & Development of Housing & Resettlement, Board of research & development Ministry of Public Works & Public Housing), 2017, pp. 1-400, ISBN: 978-602-5489-01-3.

[2] Sieh K. and D. Natawidjaja, Neotectonics of the Sumatran fault, Indonesia. J. Geophys. Res. Vol. 105, Issue 28, 2000, pp. 295-326.

[3] Bellier O., M. Sébrier, S. Pramumijoyo, T. Beaudouin, I. Harjono, I. Bahar and O. Fomi, Paleoseimicity and seismic hazard along the Ornat Sumatran Fault (Indonesia). J. Geodyn., Vol. 24, 1997, pp.169-183.

[4] Curray J. R., Techtonics and history of the Andaman sea region. J. Asian Earth Sci., Vol. 25, Issue 1, 2005, pp. 187-232.

[5] Singh S. C., R. Moeremans, J. McArdle and K. Johansen, Seismic images of the sliver strike-slip fault and bachthrust in the Andaman-Nicobar region. J. Geophys. Res. Vol. 118, 2013, pp.1-17.

[6] Morley C. K. and A. Alvey, Is spreading prolonged, episodic or incipient in the Andaman sea? Evidence from deepwater sedimentation. J. Asian Earth Sci. Vol. 98, 2015, pp.446-456.

[7] Izart A., B. M. Kemal and J. A. Malod, Seismic stratigraphy and subsidence evolution of the northest Sumatra fore-arc basin. Mar. Geol. Vol. 122, 1994, pp.109-124.

[8] Chauhan A. P., S. C. Singh, N. D. Hananto, H. Carton, F. Klingelhoefer, J. -X. Dessa, H. Permana, N. J. White and D. Graindorge, Seismic imaging of forearc backthrust at Northern Sumatra subduction zone. Geophys. J. Int. Vol. 179, Issue 3, 2009, pp.1772-1780.

[9] Singh S. C., N. D. Hananto, A. P. Chauhan, H. Permana, M. Denolle, A. Hendriyana and D. Natawidjaja, Evidence of active backthrusting at the NE Margin of Mentawai Islands, SW Sumatra. Geophys. J. Int. Vol. 180, Issue 2, 2010, pp.703-714.

[10] Mukti M., S. C. Singh, I. Deighton, N. D. Hananto, R. Moeremans and H. Permana, Structural evolution of backthrusting in the Mentawai fault zone, offshore Sumatran forearc, Geochem. Geophys. Geosystems, Vol. 13, Issue 12, 2012, pp.1-12.

[11] Siemon B., D. Ploethner and J. Pielawa, Hydrogeological Reconnaissance Survey in the Province Nanggroe Aceh Darussalam Northern Sumatra, Indonesia Survei Area: Banda Aceh/Aceh Besar 2005. Report B-1, BGR (Federal Institute for Geosciences and Natural Resources), 2006, pp. 1-114.

[12] Petersen M., J. Dewey, S. Hartzell, C. Mueller, S. Hansen, A. Frankel and K. Rukstales, Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the southern Malaysian peninsula. Tectonophysics, Vol. 390, 2001, pp.141-158.

[13] Bardet J., K. Ichii and C. Lin, EERA a computer program for Equivalent-linear Earthquake site Response Analyses of layered soil deposits. Department of Civil Engineering, University of Southern California, 2000, pp.1-40.

[14] Schnabel P., J. Lysmer and H. Seed, A computer program for earthquake response analysis of horizontally layered sites, Earthquake Engineering Research Center (EERC) Report 72-12, 1972, pp.1-114, Berkeley, California: University of California.

[15] Polom U., I. Arsyad and H. Kumpel, Shallow shear-wave reflection seismics in the tsunami struck Krueng Aceh River Basin, Sumatra. Adv. Geosci., Vol. 14, 2008, pp.135–140.

[16] Setiawan B. and W. B. Kusuma, Banda Aceh-Indonesia Ground Response Analysis During the 2004 Indian Ocean Mega Earthquake. Seventh International Conference in Geotechnical Engineering, Chicago, USA, 29 April – 4 May 2012, 2013, pp.1-7.

[17] Muzli M., A. Rudyanto, A. P. Sakti, F. S. Rahmatullah, K. R. Dewi, E. Santoso, M. Muhajirin, S. Pramono, R. P. Mahesworo, A. Jihad, T. Ardiyansyah, L. A. Satria, R. N. Akbar and R. Madijono, Studi klasifikasi tanah permukaan untuk wilayah Banda Aceh (Study of soil classification at Banda Aceh areas). Prosiding Seminar Nasional Aplikasi Sain dan Teknologi pada Pengurangan Resiko Bencana (Proceeding of National Seminar on Science and Technology for Hazard Risk Reduction), Banda Aceh, 22 November 2014, 2014, pp. 159-167.

[18] Saidi T., T. B. Aulia, B. Setiawan, N. Abdullah and M. Hasan, Spectral displacement (SD) of Banda Aceh's soft soil for seismic vulnerability assessment. MATEC Web of Conferences, Vol. 197, 10001, 2018, pp.1-4.

[19] Yunita H., B. Setiawan, T. Saidi and N. Abdullah, Site response analysis for estimating seismic site amplification in the case of Banda Aceh – Indonesia. MATEC Web of Conferences, Vol. 197, 10002, 2018, pp.1-6.

[20] Setiawan B., M. Jaksa, M. Griffith and D. Love, Passive noise datasets at regolith sites. Data in Brief, Vol. 20, 2018, pp. 735-747.

[21] Setiawan B., M. Jaksa, M. Griffith and D. Love, Seismic site classification based on constrained of measured HVSR curve in regolith sites. Soil Dyn. Earthq. Eng., Vol. 110, 2018, pp. 244-261.

[22] Badan Meteorologi Klimatologi dan Geofisika (BMKG) [Indonesian Meteorology, Climatology, and Geophysical Agency] Katalog Gempabumi (Earthquake Catalogue), Accessed on 10 June 2018, http://repogempa.bmkg.go.id/repo_new/index.php.