MATEC Web of Conferences **197**, 10002 (2018) https://doi.org/10.1051/matecconf/201819710002
AASEC 2018

Site response analysis for estimating seismic site amplification in the case of Banda Aceh - Indonesia

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Abstract. The city of Banda Aceh is potentially exposed to a significant seismic hazard of seismic site amplification. Estimation of seismic site amplification of the city is urgently required for any mitigation efforts as the city is founded on a thick, soft layer. This study aims to estimate seismic site amplification of Banda Aceh's soil. Analytical models have demonstrated that they can simulate reasonably well the seismic ground motions amplification. The most widely used model is the equivalent linear approach. The approach computes the ground response of horizontally layered soil deposits subjected to transient and vertically propagating shear waves through a one-dimensional soil column. As aforementioned, this study focuses on Banda Aceh-Indonesia which is founded on thick alluvium. Three actual historical time histories and three developed sub-surface models were used to estimate the seismic site amplification of Banda Aceh's soft soil. The used time histories are of 2012 M8.1 Simeulue earthquake, 2013 M6.0 Mane-Geumpang earthquake and 2013 M6.2 Bener Meriah earthquake. Three sub-surface models of three separate sites across the city of Banda Aceh were developed. The site response analysis results reveal the ground motions amplification of Banda Aceh's soils of up to 4.3. Thus, applying the seismic site amplification for structural design at Banda Aceh can be further works.

1 Introduction

In term of seismicity, the city of Banda Aceh and its surrounding areas is mainly generated by the north-northeast oriented convergence of the Indo-Australian plate toward the Eurasian plate with the rate of collision from about 40 -60 mm per year [1]. This high rate of deformation has triggered several strong seismic magnitude events (≥ 8.0), i.e. 1861 Nias earthquake, 2004 Sumatra-Andaman earthquake, and 2005 Simeulue earthquake [2], as shown in Figure 1. Furthermore, Banda Aceh is potentially exposed to an additional and significant seismic hazard along the Great Sumatran Fault (GSF). This major right-lateral strike-slip fault has been no significant earthquake along the northern part of the GSF during the past two centuries [2], as indicated in Figure 1. This quite segment is considered as a seismic gap (i.e., a region within a seismically active area with a longer-lasting low level of activity) [3]. The GSF must accommodate the increases stress over the plate collision. This stress will be released in a future earthquake. Ref. [4] suggested that the GSF is capable of producing up to M=7.9 earthquake, as the historically M=7.7 earthquake occurred along this GSF. This most significant seismic event occurred in 1892 near the city of Sibolga (±570 km at the southeast of Banda Aceh) (*cf.* [2]). Furthermore, the city of Banda Aceh-Indonesia is founded on thick alluvium [5]. The possibility of seismic site amplification to occur at structures founded on the thick alluvium is very high [6], [7], [8]. Therefore, the estimation of seismic site amplification of Banda Aceh is urgently required considering the future earthquakes as the city is among most at risk of a severe earthquake [9] and has experienced one of the most prominent earthquakes in the human past than any other Indonesian city. Understanding Banda Aceh's ground surface behaviour is essential for city infrastructure plan.

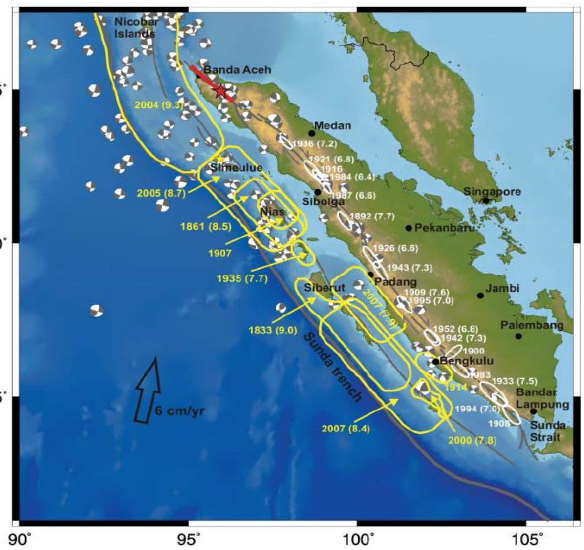

Fig. 1. Seismic activity along the subduction zone and the great Sumatran fault (GSF) [2].

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Analytical models have demonstrated that they can simulate reasonably well the seismic ground motions amplification for horizontally stratified layers [10]; [11]; [12]. The most widely used model for this site response analysis is the equivalent linear approach [13], [14]. The procedure computes the ground response of horizontally layered soil deposits subjected to transient and vertically propagating shear waves through a one-dimensional soil column.

This study examines the impact of three historical seismic events on estimating seismic site amplification in the case of Banda Aceh - Indonesia. These seismic events are determined at the Richter local magnitudes (ML) of 8.1, 6.0 and 6.2 for the 2012 Simuelue II, 2013 Mane-Geumpang and 2013 Bener Meriah earthquakes, respectively. Three sub-surface models of Banda Aceh's soft soil were developed. The three sub-surface models are located at three separate sites across the city of Banda Aceh, as shown later. Site response analysis results reveal the ground motions amplification of Banda Aceh's soils.

2 Methodology

The used methodology in this study is outlined in Figure 2. It is beginning with collecting ground motions time history. At the same time, site characterization is carried out from which sub-surface model is obtained. Both the time history and sub-surface model are employed for the ground response analysis.

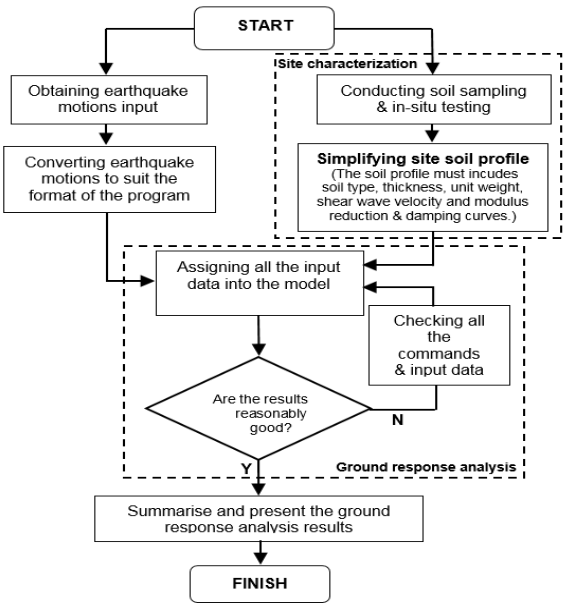

Fig. 2. The methodology of site response analysis.

2.1. Historical acceleration time histories

In this study, three events including the 2012 Simeulue II earthquake, the 2013 Mane-Geumpang earthquake, and the 2013 Bener Meriah earthquake are employed in the analysis. These three historical seismic events are outlined in Table 1. The recorded acceleration time history of the three past events is shown in Figure 3.

Table 1. Three historical seismic events used in this study.

Event	Epicentre coordinates	Magnitude (ML)	Depth & distance from Banda Aceh (km)
7:43:11 on 11-04 2012 Simeulue II	N 0.82 – 92.42 E	8,1	24 & 613
05:22:42 on 22-01-2013 Mane-Gempang	N 5.49 – 95.21 E	6,0	84 & 45
14:37:03 on 02-07-2013 Bener Meriah	N 4.70 – 96.61 E	6,2	10 & 181

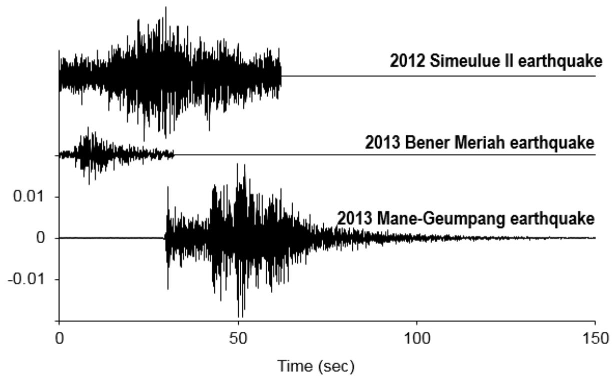

Fig. 3. Acceleration time histories of the three historical earthquakes.

2.2 One-dimensional (1D) sub-surface profile

One-dimensional (1D) sub-surface model is developed for the site response analysis at Site#A, Site#B and Site#C (see Figure 4). Detailed knowledge of the subsurface characteristics of all investigated sites is important in the construction of the profile. A study by [15] is crucial for the development of the sub-surface profile of the investigated sites, as shown in Figure 4. Other related sub-surface data are also elaborated in this development of 1D sub-surface profile.

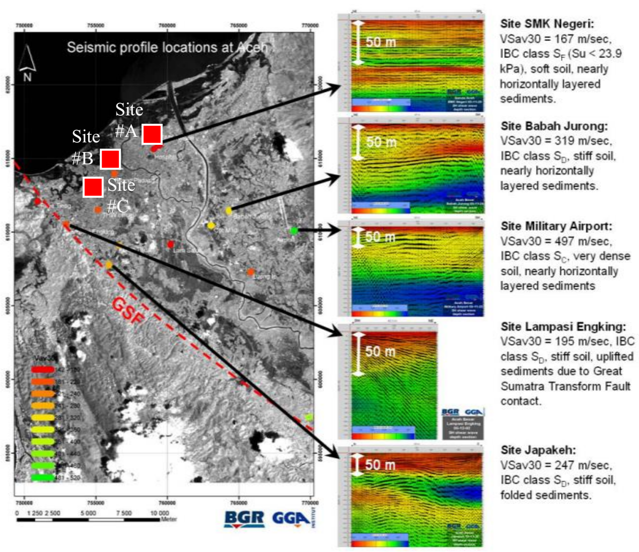

Fig. 4. Shear wave velocity at several locations in Banda Aceh and surrounding area shear wave velocity [15].

2.3 Modulus reduction & damping curves

The default modulus reduction and damping curves provided by the equivalent-linear earthquake response analysis model have worked well in most applications [16]. The present study adopts these default curves to represent each typical material behaviour during strain.

3 Results

As aforementioned, there are three investigated sites across the city of Banda Aceh. These three sites (#A, #B, and #C) are expected to represent the sub-surface of the city of Banda Aceh. Site#A is at the eastern part of the city. Site#B is at the centre of the city and is close to the downtown of Banda Aceh. The last one (Site#C) is located in the western part of the city.

The results of the site response analysis at all sites are summarized in Tables 2 to 4. The summarized results tabulate several vital parameters such as the peak ground acceleration (PGA), estimated fundamental frequency of the site, maximum spectral relative acceleration (SA), maximum spectral relative velocity (SV), and max spectral relative displacement (SD).

Table 2. Results of site-specific ground response analysis at Site#A.

Parameters	**2012 Simeulue II**	**2013 Mane-Geumpang**	**2013 Bener Meriah**
PGA (g)	0.061	0.072	0.031
Fundamental frequency (Hz)	0.6	0.6	0.6

Table 3. Results of site-specific ground response analysis at Site#B.

Parameters	**2012 Simeulue II**	**2013 Mane-Geumpang**	**2013 Bener Meriah**
PGA (g)	0.07	0.06	0.020
Fundamental frequency (Hz)	0.6	0.6	0.6

The peak ground acceleration (PGA) results are 0.049 – 0.07g for 2012 Simeulue II earthquake, 0.06 – 0.072g for 2013 Mane-Geumpang earthquake, and 0.020 – 0.31g for 2013 Bener Meriah seismic event. The PGA of the seismic events varies across the investigated sites. At the Site#A the highest PGA at this site was caused by the 2013 Mane-Geumpang seismic event (0.07g). At the Site#B the highest PGA of about 0.7g was triggered by the 2012 Simuelue earthquake. At the Site#C the highest PGA (approximately 0.06g) was produced by the 2013 Mane-Geumpang earthquake. The profiles of the PGA at all investigated sites are shown in Figures 5 to 7. Also, the estimated fundamental frequency of all studied sites is about 0.6 Hz.

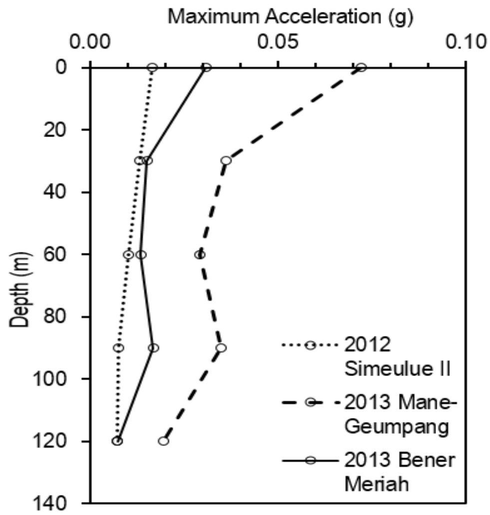

Fig. 5. PGA profiles of site response analysis at Site#A.

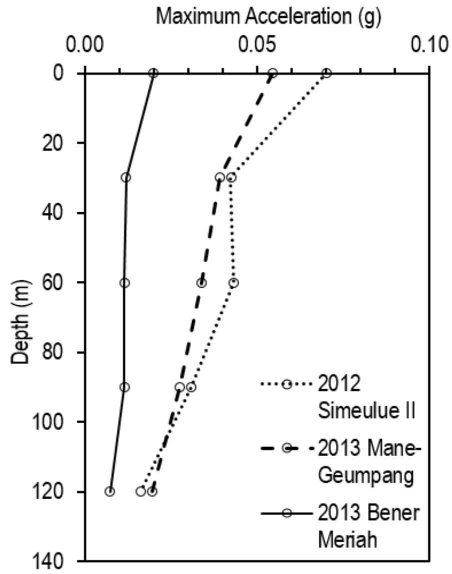

Fig. 6. PGA profiles of site response analysis at Site#B.

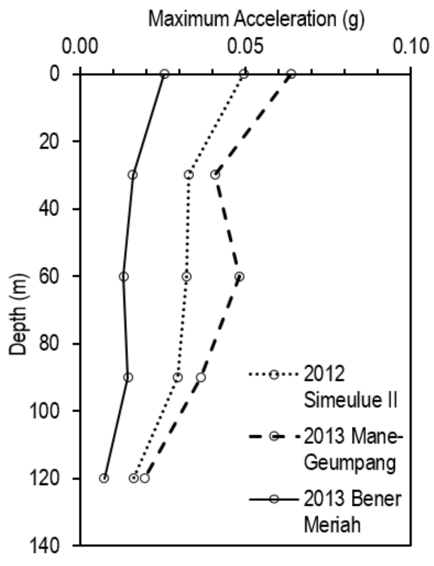

Fig. 7. PGA profiles of site response analysis at Site#C.

https://doi.org/10.1051/matecconf/201819710002

Table 4. Results of site-specific ground response analysis at Site#C.

Parameters	**2012 Simeulue II**	**2013 Mane-Geumpang**	**2013 Bener Meriah**
PGA (g)	0.049	0.064	0.025
Fundamental frequency (Hz)	0.6	0.6	0.6

Seismic site amplification in this study is estimated using a comparison between the maximum acceleration of the top surface and the maximum acceleration at bedrock level. The results of all the investigated sites are shown in Figures 8 to 10. These profiles are used to deduce the amplification factor at the investigated site. The results indicate an amplification factor at the ground surface level for Site#A of up to 4.2, Site#B of up to 4.3 and Site#C of up to 3.5.

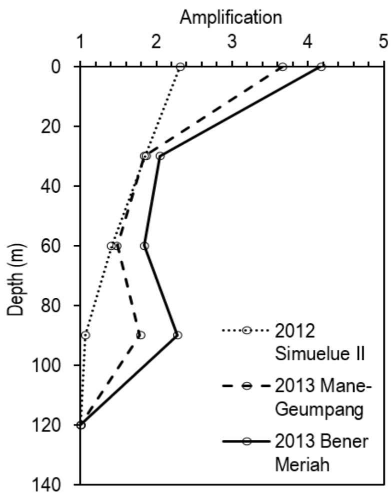

Fig. 8. Amplification profiles of site response analysis at Site#A.

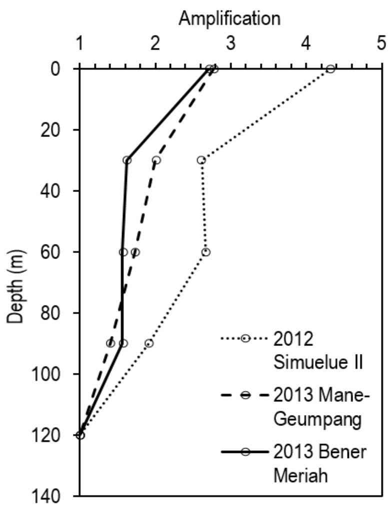

Fig. 9. Amplification profiles of site response analysis at Site#B.

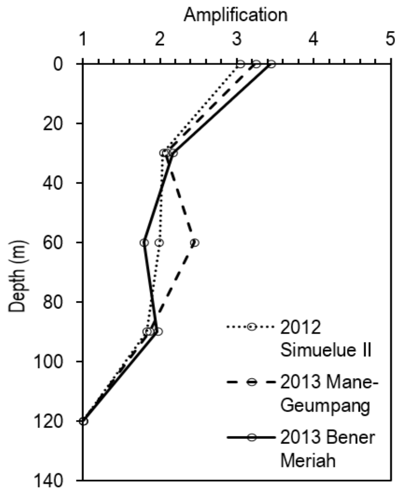

Fig. 10. Amplification profiles of site response analysis at Site#C.

4 Discussion

As aforementioned, there are three investigated sites across the city of Banda Aceh. These three sites (Site#A, Site#B, and Site#C).

This work estimates the fundamental frequency of all investigated sites of about 0.6 Hz. This site fundamental frequency is important for building seismic resistant design [17]; [18]. The building fundamental frequency, f_B can be approximated using an Equation 1, as suggested by [19].

$$f_B = \frac{10}{N} \tag{1}$$

The Banda Aceh's building frequency is estimated between 2 and 10 Hz (N is the number of building story). A resonance effect occurs when the building frequency is close or equal to the ground frequency. This resonance will increase the building vibration during a seismic event and enhanced the likelihood of structural collapse and hence human injury and fatalities. Overall, the results of the site response analysis of this study suggest a fundamental frequency of 0.6 Hz for all investigated sites, which can significantly amplify the medium-rise to high-rise buildings throughout the city.

Implementing the findings of this study into government policy to strengthen the mitigation efforts for emerging world context won't be an easy task. One of the main challenges for implementing government policy is the need to design a policy that is not only effective in achieving the objectives but is also acceptable to the public [20]. Exceptional examples of work in considering cultural, socioeconomic and the role of public attitudes into public policy are systematically discussed in the previous studies by [21], [22], [23].

5 Conclusions

In term of seismicity, the city of Banda Aceh is potentially exposed to a significant seismic hazard. Estimation of seismic site amplification of the city is urgently required for any mitigation efforts considering the future unpredicted seismic event and seismic site amplification. Analytical models have demonstrated that they can simulate reasonably well the seismic ground motions amplification. This study focuses on Banda Aceh-Indonesia which is founded on thick alluvium. Three actual historical time and three developed sub-surface models across the city were used to estimate the seismic site amplification of Banda Aceh's soft soil. The site response analysis results reveal the ground motions amplification of Banda Aceh's soils of up to 4.3. Thus, applying the seismic site amplification for structural design at Banda Aceh can be further works.

The authors wish to acknowledge the Syiah Kuala University for providing a research funding (Contract No. 154/UN11.2/PP/PNPB/SP3/2018). Also, the authors are grateful to the Faculty of Engineering of Syiah Kuala University for their support.

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