Probabilistic Seismic Hazard Analysis and Site Characterization of a Powerplant Site in Chittagong, Bangladesh

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Abstract

In the present study, the Probabilistic Seismic Hazard Analysis (PSHA) has been carried out for a powerplant site in Chittagong using the latest available information on seismicity in the region. The latest updated earthquake catalog homogenized in uniform moment magnitude scale was prepared. Seismicity analysis was carried out, and the seismicity parameters for the region were estimated from the frequency magnitude distribution plot. The peak ground acceleration (PGA) and the spectral acceleration at the bedrock for 10% and 2% probability of exceedance within 50 years were evaluated using different source models and attenuation relations in a logic tree framework. The site was characterized based on the soil investigation data from 31 boreholes and amplification factors considering the local geology (SPT-N values) were obtained through ground response analysis. Subsequently, the surface level peak ground acceleration was estimated and depicted in the form of hazard contour maps.

1. Introduction

Chittagong is one of the major cities in Bangladesh, having a significant impact on the economy of the country. Since the south-western region of Bangladesh lies in the active-tectonic region, it has experienced many large earthquakes in its history. Recently, a 225 MW combined cycle powerplant was commissioned at Sikalbaha, Chittagong. A powerplant is an essential structure that powers various sectors of the economy, hence its safety must be assured from natural disasters like earthquakes. Due to the uncertainty associated with the occurrence of an earthquake, the only preventive and precautionary measure to avoid structural damage is to carry out seismic hazard studies. The probabilistic seismic hazard analysis is the most advanced method of determining the ground motion characteristics and its associated risk. The uncertainties like the location, magnitude, and recurrence interval of an earthquake are considered in the methodology of PSHA. In the survey conducted by Goda et al. (2015) after the 2015 Nepal earthquake, it was observed that the local geology had a significant impact on the building collapse pattern. In a particular area, which had alluvial and Pleistocene soil deposits a few hundred meters apart, the number of buildings that collapsed or were severely damaged was twice in number in the alluvial deposit than the Pleistocene deposit. Furthermore, liquefaction and differential settlement of structures was also detected close to this region. This indicates the amplification of the ground motion characteristics due to the local site conditions. Historically, similar observation has been made in the 1985 Mexico earthquake, 1989 Loma Prieta earthquake, and 2001 Bhuj earthquake among many others. The liquefaction potential study of the Sikalbaha powerplant site conducted by Sengupta and Kolathayar (2020) through a deterministic approach indicated a high susceptibility to liquefaction in the region. However, they depended on the amplification factor derived from a broad NEHRP site classification.

The proximity to the convergent boundary of the Indian and Eurasian plates is one of the critical reasons for the high seismicity around the region (Morino et al. 2014, 2016; Steckler et al. 2016). There is also a significant prevalence of non-engineered construction and poor urban planning, along with a high population density. These factors escalate the seismic hazard in the region drastically, creating a need for precise knowledge of the ground motion parameters. Several researchers have carried out seismic hazard

studies for this purpose (Bhatia et al. 1999; Al-hussaini and Al-noman 2010; Trianni et al. 2014, Al-hussaini et al. 2015; Das et al. 2016; Khan et al. 2018; Rahman et al. 2018). Bhatia et al. (1999) performed the probabilistic seismic hazard analysis of India and the adjoining regions (from 0°N-40°N and 65°E-100°E) under the Global Seismic Hazard Assessment Program (GSHAP). Al-hussaini and Al-noman (2010) also performed the seismic hazard analysis with a probabilistic approach, employing several GMPEs. However, these GMPEs were not incorporated in a logic tree framework, which leaves the possibility of epistemic uncertainties. A probabilistic seismic hazard study to estimate the possible seismic risk along an oil pipeline in the Bay of Bengal was carried out by Trianni et al. (2014). Al-hussaini et al. (2015) conducted a review study of the previous seismic hazard studies of Bangladesh. They also performed the neo-deterministic seismic hazard analysis (NDSHA) and compared it to the previous SHA results. Das et al. (2016) estimated the probabilistic seismic hazard for a 100-year, 225-year, 475-year, 2475-year, and 10000-year return period for the north-east region of India, which also covered Bangladesh. Khan et al. (2018) performed the probabilistic seismic hazard assessment using a logic tree framework while also incorporating the Vs30 values over the entire country. Conversely, employing Vs30 results for such a vast region is deemed to produce conservative results due to the discontinuity and lack of sample data points in the area. The seismic zonation map of Bangladesh, as illustrated by the Bangladesh National Building Code (BNBC-2017) is based on the maximum credible earthquake (MCE), with a 2475-year return period, i.e. 2% probability of exceedance in 50 years. Using this, design basis earthquake (DBE) can be found, which is 2/3 of the MCE and is equivalent to a ground motion with a 475-year return period or 10% probability of exceedance in 50 years. According to the standard, a PGA value of 0.19g has been stipulated to Chittagong city.

There are several site response studies reported in the literature for different regions across the globe to estimate surface level seismic hazard and the application of site response analysis are popular in recent studies as well due to its critical importance (Derras et al., 2020; Régnier et al., 2020; Adampira and Derakhshandi, 2020; Pavel et al., 2020; Guzel et al., 2020; Kakhki et al., 2020). However, it can be observed that there is a lack of implementation of the site-specific soil data in the evaluation of ground motion parameters in the Chittagong region. Hence, an attempt has been made to evaluate the seismic hazard of a newly developed powerplant site in Chittagong, employing a probabilistic approach and considering the local geology of the region.

2. Study Area

Chittagong (Fig. 1) is the second most important city in Bangladesh, after the capital Dhaka. It has military and economic importance due to the presence of the busiest ports in the country. In 2017, a 225 MW combined cycle powerplant was commissioned in Sikalbaha, Chittagong. It lies along the banks of the Karnaphuli River in the north and is surrounded by other industrial establishments. The plant site lies within 22.323° N and 22.327° N latitudes and 91.863° E and 91.87° E longitudes.

According to the study conducted by Rahman et al. (2016), Chittagong primarily comprises sandstone, shale, and siltstones in its underlying geology. The city lies on the western edge of the Tripura-Chittagong

folded belt, which is made up of several parallels and sub-parallel plunging folds (Fig. 2). The major faults present in the city are the Sitakunda fault which cuts by the Karnaphuli River, the Tiger pass fault which runs along the NE-SW direction, and crosses the Karnaphuli fault almost orthogonally (Muminullah 1978). Khan and Chouhan (1996) suggested that the majority of the seismic events in the region are caused due to the subduction of the Bengal Basin region into the Burmese subplate.

3. Estimation Of Seismic Hazard

3.1 Earthquake data processing

A detailed and comprehensive earthquake catalog is an essential prerequisite to any seismic hazard assessment. The earthquake catalog for this study was obtained from the United States Geological Survey (USGS). Due to the non-uniformity of magnitude scales prevalent in such catalogs, they are homogenized to the moment magnitude scale (M_w) before any further analysis. The process of homogenization was performed using the relations proposed by Scordilis et al. (2006), as mentioned below.

$$M_w = 0.67(\pm 0.005) M_s + 2.07(\pm 0.03) \text{ (for } 3.0 \leq M_s \leq 6.1 \text{)}$$

$$M_w = 0.99(\pm 0.02) M_s + 0.08(\pm 0.13) \text{ (for } 6.2 \leq M_s \leq 8.2 \text{)}$$

$$M_w = 0.85(\pm 0.04) m_b + 1.03(\pm 0.23) \text{ (for } 3.5 \leq m_b \leq 6.2 \text{)}$$

The earthquake events of magnitude $M_w \geq 4$, in the past 120 years, i.e. 1900 to 2020 within a radius of 500 km from the site are included in the catalog. Since the earthquake events are independent and obey the Poisson distribution, the insignificant foreshock and aftershock events have to be removed. These extraneous events were removed by the process of declustering using the Reasenberget al. (1985) algorithm, which is incorporated in Z-Map (Wiemer et al. 2001). Eleven clusters (42 out of 1844 events) were found and 1813 main events of $M_w \geq 4$ in the period were finally obtained from the raw data (Fig. 3).

The completeness of the catalog was analyzed using the maximum likelihood method (Bender 1983; Aki 1965; Utsu 1999). According to this method, the earthquake events greater than the magnitude of completeness (M_c) are used to determine the 'a' and 'b' values (Gutenberg and Richter 1954). The magnitude of completeness is the minimum magnitude above which it can be reliably considered that the earthquake catalog is comprehensive. The b-value can be estimated by the relation given by the maximum likelihood method:

$$b = \frac{\log_{10}(e)}{[m_{\text{mean}} - (M_c - \frac{\Delta m_{\text{bin}}}{2})]}$$

Where Δm_{bin} is the bin size of the magnitude, M_c is the magnitude of completeness, and the m_{mean} is the average magnitude of the catalog. One of the most popular methods to estimate M_c is the power-law curve fit of the frequency-magnitude distribution (FMD) plot, as suggested by Wiemar and Wyss (2000). The increment of the magnitude values or the bin size used in this study is 0.1. Figure 4 shows the frequency-magnitude distribution for the catalogue along with the M_c value. The seismicity parameters for the region were estimated as $a = 8.657$ and $b = 1.21 \pm 0.04$.

3.2 Ground motion prediction equations (GMPE)

The ground motion models for this region are yet to be developed. Since the plant site lies in the active tectonic region, GMPEs developed for active tectonic regions in other countries have been used to evaluate the seismic hazard. Attenuation models by Ghasemi et al. (2009) (GHAS 2009), Boore and Atkinson (2008) (BOAT 2008), Akkar and Bommer (2010) (AKBO 2010), and Sharma et al. (2009) (SHAR 2009) were considered to evaluate the hazard. The GMPE developed by Ghasemi et al. (2009) was developed for the active tectonic regions of Iran, and the relation by Akkar and Bommer (2010) was for the active tectonic regions of Europe and the Middle East. Sharma et al. (2009) developed a GMPE for the Himalayan region, whereas, the relation by Boore and Atkinson (2008) was for the active tectonic regions all over the world. Ramkrishnan et al. (2019) and Ramkrishnan et al. (2020) presented GMPEs for the North and Northeastern Himalayas. However, they presented coefficients to estimate PGA only, and coefficients for spectral accelerations were missing. Hence they were not considered in the present study.

3.3 Seismic Hazard Assessment

The probabilistic seismic hazard analysis was carried out as per the procedure developed by Cornell (1968). This study has incorporated two seismic source models; a) linear source model and b) gridded seismicity model.

3.3.1 Linear Source Model

The linear sources of India and the adjoining regions have been illustrated in the Seismotectonic Atlas published by the Geological Survey of India (GSI) (Dasgupta et al. 2000). SEISAT contains the details of faults and other linear sources in and around Bangladesh as well. It has been used as a credible source of information for faults, shear zones, lineaments, and geological features by various researchers in the past. Iyengar and Ghosh (2004) had used it for their seismic hazard study of Delhi, Raghukant and Iyengar (2006) for Mumbai, Anbazhagan et al. (2009) for Bangalore, and Vipin et al. (2009) for South India. The map was first digitized, and the declustered events are layered on top of it in GIS software. The number of earthquake events and the maximum magnitude for each source were recorded. In case an event is within 15 kilometers of more than one source, then the event is considered for the source having the least distance to the event epicenter. One significant limitation of the linear source model is that some of the events do not fall within the range of any fault. To overcome this shortcoming of the model, another seismic model proposed by Frankel (1995) is implemented in the logic tree.

3.3.2 Gridded Seismicity Model

The gridded seismicity model or the zoneless approach is used to overcome the above-mentioned limitations of the linear source model. It also takes into account the inadequacy of the seismotectonic atlas in the case of the presence of hidden faults (Frankel 1995; Woo 1996; Martin et al. 2002). This method has been widely used in many research studies like Wahlstrom and Grunthal (2000); Lapajne et al. (2003); Jaiswal and Sinha (2007); Kalkan et al. (2009); Menon et al. (2010); Sitharam and Vipin (2011); Kolathayar and Sitharam (2012); Sitharam et al. (2015). In this model, the entire area is divided into several grids, and the number of events above a certain threshold magnitude is counted (M_{cut}). The recurrence interval of each magnitude range is noted, which is then smoothed using a Gaussian function to obtain the final activity of that grid cell. In this study, grids of $0.1^\circ \times 0.1^\circ$ were considered, and a threshold magnitude of $M_w = 4.0$ was chosen. Smoothing is done by the equation:

$$\hat{n}_i = \frac{\sum_j n_j e^{-\Delta_{ij}^2 / c^2}}{e^{-\Delta_{ii}^2 / c^2}}$$

where $\hat{n}_i$ is the smoothed number of events in the i -th grid, n_j is the number of events in the j -th grid, Δ_{ij} is the distance between the i -th and j -th cell and c is the correlation distance to be considered for location uncertainties.

3.3.3 Logic Tree Structure

To address the issue of epistemic uncertainty, the Logic tree framework was implemented to minimize errors (Bommer et al. 2005; Budnitz et al. 1997; Stepp et al. 2001). A logic tree is a branched structure that presents different models at each node. Appropriate weights are allocated at each node, with the condition that the sum of all the weights at a node should be unity. In the present study, the main factors of the logic tree are a) different seismic sources; b) evaluation of the maximum earthquake magnitude, and c) chosen GMPEs in the study.

In this investigation, both the seismicity models are equally relevant; hence a weightage of 0.5 has been assigned to both. The maximum earthquake magnitude is calculated using two approaches. For the linear source model: 1) the actual observed maximum magnitude and 2) the actual maximum magnitude plus 0.5; whereas for the gridded seismicity model: 1) the actual observed maximum magnitude and 2) the maximum magnitude obtained from the process described by Kijko (2004). Both these approaches were given equal weights in the logic tree. Figure 5 shows the final logic tree structure.

4. Local Site Effects

Local geology has a significant impact on the ground motion characteristics obtained at the bedrock level. Since the area of interest in the study is quite small, it was possible to take the standard penetration test (SPT-N values) results into consideration for evaluating the surface level PGA. The SPT values of all the boreholes were given as input in the DEEPSOIL software (Hashash et al. 2016), from which the

amplification factors for each borehole were obtained. On multiplying the bedrock PGA with the amplification factors, the surface PGA was evaluated. Figure 6 shows the plant area and the points where standard penetration measurements were taken. Figure 7a presents a summary of SPT N-values for BH 119 to BH 133. Figure 7b shows a typical bore log for the borehole 125, and also the corresponding variation of SPT-N value with depth.

In the DEEPSOIL program, a sample historic earthquake is given as the input motion to the software. In the case shown, the Kobe earthquake was given as the input to the program (Fig. 8). Following this, the software creates plots of several ground motion characteristics and in-situ soil properties. It also generates the response spectrum at the bedrock and the surface level. The PGA value of the surface is then divided by the PGA at the bedrock, i.e. 0.8g, which gives the amplification factor for that specific borehole. The ground response analyses were carried out for all the boreholes considering their soil properties. Sample analysis for a typical borehole (BH-125) is presented here. Figure 9 shows the Ground motion characteristics and in-situ soil properties generated by DEEPSOIL at BH-125. Figure 10 presents the response spectrum at bedrock (input motion) and surface-level (Layer 1) due to the Kobe earthquake input motion at BH-125. The amplification factors for all borehole locations were calculated through a similar analysis.

The above procedure was repeated for all the boreholes to develop a site amplification contour. Table 1 illustrates the location of each borehole in the site along with their amplification factors.

Table 1
Location of each borehole on the site along with the evaluated amplification factors

Borehole	Longitude	Latitude	Bedrock PGA (Input)	Surface PGA	Amp. Factor
119	91.869020	22.325716	0.80	0.52	0.65
130	91.868683	22.325521	0.80	0.84	1.05
125	91.868412	22.325389	0.80	0.86	1.08
120	91.869152	22.325484	0.80	0.80	1.00
126	91.86882	22.325108	0.80	0.80	1.00
121	91.869405	22.325283	0.80	1.00	1.25
127	91.869179	22.325094	0.80	0.98	1.23
128	91.869089	22.324998	0.80	1.04	1.30
129	91.868955	22.324845	0.80	0.64	0.80
123	91.869555	22.325092	0.80	0.87	1.09
124	91.869755	22.324870	0.80	0.88	1.10
132	91.869333	22.324835	0.80	0.75	0.94
133	91.869214	22.324693	0.80	0.82	1.03
114	91.866642	22.326350	0.80	0.28	0.35
115	91.866269	22.326110	0.80	0.28	0.35
117	91.86489	22.325582	0.80	0.34	0.43
103	91.867185	22.325906	0.80	0.28	0.35
101	91.866895	22.325609	0.80	0.18	0.23
102	91.866988	22.325504	0.80	0.42	0.53
116	91.866264	22.325764	0.80	0.23	0.29
112	91.866332	22.325500	0.80	0.40	0.50
118	91.866189	22.325263	0.80	0.46	0.58
109	91.866604	22.325371	0.80	0.52	0.65
104	91.867337	22.325689	0.80	0.44	0.55
106	91.867500	22.325721	0.80	0.16	0.20
105	91.867453	22.325622	0.80	0.32	0.40
107	91.867682	22.325389	0.80	0.16	0.20

Borehole	Longitude	Latitude	Bedrock PGA (Input)	Surface PGA	Amp. Factor
108	91.867186	22.325205	0.80	0.32	0.40
110	91.866748	22.325141	0.80	0.26	0.33
113	91.866548	22.324860	0.80	0.42	0.53
111	91.86691	22.324936	0.80	0.26	0.33

5. Results And Discussion

The probabilistic seismic hazard analysis was carried out by employing the logic tree framework as discussed above. Hazard contour maps were developed for 10% and 2% probability of exceedance in 50 years. Figure 11, 12 shows the bedrock peak ground acceleration contour maps for 475 and 2475 years return period respectively. A PGA value of about 0.11g was obtained for a return period of 475 years whereas, a value of 0.15g was obtained for 2475 years return period. Figure 13, 14 shows the spectral acceleration contour for the periods 0.1s and 1s for a return period of 475 years, and Fig. 15, 16 show for a return period of 2475 years. For the spectral acceleration of a 475-year return period, a PGA value of about 0.19g for 0.1s period and 0.04g for 1s period can be expected. In the case of a 2475-year return period, a PGA value of 0.29g for 0.1s period and 0.06g for 1s period can be anticipated. From all the maps a general observation can be made that, the bedrock PGA is fairly uniform over the entire powerplant site area. Table 2 provides a comparison between the results of this study with previous investigations and available codal provisions. From the table, it can be established that the results of this study are accurate.

Table 2
Comparison of the bedrock PGA from previous studies and the present analysis

Study	Method	PGA reported for Chittagong City (g)
Present Study	PSHA	0.15
Bhatia et al. 1999	PSHA	0.15
Al-hussaini and Al-noman (2010)	PSHA	0.18
Trianni et al. (2014)	PSHA	0.13
Das et al. (2016)	PSHA	0.15
BNBC (2017)	PSHA	0.19

Figure 17 shows the variation of the amplification factor over the entire site, which was obtained from the results of the DEEPSOIL analyses of 31 borehole sites (Table 1). From this, the surface level PGA was obtained for a 475 and 2475 years return period (Fig. 18, 19). On comparison of the obtained PGA values with those stipulated by the BNBC-2017 (0.19g), it can be concluded that the PGA values specified by code match fairly well. However, a site-specific study is always advisable in the case of important

structures such as a powerplant in this case, since the local geology has a very significant impact on the strong ground motion.

6. Conclusion

The probabilistic seismic hazard analysis of a powerplant site at Sikalbaha, Chittagong was carried out using the Cornell-McGuire approach using multiple seismic source models and GMPEs. The analysis was carried out with the most recent data, and a tool such as a logic tree was implemented to rule out epistemic uncertainties. It was found that a bedrock PGA of 0.11g can be expected for a return period of 475 years and 0.15g for a return period of 2475 years at the power plant site. The results were also found to be in fair agreement with previous studies and recent codal provisions.

Based on the soil investigation data available from 31 boreholes, detailed ground response analyses were carried out for all the borehole locations. It was found that the spatial variation of the soil profile was significant, and hence the amplification factors too varied across the site. The estimated hazard at the bedrock level was brought to the ground level using the amplification factors for different locations at the site. The surface level PGA for return periods of 475 years and 2475 years were found to be as high as 0.12g and 0.18g respectively in the north-eastern part of the site. Unlike the variation of bedrock level PGA, which had a uniform spatial variation, the surface level PGA varies significantly at different locations. This indicates that the effect of amplification is profound at the site. Geological surveys are required to improve the existing fault data, and further studies should be done to develop region-specific attenuation relations.

Declarations

Data and Resources

Earthquake event data used in the present work were collected from the following sources

<http://www.iris.edu/>, last accessed August, 2021,

<https://seismo.gov.in/> last accessed August, 2021,

<https://earthquake.usgs.gov/earthquakes/search/> last accessed August, 2021

All other data used in this paper came from the published sources given in the reference section.

Data Availability

The datasets analysed during the current study are available from the corresponding author on reasonable request.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

References

1. Aki K (1965) Maximum likelihood estimate of b in the formula $\log N = a - bM$ and its confidence limits. *Bull Earthq Res Inst Tokyo Univ* 43:237–239
2. Akkar S, Bommer JJ (2010) Empirical equations for the prediction of PGA, PGV, and spectral accelerations in Europe, the Mediterranean region, and the Middle East. *Seismol Res Lett* 81(2):195–206
3. Al-Hussaini TM, Al-Noman MN (2010) Probabilistic Estimates of PGA and Spectral Acceleration in Bangladesh. In: *Proceedings of 3rd international earthquake symposium*. Dhaka, Bangladesh, pp 473–480
4. Al-Hussaini TM, Chowdhury IN, Noman MN (2015), December Seismic hazard assessment for Bangladesh-old and new perspectives. In *First International Conference on Advances in Civil Infrastructure and Construction Materials* (pp. 841–856). Military Institute of Science & Technology
5. Anbazhagan P, Thingbaijam KKS, Nath SK, Kumar JN, Sitharam TG (2010) Multi-criteria seismic hazard evaluation for Bangalore city, India. *J Asian Earth Sci* 38(5):186–198
6. Bender B (1983) Maximum likelihood estimation of b values for magnitude grouped data. *Bull Seismol Soc Am* 73(3):831–851
7. Bhatia SC, Kumar MR, Gupta HK (1999) A probabilistic seismic hazard map of India and adjoining regions. *Ann Geofis* 42:1153–1164. <https://doi.org/10.4401/ag-3777>
8. BNBC (2017) Bangladesh national building code. *Hous Build Res Inst* 3:301–312
9. Bommer JJ, Scherbaum F, Bungum H, Cotton F, Sabetta F, Abrahamson NA (2005) On the use of logic trees for ground-motion prediction equations in seismic-hazard analysis. *Bull Seismol Soc Am* 95(2):377–389
10. Boore DM, Atkinson GM (2008) Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthq Spectra* 24(1):99–138
11. Budnitz RJ, Apostolakis G, Boore DM (1997) *Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and use of experts* (No. NUREG/CR-6372-Vol. 1; UCRL-ID-122160). Nuclear Regulatory Commission, Washington, DC (United States). Div. of Engineering Technology; Lawrence Livermore National Lab., CA (United States); Electric Power Research Inst., Palo Alto, CA (United States); USDOE, Washington, DC (United States)
12. Cornell CA (1968) Engineering seismic risk analysis. *Bull Seismol Soc Am* 58(5):1583–1606

13. Das R, Sharma ML, Wason HR (2016) Probabilistic seismic hazard assessment for northeast India region. *Pure Appl Geophys* 173:2653–2670. <https://doi.org/10.1007/s00024-016-1333-9>
14. Dasgupta S, Pande P, Ganguly D, Iqbal Z, Sanyal K, Venkatraman NV, Dasgupta S, Sural B, Harendranath L, Mazumdar K, Sanyal S, Roy A, Das LK, Misra PS, Gupta H et al (2000) Seismotectonic Atlas of India and its Environs. *Geol. Surv. India, Calcutta*
15. Derras B, Bard PY, Régnier J, Cadet H (2020) Non-linear modulation of site response: Sensitivity to various surface ground-motion intensity measures and site-condition proxies using a neural network approach. *Eng Geol* 269:105500
16. Frankel A (1995) Simulating strong motions of large earthquakes using recordings of small earthquakes: the Loma Prieta mainshock as a test case. *Bull Seismol Soc Am* 85(4):1144–1160
17. Ghasemi H, Zare M, Fukushima Y, Sinaeian F (2009) Applying empirical methods in site classification, using response spectral ratio (H/V): A case study on Iranian strong motion network (ISMN). *Soil Dyn Earthq Eng* 29(1):121–132
18. Goda K, Kiyota T, Pokhrel RM, Chiaro G, Katagiri T, Sharma K, Wilkinson S (2015) The 2015 Gorkha Nepal earthquake: insights from earthquake damage survey. *Front Built Environ* 1:8
19. Gutenberg B, Richter CF (1954) *Seismicity of the earth and associated phenomena*, 2nd edn. Princeton University Press, Princeton, p 310
20. Guzel Y, Rouainia M, Elia G (2020) Effect of soil variability on nonlinear site response predictions: Application to the Lotung site. *Comput Geotech* 121:103444
21. Hashash YMA, Musgrove MI, Harmon JA, Groholski DR, Phillips CA, Park D (2016) DEEPSOIL 6.1, User Manual. Board of Trustees of University of Illinois at Urbana-Champaign, Urbana, IL
22. Iyengar RN, Ghosh S (2004) Microzonation of earthquake hazard in greater Delhi area. *Curr Sci* 87(9):1193–1202
23. Jaiswal K, Sinha R (2007) Probabilistic seismic-hazard estimation for peninsular India. *Bull Seismol Soc Am* 97(1B):318–330
24. Kakhki MK, Peters FC, Mansur WJ, SadidKhoii A, Rezaei S (2020) Deciphering site response directivity in landslide-prone slopes from ambient noise spectral analysis. *Eng Geol* 269:105542
25. Kalkan Erol G, Polat Y, Nazan, C, elebi Mehmet (2009) Reassessment of probabilistic seismic hazard in the Marmara Region. *Bull Seismol Soc Am* 99(4):2127–2146
26. Kanth SR, Iyengar RN (2006) Seismic hazard estimation for Mumbai city. *Current Science*, 1486–1494
27. Khan AA, Chouhan RKS (1996) The crustal dynamics and the tectonic trends in the Bengal Basin. *J Geodyn* 22(3–4):267–286
28. Khan NW, Haque DME, Selim M, Kamal DAS (2018) M. M. Towards Improved Probabilistic Seismic Hazard Assessment for Bangladesh. *AGUFM, 2018*, T13I-0349
29. Kijko A (2004) Estimation of the maximum earthquake magnitude, m_{max} . *Pure appl Geophys* 161(8):1655–1681

30. Kolathayar S, Sitharam TG (2012) Comprehensive probabilistic seismic hazard analysis of the Andaman–Nicobar regions. *Bull Seismol Soc Am* 102(5):2063–2076
31. Lapajne J, Motnikar BS, Zupancic P (2003) Probabilistic seismic hazard assessment methodology for distributed seismicity. *Bull Seismol Soc Am* 93(6):2502–2515
32. Martin C, Secanell R, Combes Ph, Lignon G (2002) Preliminary probabilistic seismic hazard assessment of France. In: 12th European conference on earthquake engineering, Paper Ref. 870, Elsevier Science Ltd
33. Menon A, Ornthammarath T, Corigliano M, Lai CG (2010) Probabilistic seismic hazard macrozonation of Tamil Nadu in Southern India. *Bull Seismol Soc Am* 100(3):1320–1341
34. Morino, M., Kamal, A. M., Akhter, S. H., Rahman, M. Z., Ali, R. M. E., Talukder, A.,... Kaneko, F. (2014). A paleo-seismological study of the Dauki fault at Jaflong, Sylhet, Bangladesh: Historical seismic events and an attempted rupture segmentation model. *Journal of Asian Earth Sciences*, 91, 218–226
35. Morino M, Kamal AM, Muslim D, Ali RME, Kamal MA, Rahman MZ, Kaneko F (2011) Seismic event of the Dauki Fault in 16th century confirmed by trench investigation at Gabrakhari Village, Haluaghat, Mymensingh, Bangladesh. *J Asian Earth Sci* 42(3):492–498
36. Muminullah M (1978) Geology of the northern part of Chittagong district, Bangladesh. Geological Survey of Bangladesh, Government of the People's Republic of Bangladesh
37. Pavel F, Vacareanu R, Pitilakis K, Anastasiadis A (2020) Investigation on site-specific seismic response analysis for Bucharest (Romania). *Bull Earthq Eng* 18(5):1933–1953
38. Reasenbergs P (1985) Second-order moment of central California seismicity, 1969–1982. *J Geophys Res: Solid Earth* 90(B7):5479–5495
39. Régnier J, Bertrand E, Cadet H, Derakhshandi M (2020) (2020). Influence of a layered liquefiable soil on seismic site response using physical modeling and numerical simulation. *Engineering Geology*, 266, 105462
40. Scordilis EM (2006) Empirical global relations converting M_S and m_b to moment magnitude. *J Seismolog* 10(2):225–236
41. Sengupta S, Kolathayar S (2020) Evaluation of Liquefaction Potential of Soil at a Power Plant Site in Chittagong, Bangladesh. *Int J Geotech Earthq Eng (IJGEE)* 11(1):1–16
42. Sharma ML, Douglas J, Bungum H, Kotadia J (2009) Ground-motion prediction equations based on data from the Himalayan and Zagros regions. *J Earthquake Eng* 13(8):1191–1210
43. Sitharam TG, Vipin KS (2011) Evaluation of spatial variation of peak horizontal acceleration and spectral acceleration for south India: a probabilistic approach. *Nat Hazards* 59(2):639
44. Sitharam TG, Kolathayar S, James N (2015) Probabilistic assessment of surface level seismic hazard in India using topographic gradient as a proxy for site condition. *Geosci Front* 6(6):847–859
45. Steckler MS, Stein S, Akhter SH, Seeber L (2018) of EARTHQUAKE HAZARD in DEVELOPING COUNTRIES. *Eos*.

46. Stepp, J. C., Wong, I., Whitney, J., Quittmeyer, R., Abrahamson, N., Toro, G., ... Yucca Mountain PSHA Project Members. (2001). Probabilistic seismic hazard analyses for ground motions and fault displacement at Yucca Mountain, Nevada. *Earthquake Spectra*, 17(1), 113–151
47. Trianni SCT, Lai CG, Pasqualini E (2014) Probabilistic seismic hazard analysis at a strategic site in the Bay of Bengal. *Nat Hazards* 74:1683–1705. <https://doi.org/10.1007/s11069-014-1268-3>
48. Utsu T (1999) Representation and analysis of the earthquake size distribution: a historical review and some new approaches. *Seismicity Patterns, their Statistical Significance and Physical Meaning*. Birkhäuser, Basel, pp 509–535
49. Vipin KS, Anbazhagan P, Sitharam TG (2009) Estimation of peak ground acceleration and spectral acceleration for South India with local site effects: probabilistic approach. *Nat Hazards Earth Syst Sci* 9(3):865
50. Wahlström R, Grünthal G (2000) Probabilistic seismic hazard assessment (horizontal PGA) for Sweden, Finland and Denmark using different logic tree approaches. *Soil Dyn Earthq Eng* 20(1–4):45–58
51. Wiemer S, Wyss M (2000) Minimum magnitude of complete reporting in earthquake catalogs: examples from Alaska, the Western United States, and Japan. *Bull Seismol Soc Am* 90:859–869
52. Wiemer S (2001) A software package to analyze seismicity: ZMAP. *Seismol Res Lett* 72(3):373–382
53. Woo G (1996) Kernel estimation methods for seismic hazard area source modeling. *Bull Seismol Soc Am* 86(2):353–362

Figures

Figure 1

Map showing the city of Chittagong with important locations

Figure 2

Major faults and geological features in and around Bangladesh (Khan and Chouhan 1996)

Figure 3

All linear seismic sources along with declustered earthquake events within a radius of 500 km from the site

Figure 4

Frequency-Magnitude Distribution plot depicting the magnitude of completeness

Figure 5
 Logic Tree Framework

Figure 6

Powerplant area (unshaded area) along with points where SPT tests were conducted

Figure 7

- a. Summary of SPT N-values for BH 119 to BH 133
- b. Soil bore log with its SPT-N value profile for a typical borehole (BH 125) at the site

Figure 8

Ground motion characteristics of the Kobe earthquake

Figure 9

Ground motion characteristics and in-situ soil properties generated by DEEPSOIL at BH-125

Figure 10

Response spectrum at bedrock (input motion) and surface-level (Layer 1) due to the Kobe earthquake input motion at BH-125

Figure 11

PGA contour for a 475-year return period

Figure 12

PGA contour for a 2475-year return period

Figure 13

Sa contour at 0.1s for a 475-year return period

Figure 14

S_a contour at 1s for a 475-year return period

Figure 15

S_a contour at 0.1s for a 2475-year return period

Figure 16

S_a contour at 1s for a 2475-year return period

Figure 17

Spatial variation of site amplification factors

Figure 18

Surface PGA contour for a 475-year return period

Figure 19

Surface PGA contour for a 2475-year return period