Probabilistic Seismic Hazard Analysis for Offshore Bangladesh Including Fault Sources

Brian D. Carlton, Ph.D.,[1] Elin Skurtveit, Ph.D.,[2] Bahman Bohloli, Ph.D.,[3] Kuvvet Atakan, Ph.D.,[4] Emily Dondzila, P.E.,[5] and Amir M. Kaynia, Ph.D.[6]

[1]Norwegian Geotechnical Institute, Oslo, Norway; e-mail: brian.carlton@ngi.no
[2]Norwegian Geotechnical Institute, Oslo, Norway; email: elin.skurtveit@ngi.no
[3]Norwegian Geotechnical Institute, Oslo, Norway; email: bahman.bohloli@ngi.no
[4]University of Bergen, Bergen, Norway; email: kuvvet.atakan@uib.no
[5]Excelerate Energy, The Woodlands, TX, USA; e-mail: emily.dondzila@excelerateenergy.com
[6]Norwegian Geotechnical Institute, Oslo, Norway; and Norwegian University of Science and Technology, Trondheim, Norway; email: amir.m.kaynia@ngi.no

ABSTRACT

This paper presents the methodology and results of a probabilistic seismic hazard analysis (PSHA) for a site offshore Maheshkhali Island, Bangladesh. The tectonic setting of the area is complex, and the PSHA includes active crustal faults, megathrust and intraplate subduction faults, as well as a background gridded seismicity areal source zone based on historical and recorded seismicity. Previous studies only included areal source zones based on recorded seismicity, whereas this study takes advantage of recent publications to include faults sources in the PSHA. The peak ground acceleration values for return periods of 475 years and 2475 years are 0.33 g and 0.63 g, respectively. The deaggregation plots show that the main contributors to the hazard are a magnitude 6.5-7.1 earthquake 15-20 km from the site on the Maheshkhali fault and a magnitude 8.0-8.8 earthquake 120-250 km from the site on the Ramree megathrust.

INTRODUCTION

Bangladesh is building its first floating liquefied natural gas (LNG) import terminal off Maheshkhali Island in the Bay of Bengal (see Figure 1). The LNG import terminal will be composed of a floating storage and regasification unit (FSRU) connected to shore through an approximately 7.5 km long pipeline. The FSRU will be held in place by anchors attached to the seafloor.

This paper presents the methodology and results of a probabilistic seismic hazard analysis (PSHA) for the location of the FSRU anchors. We performed all of the PSHA calculations using the computer program HAZ45.2 developed by Professor Norman Abrahamson and coworkers. This program implements the PSHA methodology developed principally by Cornell (1968) and refined by McGuire (1978).

We first provide an overview of the tectonic setting of the study area and identify all relevant earthquake sources. We then describe the source characterization based on recorded and historical earthquake events as well as geologic, geodetic, and seismic data. The following section summarizes the ground motion prediction models used in the PSHA for the different source types. Finally, we present the results of the PSHA, including hazard curves, deaggregation plots, and uniform hazard spectra (UHS).

TECTONIC SETTING

The dominant tectonic element near the site is the Sunda megathrust, which is an eastward subduction of oceanic crust under continental lithosphere. Wang et al. (2014) divide the Sunda megathrust into several different neotectonic domains. The site sits about 120 km north of the Ramree domain and on top of the Dhaka domain. The Ramree domain contains a thick accretionary wedge of sediments with clear evidence of right lateral strike-slip, suggesting a partitioning of dip-slip and strike-slip between the megathrust and the structures in the accretionary prism. The Dhaka domain is a wider belt of folded and thrusted sediments related to a low-angle subduction megathrust. In the eastern section of the Dhaka domain, the rapid propagation of a fold and thrust belt forms the 400 km wide Chittagong-Tripura fold belt (CTFB). In this region earthquakes show dextral or reverse faulting.

SOURCE IDENTIFICATION

Table 1 presents the source number, name, rupture mechanism, dip angle, down dip width (W), length (L), and depth to the top of the surface rupture (Z_{tor}) used in the PSHA. We modelled the background seismicity (source no. 1) as an areal source zone and the rest as faults. Sources 1-15 represent crustal earthquakes, sources 16-18 represent subduction zone megathrust earthquakes and sources 19-20 represent deep intraplate earthquakes. When there is more than one value in a column, all values were used with equal weight in the PSHA calculations using a logic tree framework. Figure 1 shows the location of each fault with respect to the site.

We characterized these sources based on an extensive literature review of the neotectonic activity of the area. The rupture mechanism, dip angle, length, and Z_{tor} values are mainly based on the interpretations of Wang et al. (2014), Steckler et al. (2016), Morino et al. (2014) and CDMP (2009). We calculated the down dip widths for the crustal faults using the magnitude width relations given by Wells and Coppersmith (1994) and Blaser et al. (2010). For the megathrust faults, we estimated down dip widths based on the magnitude width relation of Strasser et al. (2010) and the interpretation of Wang et al. (2014) with a cut-off depth of 40 km. We also calculated the widths of the intraplate sources from Wang et al. (2014), but with a starting depth of 40 km.

The areal background source (source no. 1) represents earthquakes that could occur in the top 40 km on faults not included in the analyses. In the western offshore region, these earthquakes are most likely to occur on splay faults in the Neogene sediments on top of the thrust fault. The splay faults are mostly reverse faults, but some are strike-slip. In the eastern onshore region, these earthquakes will most likely occur on blind reverse or strike slip faults in the CTFB.

Sources 2-15 include active crustal faults as defined by Wang et al. (2014) within a radius of 250 km from the site. Most of these are within the CTFB. The area is dominated by extensive N-S trending anticlines and synclines. Most of the faults are classified as anticlines and are treated as reverse and strike slip faults. The coastal zone covers several small active faults that are referred to as the Chittagong Costal Fault by Maurin and Rangin (2009) and Steckler et al. (2016). Further to the east most faults are considered inactive according to Wang et al. (2014). However, we included the Kaladan Fault complex as it is believed to be active by Maurin and Rangin (2009) and Steckler et al. (2016).

Table 1. Source characteristics, magnitude recurrence parameters and GMPE type

No.	Name	Mech	Dip	W	L	Z_{tor}	SR	M_{max}	f_m	GMPE
		-	(°)	(km)	(km)	(km)	(mm/yr)	-	-	-
1	Background	RV, SS	45, 90	10, 20, 30	na	3	na	6.0, 6.5	TE	Crust
2	St. Martin's Island	RV, SS	45, 90	9.4	16	0	1, 3	6.5	TN	Crust
3	Dakshin Nila	RV, SS	45, 90	18	40	0	1, 3	6.9, 7.0	TN	Crust
4	Maheshkhali	RV, SS	45, 90	20	50	0	1, 3	7.0, 7.1	TN	Crust
5	Jaldi	RV, SS	45, 90	18	40	0	1, 3	6.9, 7.0	TN	Crust
6	Patiya	RV, SS	45, 90	20	50	0	1, 3	7.0, 7.1	TN	Crust
7	Sitakund	RV, SS	45, 90	24	65	0	1, 3	7.2, 7.3	TN	Crust
8	Sandwip	RV, SS	45, 90	20	50	0	1, 3	7.0, 7.1	TN	Crust
9	Lalmai	RV, SS	45, 90	32	90	0	1, 3	7.4, 7.6	TN	Crust
10	Habiganj	RV, SS	45, 90	35	105	0	1, 3	7.5, 7.7	TN	Crust
11	Minbya	RV	45	35	105	0	1	7.5, 7.7	TN	Crust
12	Laymyo	SS	90	21	175	0	1	7.6, 7.7	TN	Crust
13	Kabaw	RV	45	50	280	0	9	8.0, 8.4	TN	Crust
14	Churachandpur-Mao	SS	90	20	170	0	16	7.6	TN	Crust
15	Kaladan	SS	90	40	270	0	4	8.0	TN	Crust
16	Ramree MT	MT	16	100, 150	450	10	8, 23	8.6, 8.8	TN	Sub
17a	Dhaka MT West	MT	1	100	520	10	1	8.6, 8.9	TN	Sub
17b	Dhaka MT Central	MT	5	100	520	11.5	6	8.6, 8.9	TN	Sub
17c	Dhaka MT East	MT	14	100	520	20	11	8.6, 8.9	TN	Sub
18	Dauki MT	MT	45	50	300	0	7	8.1	TN	Sub
19	Ramree slab	Slab	30	160	450	40	na	6.5, 7.0	TE	Sub
20	Dhaka slab	Slab	33	210	520	40	na	7.5, 8.0	TE	Sub

Notes: na = not applicable; Mech = source mechanism, RV = reverse, SS = strike slip, MT = megathrust, Slab = intraplate; W = down dip fault width; L= fault length; Z_{tor} = depth to top of rupture plane; SR = slip rate; M_{max} = maximum magnitude; f_m = magnitude probability density function, TE = truncated exponential, TN = truncated normal; GMPE = ground motion prediction equation, Crust = shallow active crustal, Sub = subduction zone.

Following the interpretation of Wang et al. (2014), we modelled the megathrust interface between the Indian plate and the Sunda plate as the Ramree domain (source 16) and the Dhaka domain (source 17). Wang et al. (2014) present four different segmentation and rupture scenarios for the Dhaka megathrust. Scenarios A1 and A2 represent a full rupture of the Dhaka megathrust with coseismic slip diminishing towards the deformation front in the west. Scenarios B1 and B2 represent a partial rupture of the megathrust with uniform coseismic slip but diminishing recurrence intervals towards the deformation front in the west. Scenarios A1 and B1 represent rupture of the splay faults in the upper crust during a megathrust event, and scenarios A2 and B2 represent rupture of the splay faults in separate, independent events. To model scenarios A2 and B2, we defined the Dhaka megathrust as three separate fault segments with similar widths but different slip rates and dip angles (source numbers 17A, 17B, and 17C), and modelled each fault rupturing individually, in pairs, or all three. We modelled each scenario with equal weight. We did not include scenarios A1 and B1 because the crustal earthquakes are already modelled by the background source and the exact geometry of the splay faults is unknown. We also included the

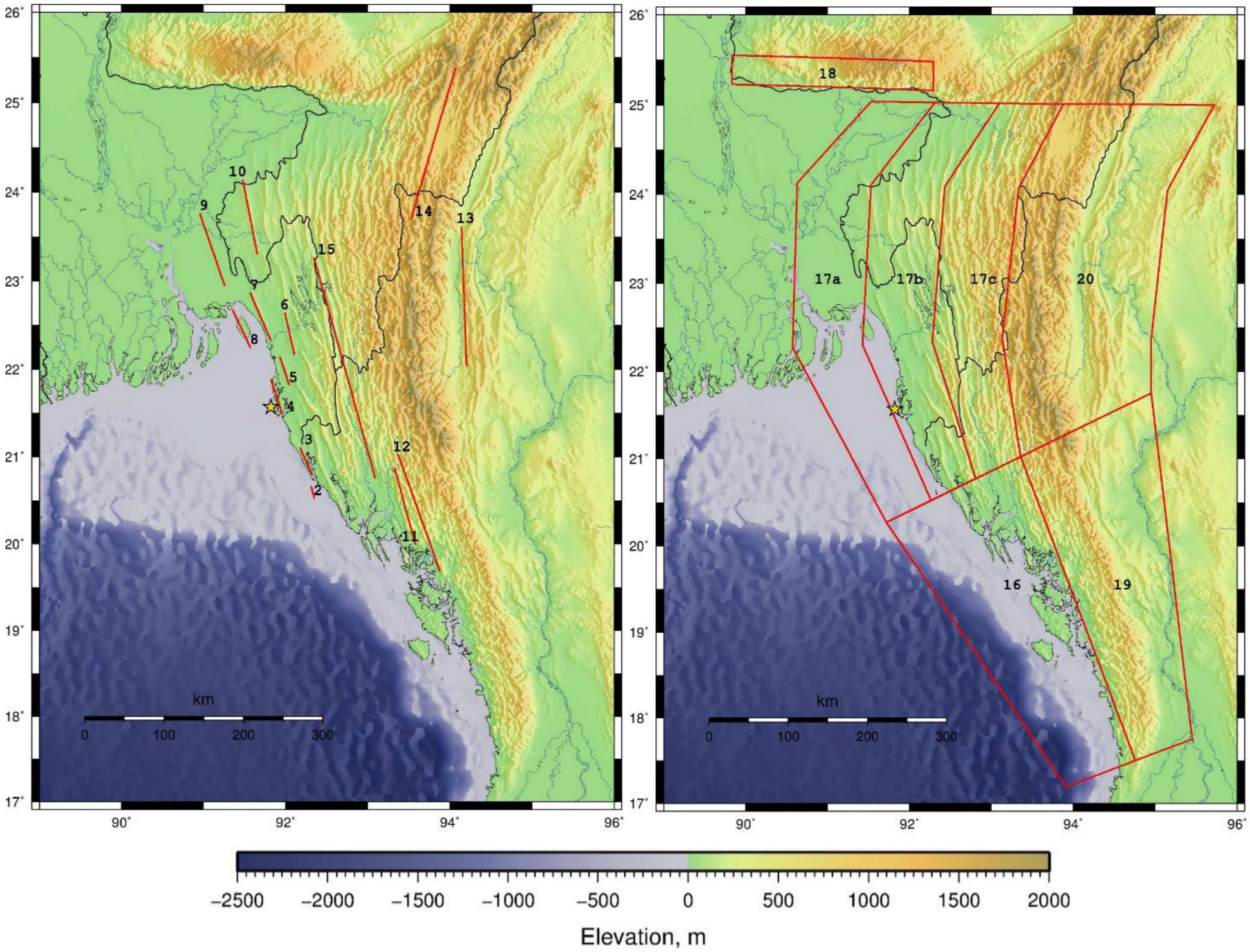

Figure 1. Seismic sources, see Table 1 for labels, site location shown as yellow star

Dauki megathrust fault to the north of the site based on information from Morino et al. (2014) and CDMP (2009).

This study defined deep intraplate deformation as seismic zones below 40 km depth in areas with a down-going tectonic slab. We defined areas with a down-going tectonic slab based on information from Wang et al. (2014), Parameswara and Rajendran (2016), and the seismic catalogue compiled in this study. The focal mechanisms are steeply dipping strike-slip and normal faulting associated with internal deformation on the down-going slab.

MAGNITUDE RECURRENCE RELATIONS

The second step in a PSHA calculation is to define the rate at which earthquakes of various magnitudes are expected to occur on each source. Table 1 lists the magnitude recurrence parameters for each earthquake source.

For source numbers 2-18, we used the truncated normal model with a standard deviation of 0.25 magnitude units and geologic and geodetic data to estimate slip rates and the maximum earthquake magnitude. All slip rates and maximum magnitudes are from Wang et al. (2014) except for the Kaladan fault, which is from Maurin and Rangin (2009) and Steckler et al. (2016), and the Dauki fault, which is from Morino et al. (2014) and CDMP (2009).

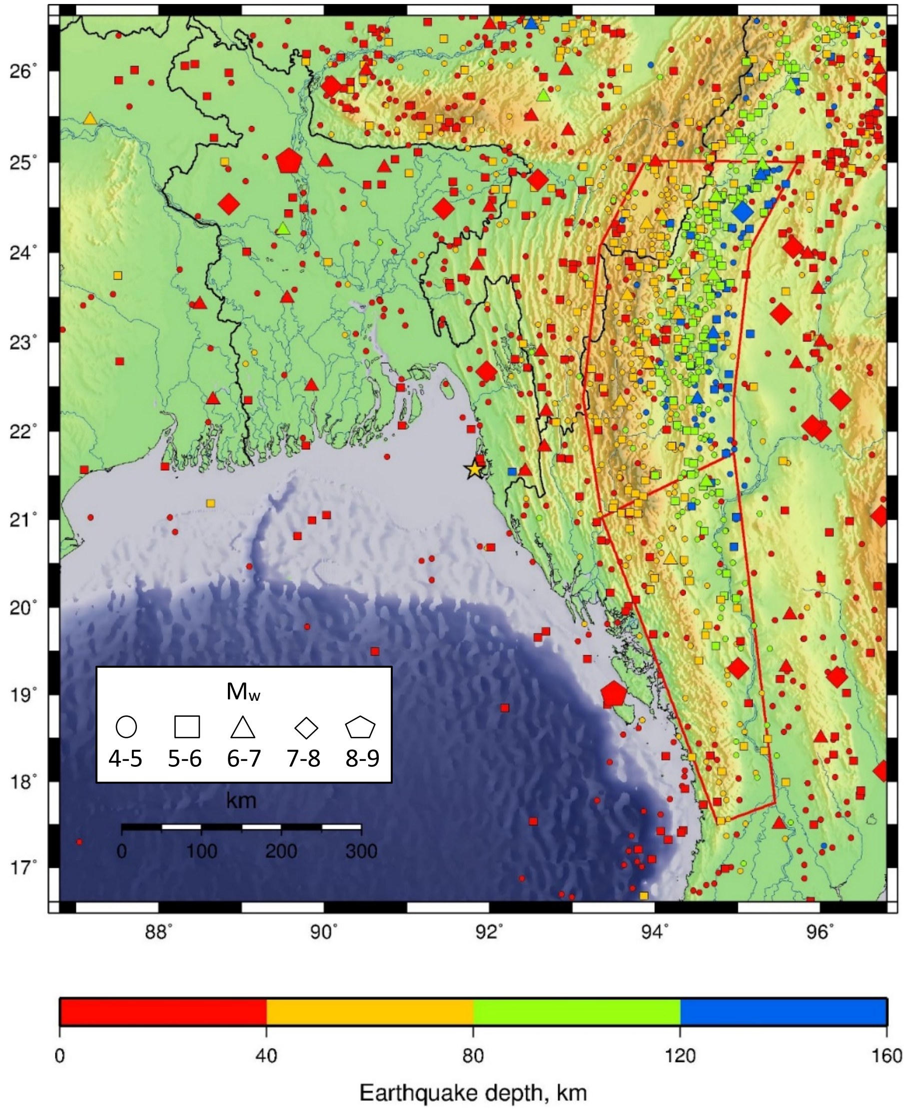

Figure 2. Location, depth and magnitude of earthquakes in the seismic catalogue, yellow star shows the site location, red boxes are the Ramree and Dhaka slab fault planes

We modelled the magnitude recurrence of the areal background source (source no. 1) using smoothed gridded seismicity with a 25 km radius Gaussian distribution and a grid of 1 km^2 cells. We used the truncated exponential model for the magnitude probability density function and estimated one b-value for the entire region from the earthquake catalogue. For source numbers 19 and 20, we also used the truncated exponential model and earthquake catalogue to calculate the activity rate (N_{min}) and b-value.

Figure 2 shows the earthquake catalogue we compiled from the International Seismological Centre on-line bulletin (ISC, 2014), Szeliga et al. (2010) and Wang et al. (2014). The reviewed ISC catalogue is based on instrument recordings manually reviewed by ISC analysts and for this area contains earthquakes from 1912 until 2014. The Szeliga et al. (2010) catalogue includes earthquakes from 1762 until 2009 for India and the surrounding regions, and Wang et al. (2014) give a list of significant earthquakes for Myanmar and the surrounding region from 1762 until

2011. Both the Szeliga et al. (2010) and the Wang et al. (2014) catalogues contain instrumental and historical earthquakes.

First, we merged the three catalogues, removed duplicates and converted the magnitudes to moment magnitude (M_w). We applied the correlations proposed by Trianni et al. (2014) to convert from surface wave magnitude (M_s), body wave magnitude (M_b), and local magnitude (M_L) to M_w.

We then split the base catalogue into three separate catalogues for sources 1, 19, and 20. For the background source (no. 1), we only used earthquakes with $4.5 < M_w < 6.5$, depths < 40 km, within 250 km from the site and more than 5 km from a defined crustal fault. For the other two sources, we used earthquakes with $4.5 < M_w$, depths > 40 km, and occurring within the surface projection of a down-going subduction slab (red boxes shown in Figure 2).

Finally, for each of the three catalogues, we removed dependent events and checked the catalogue for completeness. We employed the declustering models of Gardner and Knopoff (1974), Urhammer (1986), and Reasenberg (1985) to all three catalogues to remove dependent events. Table 2 lists the estimated completeness years (T_c) for each magnitude bin of each catalogue based on the method of Stepp (1972).

After the earthquake catalogues were corrected for earthquake magnitude, dependent events and completeness, we calculated the activity rate and b-value using the maximum likelihood method of Weichert (1980). Table 3 lists the calculated values and the weights used for the results from each method in the logic tree framework.

Table 2. Completeness years (T_c)

M_w Start	M_w End	T_c (yr)		
		no. 1	no. 19	no. 20
4.50	4.75	20	15	20
4.75	5.00	35	25	40
5.00	5.25	50	52	45
5.25	5.50	50	52	50
5.50	5.75	56	52	50
5.75	6.00	60	52	60
6.00	6.25	150	52	87
6.25	6.50	171	na	87
6.50	6.75	na	na	87
6.75	7.00	na	na	87
7.00	7.25	na	na	87
7.25	7.50	na	na	87

Table 3. Magnitude recurrence parameters for the truncated exponential model

Method	Background (no. 1)			Ramree slab (no. 19)			Dhaka slab (no. 20)		
	b	N_{min}	weight	b	N_{min}	weight	b	N_{min}	weight
GK	1.177	15.86	0.4	1.299	2.97	0.4	1.122	16.00	0.4
UR	1.232	18.75	0.3	1.315	3.29	0.3	1.241	24.64	0.3
RE	1.275	21.77	0.3	1.313	3.33	0.3	1.233	26.64	0.3

Notes: GK = Gardner and Knopoff (1974); UR = Urhammer (1986); RE = Reasenberg (1985)

GROUND MOTION PREDICTION EQUATIONS

The site is located in an active tectonic region with both shallow crustal and subduction zone earthquakes. Therefore, we used two different sets of ground motion prediction equations (GMPEs) to calculate peak ground acceleration (PGA) and spectral acceleration (Sa) values. To estimate Sa and PGA from sources that generate shallow crustal earthquakes, we used the five NGA West 2 GMPEs (Abrahamson et al., 2014; Chiou and Youngs, 2014; Campbell and Bozorgnia, 2014; Boore et al., 2014; Idriss, 2014) with equal weight. For sources with subduction zone earthquakes, we employed the models of Atkinson and Boore (2008), Zhao et al. (2006), and Abrahamson et al. (2016). We used the Abrahamson et al. (2016) model three times with three different sets of period dependent ΔC_1 values to capture better the model's epistemic uncertainty. We applied an equal weight to all five subduction zone GMPEs. For all GMPEs we used the global model and not a region specific version.

We performed the PSHA for bedrock with a shear wave velocity of V_s = 760 m/s. To estimate the depth to shear wave velocities of 1000 m/s, 1500 m/s, and 2500 m/s necessary for some of the GMPEs, we used data from the Comprehensive Disaster Management Programme (2009) report. The CDMP (2009) performed a microtremor array study for the city of Chittagong, which is about 85 km from the site. Based on their study, the depths to shear wave velocities of 1000 m/s, 1500 m/s, and 2500 m/s are 400 m, 400 m, and 900 m, respectively.

RESULTS

Figure 2 shows the hazard curves for the PGA and the spectral acceleration at 14 different periods, ranging from 0.03 seconds to 10 seconds. Figure 3 shows the hazard curves according to each source for PGA. Figure 3 shows that the main sources that contribute to the hazard are the Background source, Maheshkhali fault, Ramree megathrust and the Dhaka megathrust (Dhaka MT West, Centre, and East). The Maheshkhali fault is the closest crustal fault to the site, located only 14 km away. The site sits 11.5 km above the Dhaka megathrust fault plane and 117 km to the north of the Ramree megathrust domain. All of the other sources contribute only marginally to the total hazard. This is due either to their greater distance from the site and/or lower expected characteristic magnitude, both of which decrease the intensity of the expected ground motion at the site, or due to their lower slip rate, which decreases the frequency of earthquakes occurring on the source.

Figure 4 shows a magnitude and distance deaggregation plot for PGA and return period of 300 years. This figure, as well as the other deaggregation plots not shown, indicate that there are two main contributors to the hazard. One is a magnitude 6.5-7.5 earthquake 10-20 km from the site, and the other is a magnitude 8-9 earthquake 100-250 km from the site. The first is due to the Maheshkali fault and the second mainly to the Ramree megathrust. Megathrust earthquakes represent a larger portion of the seismic hazard for the longer periods, which is expected.

ISO 19901-2 (2004) requires offshore structures to satisfy the design criteria for Extreme Level Earthquakes (ELE) and Abnormal Level Earthquakes (ALE). The return periods for these two events are calculated based on the hazard curve of the spectral acceleration for the dominant modal period of the structure as well as the exposure level of the structure. Following the procedures of ISO 19901-2, the return periods for ELE and ALE for exposure level L2 are 300 years and 1250 years, respectively. Table 4 presents the Uniform Hazard Spectra (UHS) for return periods of 300 years, 475 years, and 1250 years.

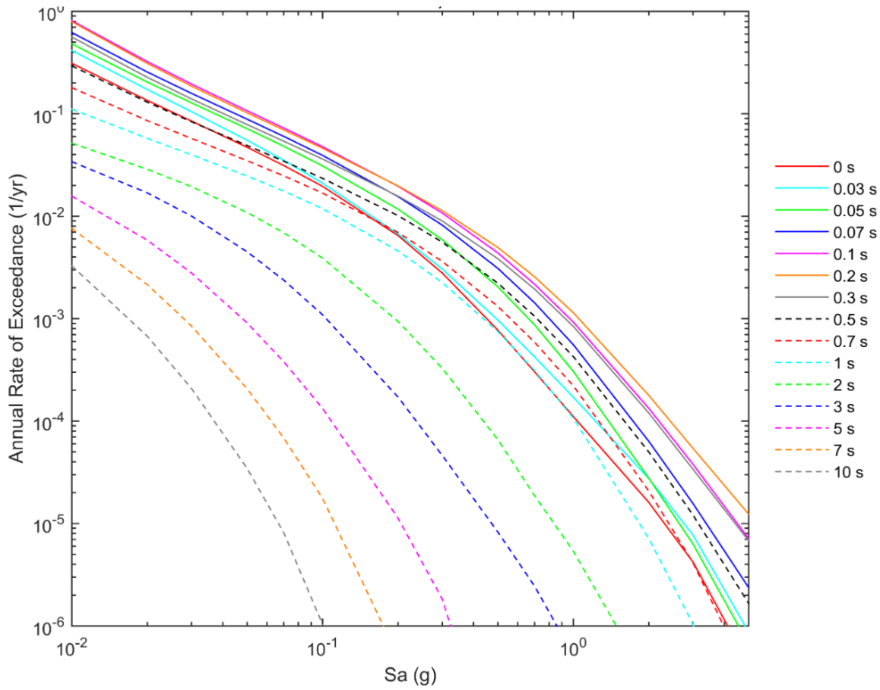

Figure 3. Total hazard curves for PGA (T=0) and Sa at 14 periods

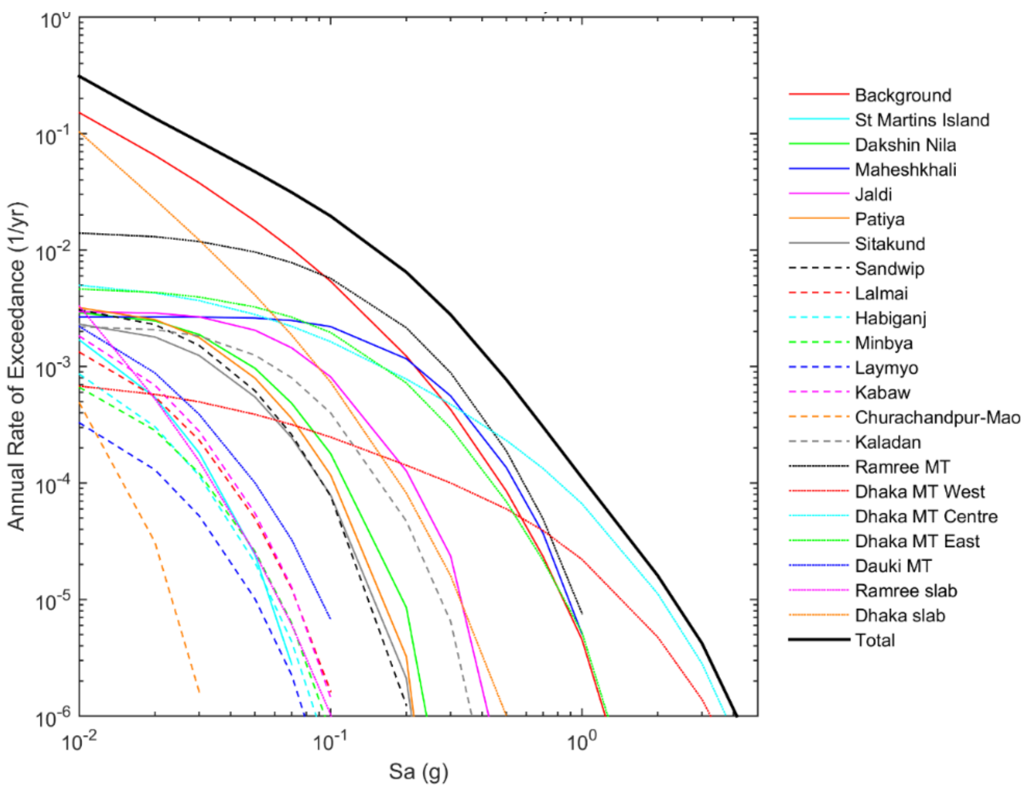

Figure 4. Hazard curves by source for PGA

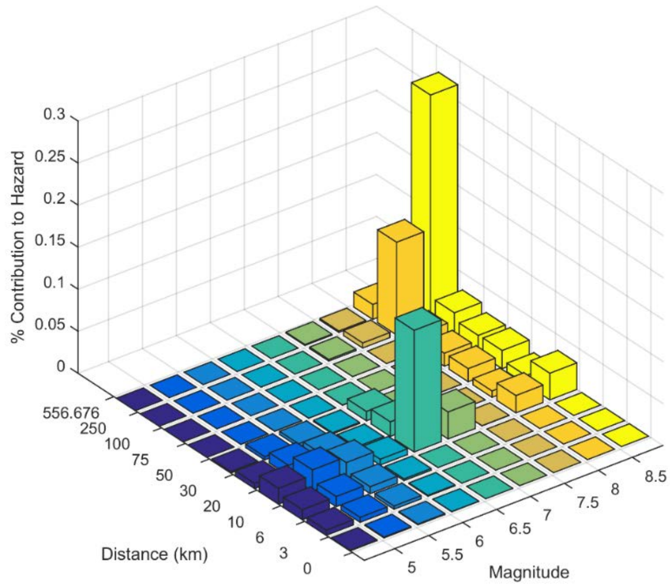

Figure 5. Deaggregation for PGA at return period of 300 years

Table 4. Uniform hazard spectra (UHS) in g for three return periods (RP)

	Period (s)														
RP (yr)	0	0.03	0.05	0.07	0.1	0.2	0.3	0.5	0.7	1	2	3	5	7	10
300	0.28	0.29	0.40	0.48	0.57	0.61	0.54	0.40	0.31	0.24	0.11	0.06	0.03	0.02	0.01
475	0.33	0.36	0.49	0.59	0.71	0.77	0.68	0.51	0.40	0.31	0.14	0.07	0.03	0.02	0.01
1250	0.49	0.54	0.72	0.87	1.05	1.14	1.01	0.78	0.61	0.48	0.21	0.11	0.05	0.03	0.02

COMPARISON OF RESULTS

Table 4 compares the estimated PGA values from this study for return periods of 200 years, 475 years and 2475 years with other studies. The total PGA values from this study are larger than those from past PSHA studies. The reason for the increased hazard is mainly due to the modelling of the crustal and subduction zone faults in this study. Past investigations generally only included a background zone based on recorded and historical seismicity. None of the other PSHA studies model the Maheshkhali fault and few include subduction zone faults. The inclusion of these faults in the PSHA is based on the research of Steckler et al. (2016), Parameswara and Rajendran (2016), Wang et al. (2014), and Morino et al. (2014), which were published at the same time or after the other PSHA studies shown in Table 4. This hypothesis is further supported by comparing the hazard results from only the Background source. Table 4 shows that the PGA values estimated for only the Background source in this study match well with the results of past studies.

Figure 3 shows that the main faults that contribute to the hazard are the Maheshkhali fault, Ramree megathrust and the Dhaka megathrust. Evidence for the existence of the Maheshkhali fault is given by Ansary et al. (2000), who reported extensional cracks that developed on the Maheshkhali anticline during a M_b = 5.2 earthquake in 1999. Wang et al. (2014) believe the Maheshkhali fault is active based on the SRTM 90 digital elevation model, optical satellite imagery, the study of Steckler et al. (2008), and the earthquake of 1999. Support for the inclusion of the Dhaka and Ramree megathrust domains comes from the 1762 M = 8.5 earthquake that occurred 300 km southeast of the site near Ramree Island, Myanmar. This earthquake as well as the 2004 M = 9.0 Sumatra earthquake that occurred further south on the Sunda Megathrust demonstrate that large interface events have occurred and therefore could happen again.

Table 5. Comparison of PGA (g) values for three return periods

Reference	200 yr	475 yr	2475 yr
Total (this study)	0.23	0.33	0.63
Background (this study)	0.12	0.17	0.30
Al-Hussaini et al. (2015)		0.19	0.28
Trianni et al. (2014)	0.10	0.15	0.27
Al-Hussaini and Al-Noman (2010)		0.18	
BNBC (2006)	0.15		
Noor et al. (2005)		0.20	
Ansary and Sharfuddin (2002)	0.15-0.25	0.30	
GSHAP (1999)		0.24-0.32	
BNBC (1993)	0.15		

CONCLUSION AND SUMMARY

This paper described the PSHA for a site in the Bay of Bengal, offshore Maheshkhali Island, Bangladesh. The tectonic setting of the area is complex with much new research being published in the past few years. Based on these new studies, we modelled 20 seismic sources, including one background gridded seismicity areal source zone over the entire region, 14 shallow crustal faults, 3 subduction megathrust faults, and 2 subduction down-going slab faults. We developed a seismic catalogue of earthquakes based on recorded and historical earthquakes. The catalogue shows that destructive earthquakes have occurred over the entire region.

The results of the PSHA show that the site lies in a highly seismic region. The main contributors to the hazard are a magnitude 6.5-7.1 earthquake 15-20 km from the site on the Maheshkhali fault and a magnitude 8.0-8.8 earthquake 120-250 km from the site on the Ramree megathrust. The results from this study are higher than previous studies due to the inclusion of fault sources. Previous studies only included a background zone based on recorded seismicity due to a lack of information about specific faults. This study takes advantage of recent publications to include faults sources in the PSHA.

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