Probabilistic seismic hazard analysis at a strategic site in the Bay of Bengal

Sara Cristina Teresa Trianni · Carlo Giovanni Lai · Erio Pasqualini

Probabilistic seismic hazard analysis (PSHA) along the route of an offshore pipeline for the transport of oil in the Bay of Bengal has been performed, in order to set up design parameters and identify possible geohazards. The complexity of geological and seismotectonic setting of the region where the pipeline is planned to be installed is the result of the interaction of the Indian, Eurasian and Burmese tectonic plates. In order to properly account for the intricate way by which these plates interact, a large area extending 450 km from the pipeline route has been considered for the compilation of a comprehensive earthquake catalogue, spanning the period 1663–2012 AD. Differently from earlier PSHA analyses conducted in the region based on assuming two-dimensional polygons as seismogenic provinces, this study adopted a seismotectonic source model which also includes for the first time a linear tectonic lineament representing the northward extension of the Sunda mega thrust, responsible for the large Sumatra–Andaman earthquake of 26 December 2004. Hazard computations have been performed over a grid of sites spaced 0.045° covering a rectangular area which contains the pipeline. Epistemic uncertainty in the hazard computations has been taken into account by a logic tree framework, incorporating different seismotectonic source models, maximum cut-off magnitude and ground-motion prediction equations. Horizontal median uniform hazard spectra and median uniform hazard spectra plus and minus one sigma on stiff ground have been calculated at the selected sites for different return periods. Peak ground acceleration with 10 % probability of exceedance in 50 years has been compared with values from previous hazard studies available for Bangladesh.
Keywords  PSHA · Earthquake catalogue · Seismotectonic source model · Uniform hazard spectra · Hazard map

1 Introduction

Seismic hazard analysis involves the quantitative estimation of ground-shaking hazard at a particular site. Therefore, it is necessary for designing structures and facilities that aim to resist at a certain level of shaking from earthquakes with a desired performance. The parameters that describe the level of shaking are specific strong ground-motion parameters (e.g. peak ground acceleration [PGA], velocity or displacement; spectral acceleration, velocity or displacement) used for design.

Probabilistic seismic hazard analysis (PSHA) is the most widely used procedure to determine the expected hazard at a given site in terms of ground-motion parameters. It models the fundamentally probabilistic nature of earthquake occurrence, providing an estimate of the frequency of exceeding specified levels of ground motion at a site by integrating the contributions of all possible combination of magnitude earthquakes and their location in a consistent manner. Moreover, competing models can be taken into account using the logic tree approach that allows to consider the epistemic uncertainty associated with the size of the earthquakes, the recurrence rates and different ground-motion prediction equations.

In this paper, the results of PSHA along the route of an offshore pipeline for the transport of oil in the Bay of Bengal are illustrated together with the adopted methodology. The design of the offshore pipeline is part of the expansion plane of the processing capacity of the Eastern Refinery Limited (ERL), situated at Chittagong (Bangladesh). The outcome of the seismic hazard analysis is expressed in terms of horizontal median uniform hazard spectra and median uniform hazard spectra plus and minus one sigma, for different return periods, on level-ground and stiff-ground conditions, at some selected points along the pipeline route.

Previous hazard studies in the region of study appear scanty and based on assumptions that often seem to be not completely justified (Ansary and Sharfuddin 2002; Al-Hussaini and Hasan 2006; Al-Hussaini and Al-Noman 2010).

Ansary and Sharfuddin (2002) performed the seismic hazard analysis in Bangladesh by applying the method described by Molas and Yamazaki (1994), based on the assumption that the PGA at a site had a frequency recurrence relationship similar to the magnitude–frequency recurrence relationship of Gutenberg–Richter (1954). Horizontal PGA on stiff-ground condition with 50-, 100-, 200- and 475-year return period was calculated at 42 sites of Bangladesh and displayed in terms of seismic hazard maps. The maximum value of PGA with 10 % probability of exceedance in 50 years was obtained in Sylhet region (i.e. northeast Bangladesh), equal to 0.51 g. A seismic zoning map based on values of PGA with 200-year return period was also proposed. This assigned a different level of seismicity to three zones of the country, adopting the same values of the previous seismic zoning map of the Bangladesh National Building Code (HBRI and BSTI 1993) (i.e. 0.25 g at zone 3; 0.15 g at zone 2; 0.075 g at zone 1), but reducing the extent of zone 1.

Al-Hussaini and Hasan (2006) performed the probabilistic seismic hazard analysis in Bangladesh adopting the procedure of the classical Cornell–McGuire approach. They compiled an earthquake catalogue spanning the period from 1845 to February 2005 and
considered a seismotectonic source model composed of 8 seismogenic zones (SZs). The outcome of the analysis was expressed in terms of hazard map of horizontal PGA having 10% probability of exceedance in 50 years. The maximum value of the hazard was obtained in northern Bangladesh (i.e. 0.245 g).

In 2010, Al-Hussaini and Al-Noman (2010) carried out a new probabilistic seismic hazard analysis in Bangladesh. They adopted the catalogue of earthquakes compiled by Al-Hussaini and Hasan (2006), with the addition of the historical earthquake of 2 April 1762, occurred at Chittagong with an estimated value of $M_w$ equal to 7.5 (Al-Hussaini and Al-Noman 2010). A seismotectonic model consisting of 7 SZs was taken into account. The outcome of the analysis was expressed in terms of hazard maps for horizontal PGA and spectral acceleration at $T = 0.2$ and 1 s, with 475- and 975-year return period. In particular, six attenuation relationships for PGA were applied in separate hazard computations. The authors themselves pointed out that the hazard results depended strictly on the adopted ground-motion attenuation relationship. The highest values of horizontal PGA on stiff soil condition were obtained in Sylhet region. These resulted equal to 0.39 and 0.135 g, by applying the attenuation relationship of Atkinson and Boore (1995) and the attenuation relationship of Chapman (1999), respectively.

In 1999, Bhatia et al. (1999) in the Global Seismic Hazard Assessment Program (GSHAP) provided the hazard map in terms of horizontal PGA with 475-year return period, for the region extending from 0° to 40°N latitude and 65°–105°E longitude. The lowest values of PGA were obtained in northeast Bay of Bengal and central Bangladesh (i.e. 0.05–0.010 g), whereas higher values were computed in northern Bangladesh and western Myanmar (i.e. 0.20–0.25 g).

The scarcity of previous hazard studies results from modest consideration attributed to seismic hazard by people of this part of the world probably due to a higher incidence of other natural, devastating hazards such as cyclones and floods. Nevertheless, despite the low incidence of large earthquakes in the last decades, a careful consideration of seismotectonic framework reveals that Bangladesh is surrounded by regions of large seismic activity. In the past, the country has been affected by large earthquakes ($M_w > 7$). Moreover, in recent years, small to moderate earthquakes having epicentres in neighbouring regions (e.g. India, Burma) and even within the country are regularly occurring. Bengal basin, where Bangladesh constitutes the major part, lies in fact at the “point of junction” of the Indian, the Eurasian and the Burma plates, which interact in a complex and intricate way over time, which needs to be carefully investigated. For this purpose, a large area of 450 km surrounding the pipeline route has been considered for the definition of input data, encompassing the main geological structures and major tectonic lineaments resulting from the interaction of the above-mentioned tectonic plates.

A comprehensive earthquake catalogue has been compiled which includes 905 events with $M_w \geq 4$, from February 1667 to January 2012. Subsequent processing of the catalogue which includes homogenization, declustering and completeness analysis has been performed.

PSHA has been carried out using two different seismotectonic models, taking into account their associated epistemic uncertainty by a logic tree framework, which also incorporates different cut-off magnitude and ground-motion prediction equations.

The first model includes eleven seismogenic provinces whose temporal earthquake occurrence is modeled using the standard Poissonian assumption. The second seismotectonic model includes besides the seismogenic provinces, also a tectonic lineament representing the northward extension of the Sunda mega thrust, responsible for the Andaman–
Sumatra earthquake of 26 December 2004. The temporal occurrence law of this geological structure is modeled through the so-called “characteristic earthquake”.

The hazard computation has been carried out over a grid of sites spaced 0.045°, covering a rectangular area which contains the pipeline. At four selected points of the pipeline route, horizontal uniform median and median ± sigma hazard spectra have been computed for different return periods.

Using the same input data and by enlarging the computation grid to include Bangladesh, a hazard map for horizontal peak acceleration with 10 % probability of exceedance in 50 years has been produced. The comparison with values from previous hazard studies shows higher predicted hazard for many districts of Bangladesh.

2 Geographical coordinates of the pipeline route and extent of the region of study

The route of the offshore pipeline consists of two main sections: a first section approximately of 9 km long connecting a single-point mooring (SPM) with a land-terminal end at Matarbari (LTE Matarbari) and a second section approximately of 65 km long, connecting LTE Matarbari with a land-terminal end at Gahira (LTE Gahira). Both LTEs lie in Chittagong Division (Bangladesh).

For the definition of input data, a rectangular area has been considered, which is 450 km from the pipeline route. This area, extending between 17.6° and 26.2°N latitude and 87.4° and 96.2°E longitude, covers Bangladesh, some states of India and of the Republic of the Union of Myanmar. It encompasses all major tectonic lineaments and geological structures surrounding the pipeline route, and furthermore, it includes some large magnitude ($M_w > 7$) historical events, neglecting which would have most likely resulted in an underestimation of the hazard (e.g. the 1923, $M_w 7.4$ earthquake; the 1932, $M_w 7.4$ earthquake; the 1943, $M_w 7.1$ earthquake; the 1957, $M_w 7.1$ earthquake; the 1839, $M_w 8.1$ Great Assam earthquake) (see Fig. 1).

3 Seismotectonic setting

3.1 Bengal basin

The dynamic nature of the Bengal basin where Bangladesh represents the major part can be attributed to the interaction of the Indian, the Eurasian and the Burma tectonic plates. According to Alam et al. (2003), the collision among them can be visualized into two different forms: the north to north-eastern continent–continent collision of the Indian plate and the Tibetan plate, which is mainly expressed by thrusting, lateral displacements and uplifts associated with the development of eastern Himalayas; and the oblique subduction of the oceanic Indian crust beneath the Burma plate, resulting in the development of accretionary wedges, the uplift of the Indo-Burman Ranges and the associated fold belt of the Chittagong Tripura Fold Belt (CTFB) region.

Many authors have pointed out the complexity of the Indo-Burmese region, with regard to the possibility of a still active subduction across the Indo-Burmesian wedge. Kundu and Gahalaut (2012) report a presumed inconsistency of the focal mechanism solutions of events within the Indo-Burmese region, having a N–S pressure axis and therefore, no east-west compression as implied by an active subduction.
On the other hand, some authors (Satyabala 2003; Socquet et al. 2006; Nielsen et al. 2004) support the hypothesis of a still active subduction, explaining that the variation of slip vector azimuths is compatible with a process of “slip partitioning”, between Indian and Burma plates, the same used to justify the accommodation of oblique motion at SE Asia trenches. Different opinions focus on the possible candidates for slip partitioning. GPS measurements indicate that with respect to Sunda, the Indian plate moves 35 mm/year NNE, while the Sunda plate is currently moving eastward with respect to Eurasia (Socquet et al. 2006). The Sagaing fault, a dextral strike-slip fault, separating the Burma from the Sunda plate, accommodates only 18 mm/year N, while at the latitude of Bangladesh there is 35 mm/year of oblique motion between India and Sunda plates (Socquet et al. 2006). Nielsen et al. (2004) performed a marine survey along the Burma scarp (14°–20°N) and proposed a model of evolution of slip, from partial (shearing on the Sagaing fault only) to full partitioning of the motion (shearing on the Sagaing fault and on dextral strike-slip faults within the Indo-Burman Ranges). Shearing on the Sagaing Fault alone leads to a predicted convergence motion at the Burma Trench in the range 10°–40°N, in agreement with the structures described along the West Burma Scarp. Dextral shearing on additional faults west of the Sagaing Fault progressively reorientates clockwise the direction of convergence to reach pure shortening in Bangladesh. The direct consequence of this model is that in northern Myanmar, major geological discontinuities (as the Kabaw fault and the Kaladan fault) could accommodate shearing and have a significant dextral strike-slip component. According to Pivnik et al. (1998), the Kabaw fault is known to be reverse but with a strong right-lateral component. Maung (1987) has postulated transcurrent movement on this fault initiated before Miocene and preceding the right-lateral movement along the Sagaing fault. However, no geological or geophysical evidence indicates any transcurrent movement along the Kabaw fault (Zaw 1990). On the other hand, Socquet et al. (2006) indicate that the oblique convergence is accommodated only on the subduction trench, from southern Myanmar to the Shillong Plateau (north of Bangladesh). These authors report that along the trench, the slip is 23 mm/year oriented 35°N.
(18 mm/year of right-lateral strike slip and 13 mm/year of convergence) in Central Myanmar (22°N). Steckler et al. (2008) point out the important need for investigating in detail the seismic hazard along the Burma Arc. These authors stress that the active convergence between Indian and Burma plates is manifested by recent $M_w$ 6 plus earthquakes on blind thrusts associated with anticlines in the fold belt. According to them, these imbricate faults are probably rooted onto a subduction megathrust (the Arakan trench at the latitude of Myanmar) representing the northward extension of the Sunda mega thrust. The unexpected large Sumatra–Andaman earthquake of 26 December 2004 ($M_w$ 9.3) has highlighted the uncertain seismic hazard along this plate boundary.

3.2 Outlining two different seismotectonic models

Two different seismotectonic models have been adopted in the hazard computation, including them within a logic tree framework.

The georeferenced maps and data handling was performed using Quantum GIS 1.7.3 computer software.

3.3 First seismotectonic model

The first seismotectonic model consists of eleven SZs (Fig. 2). They have been delineated taking into account the change of seismicity in terms of focal depth and magnitude throughout the study area, and considering clustering of events from the compiled catalogue around the main tectonic and geological structures.

Fig. 2 First seismotectonic model: 11 source zones
Seismic sources 1 through 4 cover the intervening area between Eastern Himalaya and the Burmese region. Seismic source 1 encompasses the Shillong plateau and the system of faults bounded this massif (i.e. the E–W trending Brahmaputra River fault to the north, the E–W oriented Dauki fault to the south, the N–W oriented Dhubri fault to the west and the NE–SW oriented Disang Thrust to the east). Clustering of epicentres is around these lineaments and within the massif, where significant past earthquakes are located, among them the Great Assam earthquake ($M_w 8.1$).

Seismic source 2 covers north-western Bangladesh, coinciding mostly with the Sylhet Trough, which is an active sub-basin delimited to the east and southeast by the Tripura fold belt. The seismotectonic of this zone has been assumed to be controlled by faults, such as the Sylhet fault, and lineaments (e.g. the Tista and Jamuna lineaments). Khan (1991) has reported that the transverse lineaments can be related to the resistance of motion between Indian and Burma plates offered by the Shillong plateau to the north. As a consequence, the accumulated pressure might have been released by generating these transverse lineaments. Many strong historical earthquakes are recorded in the area encompassed by the source, among them the 1918 Srimangal earthquake, reported to be related to the Sylhet fault.

Seismic source 3 covers southern Bangladesh. This zone is of moderate seismicity compared with that of source 2. In fact, historical and instrumental events with moment magnitude $M_w > 6$ are not observed. The seismotectonic is related to transverse lineaments such as the Padma fault.

Seismic source 4 is an offshore zone delineated so to encompass the observed earthquake activity in south-western part of the study region (Bay of Bengal). Biswas and Majumdar (1997) have reported a N–S compression in the Bay of Bengal, analogous to that of the Himalayan arc. According to the authors, this state of stress and seismic activity within the intraplate zone of Bay of Bengal result from the resistance to the northward moving of Indian Plate at the Himalayas, where subduction of the Indian lithosphere in mantle has been presumed to have recently stopped. As a result, to compensate the horizontal compressive force by ridge push at the Carlsberg Ridge to the south, the intraplate region of the northern Indian plate no longer remains passive, due to a strong repulsive force at the collisional plate boundary of the Himalaya, which causes a stress transmission towards south.

Seismic sources 5 through 10 cover the area whose seismotectonic is related to the oblique subduction of oceanic crust of Indian plate beneath Burma plate. Seismic sources 5 and 6 correspond to the area of Chittagong–Tripura fold belt, which constitutes the westward extension of the Indo-Burman Ranges. The dominant fold-generating mechanism is supposed to be the east–west directed compressional force from oblique subduction. The seismotectonic of these zones is complex. The earthquakes appear scattered out throughout the sources, making it difficult to correlate them with tectonic lineaments and faults. Recent earthquakes have been related to blind thrust associated with anticlines in the fold belt. Moreover, these imbricate faults have been supposed to be rooted onto a subduction megathrust (Steckler et al. 2008). Source 5 is characterized by a relatively moderate seismicity compared with that of source 6 to north, which has been traced to include some historical great earthquakes.

Seismic sources 7 through 10 encompass the Wadati–Benioff zone. Sources 7 and 8 cover the area of Arakan-Indo-Burmese ranges, where most of the events have a seismic depth in the range 30–70 km. Source 8 has higher seismic activity than source 7. Sources 9 and 10 correspond to the area of Central Burma Basin, where a deeper seismic activity has been observed (events with focal depths in the range 150–200 km). The events are supposed to be related to the system of fold and activity of major faults present in these zones.
(e.g. the Kabaw and Kaladan faults). Source 10 reflects a higher number of events than source 9 and includes some large historical earthquakes.

Seismic source 11 covers the eastern part of the study region, where a shallow seismicity has been observed, related to the activity of the dextral strike-slip fault Sagaing.

3.4 Second seismotectonic model

The second seismotectonic model accounts for the presence in the study region of a megathrust representing the northward continuation of the large Sunda mega thrust, responsible for the large Sumatra–Andaman earthquake of 26 December 2004. For this purpose, in addition to the 11 seismic source provinces included in the first seismotectonic model, a fault source has been inserted, extending from the latitude of Myanmar (where it is known as Arakan trench) as far as Bangladesh, on the basis of indications given by Socquet et al. (2006), Steckler et al. (2008), and Cummins (2007), (Fig. 3). According to Cummins (2007), in the Bay of Bengal, the deformation front lies west to the presumed plate boundary between India and Burma plates, because of the thickness of the Bengal fan sediments, reaching up to 20 km. These in fact can insulate the underlying plate enough to cause significant up-dip extension of the thermal regime required for seismogenesis (Cummins, 2007). We supported this hypothesis for southern extent of the introduced tectonic lineament. In addition, we extended it as far as Bangladesh, on the basis of indication of Socquet et al. (2006), according to which, the convergence between India and

Fig. 3 Second seismotectonic model: 11 source zones plus northward continuation of Sunda mega thrust (linear source based on indications by Cummins 2007 and Steckler et al. 2008)
Burma plates is accommodated on the Arakan trench from southern Myanmar to the Shillong plateau (i.e. northern Bangladesh). In particular, the considered northward continuation of Sunda megathrust coincides with Arakan and Tripura seismic segments indicated by Steckler et al. (2008). The former is reported to be ruptured in the 1762 Arakan earthquake, but while its southern extent has been recognized at least to Foul Island (18.1°N), its northern extent remains unclear (Steckler et al., 2008; Cummins, 2007). The latter is assumed to be ruptured during the 1548 earthquake, even if Steckler et al. (2008) point out the uncertainty related to the possibility that this event with the epicentre estimated in Assam can cause damage at Chittagong (580 km from it) (Steckler et al. 2008).

To estimate the rate of seismicity along the introduced linear source, the values of slip rate (23 mm/year), geometric characteristics (width and length equal to 125 and 700 km respectively) and crustal shear modulus (equal to 3.3*1,010 Pa) furnished by Socquet et al. (2006) have been adopted. The following relationship by Wells and Coppersmith (1994) has been exploited:

\[ M_w = 4.07 + 0.98 \cdot \log A \] (1)

where \( A \) is the area of fault rupture (the Arakan plane in this case). Equation (1) predicts an earthquake of up to \( M_w \) 9 that can be potentially triggered along the Arakan plane.

From the application of the Hanks and Kanamori’s formula (1979):

\[ M_w = \frac{\log M_0}{1.5} - 10.7 \] (2)

it is possible to infer that 500 years are required to produce an event having \( M_w \) 9, if a slip rate of 23 mm/year is assumed. In fact, in Eq. (2), \( M_0 \) is the seismic moment that has been obtained from the application of Kanamori’s formula (1977):

\[ M_0 = \mu \cdot A \cdot d \] (3)

where \( \mu \) is the crustal shear modulus (3.3*1,010 Pa), \( A \) is the area of the fault plane, and \( d \) is the average displacement on the fault plane (resulting from 23 mm/year times 500 years). Therefore, the linear source has been assumed capable to produce an earthquake of magnitude \( M_w \) 9 every 500 years. This is consistent with the conjecture of Socquet et al. (2006). These authors have also indicated the possibility of an earthquake with magnitude 8.5 every 100 years. We have neglected this scenario, because of the lack of any similar event in the last century. Moreover, the earthquake of Sumatra was of \( M_w \) 9.3, and from application of relationship by Wells and Coppersmith (1994), it is evident that a similar earthquake could be generated along the Arakan trench.

The recurrence interval of characteristic magnitude \([M_{w\min}; M_{w\max}]\) corresponding to a slip rate of 23 mm/year has been computed from the McGuire (2004) formula:

\[ s' = \frac{v_{\min}}{\gamma} \cdot \frac{M_{0\max} - M_{0\min}}{M_{\max} - M_{\min}} \cdot \frac{1}{\mu \cdot A} \] (4)

where \( s' \) is the slip rate, \( \gamma \) is a constant (3.454), \( M_{\max} \) and \( M_{\min} \) are the maximum and minimum characteristic magnitude, \( M_{0\max} \) and \( M_{0\min} \) are the seismic moment associated, respectively, with \( M_{\max} \) and \( M_{\min} \) of the characteristic recurrence interval, \( \mu \) is crustal shear modulus, \( A \) is the area of the fault plane, and \( v_{\min} \) is the activity rate (1/500 years = 0.002). The calculated recurrence interval of characteristic earthquake has been used in the program for the hazard computation.
4 Construction and processing of earthquake catalogue

4.1 Earthquake catalogue

The compilation of the earthquake catalogue represents a fundamental step in the probabilistic seismic hazard analysis following the Cornell–McGuire approach. The seismicity described by the catalogue allows, jointly with data from tectonic and geological setting, the definition of the seismotectonic source model and subsequently of the seismicity rates associated with the sources. Nevertheless, the compilation of the catalogue is a critical step of the entire procedure. It has to be composite, homogenous and obtained from merging available regional databases in order to be well defined and complete with respect to historical and instrumental seismicity.

A reliable earthquake catalogue is not readily available for the study region. Therefore, a new composite earthquake catalogue has been compiled, demarcated by geographical coordinates 17.6°–26.2°N latitude and 87.4°–96.2°E longitude. Eight international databases have been consulted: International Seismological Centre (ISC), National Earthquake Information Centre [USGS-NEIC (PDE)], Global CMT Catalogue Search, USGS Moment Tensor and Broadband Source Parameter Search, Global Significant Earthquake Database (NOAA), Incorporated Research Institutions for Seismology event catalogue (IRIS), India Meteorological Department (IMD) Earthquake Report, Bangladesh Meteorological Department (BMD). Furthermore, data reported in the catalogues compiled by Choudhury (1993) and by Hossain (1989), and information provided by personal communication of Dr. Ansary have also been considered. Moreover, in order to adequately reconstruct, especially the historical seismicity, information from catalogues referred to larger areas including that of study has been used (i.e. Ornthammarath et al. 2012; Gupta et al. 1986; Chandra 1977; Iyengar and Sharma 1998).

The composite catalogue spans a period from February 1663 to January 2012 and incorporates 905 earthquakes with $M_w \geq 4$ (see Fig. 4).

4.2 Homogenization

Moment magnitude was available only for 114 earthquakes. For the remaining part of the catalogue, 476 events were reported in body-wave magnitude ($m_b$), 76 in Richter magnitude ($M_L$) and 205 in surface-wave magnitude ($M_S$). For 34 events belonging to pre-instrumental era (i.e. events before 1968 AD), data of earthquake strength was expressed using the Modified Mercalli macroseismic Intensity Scale (MM). Thus, to homogenize magnitude measures and convert macroseismic intensity to moment magnitude ($M_w$), empirical relationships, based on catalogue data, have been developed (Table 1). They turned out to be more accurate than those available in the literature, as it can be observed by the analysis of the graphs reported in Figs. 5, 6, 7 and 8. The latter are in fact based on world-wide data and/or developed for a specific region or country. Hence, their applicability to countries with different building typologies and tectonic settings is often inappropriate.

In particular, the empirical correlation between $M_S$ and $M_w$ has been evaluated on the basis of 47 pairs of magnitude $M_S - M_w$ included in the composite earthquake catalogue. The proposed conversion relationship is compared in Fig. 5 with the bilinear correlation proposed by Scordilis (2006). As it can be observed, this relation does not fit well the data of the composite catalogue. Nevertheless, a large scatter of data is also present with respect to the proposed linear conversion relationship. This can be explained by considering that
this relationship was principally based on $M_s$ information derived from personal communication of Dr. Ansary and $M_w$ information obtained from the catalogue of Orn-thammarath (2012).

Therefore, the pairs of magnitude $M_w - M_s$ used for the development of the proposed conversion relationship could have been affected by the process of homogenization performed by these authors (Ansary and Sharfuddin 2002; Orn-thammarath 2012). However, despite of the scatter, for the conversion of $M_s$ into $M_w$, the proposed linear conversion relationship has been used, since the relation of Scordilis (2006) represents a lower boundary for the data.

The empirical correlation between $m_b$ and $M_w$ has been evaluated on the basis of 698 pairs of magnitude $m_b - M_w$ included in the composite database, where $m_b$ and $M_w$ are independently estimated. This conversion relationship is compared in Fig. 6 with the correlation proposed by Scordilis (2006), which is valid for $m_b \leq 5.5$, and the correlation of Sipkin (2003), which is valid for $5.5 < m_b \leq 7.3$. As it can be observed, the proposed linear conversion relationship and that of Scordilis (2006) are in perfect agreement, whereas the correlation of Sipkin (2003) does not fit well the data of the catalogue. For these reasons, the proposed linear relationship has been used to convert $m_b$ into $M_w$.

<table>
<thead>
<tr>
<th>Magnitude/Intensity</th>
<th>Proposed relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s$</td>
<td>$M_w = 0.6705 \ M_s + 2.2643$</td>
</tr>
<tr>
<td>$m_b$</td>
<td>$M_w = 0.8436 \ m_b + 1.0524$</td>
</tr>
<tr>
<td>$M_L$</td>
<td>$M_w = 0.8946 \ M_L + 0.7439$</td>
</tr>
<tr>
<td>$I_o$</td>
<td>$M_w = 0.2986 \ I_o + 3.8694$</td>
</tr>
</tbody>
</table>

**Fig. 4** Composite earthquake catalogue

**Table 1** Proposed conversion relationships for magnitude
Only 7 pairs of magnitude $M_L - M_w$ were available in the composite catalogue to develop the conversion relationship between $M_L$ and $M_w$. In Fig. 7, the comparison with the proposed conversion relationship proposed by Heaton and Tajima (1986) is reported. This relation represents a lower boundary for the data of the catalogue. Moreover, it is valid for $M_L \leq 6$, whereas the maximum magnitude of $M_L$ present in the catalogue is 7.6. For this reason, the proposed linear relationship has been used to convert $m_b$ into $M_w$.

The conversion relation of the epicentral macroseismic intensity (MMI) into moment magnitude ($M_W$) has been evaluated on the basis of 11 pairs $I_o - M_W$ of recent earthquakes, where $I_o$ was obtained from DYFI historical archive in the USGS website (http://
In Fig. 8, the comparison with the conversion relationship proposed by Gutenberg and Richter (1956) has been reported. As it can be observed, this represents a lower boundary for the data. For this reason, the proposed linear conversion relationship has been used.

4.3 Declustering

The process of declustering consists in removing dependent events, namely aftershocks and foreshocks from the earthquake catalogue, as requested by the Poissonian assumption implicit in the Cornell–McGuire approach. In the current study, the declustering algorithm developed by Gardner and Knopoff (1974) has been applied. The total number of
earthquakes with $M_w \geq 4$ before declustering was 1736, whereas 905 events were left after the removal of foreshocks and aftershocks (i.e. 52 % main events).

4.4 Analysis of completeness

It is generally recognized that historical earthquake catalogues are more complete for large magnitude events than for the smaller ones. Incomplete periods of the catalogue have some important consequences in the estimation of the parameters that describe the magnitude–frequency recurrence relationship of Gutenberg–Richter (1954). In this study, the completeness periods for various magnitude classes have been estimated using the Stepp (1973) method. Table 2 summarizes the computed completeness periods for all events of the catalogue.

The identification of completeness periods has also been performed for each SZ. When data were not sufficient in number (<10) to evaluate the completeness period for a certain magnitude class, two hypotheses were assumed: a completeness period coinciding with that of the nearest seismic zone; a period assumed as “fully complete” for that magnitude class.

A bounded Gutenberg–Richter recurrence relationship for magnitude (Gutenberg and Richter 1954) has been adopted on the basis of the completeness periods calculated for each SZ, considering both hypotheses for the completeness period when it was needed:

$$\hat{\lambda}_M = \hat{\lambda}_0 \cdot \frac{e^{-\beta (M_w - M_{w,\inf})}}{1 - e^{-\beta (M_{w,\sup} - M_{w,\inf})}}$$

where $\hat{\lambda}_0 = \exp (\alpha - \beta \cdot M_{w,\inf})$, and $M_{w,\inf}$ and $M_{w,\sup}$ are, respectively, the lower and upper bound of moment magnitude $M_w$.

The parameters of bounded G–R recurrence relationships have been calculated after creating appropriate magnitude classes of amplitude equal to 0.5 (for zones 1, 2, 4 and 5) and 0.8 (for zones 3, 6, 7, 8, 9, 10 and 11). The adoption of larger width of the magnitude range for some of the SZ was inevitable to avoid the frequent occurrence of fewer number of events in certain magnitude classes. When two hypotheses of completeness were applied, final parameters coincided with those resulted from the hypothesis giving higher value of “$\hat{\lambda}_0$”, conservatively.

Table 3 summarizes the parameters of Gutenberg–Richter magnitude–frequency recurrence relationship and the completeness intervals for each SZ.

<table>
<thead>
<tr>
<th>$M_w$</th>
<th>Complete period</th>
</tr>
</thead>
<tbody>
<tr>
<td>4–4.49</td>
<td>2012–1983</td>
</tr>
<tr>
<td>4.5–4.99</td>
<td>2012–1973</td>
</tr>
<tr>
<td>5–5.49</td>
<td>2012–1953</td>
</tr>
<tr>
<td>5.5–5.99</td>
<td>2012–1953</td>
</tr>
<tr>
<td>6–6.49</td>
<td>2012–1903</td>
</tr>
<tr>
<td>6.5–6.99</td>
<td>2012–1903</td>
</tr>
<tr>
<td>7–7.49</td>
<td>2012–1903</td>
</tr>
<tr>
<td>7.5–7.99</td>
<td>1663–2012</td>
</tr>
<tr>
<td>&gt;8</td>
<td>1663–2012</td>
</tr>
<tr>
<td>Zone</td>
<td>$\beta$</td>
</tr>
<tr>
<td>-------</td>
<td>----------</td>
</tr>
<tr>
<td>SZ1</td>
<td>1.667</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>SZ2</td>
<td>1.797</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>SZ3</td>
<td>3.104</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>SZ4</td>
<td>2.689</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>SZ5</td>
<td>2.324</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>SZ6</td>
<td>2.424</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>SZ7</td>
<td>2.039</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>SZ8</td>
<td>2.186</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>SZ9</td>
<td>2.156</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>SZ10</td>
<td>2.391</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>SZ11</td>
<td>1.634</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>
5 Hazard computation and results

5.1 Uniform hazard spectra along the pipeline route

The computation of the seismic hazard has been performed using the software CRISIS 2007 version 7.2 (Ordaz et al. UNAM 2007) over a grid of points spaced 0.045° (5 km), covering a rectangular area which contains the pipeline, for a total of 112 computation nodes.

Epistemic uncertainties have been accounted for through a logic tree framework composed by 52 branches (Fig. 9). They represent alternative choices concerning seismotectonic scenarios (2), maximum cut-off magnitudes (2, the maximum historical magnitude and that plus 0.5 units), ground-motion prediction available in literature (12).

Due to an almost complete unavailability of strong-motion records, it was impossible to adopt an attenuation model specific for the region under study. Therefore, Ground motion prediction equations (GMPE) have been selected from the literature on the basis of their compatibility with the tectonic environments for the region under study. These include a crustal zone in the western side of the area and in the eastern side a subduction zone.

Table 4 shows the ground-motion prediction equations selected for the study.

Concerning the weights assigned to the various branches of the logic tree, the first seismotectonic model has been assigned a higher weighting factor with respect to the second model (0.6 vs. 0.4), because of the uncertainties in defining the characteristics of the megathrust fault. Maximum historical magnitude and maximum historical magnitude plus 0.5 have been assigned equal weights (0.5).

![Fig. 9](image-url) The adopted logic tree framework (*GMPEs are reported in Table 4)
As regards GMPE, the AS (08) correlation was assigned a lower weighting factor with respect to the other GMPEs (0.0476 vs. 0.0952) since a comparison with few available strong-motion records showed that the AS (08) GMPE tends to underestimate the horizontal PGA. This is evident from the analysis of Fig. 10, which shows the comparison between the predicted values of horizontal PGA and the strong-motion records associated with the event of 6 February 1988 ($M_w = 6.1$), occurring at India–Bangladesh border. In particular, the strong-motion records for this event have been found on Cosmos Virtual Data Center database (http://db.cosmoseq.org/scripts/earthquakes.plx).

Four points have been selected for the calculation of the horizontal median uniform hazard spectra and median plus and minus one standard deviation for 5 return periods (i.e. 95, 225, 475, 975 and 2,475 years): the single-point mooring (SPM), the land-terminal end at Matarbari (LTE Matarbari), a halfway point along the pipeline route and the LTE Gahira (Fig. 11).

<table>
<thead>
<tr>
<th>Ground-motion prediction equations adopted for the study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shallow crustal zone</strong></td>
</tr>
<tr>
<td>Abrahamson and Silva (2008)</td>
</tr>
<tr>
<td>Campbell and Bozorgnia (2008)</td>
</tr>
<tr>
<td>Boore and Atkinson (2008)</td>
</tr>
<tr>
<td>Zhao et al. (2006)</td>
</tr>
<tr>
<td><strong>Subduction zone</strong></td>
</tr>
<tr>
<td>Youngs et al. (1997)</td>
</tr>
<tr>
<td>Atkinson and Boore (2003, 2008)</td>
</tr>
<tr>
<td>Zhao et al. (2006)</td>
</tr>
</tbody>
</table>

**Fig. 10** Comparison of predicted values of PGA and strong-motion records
Fig. 11 Horizontal UHS for different return periods (outcropping stiff ground and 5 % structural damping)
5.2 Hazard map and comparison of results

To the best of authors knowledge, seismic hazard studies focused in the Bay of Bengal have never been performed or at least they were not found in the accredited literature. GSHAP Project referred to a larger area including that of study, whereas hazard maps for horizontal peak ground acceleration with a 475- and 975-year return period were recently calculated by Al-Hussaini and Al-Noman (2010) only for Bangladesh.

Extending the scope of the study, a probabilistic seismic hazard map of horizontal PGA (for stiff-ground conditions) with 10% probability of exceedance in 50 years has been computed by enlarging the grid of computation to include Bangladesh (Fig. 12).

The calculation has been carried out with reference to the seismotectonic source model 2. Moreover, the results refer to the logic tree branch corresponding to the adoption of the GMPE of AS (08) for the crustal SZ and YOUNGS (97) for subduction SZ.
A comparison of the results (Fig. 13) shows that for most of the Bangladesh’s districts, the values of PGA predicted by the current study are larger than those calculated by Al-Hussaini and Al-Noman (2010).

Fig. 12 Hazard map of horizontal PGA (gal) with 475-year return period (outcropping stiff ground and 5 % structural damping)

Fig. 13 Hazard map of horizontal PGA (gal) with 475-year return period from Al-Hussaini and Al-Noman (2010)

A comparison of the results (Fig. 13) shows that for most of the Bangladesh’s districts, the values of PGA predicted by the current study are larger than those calculated by Al-Hussaini and Al-Noman (2010).

6 Conclusions

The scope of the study presented here was to obtain horizontal, uniform hazard spectra (on stiff-ground, horizontal topographic conditions and 5 % structural damping) for different
return periods, at some selected sites along an offshore pipeline route, in the Bay of Bengal.

The authors were commissioned to perform a “standard” seismic hazard study as a first initial phase of the project, since the absolute lack of PGA and SA values considered reliable for the area of interest.

PSHA has been performed using the standard Cornell–McGuire approach. Epistemic uncertainty was accounted for using a logic tree framework. Two seismotectonic models were adopted. One of them includes a megathrust tectonic lineament whose seismic activity has been modeled using a “characteristic earthquake” model. A comprehensive composite earthquake catalogue has been developed for a large area surrounding the pipeline. This operation was carried out by thoroughly consulting the web databases of numerous, accredited international (and local) agencies.

Different tectonic environments within the study area have been accounted for, in the selection of appropriate ground-motion prediction equations. Epistemic uncertainty has been addressed using a logic tree constituted by 52 branches.

The lack of previous probabilistic hazard studies in the Bay of Bengal demonstrates the need for performing a site-specific hazard analysis along the route of an offshore pipeline. A comparison of the hazard map of peak ground acceleration calculated for 475-year return period for Bangladesh, with recent results from the literature, shows that for most districts of the country, the seismic hazard predicted by this study is more severe. The authors recognize the fact that geodetic measurements of fault movement rates (particularly at the latitude of the Arakan trench) would entail the redefinition of some of the sources in the seismotectonic model. Paleoseismic studies and identification of blind faults underneath thick sediments would add important pieces of information as well. Moreover, availability of strong-motion records in Bangladesh would certainly allow for a better selection of GMPE for the hazard study.

As an object of future research, it will be important to account for ground displacements, due to their major importance for pipeline design.

Furthermore, the need of performing the disaggregation procedure is stressed, in order to better understand the contribution of each seismic source to hazard.

Acknowledgments The work presented in this paper was partly supported by the financial and technical contribution of Tecnoconsult Engineering Construction s.r.l in the framework of a Ph.D. course, which is greatly acknowledged by the authors.

References

Boore DM, Atkinson GM (2008) Ground-motion prediction equations for the average horizontal component of PGA, PGV and 5% -damped PSA and spectral periods between 0.01 s and 10.0 s. Earthq Spectra 24(1):99–138
Campbell KW, Bozogorgnia Y (2008) NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s. Earthq Spectra 24(1):139–171
Choudhury JR (1993) Seismicity in Bangladesh. WSSI Bangkok workshop on seismic risk management, February
Hossain KM (1989) Seismicity and tectonics of Bangladesh. Internal report IC/89/81, Miramare, Trieste
Iyengar RN, Sharma D (1998) Earthquake history of India in medieval times. Central Building Research Institute, Roorkee