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Extended summary

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

Curriculum: Materials, Waters, and Soils Engineering

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Abstract. The scope of the study was to perform the probabilistic seismic hazard assessment (PSHA) along the route of an offshore pipeline for the transport of oil in the Bay of Bengal. The outcome of the seismic hazard analysis is given in terms of horizontal median uniform hazard spectra (UHSs) and plus and minus one sigma for five return periods (i.e., Tr= 95, 225, 475, 975, and 2475 years), in correspondence of four selected sites of the pipeline route. In addition, two seismic hazard maps for horizontal peak acceleration and spectral acceleration at T=0.2 sec with 475 year-return period are provided, extending in Bangladesh and neighbourhood regions. 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 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 December 2004.

Different tectonic environments within the study area were accounted for in the selection of appropriate ground-motion prediction equations. A logic-tree framework constituted by 52 branches was adopted in the computation for taking into account epistemic uncertainties.

The analysis of the values of UHSs has pointed out the change of the level of hazard along the route of the pipeline. Moreover, the comparison of the hazard maps whit those available in literature, has showed higher values of hazard in the performed study, which leads to consider that for most districts of Bangladesh the earlier analyses underestimate the seismic hazard considerably.

Keywords. PSHA, UHSs, return periods, earthquake catalogue, seismotectonic scenarios

1 Introduction

Probabilistic seismic hazard analysis (PSHA) is the most widely used procedure for the quantitative estimation of ground-shaking hazard at a particular site caused by an earthquake. The parameters that describe the level of shaking are the design ground motion parameters (peak ground acceleration [PGA], velocity or displacement; spectral acceleration, velocity, or displacement , etc.).

In the PhD thesis, Probabilistic seismic hazard assessment (PSHA) along the route of an offshore pipeline for the transport of oil in the Bay of Bengal has been performed.

The design of the offshore pipeline is part of the expansion plane of the crude processing capacity of the Eastern Refinery Limited (ERL), situated at Chittagong (Bangladesh), in which Tecnoconsult s.r.l. company is involved.

As a first task a critical review of past hazard studies referred to the study region has been performed. They appear scanty and based on assumptions that are often not completely justified. This fact, along with the lack of seismic network for earthquake recording for a long time, result from the scarce consideration attributed to the seismic hazard, probably because of the higher incidence of other natural, devastating hazards (mostly cyclones and floods). Nevertheless, despite the low incidence of large earthquakes in the last years, a careful consideration of seismotectonic framework reveals that Bangladesh is surrounding by regions of high seismicity. In the past, the country has been affected by large earthquakes (Richter magnitude greater than 7). Moreover, in recent years, small to moderate earthquakes are regularly occurring, having the epicenters in neighboring regions (India, Burma) and some epicenters within the country.

Bengal Basin, whose Bangladesh is the major part, lies in fact at the "point of junction" of three tectonic plates (the Indian, the Eurasian, and the Burma plates), which interact in a complex and intricate way over the years, that 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 necessary for performing PSHA, encompassing the main geological structures and major tectonic provinces that result from the interaction of the tectonic plates.

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

The route of the offshore pipeline consists of two main sections: a section long approximately 9 km connecting a single point mooring (SPM) with a land-terminal end at Matarbari (LTE Matarbari); a second section, long approximately 65 km 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, which is 450 km from the pipeline route, has been considered. 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 provinces and geological structures surrounding the pipeline route, and furthermore, it includes some historical events with large magnitude (Mw greater than 7), in absence of which likely the hazard would have been underestimated (i.e., the 1923, Mw=7.4 earthquake; the 1932, Mw=7.4 earthquake, the 1943, Mw=7.1 earthquake, the 1957, Mw=7.1 earthquake, the 1839, Mw= 7.2 earthquake, the 1787, Mw=7.2 earthquake, the 1897, Mw=8.1 Great Assam earthquake). A comprehensive earthquake catalogue and two seismotectonic scenarios have been constructed referring to this area, as described in the following paragraphs.

3 Construction of the earthquake catalogue and processing of data

The compilation of the earthquake catalogue represents a fundamental step in PSHA as per Cornell-McGuire approach. Nevertheless, it represents also a critical issue: it has to be composite, homogenous and obtained from a merger of available regional databases and local sources in order to be well-defined 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. Height international databases have been consulted. Moreover, in order to well reconstruct especially the historical seismicity, information from catalogues referred to larger areas including that of study, such as that from Ornthammarath et al., 2011 compiled for Thailand, has been used.

The composite catalogue spans a period from February 1663 to January 2012 and incorporates 905 earthquakes with Mw ≥ 4 (see Figure 1). Processing of data has been carried out, consisting in duplicate removing, homogenizing, declustering, and completeness analysis. The duplicate removing has been based on an "order of reliability" of information (database more reliable and/or scale of magnitude used to express the strenght of the event). Homogenizing has been performed by the construction of empirical equations for the conversion of Ms, mb, ML, and Io into Mw. Declustering has been performed by applying Gardner and Knopoff method (1974). The analysis of completeness has been carried out according to the method by Stepp (1973). Details are not reported for brevity.

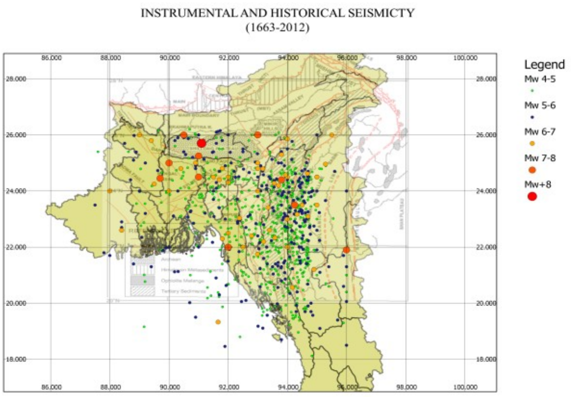

Figure 1. The earthquake catalogue

4 Seismotectonic scenarios

Two different seismotectonic scenarios have been adopted in the hazard computation, including them within a logic tree framework. They have been the result of a great deal of effort for the definition of seismicity, geology , and tectonics of the study region, with the purpose to recognize the relationship between past events and main geologic and tectonic provinces of the area.

4.1 The first seismotectonic scenario

The first seismotectonic model consists of eleven seismogenic zones (refer to Figure 2). These have been delineated taking into account the change of seismicity in terms of depth of events and magnitude throughout the study area, and considering clustering of events from the compiled catalogue around the main tectonic and geologic structures. Details about each seismogenic zone are not reported for brevity, however it is suggested to refer to the complete thesis to have insight into this.

The temporal occurrence of seismicity within the SZs has been modeled as a Poisson process.

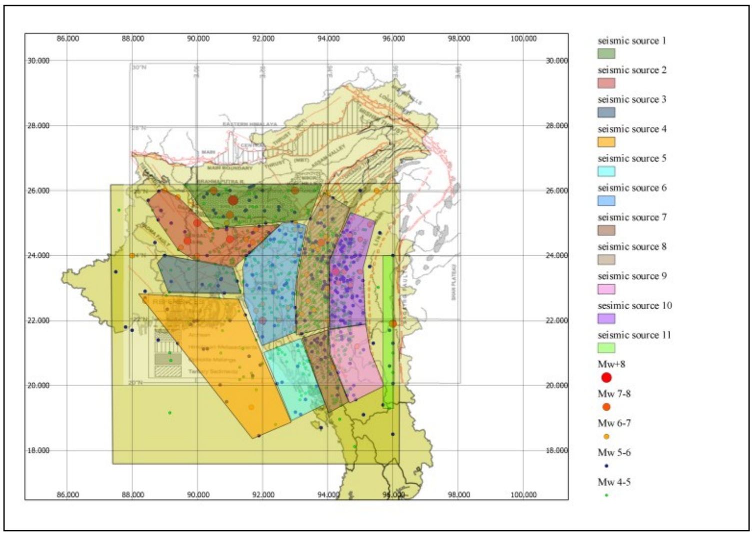

Figure 2. The first seismotectonic scenario: 11 source zones

4.2 The second seismotectonic scenario

The second seismotectonic scenario accounts for the presence in the study region of a mega thrust representing the northward continuation of the large Sunda mega thrust, responsible for the large Sumatra-Andaman earthquake of December 2004. For this purpose, in addition to the 11 seismic source zones contained in the first seismotectonic scenario, 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 by Steckler et al. (2008) (refer to Figure 3). The occurrence of seismicity along the tectonic lineament has been modeled as a "characteristic earthquake".

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 km and 700 km respectively), and crustal shear modulus (equal to 3.3*1010 Pa) furnished by Socquet et al. (2006) have been used.

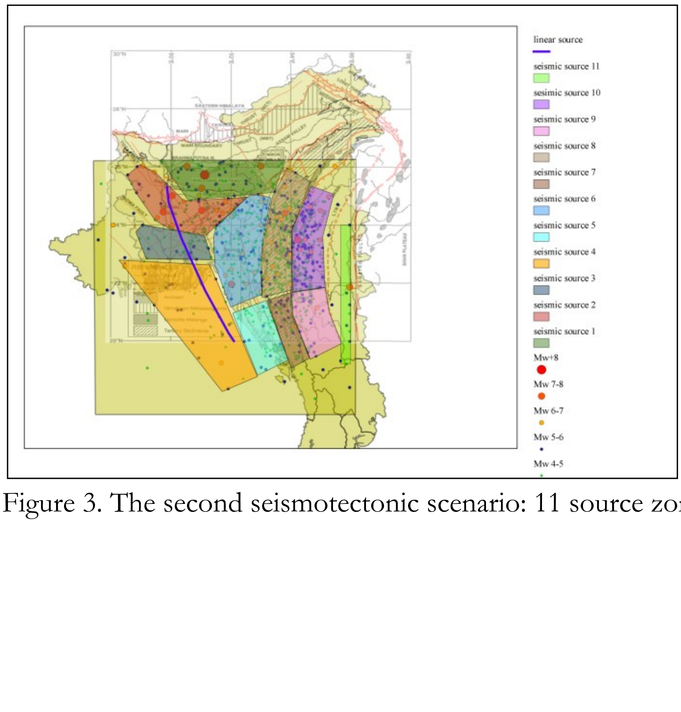

Figure 3. The second seismotectonic scenario: 11 source zones plus linear fault source

5 Hazard computation

5.1 Uniform Hazard Spectra along the pipeline route

The computation of the seismic hazard has been performed using the software Crisis 2007 v. 7.2 over a grid of points spaced 0.045° (5 km), covering a rectangular area which contains the pipeline, for a total of 112 points of computation.

Epistemic uncertainties have been accounted for within a logic-tree framework with 52 branches, incorporating two seismotectonic scenarios, two different maximum cut-off magnitude (the maximum historical magnitude and that plus 0.5), 12 pairs of selected ground-motion prediction available in literature.

Since the lack of strong motion records, a regional attenuation model for the study area is not available. Therefore ground-motion prediction equations have been selected on the basis of their compatibility with the tectonic environments in the study region, namely a crustal zone seismicity (western side of the area) and a subduction zone (eastern side).

Table 1 displays the selected ground-motion prediction equations.

Table 1. Ground-motion prediction equations

SHALLOW CRUSTAL ZONE	
Abrahamson and Silva (2008)	AS (08)
Campbell and Bozogorgnia (2008)	CB (08)
Boore and Atkinson (2008)	BATK (08)
Zhao et al. (2006)	ZHAO (06)
SUBDUCTION ZONE	
Youngs et al. (1997)	YOUNGS(97)
Atkinson and Boore (2003, 2008)	ATKB (08)
Zhao et al. (2006)	ZHAO (06)

The first seismotectonic scenario has been assigned a higher weighting factor than the second scenario (0.6), because of the higher uncertainty in the delineation of the linear fault source.

Maximum historic magnitude and maximum historic magnitude plus 0.5 have been assigned equal weighting factors (0.5), since there is no evident reason for choosing one alternative over the other.

As regards ground-motion prediction equations, the pairs containing AS (08) have been assigned a lower weighting factor, since from the comparison with an available strong-motion record it has been resulted that AS (08) underestimates the value of horizontal peak acceleration.

Four points have been selected for the construction of the horizontal mean uniform hazard spectra and plus and minus one sigma for 5 return periods (i.e., 95, 225, 475, 975, and 2475 years) : the SPM point, the LTE Matarbari point, a halfway point along the pipeline route and the LTE Gahira point (refer to Figure 4)

Table 2 summarizes the values of horizontal spectral acceleration (at T=0 sec, and T=0.2 sec) obtained for the different return periods in correspondence of the selected points of the pipeline. From the analysis of these values and the graphs plotted in Figure 4, it can be noticed that the differences among the points of the route are more evident for lower structural periods (T < 0.5 sec), where there is the maximum value of the spectrum (T=0.2 sec). Higher difference is observed between SPM point and Gahira (for a side) and halfway point and Matarbari (for the other side). In particular, the SPM point and LTE Gahira display quite similar values for the lower considered return periods (i.e., Tr=95 and 225 years). On the other hand, for higher return periods, the difference between them increases, reaching a value of 74.5 cm/sec^2 approximately.

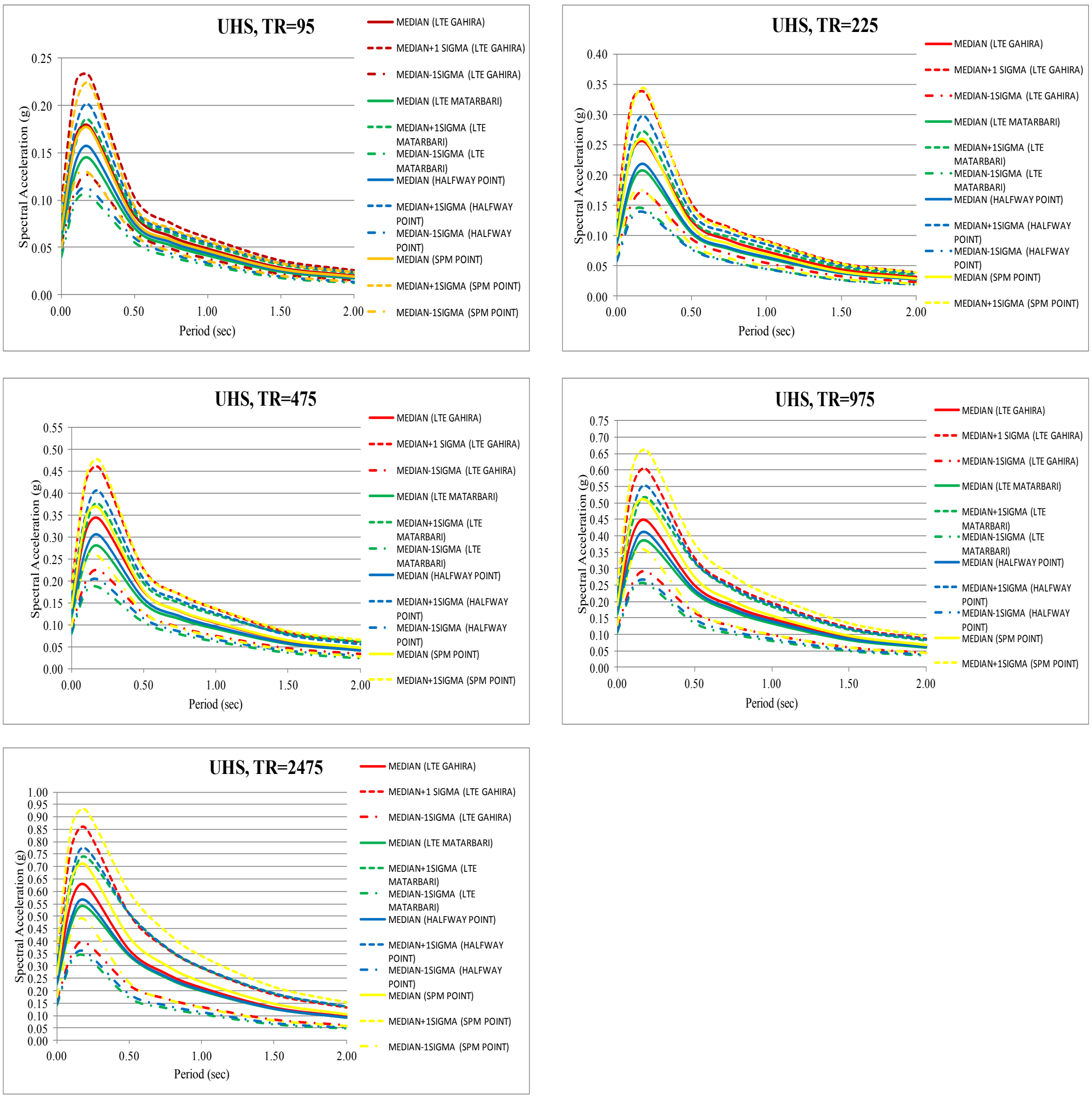

Figure 4. Horizontal UHS for different return periods

Table 2: Horizontal spectral acceleration for T=0 sec and T=0.2 sec at different points of the route and for different return periods

Tr (ys)	Pga (g)	Pga+σ (g)	Pga-σ (g)	SA (T=0.2s) (g)	SA (T=0.2s)+σ (g)	SA (T=0.2s)-σ (g)
HALFWAY POINT						
95	0.07	0.08	0.05	0.15	0.2	0.11
225	0.09	0.12	0.06	0.21	0.29	0.14
475	0.13	0.17	0.08	0.3	0.4	0.2
975	0.17	0.23	0.11	0.41	0.55	0.26
2475	0.23	0.32	0.15	0.56	0.77	0.35
SPM POINT						
Tr (ys)	Pga (g)	Pga+σ (g)	Pga-σ (g)	SA (T=0.2s) (g)	SA (T=0.2s)+σ (g)	SA (T=0.2s)-σ (g)
95	0.07	0.09	0.05	0.17	0.22	0.13
225	0.1	0.13	0.07	0.25	0.34	0.17
475	0.14	0.18	0.09	0.36	0.47	0.25
975	0.19	0.25	0.13	0.5	0.65	0.35
2475	0.27	0.36	0.18	0.7	0.93	0.48
LTE GAHIRA						
Tr (ys)	Pga (g)	Pga+σ (g)	Pga-σ (g)	SA (T=0.2s) (g)	SA (T=0.2s)+σ (g)	SA (T=0.2s)-σ (g)
95	0.08	0.1	0.05	0.17	0.23	0.12
225	0.11	0.14	0.07	0.25	0.33	0.17
475	0.14	0.19	0.09	0.34	0.45	0.22
975	0.19	0.25	0.12	0.44	0.6	0.29
2475	0.26	0.35	0.16	0.62	0.85	0.39
LTE MATARBARI						
Tr (ys)	Pga (g)	Pga+σ (g)	Pga-σ (g)	SA (T=0.2s) (g)	SA (T=0.2s)+σ (g)	SA (T=0.2s)-σ (g)
95	0.06	0.08	0.04	0.14	0.18	0.1
225	0.09	0.11	0.06	0.2	0.27	0.14
475	0.12	0.16	0.08	0.28	0.37	0.18
975	0.16	0.21	0.11	0.38	0.51	0.25
2475	0.22	0.31	0.14	0.54	0.74	0.34

Table 3 reports the difference between the values of spectral acceleration at T=0.2 sec at SPM point with those of the other points.

Table 3: Difference of SPM values with other points of the route for different return periods

Tr (ys)	SPM-Halfway (cm/sec/sec)	SPM-Matarbari (cm/sec/sec)	SPM-Gahira (cm/sec/sec)
95	19.61	29.42	0.00
225	39.23	49.03	0.00
475	58.84	78.45	19.61
975	**88.26**	**117.68**	**58.84**
2475	**137.29**	**156.91**	**78.45**

As it can be observed, for higher return periods (i.e. Tr =975 and 2475 years) there is a substantial difference with values at SPM point. Considering the seismic zoning map of Bangladesh in BNBC (1993), the difference between the higher seismic zone (zone 3) and the lowest one (zone 1) is of about 171 cm/sec^2. On the basis of these observations, it appears reasonable consider the SPM point as the most hazardous one.

5.2 The hazard maps: comparison with the available results

Unfortunately, seismic hazard studies for the Bay of Bengal have not been found in literature, whereas for Bangladesh, only hazard maps for horizontal peak ground acceleration and spectral acceleration at T=0.2 sec with 475 year-return period are available from a study performed by Al-Hussaini et al., (2010). By using input constructed in the current work, and enlarging the grid of computation so that to include Bangladesh, a hazard map for horizontal peak acceleration and spectral acceleration at T=0.2 sec with 10% probability of excedance in 50 years have been produced.

In particular, the hazard computation has been performed by referring to the second seismotectonic scenario (11 SZs plus 1 LF). As regards GMPEs, the Abrahamson and Silva (2008) and the relationship of Youngs (1997) have been applied.

Figure 5 reports the so obtained hazard map in terms of values of PGA (cm/sec/sec) with 475 year-return period.

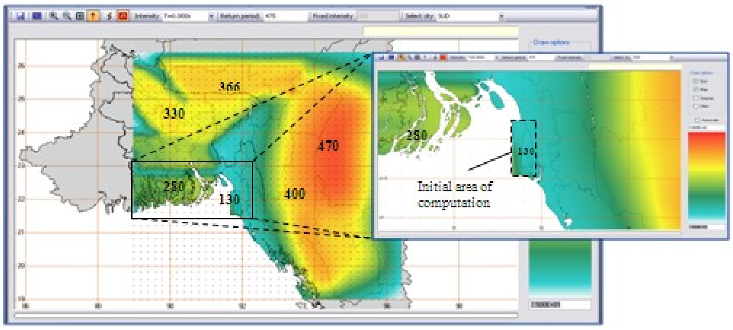

Figure 5: Hazard map of horizontal PGA (cm/sec/sec) with 475-year return period, obtained in the current work

From the comparison with the hazard map performed by Al-Hussaini et al. (2010) displayed in Figure 6, it is evident that for most of the districts of Bangladesh, the map by Al-Hussaini underestimates the hazard.

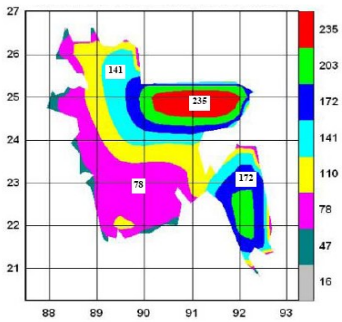

Figure 6: Hazard map of horizontal PGA (cm/sec/sec) with 475-year return period from Al-Hussaini et al. (2010)

Remarkable differences can also be noticed by the comparison of hazard maps expressed in terms of spectral acceleration at T=0.2 sec with 475-year return period, which are reported in Figures 7 and 8.

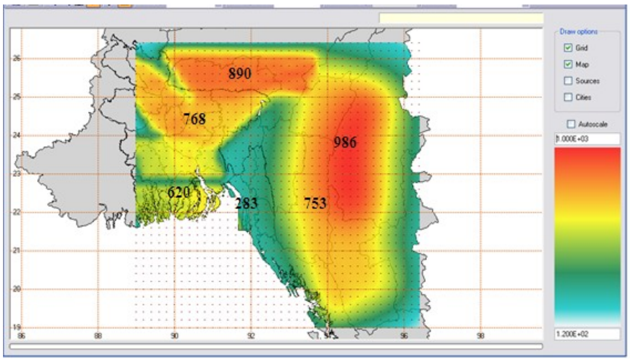

Fig. 7: Hazard map of horizontal spectral acceleration (cm/sec/sec) at T=0.2 sec with 475-year return obtained in the current work

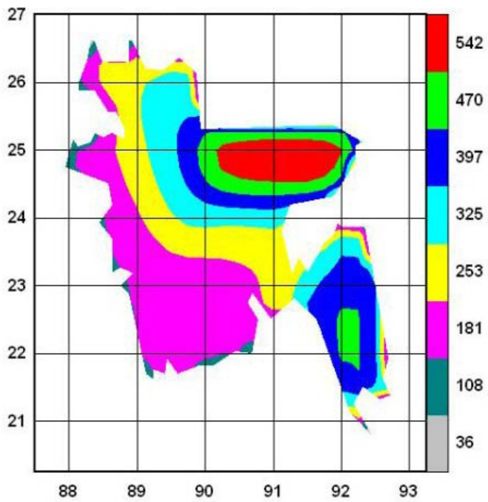

Figure 8: Hazard map of horizontal spectral acceleration (cm/sec/sec) at T=0.2 sec with 475-year return from Al-Hussaini et al. (2010)

6 Conclusions

The scope of the study was to perform the probabilistic seismic hazard assessment (PSHA) along the route of an offshore pipeline for the transport of oil in the Bay of Bengal. The outcome of the seismic hazard analysis is given in terms of horizontal median uniform hazard spectra (UHSs) and plus and minus one sigma (UHSs $\pm 1\sigma$), for five return periods (i.e., Tr= 95, 225, 475, 975, and 2475 years), in correspondence of four selected sites of the pipeline route. In addition, two seismic hazard maps for horizontal peak acceleration and spectral acceleration at T=0.2 sec with 475 year-return period are provided, extending in Bangladesh and neighborhood regions.

PSHA was performed as per classical Cornell-McGuire approach, and introducing in addition a linear source whose seismicity occurrence was modeled as "characteristic earthquake". A comprehensive earthquake catalogue was produced for a large area surrounding the pipeline, consulting numerous international and local sources. Different tectonic environments within the study area were accounted for in the selection of appropriate ground-motion prediction equations. A logic-tree framework constituted by 52 branches was adopted in the computation for taking into account epistemic uncertainties.

The analysis of the values of UHSs at different selected sites has pointed out the change of the level of hazard along the route of the pipeline, justifying the need for performing a specific hazard assessment along it. Higher difference is observed between SPM point and Gahira (for a side) and halfway point and Matarbari (for the other side). In particular, the SPM point and LTE Gahira display quite similar values for the lower considered return periods (i.e., Tr=95 and 225 years). On the other hand, for higher return periods, the difference between them increases, reaching a value of 74.5 cm/sec^2 approximately. For higher return periods (i.e. Tr =975 and 2475 years) there is also a substantial difference of the values in correspondence of the other points of the pipeline route (i.e., the LTE Matarbari, and the halfway point) with values at SPM point. This difference, considering Tr= 2475 years is about 137 cm/sec^2 for the halfway point and 157 cm/sec^2 for LTE Matarbari. Therefore, the SPM is the most hazardous point. Moreover, the comparison of the hazard maps whit those available in literature, has showed higher values of hazard in the performed study, which leads to consider that for most districts of Bangladesh the earlier probabilistic hazard analyses underestimate the seismic hazard considerably.

The authors recognize the fact that geodetic measurements of fault movement rates especially at the latitude of the Arakan trench would entail the redefinition of sources in the seismotectonic source model. Paleoseismic studies and discrimination of blind faults underneath thick sediments would add very important information as well. Similarly, strong motion records for earthquakes would be essential to make a more prudent selection of attenuation relationship for the study area. Such data could be eventually used to performed a regional attenuation model.

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