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Active Seismic Structures, Energy Infrastructures, and Earthquake Disaster Response Strategy - Bangladesh Perspective

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Abstract – *Bangladesh is situated at the juncture of the three tectonic plates and the active interaction of these plates resulted in several major active faults in and around Bangladesh, especially along its northern and eastern margins. Some of these faults are regional scale, and capable of generating moderate to great earthquakes. The rate of plate motion, presence of seismogenic gaps in the active faults, and the time since the last rupture of these faults indicate a high probability of impending earthquakes. The country and its neighboring surroundings have experienced high-magnitude earthquakes in the past and caused substantial damage of the infrastructures and lives. Although the possibility of damages arising from a seismic hazard is on the rise due to the dynamic and intensified development of engineering and energy infrastructures, human casualties may decline because of a better understanding of the earthquake mechanism, possible area of seismic hazard, recurrence interval, and the improvement of the monitoring system capabilities. However, due to the lack of a comprehensive seismic zonation map and site-specific probabilistic seismic hazard maps, the human casualty, and property losses, specifically, energy infrastructure will be disastrous. Therefore, the professionals, scientific and technological community of the country should cooperate and make joint efforts to overcome all the scientific and technological hurdles to seismic disaster management of Bangladesh. By considering the importance of the energy sector in the country's rapid economic growth, an in-depth seismic vulnerability assessment of the energy infrastructures is needed to be performed immediately.*

Keywords – *active faults, disaster response strategy, energy infrastructures, seismogenic gaps, seismic zoning map.*

1. INTRODUCTION

Earthquakes, a natural disaster have long dynamically affected the earth's landscape and caused shifting of the large river courses, serious injury to living creatures, drastic changes to the living environment, catastrophic damage to the economy and infrastructures, and even large-scale human migration. In the last few years, earthquakes, an unpredictable but impending threat for Bangladesh sparked much discussion regarding the possible disastrous consequences. Export driven economic growth of Bangladesh in recent years powered by not only the private sector but also by the public sector which has undertaken several mega engineering and energy infrastructure projects with huge investments, and therefore, the continued rise of GDP year-on-year. However, the country's economy faces a double blow in 2020 from short-duration disaster and long duration pandemic the cyclone Amphan, and COVID 19, respectively. These two incidents expose the high vulnerability of the country's economy against natural disasters. Moreover, all major earthquakes had occurred in and around Bangladesh long before the establishment of the country's energy infrastructures (*i.e.,* gas production facilities, processing plants, transmission and distribution pipelines, and oil refinery). It is worth to be mentioned that after 1950, no major to the great earthquake has occurred along the seismogenic gaps, locked thrust, and active faults in and adjacent to Bangladesh. Hence, the sustainability of these energy infrastructures in the case of major earthquakes is unknown.

The country is historically exposed to a number of natural disasters (*e.g.,* Floods, Riverbank erosion, Cyclones, Landslides, Tsunami, and Earthquakes) that disrupt the economy significantly in the past and causes substantial damage of the infrastructures and lives. However, with the advancement of science and technology, almost all the natural hazards can be predicted well before their strike, except earthquakes. This unpredictable natural disaster poses an extraordinary risk for the whole country. Bangladesh and its neighbouring countries have experienced high-magnitude earthquakes in the past [1]-[8], and the consequences were devastating. Among such seismic events, the Chittagong earthquake of 1762 (R 8.5+), Sirajganj earthquake of 1787 (MM X), Cachar earthquake of 1869 (R 7.5), Bengal earthquake of 1885 (Mw 6.8), Great Indian/Assam earthquake of 1897 (Mw 8.1), Srimangal earthquake of 1918 (Mw 7.6), Meghalaya earthquake of 1923 (Ms 7.1), Dubri earthquake of 1930 (Mw 7.1), Bihar-Nepal earthquake of 1934 (Mw 8.1), Assam earthquake of 1950 (Mw 8.6), and Nepal earthquake of 2015 (Mw 7.8) are well known.

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The maximum felt intensity of these seismic events is localised in the tectonically uplifted region of the Bengal Basin [2]. If such a magnitude earthquake occurs at present in or adjacent to Bangladesh, the devastation may get intensified manifold because of the huge population density in the poorly-planned urban areas. Recent earthquake occurrences and their colossal damages in neighbouring countries, like Nepal (7.8 Mw, 2015/4), Myanmar (6.9 Mw, 2016/4), and India (6.7 Mw, 2016/1) further exacerbate this issue. Bangladesh itself experienced several small to moderate shocks during this time, in which Mw 4.9 in Madhabpur (2017/11), Mw 4.7 in Rangamati (2016/6), Mw 4.6 in Sarankhola (2015/4), Mw 4.5 in Chhatak (2017/4), and Mw 4.5 in Sylhet (2020/1) are the noticeable one. It is thought-provoking to see that except for the Sarankhola earthquake, the rest of them belong to the high seismic prone area, as demarcated in the earthquake zonation map of Bangladesh (Figure 1).

The geodynamic development and multifaceted neotectonic evolutions of the Bengal Basin result in several active faults in and around Bangladesh, especially along its northern and eastern margins. Some of these faults are regional, and capable of generating moderate to great seismic events. The rate of motion and recurrence interval indicates that the probability of earthquakes from the existing active faults is high [8], [9]. A general increasing trend of seismic/earthquake activity has been observed in and around Bangladesh in recent years [9], [10]. This apparent increase of seismicity in the Bengal Basin indicates either new faults propagation from the preceding seismically undisturbed zones or the reactivation of some earlier faults in pre-existing seismically active zones. Considering the above risks, Bangladesh needs to devise preparation and disaster response meticulously that will contemplate every possible aspect of the potential earthquake damage, specifically the energy infrastructures. It is necessary to prepare a comprehensive seismic hazard map and all engineering constructions and energy infrastructure, specifically large-scale ones, need to strictly follow this hazard map guideline during the construction and subsequent operation/maintenance. This review study is aimed to address the current state of seismic vulnerability, and highlighting the possible disaster response strategies for energy infrastructures in Bangladesh's perspective.

2. TECTONIC SETTING OF BANGLADESH

Bangladesh constitutes a major portion of the Bengal Basin, which is the largest peripheral collisional foreland basin in South Asia [8], [11]. Hence, the geology of Bangladesh is an integral part of the geology of the Bengal Basin. Geographically, the basin also covering parts of the Indian States of West Bengal, Assam, Tripura, and Mizoram. The Bengal Basin is surrounding by four major geotectonic units, which are the Indian Shield to the west and the Shillong Plateau to the north, the Indo-Burman Ranges to the east and the Bay of Bengal to the south [12] (Figure 1). The Bengal Basin (Bangladesh) has been divided into three major geotectonic provinces: i) Geotectonic Province 1– the Stable Shelf to the northwest, ii) Geotectonic Province 2 – the Foredeep Basin at the center, and iii) Geotectonic Province 3 ¬– the Folded Flank to the east [8], [13]-[15].

Active tectonics and earthquake geology in these provinces and their adjacent regions are directly related to the oblique collision of the Indian Plate with the Eurasian Plate to the north and the Burmese Plate to the east (Figure 1). The collision developed the Himalayan Orogen to the north, and Indo-Burman Orogen to the east [7], [16], [17]. Based on recent seismic studies, it is presumed that subduction has clogged below the Himalayan arc and is only actively continuing below the Burmese–Andaman arc [18]-[20]. Due to plate convergence and resistance to subduction below the Eurasian Plate, tectonic deformation and seismic activity occur in the Indian intra-plate region, including the stable shelf in the western part of Bangladesh. To the north, tectonic loading is accommodated along the Dauki Fault zone, which is a set of high angle, deep-seated reverse faults [21], [22]. To the east, the collision results in westward migration of accretionary prism complexes and the deformation front as well [7], [8], [12], [16]. The cumulative effects of these complicated neotectonic evolutions around the Bengal Basin result in several active faults in and around Bangladesh.

Geologically, the earthquakes are not isolated events for Bangladesh, rather a part of events that have been mainly occurring along these active faults located at the juncture of three tectonic plates - the Indian, the Eurasian and the Burmese plates. Recent geodetic measurement shows that the motion of the Indian Plate is ~6 cm/yr in the northeast direction, which results ~4.5 cm/yr rate collision with the Eurasian Plate, and ~4.6 cm/yr rate collision with the Burmese Plate [23]. This contractional motion is taken up by stress accumulation and strain partitioning mainly along some major active faults, which are broadly distributed over a series of reverse and strike-slip structures. The probability of an earthquake from such an active fault depends on the rate of motion and the time since the last rupture (i.e., the recurrence interval).

3. MAJOR ACTIVE FAULT IN AND AROUND BANGLADESH

Tectonically active faults of regional-scale capable of generating moderate to strong earthquakes are present mainly in the north and eastern part of Bangladesh and its neighbouring surroundings [8], [9], [11], [24-27]. In Bangladesh, the major active faults are - about 320 km long east-west trending Dauki Fault, located along the southern edge of the Shillong Plateau; the 150 km long

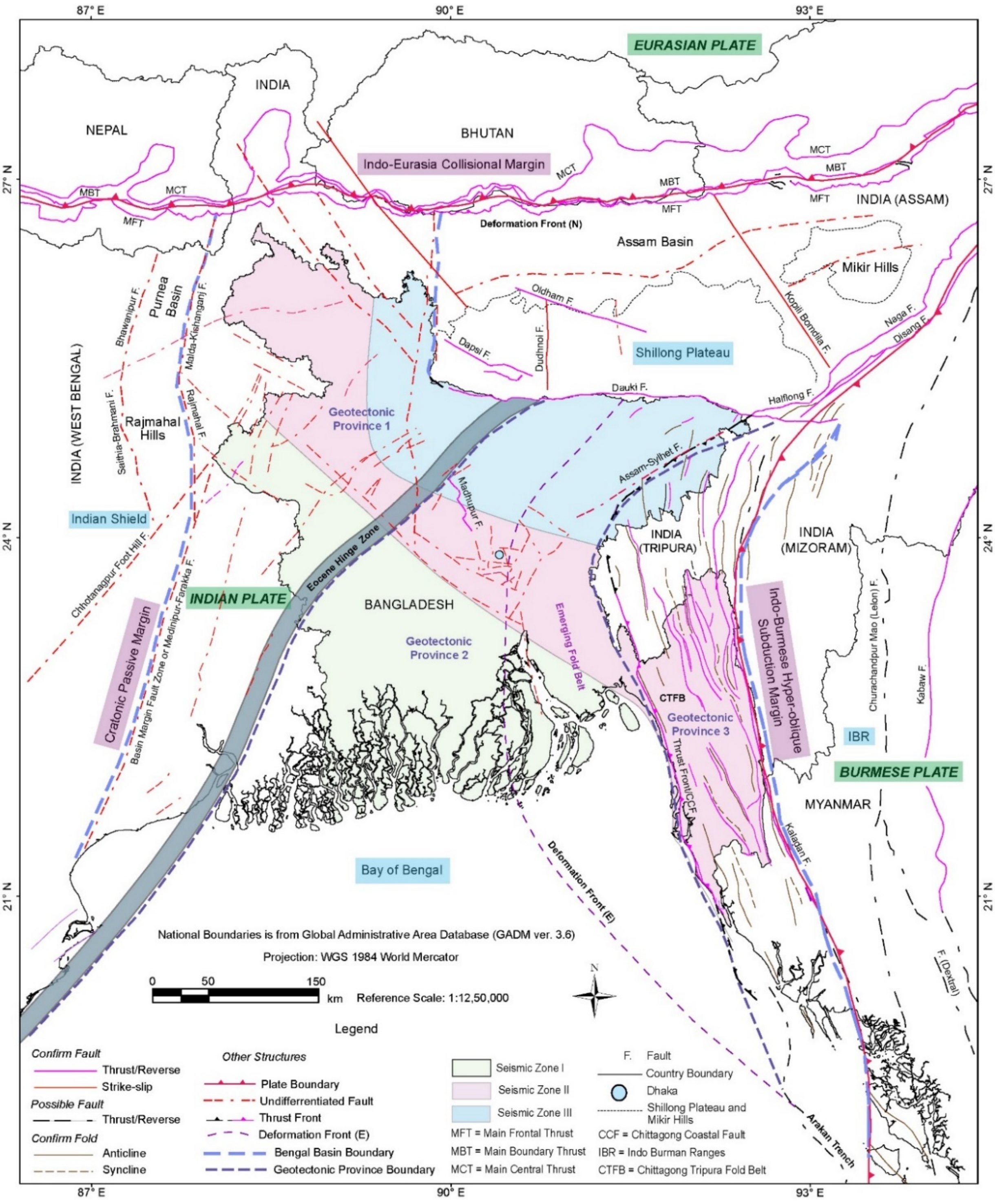

Fig. 1. Simplified tectonic map of the Bengal Basin (Bangladesh) and its surroundings (modified after Hossain *et al.* [12]) superimposed on the tectonic zonation map of Bangladesh [28]. All major active faults in and around Bangladesh have been labeled on the map. Other seismogenic features potential to major earthquakes are also labeled. BNBC [28] divides Bangladesh into three seismic zones with coefficients representing peak ground acceleration (PGA). The PGA of 0.25g (Z=0.25) for Zone III, 0.15g for Zone II, and 0.075g for Zone I. Note: g is the acceleration due to gravity, Z represents design basis earthquake (DBE). Among these three zones, Zone I is seismically less active, zone II is moderately active and Zone III is seismically most active.

Madhupur Fault trending approximately north-south located at the western edge of the Madhupur Tract; the Assam-Sylhet Fault of about 150 km length trending northeast to southwest located in the southern edge of the Surma basin; and the Chottogram-Coastal Fault (CCF), which is a plate boundary fault of about 800 km long, running parallel to the Chittagong-Arakan coast and reaches inland up to the Tichna anticline near

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Bangladesh-Tripura border; and ~450 km long west verging Kaladan Fault, which mostly follows the course of the Kaladan River along Bangladesh-Myanmar border. In the adjacent surroundings, major active faults are - east-west running Main Frontal Thrust (MFT) to the north; WNW-ESE running Oldham Fault also to the north of Shillong Plateau; the Dapsi Fault strikes WNW across the western Shillong massif; the NE-SW running Hafflong-Disang Fault to the northeast; Kabaw and Sagaing faults progressively towards the east of Bangladesh. All these faults had generated devastating earthquakes in the past and can potentially generate a large seismic event in the near future.

The Dauki Fault is an intra-plate active reverse fault with a dextral strike-slip component. The continuous active subsidence of the southern footwall of the Dauki Fault has resulted in the Surma basin [29]. Geomorphic indices suggest that the fault is tectonically more active in the eastern part than in the western portion [30], [31]. The flexural seismic event has been identified along the Dauki Fault near Jaflong (Sylhet) and is inferred to be AD 840-920 [26]. Another rupturing event in the Dauki Fault was estimated to be AD 1548 [25], [26]. It is also assumed that the 1897 Assam earthquake that occurred along the Oldham Fault also caused a slip along the Dauki Fault. Although it was previously thought that the interval between these giant plateau-building earthquakes exceeds 3,000 years [21], the paleoseismic signature indicates a recurrence interval of 350-700 years [26]. The Madhupur Fault is constituted of a series of en-echelon faults, and flanks the western side of the uplifted Madhupur High [9], [12]. It is believed that this fault resulted either from the torsion of the region or from the effect of compressive shear along the western edge of a possible buried anticline or possibly a combination of both [8], [32]. This thrust fault is east-dipping and is considered as an important structure for the seismic hazard assessment of the central part of Bangladesh. The cyclic avulsion history of the Brahmaputra River with a periodicity of about 1800 years is most likely related to the uplift of the Madhupur High due to slip along the Madhupur Fault [33]. The Assam-Sylhet Fault also known as Hail Hayalua Lineament is a major fault, which is probably the southwest extension of the Naga-Disang Thrust [34]-[38]. In November 2017, a shallow focus (30.3 km depth) earthquake with Mw 4.9 occurred at a distance of 27 km SSW of Habiganj, Bangladesh is probably related to the Assam-Sylhet Fault.

The CCF is a dextral strike-slip fault with an appreciable thrust component and is a resultant product of thin-skinned and thick-skinned tectonics [39]. This fault is seismically less active. Maurin and Rangin [39] suggest that the CCF can be interpreted as a deep-seated basement reverse fault with a dextral strike-slip component. The Moheskhali earthquake with 5.2 Mw occurred in Moheskhali Island in July 1999 is a proof of seismic slip along the CCF. This earthquake was strongly felt all over Bangladesh and caused significant damage locally [40]. Moreover, the occurrence of any large seismic event in the offshore area along the east coast of the northern Bay of Bengal is likely to produce a great tsunami [41]. In 1762, one of such large earthquakes (R 8.5+) occurred along the Arakan coast (i.e., Arakan subduction zone) known as Chittagong/Arakan earthquake [2], [4], [7], [41], [42]. The ~450 km long west verging Kaladan Fault mostly follows the course of the Kaladan River [39], [43], [44]. This fault marks the eastern boundary of the CTFB and extends from the Arakan coast in the south to the northern-most part of the CTFB and the IBR contact [4], [7], [12], [39]. Although the Kaladan Fault shows dextral strike-slip as well as west verging thrust components, it is generally considered as a thrust fault, and seismically the fault is sparsely active. While Mw 6.2 earthquake in December 1955 along the Kaladan Fault near the Bangladesh-Myanmar border region is a proof of seismic slip, mainly shallow focus and low-intensity earthquakes are observed along this fault [4].

Besides, the main active faults in the central part of Bangladesh are Madhupur, Dhaleswari, Padma, and Meghna. Around the Dhaka City, few other active faults are also present, which include the Bangshi and Turag faults to the west, Tongi Khal Fault to the north, Balu, Sitalaykha, Banar, and Arial Khan faults to the east, and Buriganga Fault to the south [8], [12]. The 1812 Dhaka earthquake (MM VIII), the 1845 Sirajganj earthquake (Mw 7.1), the 1846 Mymensingh earthquake (Mw 6.2), the 1885 Bengal (Manikganj) earthquake (Mw 7), the 2001 Dhaka earthquake (Mw 4.5), the 2008 Mymensingh earthquake (Mw 5.1), and the 2008 Chandpur earthquake (Mw 4.5) caused damage, especially in Dhaka City [2], [8], [45]. Among these, the 1846 and 2008 Mymensingh earthquakes probably occurred along the Old Brahmaputra Fault, the 1885 Manikganj earthquakes probably occurred along the Madhupur Fault, and the 2001 Dhaka earthquake possibly occurred along the Buriganga Fault. In the eastern part, medium to small-scale thrust faults with strike-slip components are present in the CTFB area. These faults are mostly parallel to the strike of the anticlines, and mostly affected the folds of the CTFB regions [8], [15], [27], [39], [46]-[49]. Few moderate magnitude earthquakes are recorded, which may be connected with these faults of the CTFB region. Among such events, the Bandarban earthquake in 1997 (Mw 6.1), and the Barkal earthquake in 2003 (Mw 5.7) are well known [8].

In the western part of Bangladesh, several faults and lineaments have been identified that have the potential to generate earthquakes of Mw 3.5 and above [45]. Major active faults are the Jangipur–Gaibanda Fault, and the Katihar-Nilphamari Fault. The Eocene Hinge Zone is also identified as a seismically active tectonic element, which is reportedly triggered two earthquakes of magnitude Mw 7.3 and Mw 6.2 in 1842, and 1935, respectively [2], [8], [45]. Although this part of the country is not subjected to any direct seismic event with high magnitude, the younger unconsolidated fluvial sediments are even prone to liquefaction under favourable ground shaking from distal seismic events. The 1737 Kolkata earthquake, the 1787 Sirajganj earthquake (MM X), the 1842 Rajshahi earthquake (Mw 7.3), the 1897 Assam earthquake (Mw 8.1), the 1934 Bihar-Nepal earthquake (Mw 8.1), and the 1935 Pabna earthquake (Mw 6.2) had widely affected the western part of the Bangladesh and adjacent Indian region [1], [2], [8], [45], [50].

4. SEISMOGENIC GAP, LOCKED THRUST, AND SEISMIC HAZARD MAPS

Among all these active faults, the presence of three important seismic gaps in three major active faults - the eastern segment of the Dauki Fault, northern segment of the Chottogram-Coastal Fault, and Bhutanese segment of the MFT causes major apprehension to the earthquake geologist [8], [11], [51]. In general, a seismic gap is a locked segment of an active fault, which is supposed to produce a significant seismic event that has not been slipped in a long time, in comparison to other segments along the same fault [8], [16]. It is worth mentioning here that the eastern segment of the Dauki Fault has not been slipped in the recent past, but was it to slip in a single earthquake, its potential maximum magnitude would constitute a significant seismic threat to nearby densely populated areas and energy infrastructures of Bangladesh, India, Bhutan and Nepal [52]. Disturbingly, the other two seismic gaps in the rest two major active faults are also close to Bangladesh, compared to the other segments of these faults. Therefore, a possible high-intensity seismic event in any of these seismic gaps will cause catastrophic consequences for a large part of the country [11]. Moreover, the faster convergence rate and presence of seismogenic gap along the East Himalayan deformation belt (Bhutan Himalaya) can produce earthquakes with great magnitudes analogous to those of oceanic subduction zones [5], [53], [54]. On top of that, the deformation to the east along which the Indian Plate subducting beneath the Burmese plate at the rate of 13–17 mm/year appeared to be loading the locked shallow megathrust (Deformation Front- E) that connects CCF, Kaladan, and Kabaw Faults (Figure 1). As in the case of other subduction zones, the accumulated strain from this locked thrust will likely be released in future large earthquakes [16], [51]. The three seismogenic gap and locked shallow-mega thrusts to the north and to the east will significantly control the seismic activity within Bangladesh and its surroundings in the future [11].

Despondently, in producing the earthquake zonation map of Bangladesh [28], [55]-[57], these three seismogenic gaps and locked shallow-mega thrusts have not been considered yet. Even, none of the probabilistic seismic hazard maps of Bangladesh [57]-[61] comprehensively considered these seismic gaps, and therefore, we are completely unaware of the possible consequences. Besides, the basement rock in most parts of Bangladesh is covered by an enormous thick pile of Tertiary soft sedimentary rocks, and therefore, it is necessary to accurately estimate the attenuation of seismic waves through these soft sediments. In the absence of specific attenuation laws for Bangladesh geology, an attenuation relationship for the country has been developed by Islam *et al.* [62], but required validation and further improvement with consideration of local geological structures and tectonic deformation.

5. SEISMIC VULNERABILITY OF THE ENERGY INFRASTRUCTURES

It is a point to be noticed that all major earthquakes had occurred in Bangladesh and adjacent regions long before the establishment of the energy infrastructures (gas production facilities, processing plants, transmission and distribution pipelines, and oil refinery) across Bangladesh. Moreover, it has to be emphasized here that after 1950, no major to great earthquake have occurred along the seismogenic gaps, locked thrust, and active faults in and around Bangladesh as mentioned earlier sections. Therefore, it is difficult to determine how sustainable will be these energy infrastructures if major earthquakes that have witnessed in the past occur during the present times. It is speculated that the Dauki, Assam-Sylhet, CCF, Kaladan, and Madhupur faults which have already generated great earthquakes are capable of doing the same in the near future [7]-[9], [11], [25], [26]. Moreover, recent studies also suggest that the locked shallow megathrust (i.e., Deformation Front- E; Figure 1) is also highly potential for a major earthquake [16], [51], [63], [64].

Now if we look to the map of the gas fields, gas processing plants, gas transmission networks, oil refinery, Moheshkhali Floating LNG (MLNG) Terminal, and Matarbari LNG Terminal, all these energy infrastructures belongs to the eastern and southeastern part of the country (Figure 2). Moreover, Chittagong and its adjacent area are heavily industrialized and several export processing zones also present in this area. If we compare the energy infrastructures map (Figure 2) with the tectonic zonation map of the country (Figure 1), it is clear that most of these infrastructures are belongs to the Zone II and Zone III (Figure 2). Interestingly enough, the major gas transmission pipelines pass transversely over the CCF, Assam-Sylhet, and locked shallow megathrust (Figures 1 and 2). Since these pipelines are essential for the economic lifeline of the country, it is very important that the pipelines withstand the shaking from a major earthquake. However, no such study is yet performed. On the other hand, the Ruppur Nuclear

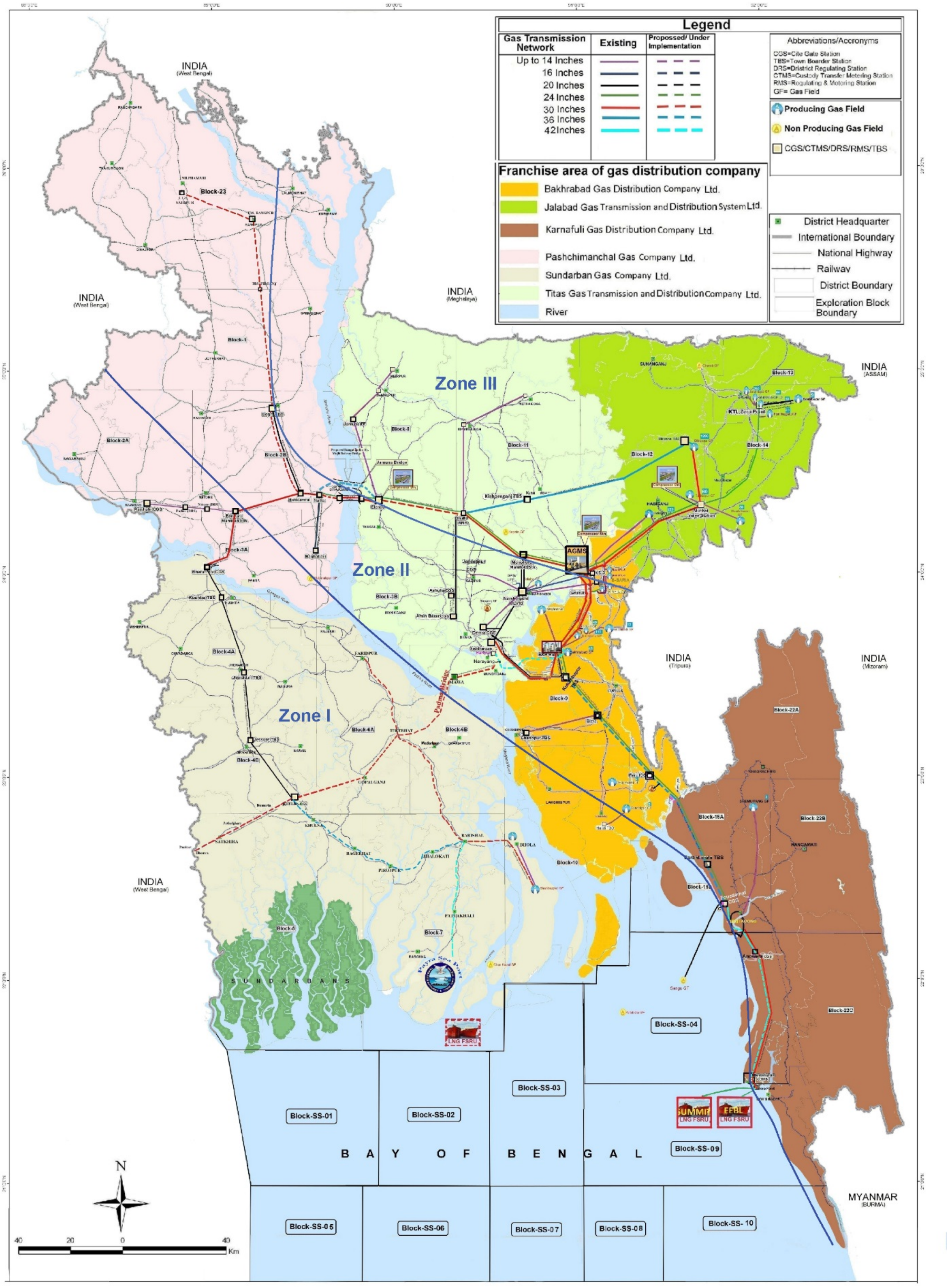

Fig. 2. Energy infrastructures (gas fields, gas production facilities, processing plants, gas transmission network, and oil refinery) map of Bangladesh [66]. The three earthquake zones [28] are marked (solid blue lines) on top of the map to show the spatial distribution of the energy infrastructures.

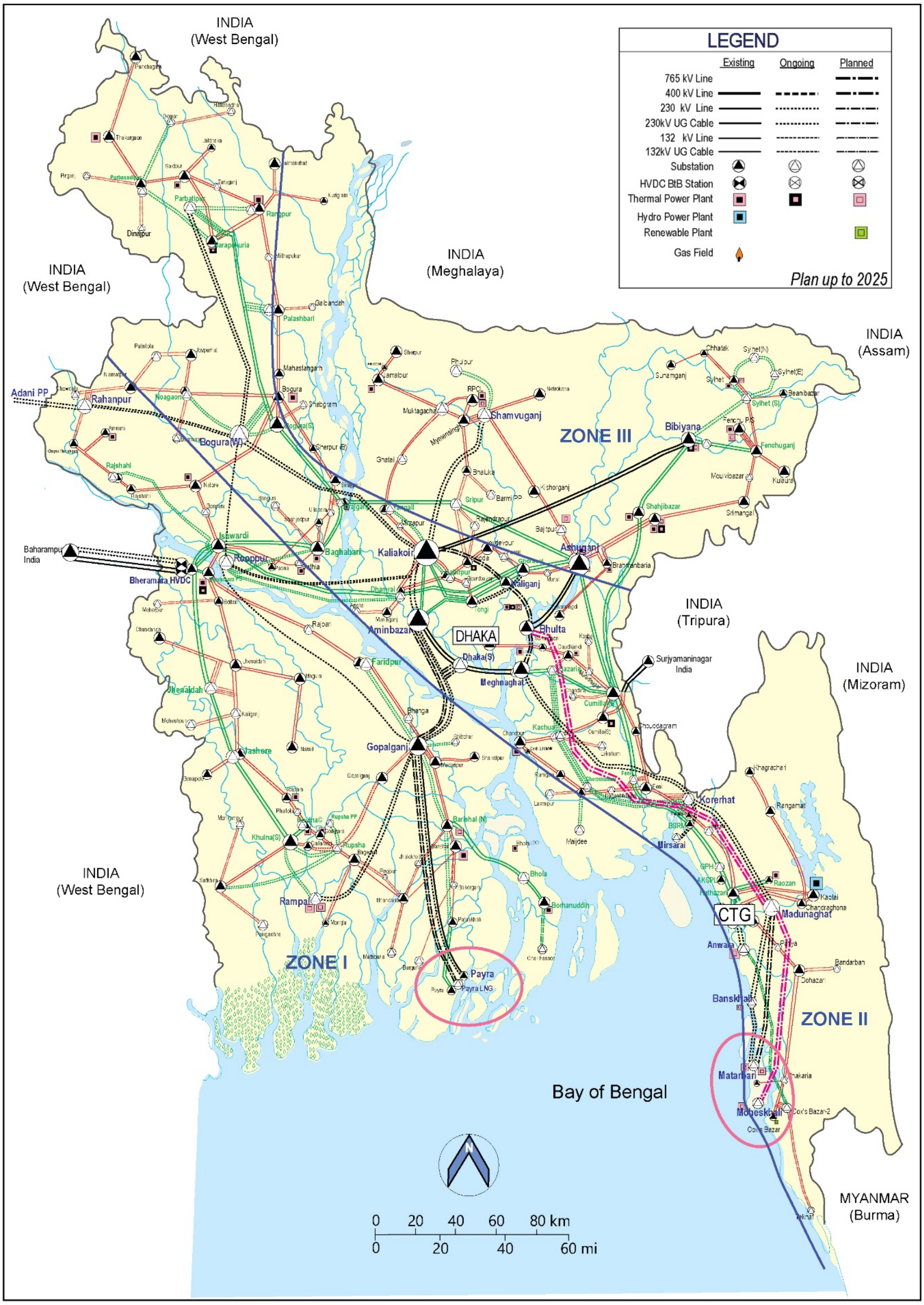

Fig. 3. Map of the Power Grid Plan 2020-25 of Bangladesh [67]. The three earthquake zones are marked (solid blue lines) on top of the map to show the spatial distribution of the power grid infrastructures. Red ellipses mark the three under construction power hubs [65] in which in Matarbari and Maheskhali located in the south-east, and Payra is located south-west of the map.

Power Plant of Bangladesh, which is under construction, belongs to the southern edge of the Zone II.

In addition, the concentration of major power grid infrastructures of Bangladesh is located in seismic Zone II, except the Asuganj hub, which is situated in the south-eastern corner of the seismic Zone III (Figure 3). As part of the Power System Master Plan 2016 [65], the Bangladesh government is setting up three new energy hubs in three locations to boost the country's power generation capacity over the next two decades. Two of them are located in Matarbari and Maheskhali of Cox's Bazar district (south-east Bangladesh), and the other one is located in the Payra of Patuakhali district (south-west Bangladesh). These power hubs will use imported coal and liquefied natural gas (LNG), and therefore, situated in the coastal areas. These hubs will house 21 mega power plants with a total generation capacity of 28,600 MW in which the Maheskhali hub will have eight mega power projects with a generation capacity of 12200 MW, the Matarbari hub will house seven plants with 6200 MW capacity, and the Payra hub will house six plants with 10200 MW capacity. Although, the Matarbari and Maheskhali Island located in the seismic Zone II [28] (Figure 3), Carlton *et al.* [59] did probabilistic seismic hazard analysis (PSHA) of this offshore area found that the area is a highly seismic region due to presence several active faults (*e.g.,* CCF, Kaladan faults) (Figure 1). Furthermore, Cummins [41] suggests that the occurrence of any large seismic event in this part of the offshore area is likely to produce a great tsunami. As the uninterrupted power supply is the backbone of an economy, hence it is very important that the power grid infrastructures of Bangladesh withstand the shaking from a major seismic event. However, a comprehensive study is yet to be performed.

Historically, energy infrastructures, specifically gas and oil pipelines underwent damages across the globe due to major earthquakes in the past. Ground fissures and lateral spreading due to liquefaction triggered by the 1971 San Fernando earthquake (Mw 6.6) results in major damage to pipelines. Underground ductile steel pipes are subjected to substantially damaged due to faulting and lateral spreading of the ground [68]. Interestingly, although there were no reports of liquefaction, landslides, or faulting during the 1985 Michoacan earthquake (Mw 7.6), there were reports of damages to water pipelines. Later it has been determined that the damage in the pipelines was mostly due to amplification of the propagated surface wave through clay deposits [69]. During the 1989 Loma Prieta earthquake (Mw 6.9), the gas mains and service lines of Pacific Gas and Electric Company underwent damages due to liquefaction and ground fissures [70]. During the 1994 Northridge earthquake (Mw 6.7), a total of 1400 pipeline breakages were reported across the San Fernando Valley due to high liquefaction, and led to fire breakouts at several locations across the valley [70], [71]. During the 1999 Izmit earthquake (Mw 7.6), the highest damage was reported from the water supply distribution system in Adapazari due to the crossing of pipelines over the right lateral strike-slip fault. Similar damage was also observed in a pipeline crossing the North Anatolian Fault [72]. During the 1999 Chi-Chi earthquake (Mw 7.6) in Taiwan, several buried gas pipelines were bent as a result of ground deformation due to the movement at a reverse fault [72]. The 2011 Great East Japan Earthquake (Mw 9) also known as Tohoku Earthquake is a classic example of the triple disaster of earthquake, tsunami and nuclear accident [73], [74]. About 20,000 people were dead or missing and around 500,000 people were forced to evacuate due to the tsunami and subsequent meltdown of the Fukushima Daiichi nuclear power plant triggered a nuclear emergency. The direct economic loss from this triple disaster is estimated at $360 billion.

From the above discussion, it is apparent that energy infrastructures, specifically gas transmission pipelines in the north-eastern, eastern and south-eastern parts of Bangladesh are vulnerable to possible seismic hazard. From the historical observation of pipelines damage related to the earthquake as discussed earlier, it is observed that most damages in the pipelines have occurred due to local site effects (ground condition or rock types) and/or crossing over active faults. As mentioned earlier that the pipelines in Bangladesh have not yet experienced any major to great earthquakes, and therefore, have not undergone any damages related to local site effects and faulting. However, it can be logically argued that the upper ground surface of the north-eastern, eastern, and south-eastern parts of the country is vulnerable to local site effects and thus the pipelines crossing through these areas are equally at risk.

6. SEISMIC VULNERABILITY ASSESSMENT AND ITS IMPLEMENTATION

Now the important questions are: what should be done in preparation, and what makes us well prepared for seismic disasters? It is worth remembering that what we cannot do normally, cannot be done well during the emergency period. Good preparation will enable us to respond successfully to seismic disasters. In this connection, we need to do nationwide collaborative research involving geologists, seismologists, urban planners, and civil engineers to develop a comprehensive probabilistic seismic hazard map for the whole country. Earthquake geologists can play a vital role in interlinking the earthquakes and the underlying geology. The things that to be noticed are where an earthquake can possibly occur (major active faults), segmentations in the major faults (seismogenic gap), the geological setting of specific focus areas (collisional or subductional plate boundary zone), the possible surface effects of an earthquake (liquefaction and lateral spreading), identification of the past seismic events recorded geomorphologically (paleoseismicity for recurrence interval), and how to apply all these knowledge to comprehensively evaluate possible seismic hazards and their impact on the present-day society [75], [76]. A number of researches have been done on structural geology and tectonics by taking into account all the relevant geological/seismological attributes [2], [7], [8], [9], [11], [16], [24]-[26], [29], [39], [41]. Recently, a comprehensive tectono-structural framework map of Bengal Basin (Bangladesh) has been published, which documents all active faults in and around Bangladesh ([12]: Main Map). During the development of the future earthquake zonation map and probabilistic seismic hazard maps of Bangladesh, these studies need to consider and new research should be performed.

In addition, to evaluate the seismic vulnerability of the energy infrastructures, specifically gas pipelines, it is essential to estimate the seismic hazard potential of the upper ground surface (soil) within which the pipeline is laid. Geologically, basement rock in the eastern part of Bangladesh is covered by a huge thickness of Tertiary sedimentary rocks. The upper surficial parts of these rocks are made of soft sediments (soil), which is susceptible to liquefaction. According to Honegger and Wijewickreme [77], liquefaction induced lateral spreads tend to cause more damage to pipelines than liquefaction itself. Studies suggest that lateral spread is generally common at places close to river banks, and coastlines. Raghukanth and Dash [78] report the occurrence of lateral spreading along the banks of Brahmaputra due to the 1897 Assam Earthquake. The gas pipelines in Bangladesh also cross the Meghna, Jamuna, and many other small rivers that flow from the north, north-east, and east. By taking into consideration of the past studies and damage reports [78], it could be said that at several points, the pipelines in Bangladesh may be susceptible to damage from lateral spreading triggered by a possible earthquake. However, to understand the possible extent of damage, no such studies are performed yet. Therefore, assessment of lateral spreading of soils needs to be performed using empirical (for regional assessment of lateral ground deformation) as well as mechanistic (for site-specific assessment of lateral ground deformation) approaches [77], [79]. The empirical approach is good for estimation of Liquefaction Severity Index (LSI) for lateral spread occurring along gently sloping sediments deposited during Late Holocene, which is the case of Bangladesh.

7. DISASTER RESPONSE STRATEGIES

Considering the above risks we, therefore, need to devise our preparation and disaster response meticulously that will contemplate every possible aspect of the potential earthquake damage. We should immediately record and preserve detailed drawings, photos, images, and technical reports of all energy infrastructures. It is also imperative to make a disaster response master plan immediately by considering the possible worst-case scenarios. The plan also needs to be updated and evaluated based on the spatial extent of energy infrastructures, and the current state of scientific and technical advancement in every five years interval. This disaster response master plan needs to consider the following major issues: a) Up to date records of the available competent energy infrastructure professionals in the country. b) Immediate after a major earthquake, geotechnical and engineering professionals must need to conduct quick temporary safety assessment checks and related measures for partly damaged energy infrastructures; inform the associated risk to the concerned authorities or organizations accordingly. c) Making short notice availability of heavy logistics, accessories, and other emergency supplies. d) Repair and reconstruction should be based on economic feasibility, the urgency of demand, and considering the importance of national energy interest. It is essential to devise policy by involving local experts and professionals for repair, reconstruction, maintenance, and management of the energy infrastructures.

Besides, all major engineering constructions, specifically large-scale ones, need to strictly follow the probabilistic seismic hazard map guideline during the construction and subsequent operation/maintenance. Following any disaster, it is indispensable to compare the pre and post-disaster aerial photos immediately to pinpoint the relevant disastrous impacts in the affected areas. Repair and rescue workers in remote areas heavily rely on maps in the planning of their post-disaster operations, and therefore, pre-disaster maps need to immediately update based on the post-disaster aerial photos. Archiving relevant maps and aerial photos to make them readily available for disaster response is the strategic responsibility of the Power Division and its utility companies, Petrobangla and its subsidiary companies, Geological Survey of Bangladesh (GSB), Bangladesh Space Research and Remote Sensing Organisation (SPARRSO), and Survey of Bangladesh (SoB). Post-disaster aerial photo surveys can be done by the Bangladesh Air Force (BAF) and the photos need to be immediately transferred to the GSB, SPARRSO, and SoB for processing and interpretation. The total process needs to be completed in the shortest possible time, and necessary information needs to be disbursed to relevant authorities. Regular emergency drills are necessary to train the professionals/employees of the energy sectors and emergency response workers to be well prepared for seismic disasters.

To the end, it is indispensable to study the earthquake resilience of critical infrastructures as a part of the comprehensive Disaster Risk Reduction (DRR) [80] for Bangladesh. Critical infrastructures are the organizations, facilities, and assets (physical or virtual), whose incapacity or impairment would have a debilitating impact on national security, economic security, public health safety, significant disruptions to public order, or other dramatic consequences [81]. As mentioned earlier, the current development of Bangladesh is characterized by high economic growth rates, and critical infrastructures are constantly expanding. Therefore, possible major seismic events, and their associated critical infrastructure impacts and recovery trajectories are needed to be carefully assessed. It is also important to understand the interlink and dependence of critical infrastructures [82]. Focusing on critical infrastructure protection and management should be a part of the core strategy of the DRR when investing and extending these infrastructures to improve their resilience.

8. CONCLUSIONS

Taking into account past energy infrastructures damage reports, it is to remember that the cost of the damage and number of fatalities primarily depend on the intensity of the earthquake, depth of the hypocentre, distance of the relevant infrastructures from the epicentre, geology of the area, and quality of the engineering constructions. We need to keep in mind that earthquake is a natural calamity; it does not kill people directly; rather engineering and energy infrastructure damages during an earthquake kill people. The cumulative effects of very high population densities, the vulnerability of the existing poorly constructed energy and engineering infrastructures, the potential for liquefaction and seismic-wave amplification within the thick pile of soft sediments, and the low seismic attenuation of the Indian Shield may results catastrophic damage in Bangladesh during a major earthquake. The destruction or partial damage of engineering and energy infrastructures can be possible to control largely by implementing guidelines based on a comprehensive seismic zonation map and site-specific probabilistic seismic hazard map during construction. For existing energy infrastructures, an in-depth seismic vulnerability assessment study is needed to be performed immediately. More than anything, it's crucially important to make all the energy infrastructures professionals and relevant authorities understand that earthquake disaster risk is real, and to convince them to act accordingly in order to make earthquake-resilient energy infrastructures for Bangladesh.

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