



Modeling on management strategies for spatial assessment of earthquake disaster vulnerability in Bangladesh

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Abstract

This paper explores sustainable management strategies for mitigation destructive geological disaster earthquake spatial susceptibility in Bangladesh, is located south piedmont plain of Himalaya mountain ranges in South Asia. During the contemporary time, earthquake is regarded as most destructive geological disaster due to its devastating impact on physical environment, socio-economic infrastructure, people's lives, livelihood and biodiversity of the world. In Bangladesh, earthquake destruction vulnerability is the results of two major factors natural (geological formation, plate tectonic framework, plate margin, geographical location, location of fault and fold) and human intervention (tremendous increase of population, construction of multi-storied concrete building in urban environment, rapid growth of urbanization and industrialization). Both physical and manmade factors accelerated extreme earthquake disaster which impacts on sustainable life style and livelihood patterns of poor peoples as a developing nation Bangladesh of the world. To ensure sustainable management strategies of earthquake spatial susceptibility, the aim of this paper is selected to access earthquakes susceptibility using geostatistical modeling for producing detailed risk to support mitigation approach of earthquakes in present and future in Bangladesh. For this study, almost 94 earthquakes samples are collected from Google Earth during the time period (1961–2018) in inland Bangladesh. In this study, spatial susceptibility map developed by applying geostatistical models with GIS approach which based on earthquakes magnitude (Richter scale) and focus depth (km). Predictive spatial earthquake susceptibility map and risk estimation process will help geologist, geomorphologist, environmental engineers, urban planner, government and non-government organizations for vulnerability assessment including structural (settlement planning, building materials and building code development) and nonstructural mitigation (disaster preparedness approach: pre-disaster, during disaster and post-disaster), spatial risk estimation, disaster crisis and conflict mitigation, relief distribution at national and global level.

Keywords Earthquake disaster · Geostatistical modeling · Spatial susceptibility · Disaster management · Bangladesh

Introduction

Sustainable management strategies is essential for mitigation earthquake spatial vulnerability throughout the world. During the recent decade, earthquake management strategies has a major concern in Bangladesh (Paul and Bhuiyan 2010; Sharmin and Saadi 2010; Sultana et al. 2013; Alam 2016; Al-Hussaini et al. 2015; Rahman et al. 2015; Islam et al. 2016). Tertiary hilly terrain and urban cities (e.g. Dhaka City and Chittagong City) of Bangladesh facing the earthquake seismic problem (Choudhury 1993; Rashed and

Weeks 2003; Paul and Bhuiyan 2010; Sattar et al. 2009; Sarraz et al. 2015; Ziauddin 2016) which increasing spatial vulnerability due to several reasons such as plate tectonic movement, geographical location of active fault and Neotectonic depressions (Khan and Hoque 2002), fold structure, geological formation (Alam et al. 2008), weak in soil structure, tremendous increase of urban population, rapid growth of urbanization and industrialization (Hossain 2014) with their unplanned multi-storied building (Islam et al. 2016), improper urban planning, vulnerable structures due to age of buildings, non-engineered constructions (Ansary and Ali 2004; Reja 2008; Jahan et al. 2008; Kamal 2009; Hossain 2014), declining groundwater level by over extraction, climatic variability and anthropogenic intervention. History of earthquake disaster spatial vulnerability of Bangladesh reported that this country lies high risk of this disaster and

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there is a possibilities to occur major's earthquake in near future (CDMP 2010; Paul and Bhuiyan 2010).

However, earthquake spatial vulnerability in Bangladesh will increase due to geographical location of several active tectonic plate boundaries such as Indian plate and the Eurasian plate and it is also disclose from the past history that several gigantic earthquakes occurred along the margin of these plate boundaries (Paul and Bhuiyan 2010; Islam et al. 2016). Furthermore, Duke Fault lies along the northern margin and underlying earth crust active fault Palaeo Continental Hing Zone lies southern aliment at Bogra Shelf of Bangladesh are prone to earthquake disaster (Sultana et al. 2013). The geological formation, geomorphological landforms and geo-physical environment of this country create more susceptible to earthquake disaster special vulnerability which made risk position at natural resources, people's property and lives and livelihoods (Rahman et al. 2015). On the other hand, urban structural development of major's cities (e.g. Dhaka and Chittagong City) of Bangladesh are susceptible to earthquake disaster risk due to poor building materials; construction of high raise building without flowing proper building codes and proper soil testing, and numerous earthquake specialist predict that if an earthquake with magnitude 7.0 Richter scale occurred then urban multistoried building totally ruined within a few seconds (Paul and Bhuiyan 2010). The capital Dhaka City lies comparatively more susceptible zone of earthquake disaster as a consequence of increasing trends of urban population density; expansion of urbanization and industrialization with multi-storied building during the few decades and proximity to active Madhupur Fault (Rahman et al. 2015; SAARC 2010). There is another prediction about earthquake catastrophe regarding Dhaka City is that, if an earthquake with Richter scale 6.0 magnitude origins within this city then 78,323 urban structures will be totally devastated along with US \$1075 million financial loss (CDMP 2010; Rahman et al. 2015). Old building structures with constricted road network of Old City Dhaka City lies at danger level of earthquake and any minor scale of earthquake will ruined the oldest heritage of this city (Rahman et al. 2015). Seismic specialists concern about frequent occurring minor to medium scale magnitude of earthquake as an early warning of gigantic dangerous earthquake disaster in the near future, where urban earthquake disaster management strategies are inadequate regarding this phenomena (Bolt 2005, DPF 2003).

However, earthquake spatial vulnerability is also a great concern on people's lives and livelihood owning the destruction of property, causing human life losses and material damages (Moscatelli et al. 2009; Hossain and Miah 2011), natural resources, and communication systems in Bangladesh. Sustainable management strategies and upgrading earthquake spatial vulnerability zoning map will help human being, lessen environmental damage and accelerated

mitigation approach. The first earthquakes spatial vulnerability map of Bangladesh along with its surrounding countries was developed by Geological Survey of India (GSI) in 1935 (Auden 1959; Choudhury 1993; Mohapatra and Mohanty 2010; Al-Hussaini et al. 2015; Islam et al. 2017). About 37 year later, after the independent of Bangladesh, Bangladesh Metrological Department (BMD) developed earthquakes spatial vulnerability zoning map in 19,972 (Choudhury 1993; Islam et al. 2016). After 5 year later in 1977, the Govt. of Bangladesh again developed earthquake spatial zoning map into three distinctive zone (Zone I: High seismic vulnerability; Zone II: moderate seismic vulnerability and Zone III: moderate seismic vulnerability) by the seismologist expert examination and recommendation to mitigation of earthquake vulnerability (Choudhury 1993; DDC 1993; Ali and Choudhury 2001; Paul and Bhuiyan 2010; Sultana et al. 2013; Islam et al. 2016). It was long since about 41 years from 1977, the earthquake spatial vulnerability map and their spatial allocation maps was not upgrading. It is crucial need to update earthquake spatial vulnerability map and their proper distribution for the acceleration mitigation approach in field of earthquake disaster management in Bangladesh.

One of the major rationale of this research paper is to provide sustainable management strategies of earthquake vulnerability mitigation, assessment, preparedness, risk estimation, risk reduction, crisis and conflict analysis, future propagation process, prospect and issued to be solved in recommendation portion of the paper can be fruitful for earthquake vulnerable zone population of the country of Bangladesh; which could bring long-term sustainable progress in the field of disaster management in Bangladesh and also accelerated future analysis of earthquake vulnerability.

So, this paper has been intended to decoratively demonstrate combined tactics that includes earthquake inventory mapping with their spatial allocation through investigation tectonic framework, geological formation, active fault, fold structure and active plate margin; evaluation of seismic vulnerability by standard values to category earthquake spatial risk; review earthquake risk zone with spatial allocation of earthquake samples (ES = 94) to generalized the present status; applying descriptive statistical analysis of earthquake samples with their magnitude and focus depth to analysis the risk factor and Geostatistical modeling to prepare predicted spatial vulnerability of earthquake maps of Bangladesh and recommend sustainable earthquake management guidelines as national and global needs.

Numerous researcher worked hard to improve a wide ranges of earthquake management strategies for mitigation, assessment, and recommended preparedness in disaster period and the choice of sustainable management strategies depends on desired information utilization, their proper application for all level of human being

before considering crucial needs of national and global level (Rahman et al. 2015). However, the inventory maps have limitation, which cannot provide evidence of real cause of earthquake due to information gap of Google Earth. The earthquake magnitude and focus depth values, thus have to be used together with evaluation of seismic vulnerability, predictive earthquake spatial vulnerability map for the mitigation of earthquake risk in Bangladesh. So, above all management strategies will play great role for environmental engineer, urban planner, decision maker, geologist and geomorphologist achieving their certain goal. Moreover, they can also play significant role in earthquake management for sustainable development of a nation by applying their combined contribution in won field knowledge.

In this paper, geostatistical modeling techniques are selected for inventive assessment of spatial susceptibility of earthquake parameters (e.g., earthquake magnitude and focus depth). The spatial distribution of these parameters can assist in understanding possible extents of earthquake spatial vulnerable area in Bangladesh. The earthquake parameters spatial vulnerability are mainly controlled by the tectonic framework, active fault line, plate margin, geological formation, physiographic province and populated urban multi-storied structures of the landscape in Bangladesh. In this regard, this modeling technique will help to estimate earthquake parameters spatial distribution at earthquakes non-occurring geographical reference point or non-sampling locations, which intend to illustrate spatial vulnerability of earthquake disaster in Bangladesh.

The applied geostatistical models are classified into two ways such as kriging geostatistical models and deterministic geostatistical models (Burrough and McDonnell 1998; Islam et al. 2017). Two types of model of kriging geostatistical interpolation such as simple kriging (SK) and ordinary kriging (OK) with their four optional semivariogram models along with inverse distance weighting (IDW) models with power (1, 2) are used for spatial assessment of earthquake susceptibility in Bangladesh. Above mentioned geostatistical approaches are used on the basis of similitude spatial geographical references of earthquakes sampling sites. In this study, from several geostatistical models approaches, robust models are selected through comparing their cross validation accuracy results (Ghanbarpour et al. 2013; Islam et al. 2017). Cross validation results also represent suitable technique for geostatistical models to predict more precisely spatial susceptibility. Moreover, research aim is to progress a consistent geostatistical approaches to develop sustainable management strategies for mitigation earthquake spatial vulnerability in Bangladesh, and which will be essential for further research, planning and assessment of long-term sustainable earthquake management strategies.

Background of the study area

Bangladesh is located 200 km southern border from Himalayan Mountains in South Asia. The graticule references of this country from 20°26'N to 26°38'N latitude and 88°01'E to 92°38'E longitude and the Bay of Bengal bounded by the southern part of this country (Fig. 1). Bangladesh is enclosed by highly susceptible several earthquakes zones such as Shillong Plateau and Himalayan Mountain Arc zones located at the northern margin; Arakan Yoma anticlinorium and the Burmese Mountain Arc region situated at the east border and complex geological thrust area Naga-Disang-Jaflong lies at the northeast margin of Bangladesh (Ali and Choudhury 2001).

Materials and methods

Earthquake sample collection procedure

Earthquake magnitude and focus depth samples collected from 94 sampling points of Bangladesh from Google Earth. Each earthquake sample geographical location was determined with Google Earth place mark techniques. The spatial distribution of earthquake sample sites (E1–E94) in the area display in Fig. 1. The earthquake sampling sites were collected systematically from inside Bangladesh for analyzing spatial vulnerability.

Earthquake factors and data collection sources

Earthquake factors data collected from various sources for evaluation of spatial vulnerability of earthquake disaster in Bangladesh (Table 1). Geological formation, tectonic framework, fault and fold data collected from United States Geological Survey (USGS) and Geological Survey of Bangladesh (GSB). Other factors of earthquake disaster data are collected from various sources including books, articles, journals, Government and non-government organizations (NGOs), unpublished reports and thesis etc.

Statistical and cartographic analysis

Descriptive statistical analysis are used to simplify of earthquake parameters to realize the earthquake vulnerability in Bangladesh. Cartographic analysis as like as produced tables, linear graphs, histograms, scenario analysis were used for both qualitative and quantitative analysis

Fig. 1 Digital elevation model (DEM) of the study area showing spatial distribution of earthquake sampling sites

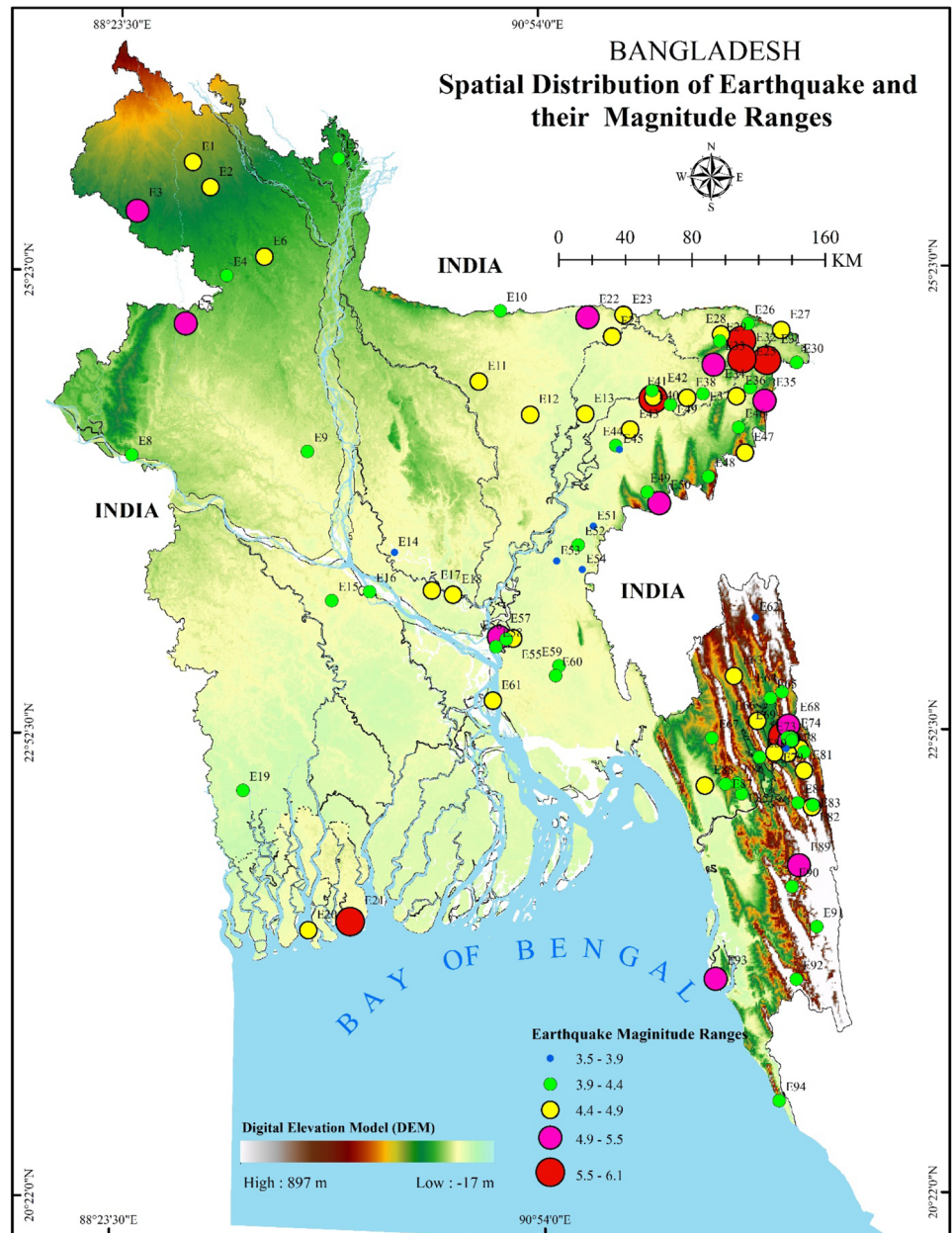


Table 1 Earthquake disaster factors and their respective data sources

Serial no.	Data	Source	Data type
01	Tectonic framework map	United states Geological Survey (GSB) and complied by author, 2018	Vector data
02	Geological formation map	United states Geological Survey (GSB) and complied by author, 2018	Vector data
03	Tectonic fault and map	United states Geological Survey (GSB) and complied by author, 2018	Vector data
04	Earthquake zone map	Choudhury (1993) and complied by author, 2018	IMG
05	Elevation map	SRTM DEM (30 m ×30 m) and complied by author, 2018	DEM (TIFF)

of this research. Geographic information system (GIS) and its cartographic tool and techniques are also used for visualization maps of earthquake spatial vulnerability in Bangladesh.

Geostatistical analysis

Earthquake magnitude and focus depth data are assessed by GIS tools and techniques. These data are prepared for computing geostatistical spatial modeling. Geostatistical modeling approaches are suitable for spatial vulnerability assessment. The spatial susceptibility of earthquake parameters are evaluated through different geostatistical modeling techniques with their optional semivariogram models and power (Sultana et al. 2013). In this study, four optional semivariogram models such as circular, spherical, exponential and Gaussian of ordinary kriging (OK) and simple kriging (SK) models along with inverse distance weighting (IDW) models power (1, 2) are applied for the present research to explore spatial vulnerability of earthquake disaster for mitigation earthquake destruction at present and future in Bangladesh.

Kriging model

Geostatistical kriging interpolation model is suitable for spatial vulnerability assessment of earthquake disaster. Generally, kriging models assess both unsampling and isolated spatial geographical references point data of earthquake parameters, and based on semivariogram operational structural models to predict spatial susceptibility. In this study, simple kriging (SK), ordinary kriging (OK) and their optional semivariogram models are used to predict spatial susceptibility of earthquake disaster vulnerability in Bangladesh (Rahman et al. 2015). These interpolation techniques estimate more precision and consistency of spatial variation and vulnerability of earthquake discrete data set. Kriging interpolation models also integrate together correlation and interdependency among the spatial geographical references point data variables. This spatial models interpolate on the basis of weighted average of sampling data. Kriging models are categorized into different models on the basis of their operations. However, in this study geostatistical kriging modeling by their sub four semivariogram modeling results compare with deterministic power modeling outcomes for better understanding spatial susceptibility of earthquake variables. Ordinary kriging (OK) of geostatistical modeling is computed by flowing the Eq. (1), then ensure the results of the weights (λ_i) of the variables that requisite equivalent to 1 for confirmation the approximations are impartial (Ghanbarpour et al. 2013).

$$\hat{z}(x_0) = \sum_{i=1}^n \lambda_i z(x_i), \quad (1)$$

where $\hat{z}(x_0)$ denotes prediction value at the sampling site x_0 ; $z(x_i)$ represents detected spatial value at the sampling site x_i ; λ_i are assigned weight from tailored semivariogram model and n denotes observed sampling numbers which are spatially neighboring the prediction sites; (Webster and Oliver 2001). Ordinary kriging method appraisals the native persistent average value of the sampling sites (Goovaerts 1997). Simple kriging computed by applying the flowing Eq. (2).

$$\hat{z}(x_0) = m + \sum_{i=1}^n \lambda_i [z(x_i) - m], \quad (2)$$

where, m is defined as mean of earthquake samples parameters and almost additional variables in Eq. (2) are well-defined as previously, in Eq. (1)

Semivariogram models measure spatial variation (Burgess and Webster 1980) and susceptibility zone of earthquake isolated data set. This model $\gamma(h)$ approach measured through flowing Eq. (3) given by Journel and Huijbregts (1978), for predicting spatial variation and vulnerability of earthquake disaster in Bangladesh.

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^n [z(x_i) - z(x_i + h)]^2, \quad (3)$$

where, n denotes number of sampling pairs detached by the standard distance h (lag distance) and $z(x_i)$ represents the sampling value of parameters z , at the sampling site x_i (Burrough and McDonnell 1998).

The semivariogram model $\gamma(h)$ is computed to recognize robust model and is its strength. Model strength is computed by the ratio of nugget (C_0) and sill ($C_0 + C$). These two parameters controlled by lag (h) distance, partial sill (C) and major's range (a). Moreover, the spatial variation of measured variables of earthquake data set is displayed through computing nugget and sill those are constantly equivalent to variance of isolated variables (Webster and Oliver 2001). To select suitable semivariogram model from spherical, exponential, Gaussian and circular semivariogram, cross validation test approach is applied which is constructed on trial and error basis. In this study, four semivariogram models (Eqs. 4–7) such as spherical, exponential, Gaussian, and circular (Zubrzyckis 1957; Dalenius et al. 1961; McBratney and Webster 1986; Oliver and Webster 2014) approaches are computed for evaluation spatial interdependency of the variables, and measuring spatial autocorrelation among the parameter of the earthquake sampling sites and spatial susceptibility of earthquake disaster.

$$\gamma(h) = c_0 + c \left\{ 1 - \frac{2}{\pi} \cos^{-1} \left(\frac{h}{a} \right) + \frac{2h}{\pi} \sqrt{1 - \frac{h}{a^2}} \right\} \quad (\text{circular semivariogram model}) \quad (4)$$

$$\gamma(h) = c_0 + c \quad \text{for } h > a$$

$$\gamma(h) = 0$$

$$\gamma(h) = c_0 + c \begin{cases} \frac{3}{2} \left(\frac{h}{a} \right) - \frac{1}{2} \left(\frac{h}{a} \right)^3 & h = 0 \\ 0 & 0 < h < a \\ h \geq a & \end{cases} \quad (\text{spherical semivariogram model}) \quad (5)$$

$$\gamma(h) = c_0 + c \left\{ 1 - \exp \left(-\frac{h}{a} \right) \right\} \quad (\text{exponential semivariogram model})$$

$$= 0 \text{ for } h = 0$$

(6)

$$\gamma(h) = c_0 + c \left\{ 1 - \exp \left(-\frac{h^2}{a^2} \right) \right\} \quad (\text{Gaussian semivariogram model})$$

$$= 0 \text{ for } h = 0$$

(7)

where, $\gamma(h)$ is particular optional semivariogram models (e.g. circular, spherical, exponential and Gaussian) of simple kriging and ordinary kriging models, c_0 is nugget value, c is partial sill, $(c_0 + c)$ is sill, a is range and h is lag distance (Oliver and Webster 2014).

Deterministic inverse distance weighting (IDW) model

IDW deterministic interpolation approach is used widely by earth scientists (Lu and Wong 2008) and it is more reliable model for spatial vulnerability assessment of various disasters. In operation IDW interpolation model, the weight (λ_i) determined by the prediction location of earthquake variables. This model estimates spatial detachment among the earthquake samples variables spatial references sites and their prediction distribution site along with overall spatial autocorrelation compared to kriging models for organized the weights of IDW interpolation model. IDW model weighted values are principally determined via the power of weights and there is a significant relationship between power of weights and distance of spatial sampling point sites that expressed as, if the power raise then it influence on the spatial sampling points distance at a noticeable extent than actually anticipated (Goovaerts 2000). In this model, the power weights of earthquake variables declines with raising distance from the prediction samplings point spatial sites and the summation of the power weights (λ_i) is equivalent to 1. The flowing Eq. (4) is calculated for power of weights (λ_i) of IDW model.

$$\lambda_i = d_{i0}^{-p} / \sum_{i=1}^n d_{i0}^{-p}, \quad (8)$$

where, d_{i0} designates as the spatial distance differences between the earthquake samples geographical references sites and their prediction locations. Generally, while spatial distance of measured variable turn into greater extent, then the weights power of this model is significantly declined that is expressed as p . Consequently, this modeling approach generate relatively uneven topography that is generally reliant on the spatial remoteness between spatial sampling sites. Generally, IDW model weight powers (1, 2) are applied to signify the influence of power variables (Lu and Wong 2008).

Cross validation test

In this study, cross validation test applied for comparing different geostatistical interpolation models and find out the best fit optimal model for earthquake parameters (Isaaks and Srivastava 1989). It is the best way to select the best semivariogram models for evaluation spatial vulnerability of earthquake magnitude and focus depth to categorized earthquake. The robust model is applied for generating the best prediction of spatial vulnerability of earthquake parameters (Goovaerts 2000). Furthermore, earthquake calculated data point and predicted data point compared with error analysis results for accuracy assessment of models and find out the most robust model. In this study, mean square error (MSE) close to zero value of models is taken as a best fitted and robust model. Hu et al. (2004) stated various standards are applied to error calculation for the authentication of geostatistical interpolation models. Geostatistical interpolation models prediction results accuracy are determined by minimum ME and RMSE (Islam et al. 2017). The subsequent Eqs. (9)–(13) are used to errors analysis and find out the robust geostatistical model (Hu et al. 2004).

$$\text{ME} = \frac{1}{n} \sum_{i=1}^n (p_i - o_i) \quad (9)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (p_i - o_i)^2} \tag{10}$$

$$ASE = \sqrt{\frac{1}{n} \sum_{i=1}^n \left(p_i - \frac{\sum_{i=1}^n p_i}{n} \right)^2} \tag{13}$$

$$ME = \frac{1}{n} \sum_{i=1}^n (ps_i - os_i) \tag{11}$$

$$ME = \sqrt{\frac{1}{n} \sum_{i=1}^n (ps_i - os_i)^2} \tag{12}$$

Results and discussion

Descriptive statistics of earthquake vulnerability

Earthquake seismic information of Bangladesh is concise in Table 2 with appraisal descriptive statistics such as minimum, maximum, mean, and standard deviation values. Earthquakes sample (ES = 94) data shows that the magnitude

Table 2 Descriptive statistics of earthquake magnitude and focus depth (km) in the study area

	Minimum	Maximum	Mean		Std. deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Std. error			Statistic	Std. error	Statistic	Std. error
Magnitude	3.5	6.1	4.539	0.0563	0.5460	0.298	0.891	0.249	0.529	0.493
Depth (km)	6	100	28.68	1.516	14.624	213.871	1.044	0.250	4.711	0.495

Table 3 Earthquake vulnerability category and their impacts on physical and socio-economic structure

Magnitude	Earthquake category	Earthquake effect	Frequency of occurrence
<2.0	Micro earthquake	Micro earthquake, not felt	Continual
2.0–2.9	Minor earthquake	Generally not felt, but recorded	1,300,000 per year (est.)
3.0–3.9		Often felt, but rarely causes damage	130,000 per year (est.)
4.0–4.9	Light earthquake	Noticeable shaking of indoor items, ratting noises. Significant damage unlikely	13,000 per year (est.)
5.0–5.9	Moderate earthquake	Can causes major damage to poorly constructed building over small regions. At most slight damage to well-designed buildings	1319 per year
6.0–6.9	Strong earthquake	Can be destructive in areas up to about 160 km across in populated areas	134 per year
7.0–7.9	Major earthquake	Can causes serious damage over large area	15 per year
8.0–8.9	Great earthquake	Can cause serious damage in areas several hundred km across	1 per year
9.0–9.9		Devastating in areas several thousand kilometer across	1 per 10 year (est.)
10.0+	Massive earthquake	Never recorded, widespread devastation across very large areas; see below equivalent seismic energy yield	Extremely rare (unknown/may not be possible)

<https://wordlesstech.com/what-does-earthquake-magnitude-mean/>

Table 4 Evaluation earthquake category in Bangladesh

Magnitude class	Category	Number of earthquake sample (ES)	Earthquake sample (%)	Earthquake samples
3.0–3.9	Minor earthquake	7	7.446809	E14, E45, E51, E54–E55, E62, E76
4.0–4.9	Light earthquake	70	74.46809	E1, E2, E4–E6, E8–E13, E15–20, E23, E24, E26–30, E34, E36–E41, E43, E44, E46–E49, E52, E55, E56, E58–61, E63–E67, E70–E73, E75, E77–E88
5.0–5.9	Moderate earthquake	15	15.95745	E3, E7, E22, E25, E32, E33, E35, E42, E50, E57, E68, E69, E74, E89, E93
6.0–6.9	Strong earthquake	2	2.12766	E21, E31

value range between minimum 3.5 and maximum 6.1 Richter scale (10 based logarithm scale and developed in 1930) with mean value 4.539 which is generally indicating light to strong earthquake vulnerability nature in Bangladesh (Table 3). Present study results reveal that strong earthquake vulnerability area are North-eastern tertiary hilly region but height magnitude earthquake occurred in Sundarban Mangrove forest near the coastal region. The focus depth in the study area varied from 6 to 100 km under the earth crust with a mean value 28.68 km. However, present study results

identified that 98.94% earthquake sample fall shallow focus where only 1.06% was intermediate focus.

Evaluation of spatial vulnerability of seismic hazard

Earthquake magnitude in Richter scale and their vulnerability ranges are used to evaluate seismic catastrophe vulnerability. To determine spatial vulnerability of seismic hazard, is using earthquake vulnerability category (EVC)

Fig. 2 Tectonic framework affecting earthquake spatial vulnerability in Bangladesh

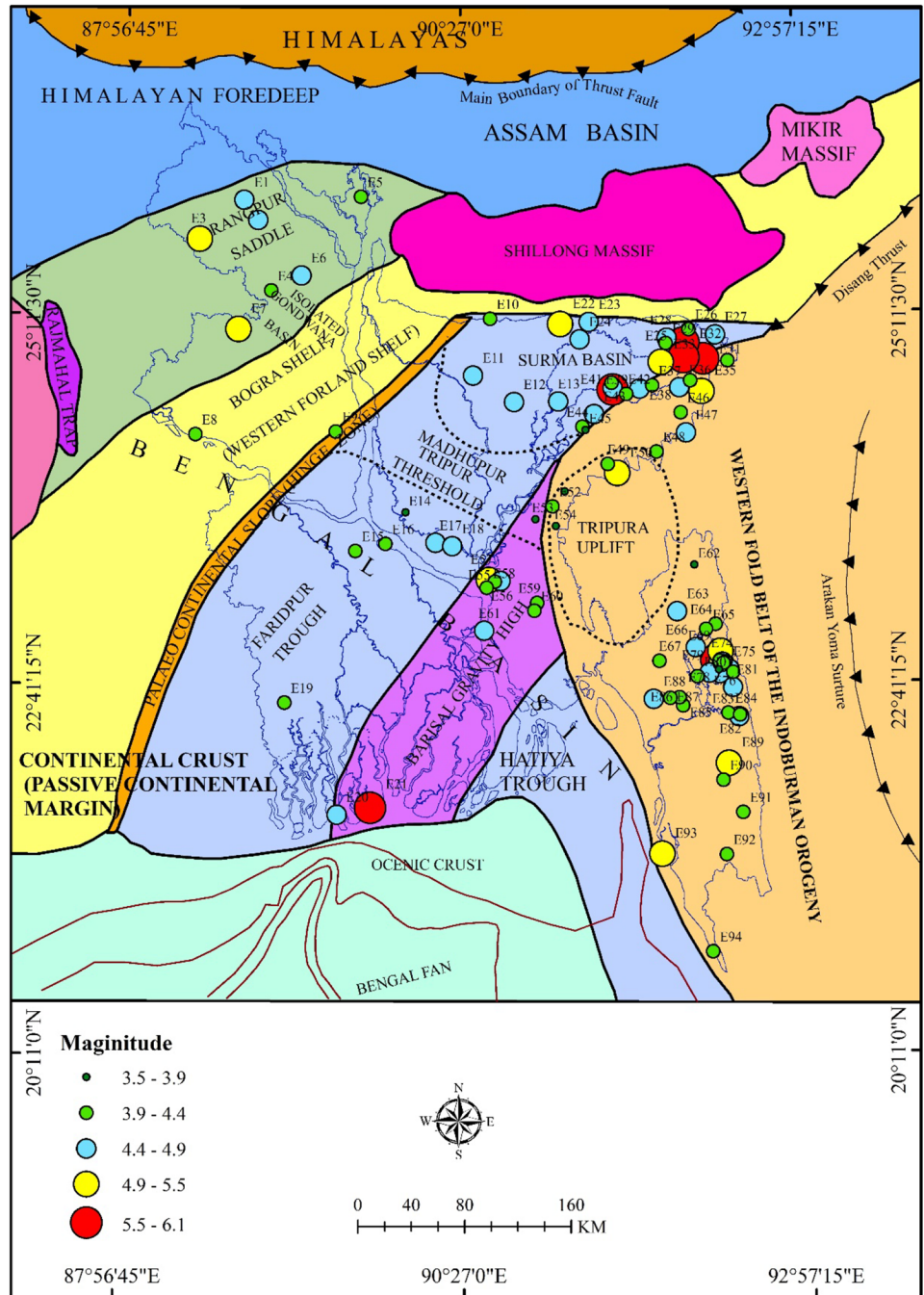


Table 5 Spatial susceptibility of earthquake disaster in tectonic framework

Tectonic framework	Area (sq.km)	Area (%)	Earthquake samples (ES)	ES%
Western Fold Belt of the Indoburman Orogeny	2212309.74	16.16637796	42	44.7
Surma Basin	14380.46377	0.105084748	21	22.3
Tripura Uplift	4133.779151	0.03020745	5	5.32
Madhupur Tripura Threshold	8479.552131	0.061964038	1	1.06
Faridpur Trough	31501.14961	0.230193576	6	6.38
Barisal gravity high	16921.96512	0.123656683	10	10.6
Rangpur Saddle	16571.99632	0.121099298	7	7.45
Paleo continental slope (Hing Zone)	2393.753172	0.01749227	1	1.06
Bogra Shelf	16846.2838	0.123103644	1	1.06
Total	2323538.683	16.97917967	94	100

standard values. The EVC of the study area are identified (3.0–3.9), (4.0–4.9), (5.0–5.9) and (6.0–6.9) which represent minor, light, moderate and strong earthquake vulnerability, respectively (Table 4). Present results demonstrates that about 7.45% of the earthquake samples fall into minor vulnerability (3.0–3.9) of EVC. Furthermore, in case of EVC, 74.47% earthquake samples reported light vulnerability type, 15.96% represent strong vulnerability type, whereas, 2.13% exhibited strong vulnerability.

Factors of earthquake vulnerability

There are several factors are identified for earthquake vulnerability in Bangladesh. These are tectonic framework and their plate movement along the plate margin; geological formation, fault and fold region, physiographic province, tremendous increase of building construction and population in urban areas, extracted groundwater which subsiding water level, fault and fold region (Sultana et al. 2013). However, tectonic framework regarded as dominant controlling factors of earthquake for Bangladesh. From the Fig. 2 and Table 5, analysis results demonstrate that about 44.68% earthquake samples fall Western Fold Belt of the Indoburman Orogeny tectonic framework. Analysis results discloses that earthquake vulnerability in sampling sites explained 22.34% of the whole earthquake samples, which were mostly distributed in Surma Basin. In tectonic framework from earthquakes data accounting for 10.64% of earthquake samples, which were widely distributed in Barisal Gravity High region. Rangpur Saddle, Faridpur Trough and Tripura Uplift tectonic framework region of Bangladesh are also earthquake vulnerable region where 7.45%, 6.38% and 5.32% earthquake samples widely distributed, respectively. Madhupur Tripura Threshold, Paleo Continental Slope (Hing Zone) and Bogra Shelf have less vulnerable where 1% earthquake samples distributed. On the other hand, plate tectonic movement increased earthquakes vulnerability along the plate's margin. Moreover, Bangladesh is situated adjacent to Indian

Plate at the west margin and Eurasian plate at the northeastern boundary which in influence on spatial susceptibility of earthquakes disaster (Islam et al. 2016). The rate of plate movement per year increase the susceptibility of earthquakes disaster during the recent decades, for instances active Indian plate movement was 6.0 cm towards the northeast direction per year, while active Eurasian Plate and Burmese Plate flowed by 45 and 35 mm at the north and east direction every year, respectively (Sultana et al. 2013).

Geological formation of Bangladesh includes into ten group such as Tipam group, Surma group, Jainta Group, Residual Deposits, Alluvial Deposit, Alluvial Fan Deposit, Bedrocks, Lake, Plaudal Deposits, Deltaic Deposit and Ocean and Wide River with their distinct sub-groups (Fig. 3). From the Table 6 it is observed that highest 18.09% earthquakes occurred in Surma sub group formation Tbb [Bhuban Formation (Miocene)]. On the basis of group formation it is also observed that maximum 29.79% earthquakes occurred in Alluvial Deposit group and second 23.40% maximum in Surma Group. In geological formation of Bangladesh earthquake partially save zone identified as Deltaic Deposit group formation where only 2.125 earthquakes occurred during the time span 1961–2018.

Earthquake risk also lays along majors active fault zones in Bangladesh (Fig. 4). These active faults zones are Bogra fault zone, Tanore fault zone in Rajshahi, Tripura fault zone, Sitakunda-Teknaf fault zone, Dauki fault zone (Haluaghat Fault), Dhubri fault zone, Chittagong fault zone, Shahjibazar fault zone (sub-Dauki fault) and Rangamati fault zone (Borcal) (Islam et al. 2016). The predictive earthquake seismic (e.g. particularly magnitude) vulnerability along the active fault zones with magnitude are Bogra fault zone 7.0, Tripura fault zone 7.0, Sub Dauki fault zone 7.3, Shillong fault zone 7.0 and Assam fault zone 8.5 (Sultana et al. 2013; Islam et al. 2016). These active fault zones produce immense destruction near future in Bangladesh (Sultana et al. 2013).

Communities of urban regions of Bangladesh are vulnerable of earthquake disaster due to several factors. For

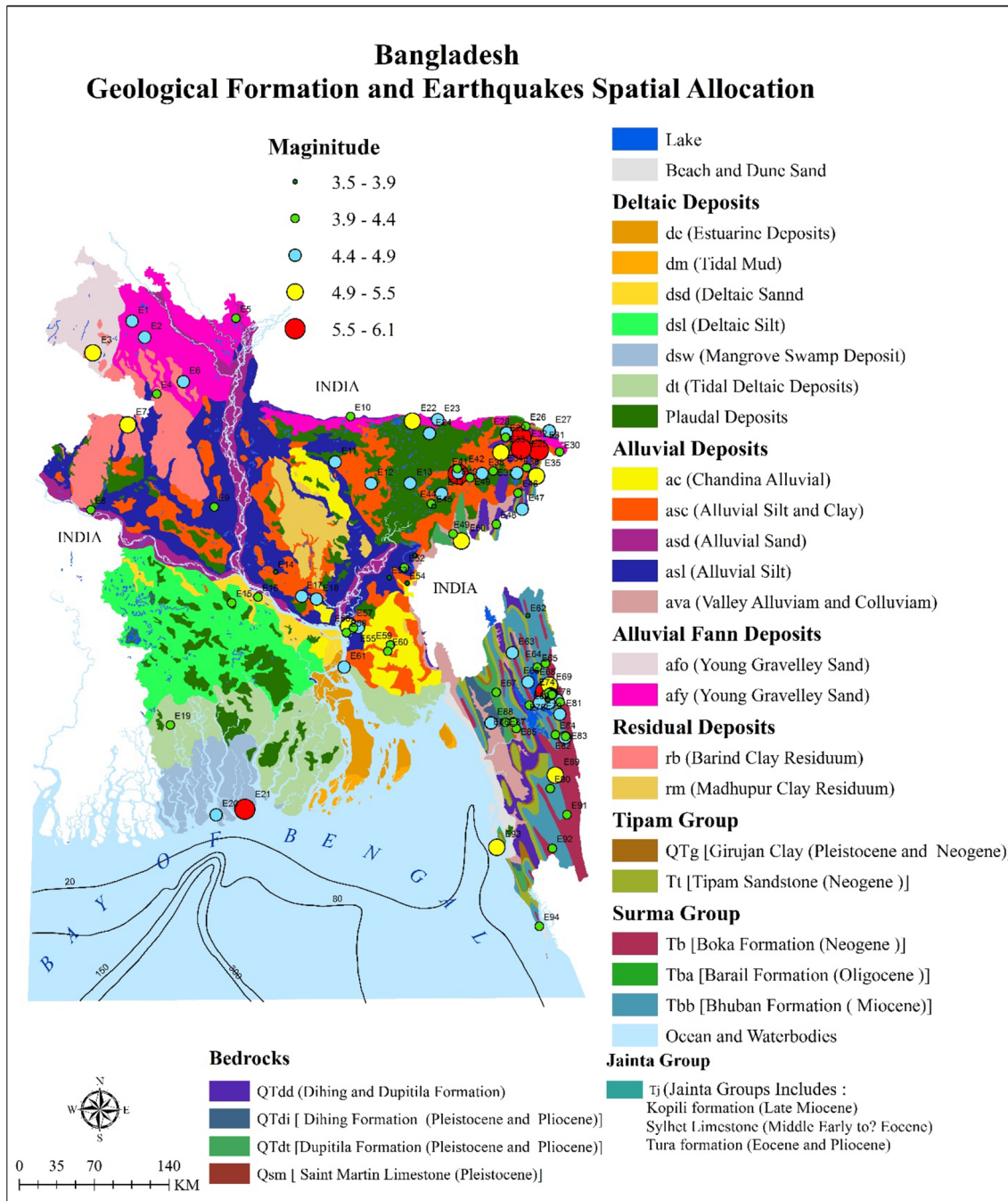


Fig. 3 Geological formation affecting earthquake spatial vulnerability in Bangladesh

instance, tremendous increase of population which is resulting from extensive construction of multi-storied building are responsible for earthquake vulnerability in urban areas of Bangladesh. In urban areas, there were almost non-existence of legal implementation steps to develop building code for raising public awareness by formal urban development authorities and due to lake of legal steps high raise building become more susceptible to future earthquake disaster.

Earthquake risk zone

In 1977, Bangladesh government made a countrywide earthquake disaster risk map for vulnerability assessment and developing building codes for earthquake resistant building schemes (Paul and Bhuiyan 2010). In this earthquake vulnerability map, developed code was established three distinct risk zones: Zone I (high risk), Zone II (moderate risk) and

Table 6 Spatial susceptibility of earthquake disaster in geological formation

Group	Sub-group	Area (sq.km)	Area (%)	Earthquakes samples (ES)	Total (ES)	Sub-group percentage	Group percentage
Tipam group	QTg [Girujan Clay (Pleistocene and Neogene)]	581.30	0.394	E26	1	1.06	8.51
	Tt [Tipam Sandstone (Neogene)]	2977.14	2.017	E27, E48, E63, E71, E72, E73, E80	7	7.45	
Surma	Tb [Boka Formation (Neogene)]	3602.61	2.441	E70, E74, E77, E84, E91	5	5.32	23.40
	Tba [Barail Formation (Oligocene)]	18.64	0.013		0	0	
	Tbb [Bhuban Formation (Miocene)]	5606.10	3.799	E47, E62, E64, E68, E69, E75, E76, E78, E81, E82, E83, E89, E90, E92	17	18.09	
Jainta group	Tj [Kopili Formation (Late Miocene); Sylhet Limestone (Middle Early to? Eocene); Tura Formation (Eocene and Pliocene)]	2.72	0.002		0	0	
Residual deposits	rb (Barind Clay Residuum)	7197.07	4.877	E4, E7, E8	3	3.19	3.19
	rm (Madhupur Clay Residuum)	3538.17	2.398		0	0	
Alluvial deposit	ac (Chandina Alluvial)	4546.89	3.081	E54, 59	2	2.13	29.79
	asc (Alluvial silt and clay)	13963.97	9.463	E11, E12, E17, E28, E29, E30, E32, E34, E38, E39, E40, E60	12	12.77	
	asd (Alluvial sand)	4659.52	3.157		0	0	
	asl (Alluvial silt)	15407.79	10.441	E9, E14, E18, E51, E52, E53, E55, E56, E57, E58	10	10.64	
Alluvial Fan Deposit	ava (Valley alluvium and colluvium)	3175.61	2.152	E49, E85, E86, E88	4	4.26	
	afo (Young gravelly sand)	3973.54	2.693	E3	1	1.06	5.32
	afy (Young gravelly sand)	9011.40	6.107	E1, E2, E5, E6	4	4.26	
Bedrocks	QTdd (Dihing and Dupitila formation)	3104.78	2.104	E10, E23, E46	3	3.19	6.38
	QTdi [Dihing Formation (Pleistocene and Pliocene)]	644.40	0.437		0	0	
	QTdt [Dupitila Formation (Pleistocene and Pliocene)]	1372.69	0.930	E50, E67, E87	3	3.19	
	Qsm [Saint Martin Limestone (Pleistocene)]	2.89	0.002		0	0	
Lake		1663.45	1.127	E22, E36, E65, E66, E79	5	5.32	5.32
Plaudal Deposits		15696.50	10.637	E13, E15, E24, E25, E33, E37, E41, E42, E43, E44, E45	11	11.70	11.7

Table 6 (continued)

Group	Sub-group	Area (sq.km)	Area (%)	Earthquakes samples (ES)	Total (ES)	Sub-group percentage	Group percentage
Deltaic Deposit	de (Estuarine deposits)	2461.69	1.668			0	2.13
	dm (Tidal mud)	684.89	0.464			0	
	dsd (Deltaic sand)	1909.71	1.294	E16	1	1.063	
	dsl (Deltaic silt)	12531.25	8.492			0	
	dsw (Mangrove Swamp Deposit)	4546.87	3.081			0	
	dt (Tidal deltaic deposits)	10048.84	6.810	E19	1	1.064	
Ocean and Wide River		72742.43		E20, E21, E61, E93	4	4.26	4.26
Total					94	100.00	100.00

Zone III (low risk). On the basis of this earthquakes susceptibility map, present study also integrate the proper strategies for earthquake resilient scheme of Ali and Choudhury (2001). According to Ali and Choudhury (2001) seismic risk zoning map, 44.81% (61861.8 sq.km) area fall high risk zone where 36.17% earthquakes occurred from 1961 to 2018, this result indicated that this area liable to severe damage. Moderate and low seismic risk zone results reveal that 35.48% (48985.06 sq.km) and 19.71% (27213.44 sq.km) area liable to moderate and slight damage, where 56.38 and 7.45% earthquakes occurred, respectively (Fig. 5; Table 7).

Performance of geostatistical modeling

Earthquake variables spatial susceptibility of Bangladesh are analyzed via several geostatistical modeling approaches. In this study, for the generalization of earthquake variables spatial susceptibility cross validation test approach is carried out for select robust geostatistical model. To measure the strength of geostatistical models earthquake field values and predicted values are evaluate with error analysis equations (Eqs. 5–9). The strong and robust semivariogram models is select on the basis of mean error (ME), mean standard error (MSE), root mean square error (RMSE), average standard error (ASE) and root mean square standardized error (RMSSE) principles (Biswas et al. 2017). In geostatistical modeling approaches, a model is regarded strong, precise and robust while mean error (ME) and mean standard error (MSE) close to zero, root mean square error (RMSE) and average standard error (ASE) are least as possible, and root mean square standardized error (RMSSE) close to zero (Adhikary et al. 2010; Biswas et al. 2017; Islam et al. 2017). The cross validation analysis results summarized in Table 8 for evaluation the performance of geostatistical modeling. Analysis results reveal that earthquake magnitude and focus depth prediction values of various semivariogram model provides precise performance to predict spatial susceptibility of earthquake disaster. Earthquake magnitude spatial

susceptibility better performance provided by exponential semivariogram model of simple kriging approach in geostatistical modeling and also recognize strong, precise and robust model in comparison RMSE with other semivariogram models of ordinary kriging and IDW approach. On the other hand, Gaussian semivariogram model of ordinary kriging (OK) cross validation results shown that due to minimum RMSE this model regarded robust for spatial susceptibility prediction of earthquake focus depth.

Geographic information system (GIS) cartographic techniques are applied to analyze the semivariogram $\gamma(h)$ model and the relationship between semivariogram $\gamma(h)$ model and distance (h) representing in scatter plot using ArcGIS software (version 10.3). Generally, geostatistical semivariogram models are applied to find out more accurate prediction values from spatial geographical references measured point values and robust model select through choice of least nugget values (Goovaerts 1997). The semivariogram model parameters are compute in Table 8. Semivariogram models strength are measured by the ratio of nugget and sill which is also called nugget/sill effect, and then classify their performance into three distinct ways for model evaluation. The ratio of nugget and sill results less than 25% (<0.24), between 25 and 75% (0.25–0.75), and more than 75% ($0.75 <$) represented by strong, moderate and weak spatial susceptibility of earthquake variables, respectively (Shi et al. 2007). Major ranges of earthquake magnitude spatial vulnerability varied from 99.306 to 480.6 km, wherever highest range was computed by the OK approach via the exponential semivariogram model and the smallest value shown the SK approach via the circular, spherical, exponential and Gaussian semivariogram models. Moreover, major ranges for earthquake focus depth spatial susceptibility ranging from 9.45 to 610.14 km wherever highest range was calculated by the OK approach via the both spherical and exponential semivariogram model and the smallest on is calculated by the SK approach with the circular semivariogram model. Semivariogram models parameters analysis results designated

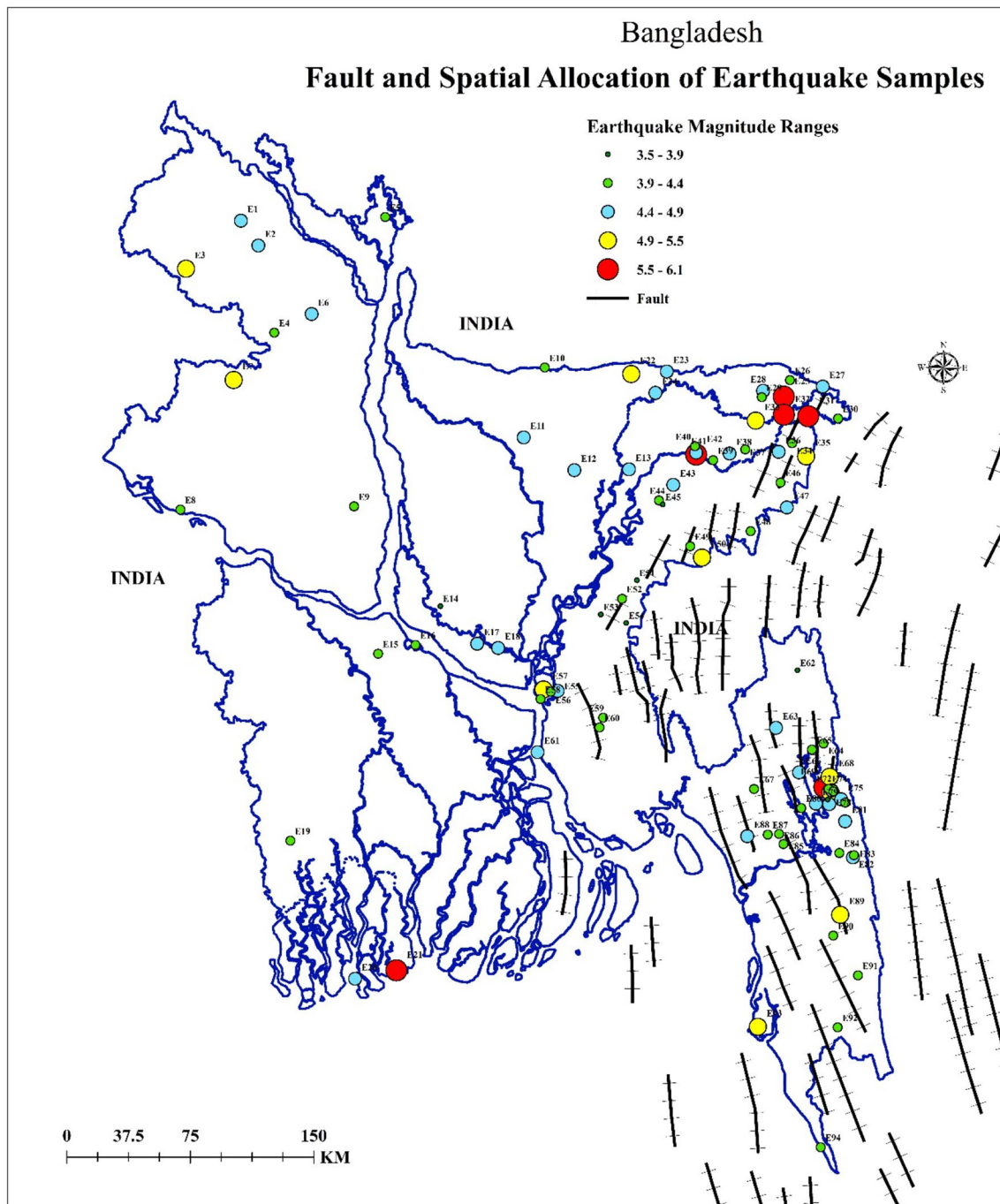


Fig. 4 Fault structure affecting earthquake spatial vulnerability in Bangladesh

that exponential semivariogram model of OK demonstrate highest spatial susceptibility for larger ranges of earthquake samples magnitudes spatial distribution, whereas the circular, spherical, exponential and Gaussian semivariogram model of SK represent less spatial susceptibility due to lower ranges of earthquake magnitudes distribution. In the case of earthquakes focus depth, the spherical and exponential

semivariogram model shows highest spatial susceptibility due to larger range of their distribution, whereas the circular semivariogram model represents less spatial susceptibility because of lower ranges of focus depth. The diverse ranges are occurred because of location of tectonic framework, tectonic block, fault structure, and plate margin factors such as topography and geological formation.

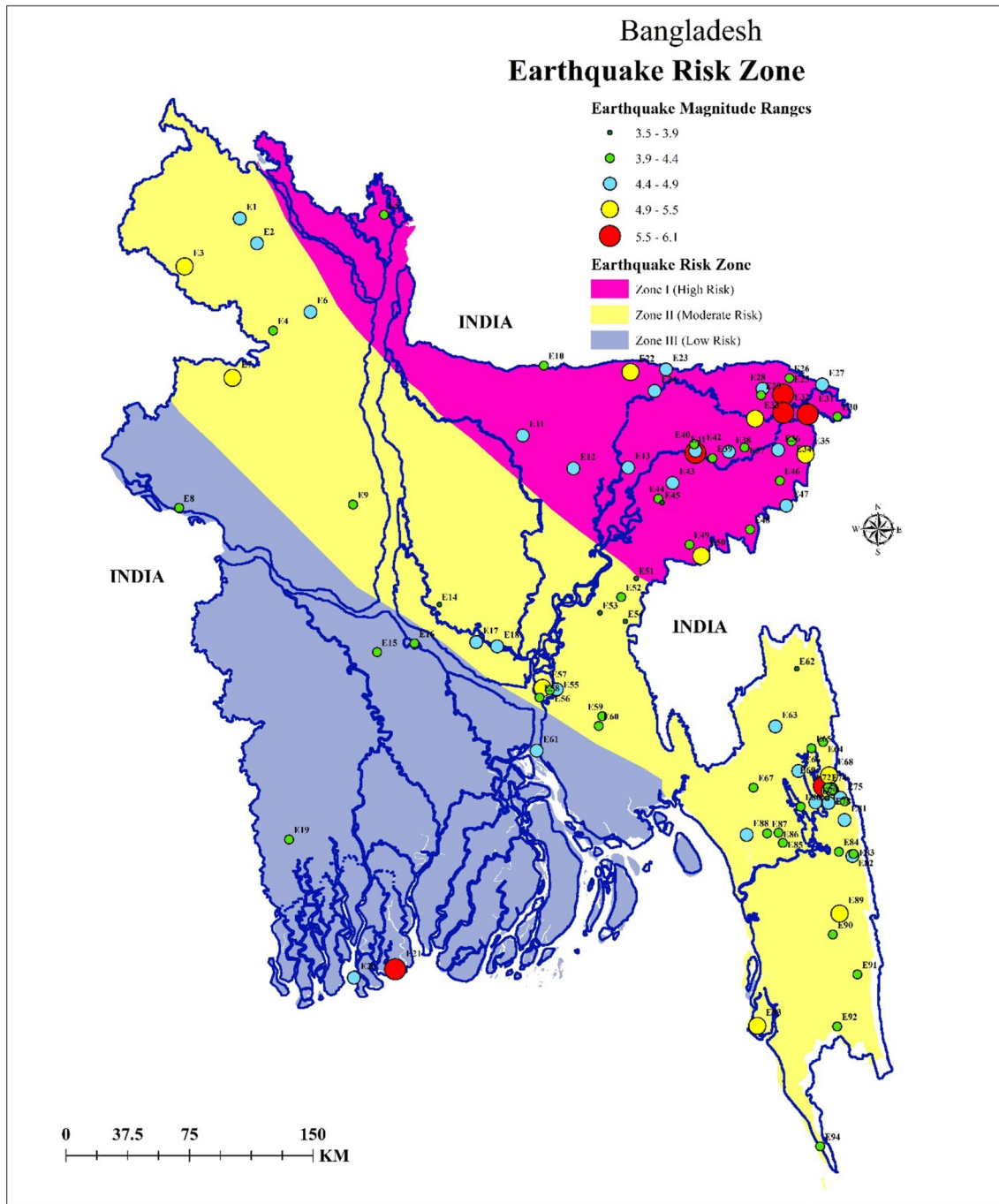


Fig. 5 Spatial distribution of earthquake sample in earthquake risk zone

Table 7 Risk zones of earthquake

Risk zone	Area (sq.km)	(%) Area	Earthquake sample (ES)	Percentage earthquake sample (%)
Zone I (high risk zone)	61861.8	44.81	34	36.17
Zone II (moderate risk zone)	48985.06	35.48	53	56.38
Zone III (low risk zone)	27213.44	19.71	7	7.45

Table 8 Comparison between interpolation models for magnitude and focus depth of earthquake using cross validation results

Model	Fit model	ME	RMSE	MSE	RMSSE	ASE	Partial sill	Nugget	Major range (m)	Major range (km)	Sill	Nugget/sill	Lag size	Effect of nugget/sill
Earthquake magnitude														
SK	Circular	0.012	0.542	0.017	0.973	0.556	1.0215	0.186	99,306	99.306	1.21	0.15	8275.4748	Strong
	Spherical	0.011	0.541	0.018	0.972	0.555	1.0345	0.150	99,306	99.306	1.18	0.13	8275.4748	Strong
	Exponential	0.004	0.541	0.008	0.976	0.553	1.08	0.072	99,306	99.306	1.15	0.06	8275.4748	Strong
	Gaussian	0.012	0.542	0.017	0.976	0.556	1.028	0.206	99,306	99.306	1.23	0.17	8275.4748	Strong
OK	Circular	-0.006	0.549	-0.011	0.981	0.559	0.291	0.014	293,210	293.21	0.30	0.05	40050.182	Strong
	Spherical	-0.005	0.551	-0.009	0.983	0.560	0.2917	0.013	343,790	343.79	0.30	0.04	40050.182	Strong
	Exponential	-0.007	0.550	-0.013	0.978	0.562	0.295	0.009	480,600	480.6	0.30	0.03	40050.182	Strong
	Gaussian	-0.006	0.550	-0.010	0.983	0.559	0.292	0.014	340,920	340.92	0.31	0.05	40050.182	Strong
IDW	Power 1	0.023	0.569											
	Power 2	0.022	0.609											
Focus depth														
SK	Circular	-0.691	14.371	-0.048	1.022	14.163	0.900	0.260	9453.5	9.4535	1.16	0.22	1215.9451	Strong
	Spherical	-0.681	14.377	-0.048	1.023	14.151	0.9101	0.246	10,311	10.311	1.16	0.21	1215.9451	Strong
	Exponential	-0.582	14.343	-0.040	1.013	14.257	0.945	0.228	14,591	14.591	1.17	0.19	1215.9451	Strong
OK	Gaussian	-0.699	14.372	-0.049	1.015	14.318	1215.945	0.285	10,636	10.636	1216.23	0.00234	1215.9451	Strong
	Circular	-0.067	13.611	-0.005	0.954	14.314	186.71	51.924	549,340	549.34	238.63	0.22	50845.398	Strong
	Spherical	-0.066	13.615	-0.005	0.954	14.311	186.4	50.986	610,140	610.14	237.39	0.21	50845.398	Strong
	Exponential	-0.082	13.643	-0.006	0.951	14.398	186.58	41.113	610,140	610.14	227.69	0.18	50845.398	Strong
IDW	Gaussian	-0.048	13.564	-0.004	0.957	14.208	187.15	51.309	449,210	449.21	238.46	0.22	50845.398	Strong
	Power 1	-0.020	15.189											
	Power 2	-0.327	17.287											

Bold expression designate robust models

ME mean error, MSE mean square error, RMSE root mean square error, ASE average standard error, RMSSE root mean square standardized error

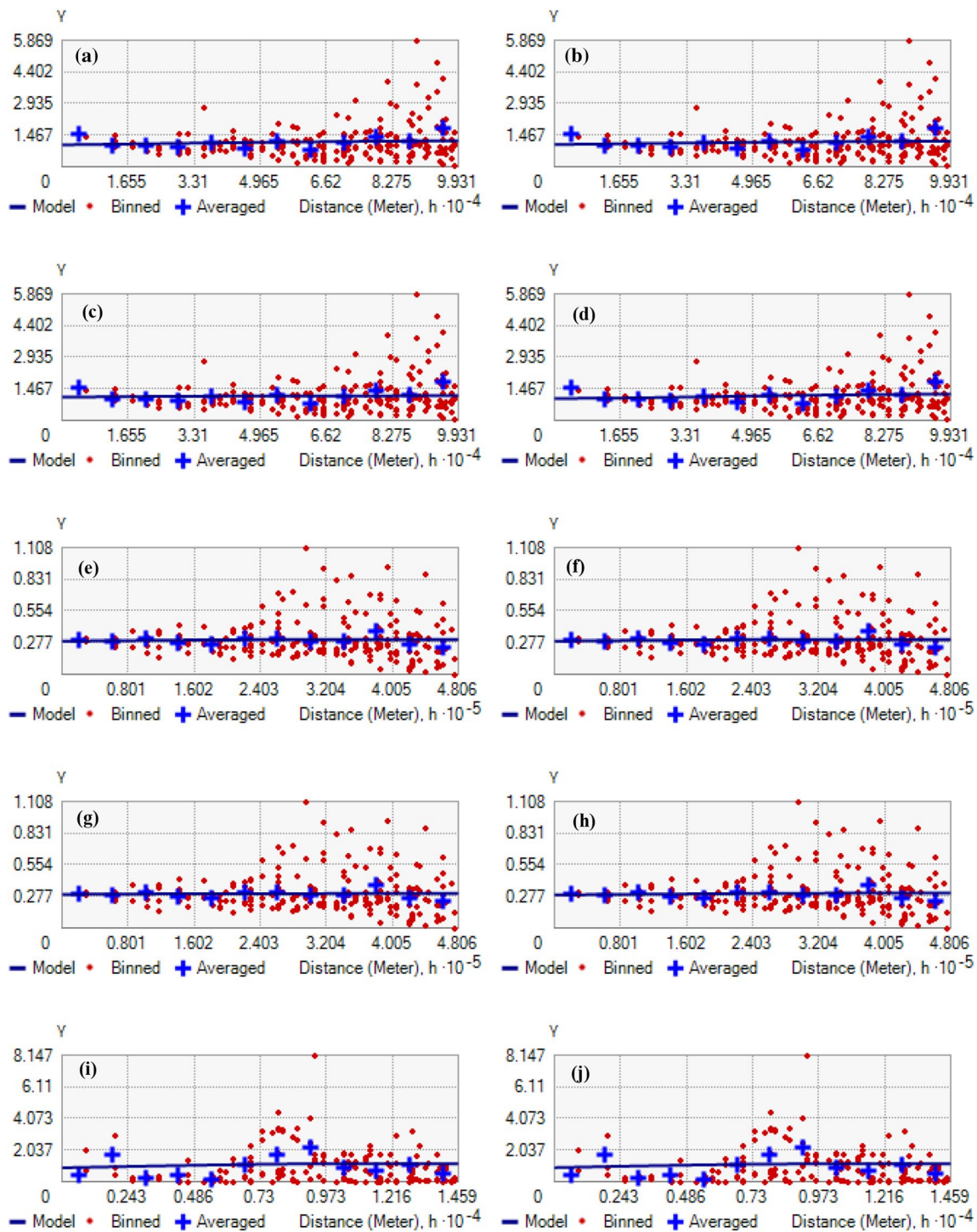


Fig. 6 Best fitted semivariogram models of earthquake parameter in the study area. Concentration of earthquake magnitude in simple kriging (SK) model: **a** circular semivariogram model; **b** spherical semivariogram model; **c** exponential semivariogram mode; **d** Gaussian semivariogram model and ordinary kriging model (OK); **e** circular semivariogram model; **f** spherical semivariogram model; **g** exponential semivariogram model; **h** Gaussian semivariogram model; and

concentration of earthquake focus depth in Simple Kriging model (SK) Model; **i** circular semivariogram model; **j** spherical semivariogram model; **k** exponential semivariogram mode; **l** Gaussian semivariogram model, and ordinary kriging model (OK); **m** circular semivariogram model; **n** spherical semivariogram model; **o** exponential semivariogram model; **p** Gaussian semivariogram model

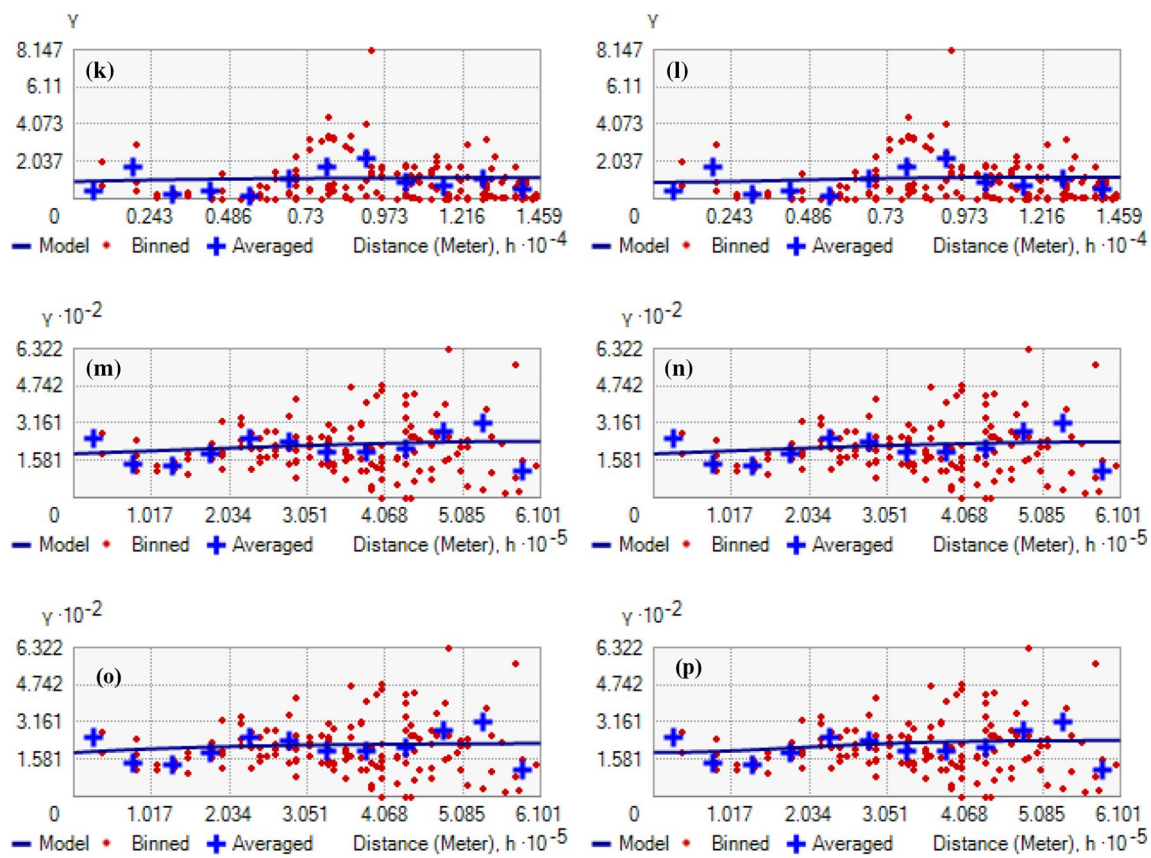


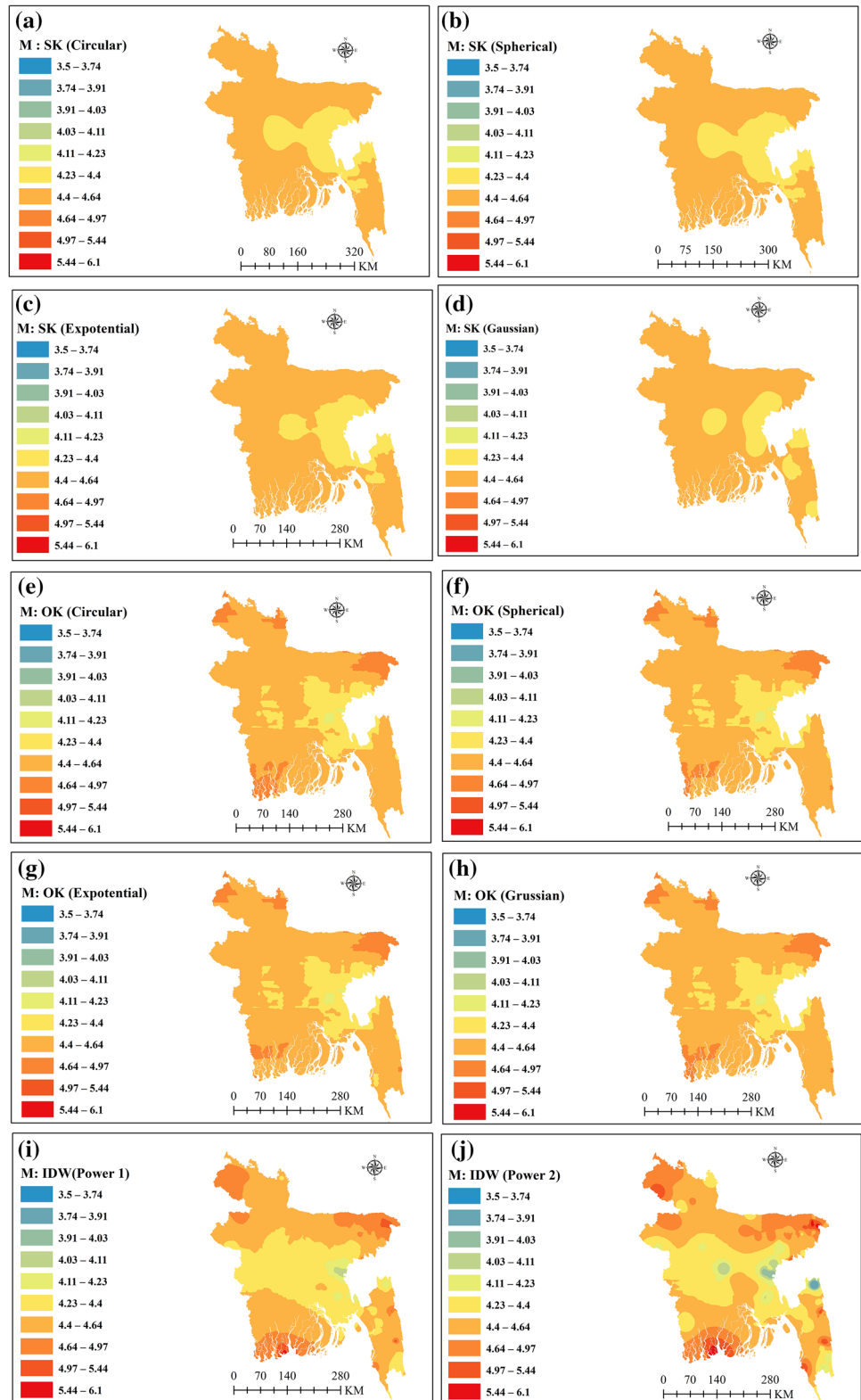
Fig. 6 (continued)

Semivariogram model linear curve provides precise satisfied influence zone of earthquake sampling sites (Fig. 6). Even, earthquake spatial susceptibility increasing or decreasing pattern can easily find out from isolated sampling sites by representation of semivariogram model curve. Moreover, the more or less constancy of earthquake spatial susceptibility characterized by the high or low consistent performance of semivariogram model $\gamma(h)$ linear representation adjacent the origin provides better decision of influence zone. The best fitted semivariogram model for earthquakes magnitude spatial concentration is exponential semivariogram model of OK, having classical notion of variables and showing strong dependence by sill/nugget effect (0.03) of earthquake samples (Fig. 6g). On the other hand, the best fitted semivariogram model for earthquakes focus depth spatial concentration is Gaussian semivariogram model of SK, having also classical notion of variables and showing strong dependence by sill/nugget effect (0.000234) of earthquake samples (Fig. 6k).

Prediction spatial vulnerability of earthquake

In this study, try to prepared spatial vulnerability of earthquake maps by applying the optimal interpolation models using earthquake magnitude and focus depth of 94 earthquake samples. Earthquake magnitude and focus depth spatial vulnerability display complex spatial pattern in in Bangladesh. However, earthquake magnitude spatial susceptibility prediction maps are classified into 10 ranges (3.5–3.74), (3.74–3.91), (3.91–4.03), (4.03–4.11), (4.11–4.23), (4.23–4.4), (4.4–4.64), (4.64–4.97), (4.97–5.44), (5.44–6.1) by applying the SK and OK with their semivariogram models and IDW models power (e.g. circular, spherical, exponential, Gaussian and power 1, 2) (Fig. 7). In SK model, two major ranges (4.23–4.4) and (4.4–4.64) of earthquakes vulnerability zone are observed dominantly in four (e.g. circular, spherical, exponential and Gaussian) optional semivariogram models. From the Table 9 present study reveal that, only 85.87% (118,558 sq. km) area is vulnerable to earthquakes magnitude high spatial susceptibility (HS) in the best fitted exponential semivariogram model of SK with comparing other semivariogram model which indicated lighter earthquake category. Moreover, exponential semivariogram model of SK results

Fig. 7 Spatial vulnerability of earthquake magnitude (M) in Bangladesh with OK, SK and IDW models



impacts show that 85.87% inland area of Bangladesh are liable to manifest trembling of household objects, intolerable sounds and wherever remarkable destruction will be occurred. On the other hand, pre-selected four optional

semivariogram model of OK, four major earthquake vulnerability zones ranges (4.03–4.11), (4.11–4.23), (4.23–4.4) and (4.4–4.64) are observed in Bangladesh. However, only 8.38% (11566.1 sq.km) area lies earthquake magnitude

Table 9 Spatial susceptibility of earthquake disaster in Bangladesh

Model	Type	Range number	Earthquake focus depth			Earthquake magnitude			Susceptibility
			Range	Area (sq.m)	Area (%)	Range	Area (sq.km)	Area (%)	
SK	Circular	1	5.8–22.1	150.03	0.11	3.5–3.74			VLS
		2	22.1–28.8	134654.00	97.53	3.74–3.91			
		3	28.8–31.5	2653.27	1.92	3.91–4.03			LS
		4	31.5–32.6	217.00	0.16	4.03–4.11			
		5	32.6–33	69.14	0.05	4.11–4.23			MS
		6	33–34.1	130.23	0.09	4.23–4.4	27547.5	19.95329563	
		7	34.1–36.8	163.10	0.12	4.4–4.64	110,513	80.04713896	HS
		8	36.8–43.5	23.17	0.02	4.64–4.97			
		9	43.5–59.8			4.97–5.44			VHS
		10	59.8–100			5.44–6.1			
	Spherical	1	5.8–22.1	130.53	0.09	3.5–3.74			VLS
		2	22.1–28.8	134607.00	97.50	3.74–3.91			
		3	28.8–31.5	2712.96	1.97	3.91–4.03			LS
		4	31.5–32.6	228.81	0.17	4.03–4.11			
		5	32.6–33	69.93	0.05	4.11–4.23			MS
		6	33–34.1	137.18	0.10	4.23–4.4	23,228	16.82458121	
		7	34.1–36.8	155.62	0.11	4.4–4.64	114,832	83.17549122	HS
		8	36.8–43.5	17.79	0.01	4.64–4.97			
		9	43.5–59.8			4.97–5.44			VHS
		10	59.8–100			5.44–6.1			
	Exponential	1	5.8–22.1	50.51	0.04	3.5–3.74			VLS
		2	22.1–28.8	133943.00	97.02	3.74–3.91			
		3	28.8–31.5	3750.86	2.72	3.91–4.03			LS
		4	31.5–32.6	175.51	0.13	4.03–4.11			
		5	32.6–33	50.44	0.04	4.11–4.23			MS
		6	33–34.1	71.29	0.05	4.23–4.4	19501.9	14.12568023	
		7	34.1–36.8	19.04	0.01	4.4–4.64	118,558	85.87431977	HS
		8	36.8–43.5			4.64–4.97			
		9	43.5–59.8			4.97–5.44			VHS
		10	59.8–100			5.44–6.1			
Gaussian	1	5.8–22.1	137.14	0.10	3.5–3.74			VLS	
	2	22.1–28.8	132508.00	95.98	3.74–3.91				
	3	28.8–31.5	4615.97	3.34	3.91–4.03			LS	
	4	31.5–32.6	309.39	0.22	4.03–4.11				
	5	32.6–33	104.40	0.08	4.11–4.23			MS	
	6	33–34.1	166.20	0.12	4.23–4.4	19604.8	14.2002131		
	7	34.1–36.8	204.71	0.15	4.4–4.64	118,455	85.79971447	HS	
	8	36.8–43.5	14.39	0.01	4.64–4.97				
	9	43.5–59.8			4.97–5.44			VHS	
	10	59.8–100			5.44–6.1				

Table 9 (continued)

Model	Type	Range number	Earthquake focus depth			Earthquake magnitude			Susceptibility
			Range	Area (sq.m)	Area (%)	Range	Area (sq.km)	Area (%)	
OK	Circular	1	5.8–22.1			3.5–3.74			VLS
		2	22.1–28.8			3.74–3.91			
		3	28.8–31.5			3.91–4.03			LS
		4	31.5–32.6			4.03–4.11	938.414	0.68	
		5	32.6–33	938.41	0.68	4.11–4.23	20448.7	14.81	MS
		6	33–34.1	20448.70	14.81	4.23–4.4	105,107	76.13	
		7	34.1–36.8	105107.00	76.13	4.4–4.64	11566.1	8.38	HS
		8	36.8–43.5	11566.10	8.38	4.64–4.97			
		9	43.5–59.8			4.97–5.44			VHS
		10	59.8–100			5.44–6.1			
	Spherical	1	5.8–22.1	31670.80	22.94	3.5–3.74			VLS
		2	22.1–28.8	85246.40	61.75	3.74–3.91			
		3	28.8–31.5	11257.80	8.15	3.91–4.03			LS
		4	31.5–32.6	1827.27	1.32	4.03–4.11	934.39	0.68	
		5	32.6–33	441.88	0.32	4.11–4.23	20325.6	14.72	MS
		6	33–34.1	1389.71	1.01	4.23–4.4	106,189	76.92	
		7	34.1–36.8	3345.71	2.42	4.4–4.64	10610.8	7.69	HS
		8	36.8–43.5	2880.52	2.09	4.64–4.97		0	
		9	43.5–59.8			4.97–5.44			VHS
		10	59.8–100			5.44–6.1			
	Exponential	1	5.8–22.1	30615.80	22.18	3.5–3.74			VLS
		2	22.1–28.8	84928.80	61.52	3.74–3.91			
		3	28.8–31.5	12896.00	9.34	3.91–4.03			LS
		4	31.5–32.6	1590.08	1.15	4.03–4.11	935.211	0.68	
		5	32.6–33	554.33	0.40	4.11–4.23	19633.3	14.22	MS
		6	33–34.1	1264.86	0.92	4.23–4.4	107,348	77.75	
		7	34.1–36.8	3092.12	2.24	4.4–4.64	10143.5	7.35	HS
		8	36.8–43.5	3118.22	2.26	4.64–4.97			
		9	43.5–59.8			4.97–5.44			VHS
		10	59.8–100			5.44–6.1			
Gaussian	1	5.8–22.1	31670.80	22.94	3.5–3.74			VLS	
	2	22.1–28.8	85246.40	61.75	3.74–3.91				
	3	28.8–31.5	11257.80	8.15	3.91–4.03			LS	
	4	31.5–32.6	1827.27	1.32	4.03–4.11	803.641	0.58		
	5	32.6–33	441.88	0.32	4.11–4.23	20569.3	14.90	MS	
	6	33–34.1	1389.71	1.01	4.23–4.4	105,858	76.68		
	7	34.1–36.8	3345.71	2.42	4.4–4.64	10829.1	7.84	HS	
	8	36.8–43.5	2880.52	2.09	4.64–4.97				
	9	43.5–59.8			4.97–5.44			VHS	
	10	59.8–100			5.44–6.1				

Table 9 (continued)

Model	Type	Range number	Earthquake focus depth			Earthquake magnitude			Susceptibility
			Range	Area (sq.m)	Area (%)	Range	Area (sq.km)	Area (%)	
IDW	Power 1	1	5.8–22.1	22735.30	16.47	3.5–3.74			VLS
		2	22.1–28.8	83074.30	60.17	3.74–3.91			
		3	28.8–31.5	20682.30	14.98	3.91–4.03			LS
		4	31.5–32.6	2382.60	1.73	4.03–4.11	92.2027	0.07	
		5	32.6–33	798.48	0.58	4.11–4.23	3766.23	2.73	MS
		6	33–34.1	2022.83	1.47	4.23–4.4	46534.1	33.71	
		7	34.1–36.8	2698.91	1.95	4.4–4.64	68,255	49.44	HS
		8	36.8–43.5	2698.91	1.95	4.64–4.97	18200.9	13.18	
		9	43.5–59.8	1.86	0.00	4.97–5.44	1211.7	0.88	VHS
		10	59.8–100			5.44–6.1			
	Power 1	1	5.8–22.1	32905.80	23.83	3.5–3.74		0	VLS
		2	22.1–28.8	61791.30	44.76	3.74–3.91	474.238	0.34	
		3	28.8–31.5	20113.90	14.57	3.91–4.03	986.102	0.71	LS
		4	31.5–32.6	8160.04	5.91	4.03–4.11	1359.53	0.98	
		5	32.6–33	2694.28	1.95	4.11–4.23	6619.01	4.79	MS
		6	33–34.1	3509.09	2.54	4.23–4.4	42033.1	30.45	
		7	34.1–36.8	4010.91	2.91	4.4–4.64	59288.3	42.94	HS
		8	36.8–43.5	4301.17	3.12	4.64–4.97	22705.5	16.45	
		9	43.5–59.8	573.68	0.42	4.97–5.44	4100.44	2.97	VHS
		10	59.8–100			5.44–6.1	494.046	0.36	

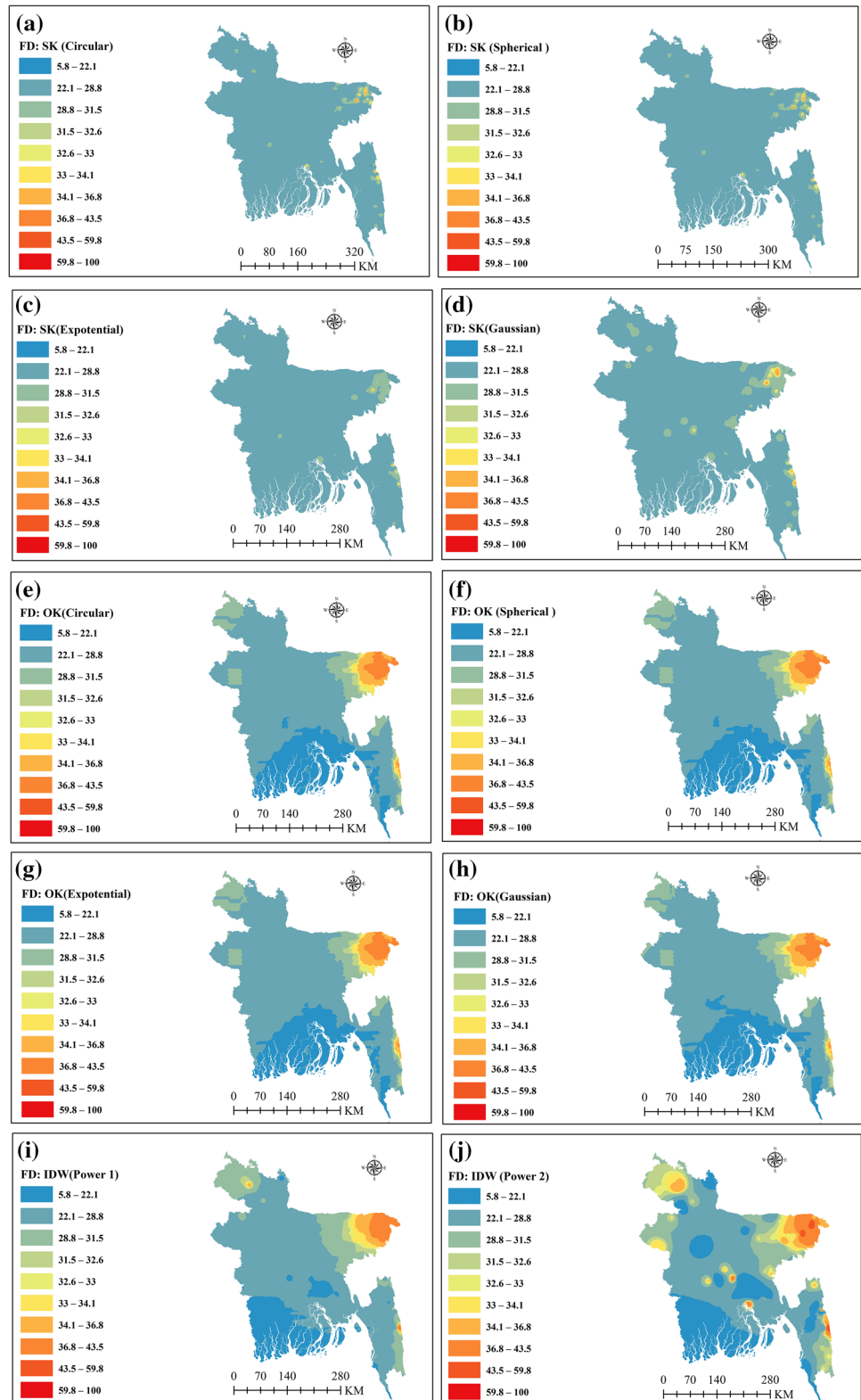
VLS very low susceptibility, LS low susceptibility (LS), MS medium susceptibility, HS high susceptibility, VHS very high susceptibility

high spatial susceptibility (HS) in circular semivariogram model of OK. In exponential semivariogram model of OK outcome demonstrates that, only 77.75% (107,348 sq.km) area lies to medium spatial susceptibility (MS) of earthquake magnitude and express lighter earthquake category. Furthermore, Impacts results of circular semivariogram model disclose that, as the impact of exponential semivariogram model of SK, but lesser as spatial area context of earthquake susceptibility. In IDW model, six (4.03–4.11), (4.11–4.23), (4.23–4.4), (4.4–4.64), (4.64–4.97), (4.97–5.44) and nine (3.74–3.91), (3.91–4.03), (4.03–4.11), (4.11–4.23), (4.23–4.4), (4.4–4.64), (4.64–4.97), (4.97–5.44), (5.44–6.1) majors earthquake vulnerability zones ranges are observed in power 1 and 2, respectively in inland Bangladesh. About 0.88% (1211.7 sq.km) and 0.36% (494.046 sq.km) area lies to earthquakes magnitude high spatial susceptibility (HS) ranges [(4.97–5.44) and (5.44–6.1)] in power 1 and 2, respectively of IDW model. The impact results of IDW model in spatial context dissimilar from SK and OK model. Spatial vulnerability of this model with power 1 results indicated that, it is liable to moderate earthquake vulnerability in Bangladesh. It could be causes major destruction to the old building and minor destruction to the new constructions. In the case of power 2 of IDW model outcome expressed that, it is liable to strong earthquakes vulnerable in inland Bangladesh. The effects of this results also indicated that

it can be more damaging in the high population density places which can across about 160 km buffer area. But during the contemporary time, tremendous increase of population, rapid growth of urbanization and industrialization with their multistoried building, extraction of groundwater ignoring ground water level will great concern to occur major earthquake disaster in urban area like Dhaka City and Chittagong City. The impact of the future upcoming major’s earthquake results will unbound and its destruction cannot be measurement.

In this study, earthquake in Bangladesh are classify on the basis of focus depth. They are termed as shallow focus depth which range from 0 to 70 km; intermediate focus depth which varied from 70 to 300 km and deep focus depth which range more than 300 km (Islam et al. 2016). Present study reveal that, Bangladesh lies shallow focus depth to intermediate focus depth of earthquake vulnerability. Moreover, earthquake focus depth spatial susceptibility prediction maps are classified into 10 ranges (5.8–22.1), (22.1–28.8), (28.8–31.5), (31.5–32.6), (32.6–33), (33–34.1) (34.1–36.8), (36.8–43.5) and (59.8–100) by applying the SK and OK with their semivariogram models and IDW models power (e.g. circular, spherical, exponential, Gaussian and power 1, 2) (Fig. 8). Focus depth spatial vulnerability of earthquake in SK and OK models demonstrate that eight major

Fig. 8 Spatial vulnerability of earthquake focus depth (km) in Bangladesh with OK, SK and IDW models



ranges (5.8–22.1), (22.1–28.8), (28.8–31.5), (31.5–32.6), (32.6–33), (33–34.1) (34.1–36.8) of earthquakes vulnerability zone are observed dominantly in optional semi-variogram models except exponential model. Only 7.84%

(10829.1 sq.km) area is vulnerable to high earthquakes focus depth concentration range (34.1–36.8) in the best fitted Gaussian semivariogram model of OK, which indicated shallow focus earthquake vulnerability. The impacts

of shallow focus earthquake have large spread and greater damage at the earth crust because it caused by faults in the tertiary hilly region and the movement of continental plates. On the other hand, only 8.377589% (11566.1 sq. km) area is vulnerable to high earthquakes focus depth concentration range (34.1–36.8) in circular semivariogram model of OK with comparing other semivariogram model which also indicated shallow focus earthquake vulnerability. The OK model impacts results are similar with SK model.

Earthquake disaster management

Earthquake disaster cannot be prevented but applying systematic disaster management approach can reduce its risk and help in development mitigation scenarios. Earthquake disaster management can be accelerated through two phases, i.e. pre-disaster prevention/reduction and preparedness, post-disaster, response and recovery.

Preparedness phase

- a. Regular monitoring the earthquake disaster and explore probable vulnerable area.
- b. Earthquake vulnerability modelling is an essential process in this phase which can deliver realistic scenarios recognizing areas that may be affected in the future.
- c. Updating seismic vulnerability map remaining small and large scale area on the basis of earthquake magnitude, intensity and focus depth.
- d. Developing standard building code for future new construction and all the public and private construction should follow mandatory. In this regards, law administration authorities to take proper steps whose are contrary to malefactor of the building codes.
- e. Mass communication systems such as electric and print media should enroll video coverage and writing, respectively to aware about the earthquake disaster vulnerability.
- f. All level of education disaster management course will be include.
- g. Adequately training to the volunteers and evacuation plans are considered part of the preparedness activities.

Response phase

- a. Search and rescue operation should be carried out for finding the affected and injured people as soon as possible. In this regards, fire service, police and ambulance

crews should be taken great role in search and rescue operation.

- b. Admitted injured people in medical hospital urgent.
- c. Evacuation such as relocate injured people from the impacted zone and provide temporary shelter.
- d. Relief (food supplies, clothing, water, and medicine) supplies should be provide free of charge, in the days and weeks immediately following a sudden earthquake disaster.

Recovery phase

- a. Damage assessment should be carried out quickly.
- b. Providing emergency shelter among the victim people.
- c. Water, sanitation and hygiene should be ensured among the victim's people.
- d. Reconstruction of affected settlement.
- e. Restoration of physical and socio-economic environment.
- f. Emergency communication system should be developed.
- g. Emergency medical care should be ensured among the injured peoples.

Development

- a. Earthquake affected zone should turned into previous condition by developing activities such as reconstruction of transportation network, damage socio-economic organization.
- b. All the development infrastructures should build remaining the geographical, geological, geomorphological, hydrological and climatological characters of the environment.
- c. Government and non-government financial organizations should provide loan and micro credit for acceleration rehabilitation practice those are the victims of earthquake disaster.
- d. Develop disaster communication systems.

Mitigation phase

- a. Relocation of different government organization from vulnerable place. In this sense, Dhaka is the most vulnerable due to high population density, large number of government, non-government organization and educational institutions. These organization should be relocated from Dhaka city to low vulnerable zone.

- b. Socio-economic institutions such as school, college, university, hospital, religious prayer hall have to be build earthquake resistances.

Conclusion

Bangladesh is susceptible to several natural disasters and regarded as extreme vulnerable country of the earth. Among the various disasters, earthquake spatial vulnerability is increasing during the contemporary time in this country. Several factors increase the risk of earthquake such as geological formation, location of plate boundary, location of fault and fold and tremendous increase of population in major cities of this country. Tertiary hilly regions of this country are susceptible to earthquake disaster due to location of plate boundary and fold and fault structures. Moreover, central region of Bangladesh particularly Dhaka City is more vulnerable to earthquake due to large number of population living here. Furthermore, the average magnitude of earthquake in Bangladesh is 4.539 Richter scale and 98.94% earthquakes are shallow focus with average 28.68 km focus depth. About 44.68% earthquake occurred along Western Fold Belt of the Indoburman Orogeny tectonic frame work. Nearly, 44.81% (61861.8 sq.km) area fall high risk zone where 36.17% earthquakes occurred from 1961 to 2016. Geostatistical model results shows that, 85.87% (118,558 sq.km) area is vulnerable to high earthquakes magnitude in exponential semivariogram model of SK with comparing other semivariogram model which indicated lighter earthquake category. Sustainable management strategies of earthquake can mitigate vulnerability on resources, lives and livelihood in Bangladesh. Integrated disaster management approach by local community, government and non-government organization will reduce the risk of earthquake disaster vulnerability at present and future and ensure sustainable management. In this regards, fire fighter, army admiration, local administration, registered doctors and students, environmental engineers, lawyer's representatives and government media, print media, mass media and all level of conscious people should come forward to work for the development distress people of earthquake affected.

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