Deterministic Seismic Hazard Analysis of Bharuch City and Surrounding Region

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Abstract
The research of seismic hazards along with their preparedness is critical for the development of structures which are both safe and economically effective. Ankleshwar, also known as the "Chemical Capital of India," is located in Bharuch district situated on Gujarat's south-west coast and it is categorised as seismic zone III by the Indian seismic zonation system. Past earthquake data and accessible seismotectonic information were used to conduct a deterministic seismic hazard study of the Bharuch region. After processing earthquake data obtained from 1819 to 2019, a separate seismic catalogue encompassing a 400-kilometer radius around Bharuch city was created.

To get rid of the dependent events, the complete catalogue was declustered. Using basic mathematical procedures, the minimum distances from every seismic source generating tectonic activity were estimated. Predictive correlations for the region were used to estimate the Peak Ground Acceleration (PGA) values at bedrock level. The present analysis shows that with a maximum probable earthquake of magnitude 5.8 triggered by the Narmada Son Fault (NSF), the values of PGA of Bharuch region have ranged from 0.086 to 0.51 g. The key design parameters for the Bharuch city and surrounding region are provided by the PGA model discussed in this study.

Keywords: Seismic Hazard, Seismotectonic Information, Earthquake Catalogue, Peak Ground Acceleration (PGA).

Introduction
In last two centuries, India has experienced numerous major earthquake events in various parts of the country. The earthquakes in Kutch, Dammoh Hill and Mount Abu were experienced in early to mid-eighteenth century in 1819, 1846 and 1848 respectively reporting significant effects.

Later in nineteenth century, in the year 1900, 1927 and 1938, the earthquake activities with magnitude greater than 5.0 was reported in Coimbatore, Son-valley and Saputara respectively. The occurrence of such events was further continued with higher magnitudes ranging from (M_w 5.4-7.7) where the Anjar earthquake 1956, Koyna earthquake in 1967, Bharuch earthquake 1970, Killari earthquake 1993, Jabalpur earthquake 1997 and the noteworthy Bhuj earthquake 2001 had significantly affected the infrastructures and losses of lives.

Due to the high concentration of earthquake epicentres in the country, the majority of seismic investigations in India are undertaken around the seismic belt from Himalayan region and the Kutch region from Gujarat. The scientific community's interest in Peninsular India (PI) has expanded intensely in recent years, particularly in the land of urban seismic risk assessment and mitigation.

Bharuch, earlier known as Broach, a city located at the doorway of Narmada River in Gujarat State, is famous for its fertilizers and chemical industries. Due to the collaborative efforts of state and central government, the tallest statue of world “Statue of Unity” was built in the Kevadia Colony, Bharuch which is located in the Narmada River Waterway. It has raised the interest of the investors and entrepreneurs to set up the various projects in and around the Bharuch city. Along with this, the execution of the foundation of few bridge piers for the high-speed rail project has started near the Narmada River and Bharuch city. All these factors make city of national importance.

According to official estimates, the city is around 400 kilometres far away from the epicentre of the 2001 Bhuj earthquake (M_w 7.7) and it has previously sustained extensive damage. It has also been subjected to seismic activity from nearby sources. Bharuch is situated above the Son-Narmada fault and as per IS 1893: 2016[8], it falls under the zone III on the seismic zoning map which indicates 0.16g as the basic peak ground acceleration of Bharuch.

The upper crust of the Bharuch comprises of loose silty sandy soils of varying thicknesses which make it vulnerable even for the moderate earthquake events[21]. In order to limit the hazardous effects of disastrous earthquake events, the seismic hazard assessment for the Bharuch region is necessary. The current work employs a deterministic seismic hazard analysis approach to characterise the Peak Ground Acceleration (PGA) at bed rock level of spatial variability.

Material and Methods
Geological Characteristics of Bharuch Region: Previous research has shown that large earthquakes can cause damage up to 350 kilometres away from the epicentre[23]. Thus, in accordance with the regulatory guide 1.167[24] and the consideration of damages experienced by the city during the 2001 Bhuj earthquake, a 400-kilometer radius around Bharuch is considered for the analysis. As a result, the region

is bound by latitudes ranging from 18.06 N to 25.30 N and longitudes ranging from 69.15 E to 76.87 E and it includes the majority of the State of Gujarat, a portion of Madhya Pradesh (MP) State, a portion of Rajasthan state and eastern portion of Maharashtra State.

The two major Precambrian trends that govern Gujarat's structural layout are, the mountain range of Aravalli (NE-SW) and the Satpura range (ENE-WSW)[18]. These reactivated motions culminated in the development of three important basins: the Kutch, Narmada and Cambay.

During late Triassic to early Jurassic, once the Indian plate gets separated from Gondwanal and the rifting occurred in stages. During the late Triassic-early Jurassic period, the Kutch rift was formed then the Cambay rift during the Early Cretaceous period and the Narmada rift during the Late Cretaceous period were formed[18].

The southern peninsular section and the northern foreland section are the two blocks of Indian shield which are detached due to the tectonic boundary of the Narmada-Son lineament. The Cambay basin and the western continental shelf are opened up by a series of parallel extension faults. At its southernmost extent, the Aravalli trend is divided into three distinct components. The prime NE-SW trend continues as a south-westerly descending arch across the Cambay graben into Suarashtra, with the main NE-SW trend reversing. It runs the length of the continental shelf, splitting it into two portions: the southern Kerala-Bombay shelf and northern Saurashtra-Kutch shelf. The mountain range of Aravalli in north starts from Delhi and connects the Kutch in western part of India through Cambay basin. Another southern range of Aravalli which rotates anticlockwise, usually joins the mountain range of Satpura[2].

In terms of geology, there are three primary land cover divisions, each of which is distinguished by various structural, stratigraphic and lithological properties which may be observed in the three major physiographic divisions. Each division has an evolutionary history distinct from the others. A substantial portion of Gujarat is composed primarily of Deccan trap rock, with Cretaceous and Tertiary strata appearing in a few locations. Precambrian crystalline and sedimentary rocks from the quaternary, tertiary periods as well as the well-known Deccan trap, distinguish Gujarat's mainland from the rest of the country.

The Saurashtra peninsula is characterised by an upper Jurassic sedimentary sequence, with basalts occupying large parts. Kutch's geology is defined by Jurassic sandstones, Deccan volcanic rocks and quaternary/tertiary sediments, lying on an Achaean basement[6]. This region is characterised by several large faults including the Kutch Mainland fault, the Katrot Hill Fault, the Island Belt fault, the Nagar Parkar fault and the South Wagad fault[18]. The Narmada basin is formed by the 'Dhuandhar falls,' flowing across the States of Madhya Pradesh and Gujarat. The Narmada river flows west for 1,312 kilometres (815.2 miles) before emptying into the Arabian Sea via the Gulf of Khambhat, 30 kilometres (18.6 miles) west of Bharuch, Gujarat. The Narmada Rift Valley, a linear trench in the heart of the Indian subcontinent, provided an ideal elongated depression for sediment build-up. Dolerite and other mafic and siliceous dykes and sills infiltrate the rift trench along various tectonic deformation lineaments.

Chamyal et al[3] investigated the Cambay basin's geomorphology in depth. According to them, the Narmada valley is divided into four major geomorphic zones. This zone is dominated by basaltic flows and patches of Cretaceous sedimentary rocks from the Bagh formation and it is divided into three sections: a low highland made up of tertiary rocks, a massive stretch of alluvial zone corresponding to the basin section and a limited coastal zone consisting primarily of mud flats.

The structural basis of this zone's westward expansion into the lower Narmada valley is less complicated than that of the adjacent zone. Data on NSF that is presented in this part generally stems from large-scale geophysical studies carried out in preparation for commercial extraction of subsurface petroleum resources. Seismic activity at deep level sounding studies have confirmed that there is a single deep-seated fault (NSF) in the lower Narmada basin, which is consistent with previous findings[12]. Seismic reflection experiments have firmly demonstrated that the NSF is a typical subsurface fault with significant reversal near the surface[19].

Seismic Features of Study Region

It can be seen from IS 1893_part 1[8] that Gujarat is the only State which comprises all four seismic zones. The Kutch region of north-west part of the Gujarat falls under seismic zone V whereas the adjacent parts like Banas katha, Patan, Morbi and some parts of Jamnagar and Dwarka fall under the zone IV and remaining portion Gujarat State except Dahod falls under the zone III.

Hence, all these areas are prone to experience the earthquakes ranging magnitude from M_w 5 to M_w 8. This makes Gujarat as one of the most dynamic pancontinental zones of earthquake events. Since 1800, the State has experienced seven to eight earthquakes with the magnitudes higher than 6 and two major earthquakes with magnitudes of 7.7 and 7.8 in 1891 and 2001 respectively.[11,16]

Mandal and Johnston[14] reported in their study that the influence of Bhuj earthquake was experienced for several years in terms of aftershocks. The details of the aftershocks of Bhuj earthquake are mentioned in table 1[18]. As a result, the frequency of earthquake events with magnitude of 5 and accompanying aftershock-foreshock has been increased.

Even though the distance between Bharuch and Kutch is about 400 km, it has experienced significant damage during the 2001 Bhuj earthquake.

Table 1
Magnitudes of Aftershocks

S.N.	Magnitudes of aftershocks	No. of aftershocks
1.	Mw < 3.0	several thousand
2.	3.0 < Mw < 3.9	≈ 1600
3.	4.0 < Mw < 4.9	> 200
4.	5.0 < Mw < 5.9	14

As per IS 1893_part 1[8], Bharuch falls under seismic zone III and it may also experience high seismic activity as a result of its proximity to the far-field sources. Since the ancient time, it has experienced many shocks and hence is considered as one of the seismically active zones. The area near by the Gulf of Khambhat of Cambay region, adjacent Kutch region and Foreland India's most dynamic continental margin is located in the Narmada-Tapti region. Jaiswal and Sinha[10] also conveyed that the majority of seismic events in Peninsular India (PI) was experienced near the weak liner zones of Narmada and Kutch lineament where the lithosphere is being pulled out.

Earthquake Catalogue: For any seismic hazard study, it is important to have a thorough, precise catalogue of past seismic events consisting of the exact location of earthquake with accurate date and time. The present work compiles a complete earthquake catalogue for the Peninsular India region confined by latitudes 18.06 N to 25.30 N and longitudes 69.15 E to 76.87 E from 1819 to 2019. To prepare a complete earthquake catalogue, significant data of earthquake events were collected from several governing bodies which include Geological Survey of India, Gujarat Engineering Research Institute, Indian Meteorological Department and the Institute of Seismological Research. Some of the data were also collected from International Seismological Centre and the National Geophysical Research Institute. Along with this, few technical publications were also used to collect further supporting data[4,9,13,22].

The information received from the various sources was meticulously evaluated to eliminate the repetitions. In few cases, the deviation in the magnitudes of earthquake events was observed in the record of multiple sources. For such cases, the occurrence of greater magnitude was chosen. The magnitude scales used by various agencies varied and some occurrences in the literature incorrectly recorded the strong values for previous earthquakes. The accurate assessment of hazard levels for any place needs complete details of previous seismic events with uniform magnitude scale. As a result, all data were transformed into a single moment magnitude scale using the empirical relationship introduced by Scordilis[20].

Additionally, the intensity values are translated using Gutenberg and Richter's[7] empirical relationship [Moment Magnitude (M_w) is equal to two-thirds of an earthquake's intensity (I) plus one.] which has been validated against recorded values of M_w and I for the region.

Because aftershocks and foreshocks are dependent on the primary shock, they must be excluded from the analysis set. Generally, earthquake catalogues make no difference between primary and secondary occurrences[15]. In this situation, the primary shock event and its dependent events should be separated. Numerous scholars have offered several empirical criteria for identifying major events over the last several years[1,5,25].

Two commonly utilised approaches suggested by Urhammer[25] in 1986 as well as Gardner and Knopoff[5] in the year 1974 were used in this investigation to separate the catalogue from the dependent events. It is necessary to isolate aftershocks and foreshocks from seismic clusters using the methods of spatial and temporal windowing.

In this study, the entire catalogue was scanned with the help of ZMAP software. This was done in a certain area and time[26]. The epicenters those are falling under the windows as shown in fig. 1(a) and (b) are eliminated. Due to the lack of advanced equipments, in literature as well as in the data of various agencies, the earthquakes of lesser magnitude are reported less as compared to higher magnitude earthquakes for the years before 1958. After declustering, a total of 293 events have been finalized for final earthquake catalogue (Fig. 2).

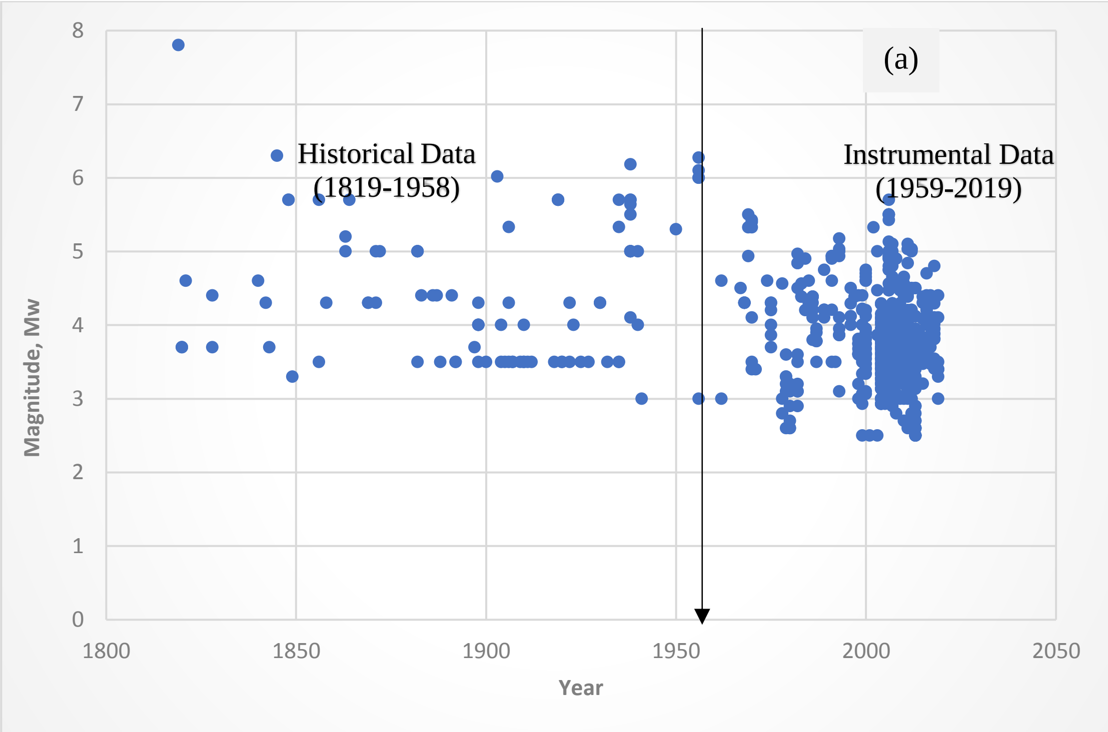
Seismic Hazard Analysis: The occurrence of any seismic activity generates the ground motion at respective site locations. The approximate evaluation of such ground motion which is known as “seismic hazard analysis”, is mandatory for the design of earthquake resistance structures. One of the primary practices of seismic hazard assessment is in the preparation of the seismic microzonation maps for the comprehensive applications. Specifically, for the evaluation of the parameter which measures the vertical characteristics of the surface deviations that unfold the ground motion or for the development of closely spaced grid of zones which counter the equal risk across the whole area, the seismic hazard analysis is helpful.

Peak ground accelerations can be estimated at any site using a deterministic technique that takes into account the region's seismotectonic setup and the largest earthquake magnitude from previous seismicity. Therefore, it is necessary to assign a maximum earthquake magnitude to each fault when using a deterministic technique. This is the most important thing to take into consideration. Maximum earthquake magnitudes for each seismic source have been estimated using historical records and an earthquake model using a deterministic technique has been constructed as depicted in table 2.

In order to conduct out the DSHA, fifteen seismic sources were taken into account. The entire Bharuch region is divided into 3 km x 3 km grid cells and the shortest epicentral distance between the centre of each grid cell and each fault is calculated. The PGA is assessed in accordance with the relationships established by Raghukanth and Iyengar.[17]

$$lnY = C_1 + C_2(M-6) + C_3(M-6)^2 - lnR - C_4R + ln\varepsilon \quad (1)$$

In equation (1), the coefficients (C1, C2, C3 and C4) can be calculated from the work of Raghukanth and Iyengar[17] where Y denotes the peak ground acceleration/spectral acceleration (g) at bedrock level, M denotes the moment magnitude, R denotes the hypo central distance and E denotes the error associated with the regression.



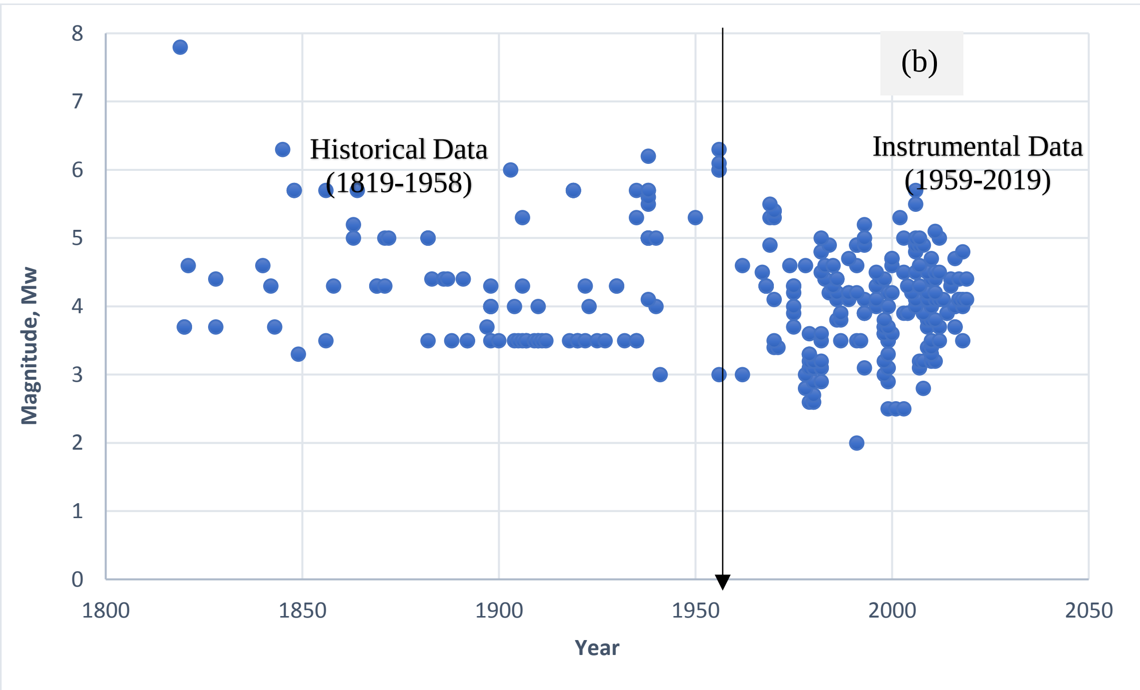


Figure 1: (a) Earthquake Events before Declustering; (b) Earthquake Events after Declustering

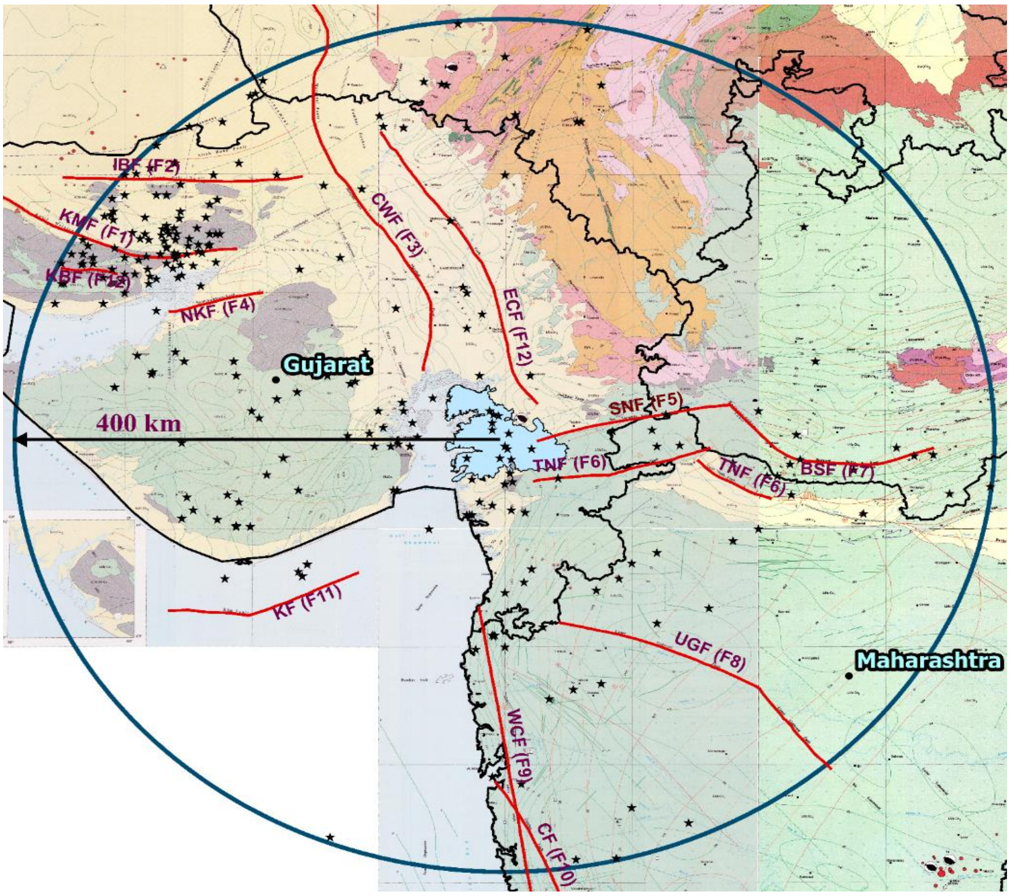


Figure 2: Seismotectonic Model

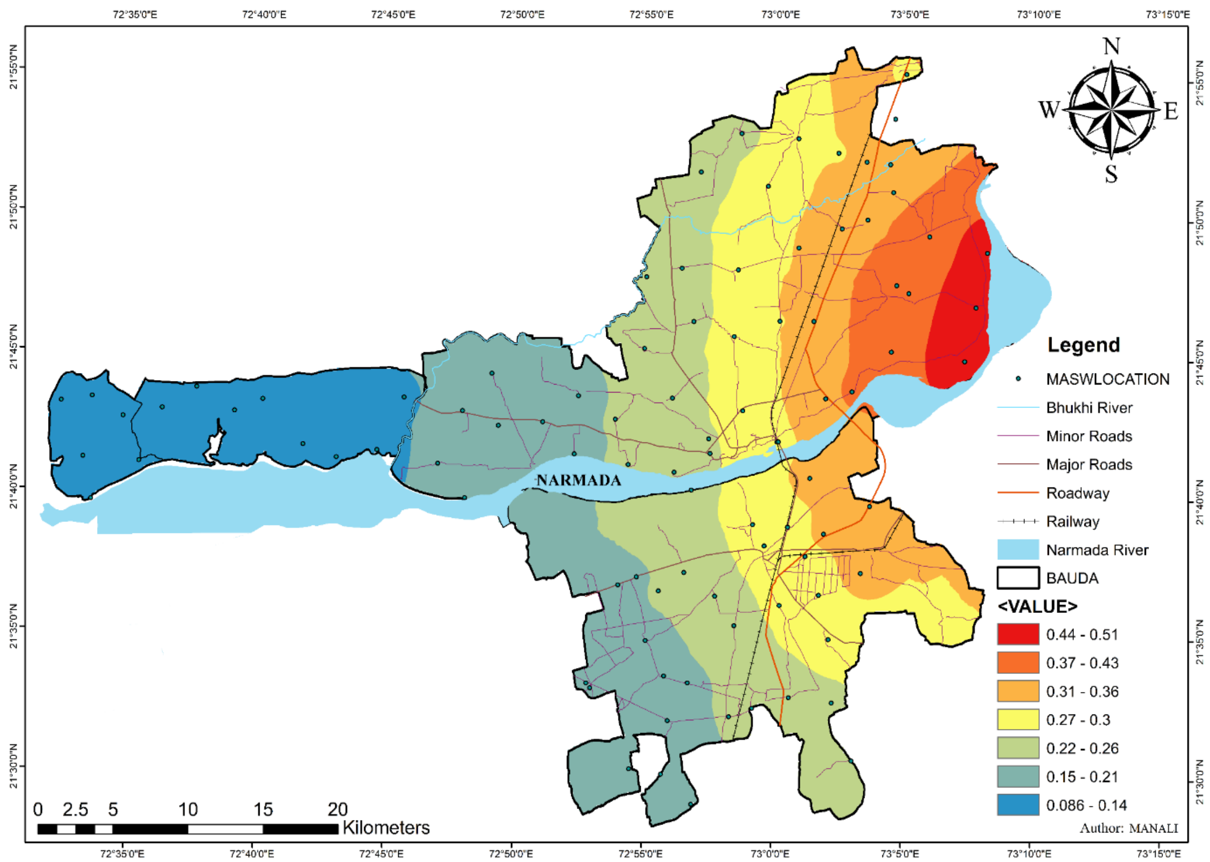


Figure 3: Spatial Distribution of Peak Ground Acceleration in Bharuch and Surrounding Region

Table 2
Estimation of PGA by Deterministic Approach

S.N.	Major Faults	Length (km)	Shortest R_{hyp}	Longest R_{hyp}	m_{max}	PGA
F1	Kutch Mainland Fault	209	285.24	474.07	7.8	0.019
F2	Island Belt Fault	194	301.12	438.45	6.3	0.005
F3	Cambay West Fault	200	96.67	486.51	5.7	0.033
F4	North Kathiawar Fault	79	243.44	301.07	5	0.002
F5	Son Narmada Fault	550	28.45	187.16	5.8	0.191
F6	Tapti North Fault	395	42.12	224.10	5	0.052
F7	Barwani Sukta Fault	192	186.93	350.66	6.2	0.015
F8	Upper Godavari Fault	275	172.22	406.19	4.6	0.004
F9	West Coast Fault	370	152.74	517.52	5.7	0.015
F10	Chiplun Fault	220	315.31	523.22	4.2	0.0004
F11	Kim Fault	166	169.00	317.34	5.7	0.012
F12	East Cambay Fault	291	48.65	311.42	5.7	0.089
F13	Katrot Bhuj Fault	47.05	353.94	397.79	6	0.003
					Max	0.191
					Fault	Son Narmada Fault

Results and Discussion

In fig. 3, the PGA model for the Bharuch region has been developed deterministically by taking into account the maximum value of PGA that has been obtained by different sources at each grid site. The analysis finds that the Chiplun fault is responsible for the lowest value of PGA at 0.0004 g and the Narmada Son fault is responsible for the highest value of PGA at 0.191 g (Table 2). Due to the fact that the influence of other sources cannot be ignored, the peak ground acceleration from all 13 seismic sources has been estimated by calculating the shortest and longest distances between 293 historical earthquake events. Finally, the maximum value of peak ground acceleration is extracted from each source.

Conclusion

The purpose of this research is to use deterministic seismic hazard analysis to estimate the peak ground acceleration of Bharuch city and surrounding region. By comparing PGA values between 0.086 g and 0.51 g, it can be concluded that the eastern section of the region is more severely affected than the western part. The highest concentration of PGA is found in the eastern half of the region at 0.44 to 0.51g.

Seismic zone III's PGA value has been estimated by the BIS (1893:2016)[8] to be 0.16 g. With this information, it is possible to safeguard existing structures as well as to design new ones. In order to make an informed decision, additional studies such as probabilistic seismic hazard analysis, ground response analysis and liquefaction studies are needed.

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