Deterministic Seismic Hazard Assessment at Bed Rock Level: Case Study for the City of Bhubaneswar, India

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Abstract— In this study an updated deterministic seismic hazard contour map of Bhubaneswar (20°12'0"N to 20°23'0"N latitude and 85°44'0"E to 85° 54'0"E longitude) one of the major city of India with tourist importance, has been prepared in the form of spectral acceleration values. For assessing the seismic hazard, the study area has been divided into small grids of size 30″×30″ (approximately 1.0 km×1.0 km), and the hazard parameters in terms of spectral acceleration at bedrock level, PGA are calculated as the center of each of these grid cells by considering the regional Seismo-tectonic activity within 400 km radius around the city center. The maximum credible earthquake in terms of moment magnitude of 7.2 has been used for calculation of hazard parameter, results in PGA value of 0.017g towards the northeast side of the city and the corresponding maximum spectral acceleration as 0.0501g for a predominant period of 0.05s at bedrock level.

Keyword- Maximum credible earthquake, Peak ground acceleration, Spectral acceleration, Seismic hazard, Seismotectonic activity.

I. INTRODUCTION

Earthquakes are one of the most destructive natural hazards of the world, causing massive damage to structures and lead to the total devastation of cities. Since last few years the seismic activity in India has gone up as Indian plate is driven into the Eurasian plate at a rate of approximately 45 mm/year (Roger Bilham, 2004) making about 59% of the country's land area as vulnerable to earthquake (BMTPC) [1]. The damages caused by recent earthquakes in India have been a wakeup call for people to take proper mitigation measures. Past activities, shows a time was there when Latur region in Maharastra was mapped as a seismically quiet region but it later proved to be wrong. A massive earthquake in September 1993 of magnitude 5.5 to 6 killed as many as 10,000 people in this region. Similarly a lower magnitude earthquake of Mw=5 in Kerala has been reported as damaging (Erattapeta earthquake of 12th Dec, 2000). After the Bhuj earthquake (2001), Indian standard IS: 1893 was revised and seismic zoning of many cities was upgraded. Study area Bhubaneswar is the state capital of Odisha, one of the major cities of India with heavy population density. The city is supposed to have had over one thousand temples earning the tag of the Temple City of India delighting archaeologists, historians and tourist. After the fifth revision of the Indian standard code (IS 1893:2002) the seismic zoning of the city has been upgraded from zone II to zone III (moderate risk zone), where the maximum expected magnitude is 6.9. The historical record shows Bhubaneswar has not experienced any damaging earthquake till date but the city may be affected due to some great events in surrounding regions. In order to evaluate the seismic hazard parameters seismic hazard assessment of a particular area should be conducted which represent the quantitative estimation of ground acceleration or spectral acceleration. Seismic hazard can be analyzed deterministically taking a particular earthquake scenario (MCE) or probabilistically considering uncertainties in earthquake size, location and occurrence time, etc. It is required to identify all possible sources of seismic activity and their potential for generating future strong ground motion or spectral acceleration for evaluation of seismic hazard over a particular site. For a developing city like Bhubaneswar the steps towards seismic hazard evaluation are very essential to estimate an optimum and reliable value of spectral acceleration during a specific time period which will be an input for assessment of seismic vulnerability of the same area. Using this seismic hazard assessment outcome new construction works and retrofitting works of existing structures can also be carried out.

In the present study hazard assessment has been carried out to assess the seismic hazard of Bhubaneswar, by a deterministic approach to generate a maximum credible earthquake (MCE) and acceleration time history plot for the study region considering the regional seismotectonic activity within 400 km radius around the city center.

II. STUDY AREA AND REGIONAL BACKGROUND

Bhubaneswar city (Fig. 1) is the capital state of Odisha in India and coming under district Khurda. The city covers an area of 419 square kilometers and is at an average altitude of around 45m above mean sea level. Geographically it lies between 20°12'0"N to 20°23'0"N latitude and 85°44'0"E to 85° 54'0"E longitude on the western fringe of coastal plain across the main axis of the Eastern Ghats. As per 2011 census report of India the city had a total population of 837,737 and divided into 60 numbers of wards coming under BMC [2] has been listed among the top ten emerging cities in India by Cushman and Wakefield with respect to factors like physical, social demographics, and real-estate infrastructure etc. The city is primarily an administrative and a tourism city and was designed to be a largely residential city with outlying industrial areas. From the seismic point of view, it comes under zone III (IS-1893:2002) [3], which is a moderate risk zone.

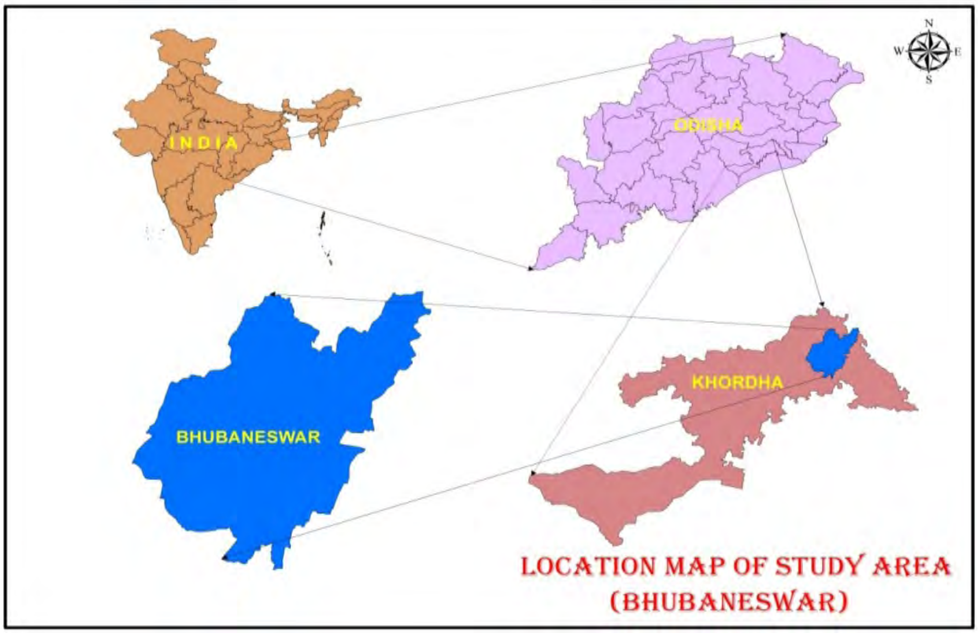

Fig. 1. Location Map of the Study Area

A. Geology of Study Area

The study area belongs to the old Gondwana landmass of India with an average elevation of 45meters above the sea and mostly covered with laterite soil. Topographically the city is divided into two major parts namely western upland and eastern lowland. As per a study in the early part of the nineties on geology of Bhubaneswar about 65% of the land consists of the lateritised peneplain, 25% of alluvial plains and only 10% of the land is composed of sandstone ridges. The height of the lateritic peneplain varies from 20m to 60m above mean sea level. The average slope of the land is between 1:60 to 1:20 and alluvial plain is below 20m-ground contour. The geology of the city and its surrounding has an influence over the construction of houses. Most of the old building foundations and walls were built using laterite blocks extracted from the city land till the middle part of nineties until laterite block extraction was prohibited.

III. EARTHQUAKE CATALOGUE AND SEISMICITY

Seismic susceptibility of the area can be assessed with the help of the regional seismicity data on the occurrence of past earthquakes and the seismotectonic details that presents the tectonic features around the area. As per Indian seismicity the study area is coming under a relatively low frequency of moderate earthquakes. A comprehensive earthquake catalogue (Technical report of WCE constituted by the National Disaster Management Authority Govt. of India, New Delhi) [4] was compiled from various national and international agencies like IMD, GSI, NGRI, CWPRS, ISR, IITR, and ONGC, which provides details regarding time of earthquake in the year, month, and day format for India and its surrounding. Also the catalogue tabulated the earthquake location in latitude and longitude coordinates, focal depth in km and earthquake magnitude in terms of moment magnitude M_w. This catalogue covers the period from 2474 BC to 31st December 2008 with a total of 38860 events. From 2008 to till date the other earthquake events are obtained from Indian Meteorological Department Report. The historic earthquake shows that a moderate earthquake of moment magnitude 4 to 4.9 occurred many times in the study area.

The magnitude scales of earthquake events in the catalogue may not be uniform. Most of the historic events were in the Intensity *(I)* scale and instrumental data were reported in body wave magnitude (m_b), surface wave magnitude *(M_S)*, local magnitude *(M_L)* or moment magnitude *(M_W)*.The moment magnitude scale is the most widely used as the moment magnitude scale does not saturate. Lots of empirical relations are available to convert different magnitude scales to M_W. Several relations were proposed by different researchers to convert different magnitude scales to M_W (Gutenberg and Richter 1956 [5]; Heaton *et al.* 1986 [6]; Engdahl *et al.* 1998 [7]; Shedlock 2000 [8]; Papazachos *et al.* 2001 [9] ; Scordilis 2006 [10]). In estimating the earthquake hazard, generally, a Poisson model of earthquake occurrence is assumed. The instrumental catalogues involve a lot of aftershocks and foreshocks along with the mainshocks. Aftershocks and foreshocks show a major deviation from a Poisson process and several methods have been suggested for the separation of aftershocks from the raw earthquake data (Gardner and Knopoff 1974 [11]; Reasenberg 1985 [12]; Davis and Frohlich 1991 [13]; Molchan and Dmitrieva 1992 [14]). Deleting aftershocks and other dependent events leads approximately to a Poisson, or random dataset for a better estimation of return periods of randomly occurring events which is an important goal of seismic hazard studies. Declustering is the separation of the dependent events (i.e., foreshocks, aftershocks and clusters) from the background seismicity (Reasenberg 1985 [12]). In the present study, dependent shocks as those falls within the space and time intervals of the main shock are eliminated to obtain a dataset of main shocks which are assumed to show a Poisson distribution. Declustering of the catalogue in estimating the earthquake hazard, generally, a Poisson model of earthquake occurrence is assumed. In the present study, dependent shocks as those falls within the space and time intervals of the main shock are eliminated to obtain a dataset of mainshocks which are assumed to show a Poisson distribution. The declustering was done by an algorithm developed by Gardner and Knopoff (1974) [11], Uhrhammer (1986) and Gruenthal [15]. After declustering out of total 80 events only one event is excluded. The distribution of earthquake events in the declustered catalogue is shown in Fig. 2. The details of major earthquakes in the region are listed in table 1.

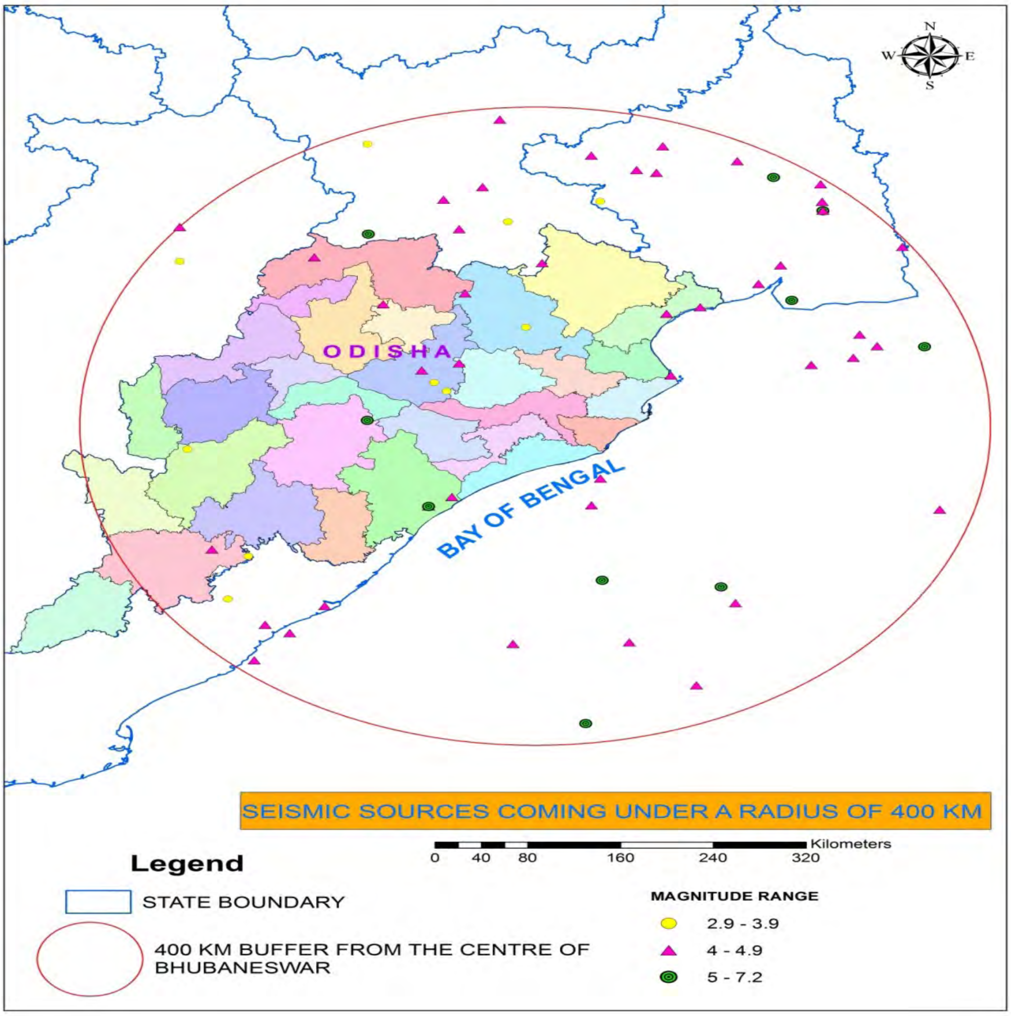

Fig. 2. Distribution of earthquake events (after declustering) within 400km from Bhubaneswar Centre

TABLE I
List of Historic Earthquakes in and Around the Study Area

Year	Longitude	Latitude	Month	Date	Mw	Depth	Hrs.	Mints
1737	88.4	22.6	10	11	7.2	0	0	0
1762	88.4	22.6	7	13	4.3	0	0	0
1808	88.4	22.6	4	13	4.3	0	0	0
1811	88.4	22.6	2	1	4.5	0	0	0
1822	88.4	22.6	8	16	4.5	0	0	0
1823	88.4	22.6	4	3	4.3	0	0	0
1827	83.4	17.7	1	6	4.3	0	0	0
1827	88.4	22.6	1	16	4.5	0	0	0
1829	88.4	22.6	9	18	4.5	0	0	0
1836	88.4	22.9	1	24	4.3	0	0	0
1837	85.1	19.5	6	15	4.3	0	0	0
1845	88.4	22.7	7	24	4.3	0	4	30
1845	88.4	22.7	8	6	4.9	0	23	30
1847	88.4	22.6	5	5	4.7	0	17	0
1848	88.4	22.6	2	20	4.2	0	17	0
1848	88.4	22.6	11	30	4.3	0	0	2
1850	88.4	22.6	5	7	4.2	0	0	0
1851	88.4	22.6	2	9	5.7	0	0	0
1852	88.4	22.6	2	9	4.3	0	13	55
1858	84	18.3	10	12	4.3	0	0	0
1858	87	21.5	3	16	4.2	0	7	0
1859	83.5	18.1	8	24	4.3	0	0	0
1860	84.9	19.4	2	25	4.3	0	0	0
1861	88.4	22.6	2	16	5	0	0	0
1866	87.8	21.8	1	23	4.7	0	0	0
1869	88.4	22.6	6	9	4.2	0	15	15
1886	87.7	23.2	5	19	4.2	0	0	0
1888	88.4	22.6	12	23	4.2	0	0	0
1891	87	20.8	6	17	4.3	0	0	0
1897	84.9	19.4	6	22	5.5	0	0	0
1911	88	23	12	7	5	0	0	0
1963	84.5	22.5	5	8	5.2	0	14	15
1963	85.5	23	4	9	4.5	0	0	3
1964	88.07	21.6	4	15	5.2	6	16	35
1976	88.62	21.18	6	23	4.9	0	15	38
1978	89.16	19.16	4	23	4.1	0	7	49
1979	85.97	22.12	8	5	4.6	33	1	18
1980	88.19	20.86	1	16	4.4	33	0	54
1981	85.54	17.82	10	9	4.4	0	14	31
1982	86.31	18.51	4	8	5.4	18	2	41

1982	84.42	20.39	10	14	5	0	12	56
1983	85.68	23.76	10	26	4.3	0	1	49
1985	87.29	18.39	7	1	5.3	47	2	23
1986	84.9	20.94	1	18	4.3	33	5	42
1986	84.9	20.94	1	19	4.8	0	5	42
1986	85.22	21.01	1	19	4.3	0	6	52
1986	85.16	22.87	3	17	4.2	33	3	3
1992	86.5	17.8	12	8	4.4	33	23	22
1992	83.2	18.4	5	22	3.9	0	6	30
1992	88	22	6	27	4.1	33	16	58
1993	87	23.1	5	6	4.5	33	9	5
1993	86.83	23.14	5	16	4.9	0	9	5
1995	83.7	18	12	18	4.4	33	11	28
1995	84.6	21.7	3	27	4.4	33	7	52
1995	85.3	21.8	6	21	4.4	33	18	35
1996	87.4	18.2	7	27	4.6	0	8	16
1996	82.89	22.62	2	12	4.2	33	20	39
1997	87.03	17.29	4	10	4.5	0	14	44
1998	85.28	22.53	5	22	4.2	33	23	13
1999	84.53	23.52	5	25	3.9	33	16	16
2000	82.88	22.23	2	27	3.9	33	11	42
2001	83.38	18.88	3	26	3.9	15	18	55
2001	84.03	22.25	6	12	4.6	33	12	41
2003	86.45	23.32	10	20	4.7	33	0	39
2004	86.26	19.36	7	13	4.4	32.1	9	39
2004	86.35	19.66	1	8	4	0	19	57
2005	83.08	18.96	3	14	4	14	17	37
2005	89.16	21.01	11	28	5	10	16	57
2005	87.29	21.56	1	1	4.4	10	12	35
2007	88.55	20.92	1	7	4.1	0	20	50
2007	88.76	21.04	1	7	4	9.4	19	50
2008	89.05	22.15	8	22	4.9	650	18	7
2008	87.07	23.4	2	6	4.2	10	6	9
2009	85.7	22.6	3	26	3.8	10	44	10
2009	86.1	16.9	5	28	7	10	24	44
2011	86.5	22.8	8	9	3.4	5	3	33
2011	85.8	21.4	11	5	3.7	10	2	32
2012	82.9	20.1	6	9	3.9	5	8	14
2012	85	20.8	8	31	3.7	20	3	43
2013	85.1	20.7	2	20	2.9	5	5	15

A. Seismo-tectonic map of study area

Seismic sources involved in the study area were identified from the seismotectonic atlas (SEISAT, 2000) [16], published by the Geological survey of India (GSI). The SEISAT maps are available in A_0 size sheets, each covering an area of $3^{\circ} \times 4^{\circ}$. Required sheets for study area 11 in number, were scanned and Geo-referenced to develop the seismotectonic map by superimposing the earthquake records (Fig. 3). This seismotectonic map includes 125 linear sources along with 79 events. Though the identified sources are linear sources, but many events are not associated with any of the sources. Therefore, all the seismic sources identified were treated as point sources for better result during hazard analysis.

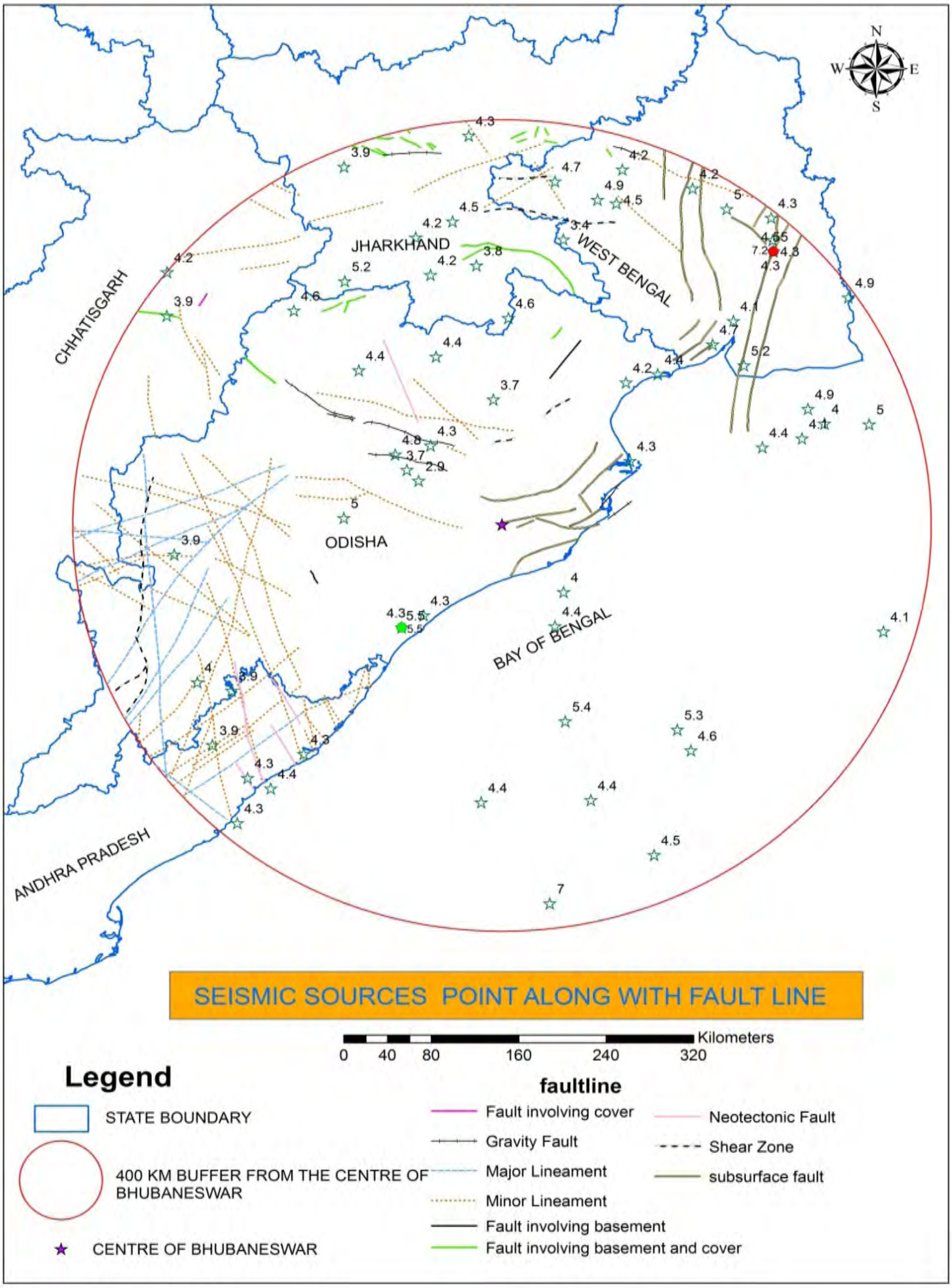

Fig. 3. Seismo-tectonic map of study area

IV. METHODOLOGY FOR SEISMIC HAZARD ASSESSMENT

Earthquakes mainly cause ground shaking that can be devastating for buildings and subsequently the populace. Therefore hazard analysis, aims at the assessment of the ground motion potential of the site based on the identification of all possible sources of seismic activity, estimation of their associated seismicity and prediction of the probable consequent ground motions. These predicted values will be an input for the assessment of seismic vulnerability of an area based on which new construction and the restoration works of existing structures can be carried out. Amongst several peak ground motion attributes (i.e. peak acceleration, peak velocity and peak displacement) peak ground acceleration *(PGA)* is often preferred as the hazard quantifier, which represents a short period ground motion parameter. However, it is well recognized that *PGA* does not uniquely influence damage in manmade structures. Hence designers or engineers prefer the response spectrum as a better description of seismic hazard which is a frequency domain representation of the ground motion. This response spectrum provides an additional advantage of analyzing the behavior of a structure under a postulated earthquake event. Seismic hazard analysis can be carried out either by deterministically or probabilistically. The DSHA involves determination of maximum credible earthquake that produces the severest ground motion. The related strong motion parameters are estimated accordingly without considering probability of its occurrence. While PSHA considers quantitative uncertainties in the size, location, rate of recurrence and effects of earthquakes. Each methodology has specific field of applicability. DSHA is applicable for projects of establishing a seismic framework towards disaster mitigation and management and long-term hazard appraisal, while PSHA is applicable where the nature of decision making is to be based on quantitative information involving uncertainties allowing constraints on investments according to the applicable scheme. As per research objective of the present study the seismic hazard for Bhubaneswar was estimated by conducting deterministic seismic hazard analysis adopting the procedure specified by Reiter (Kramer 1996) [17] and finally providing the spectral acceleration values for different parts of Bhubaneswar.

The DSHA requires three input data like earthquake source, controlling earthquake at the source and an attenuation model for evaluation of seismic hazard. In DSHA the controlling or maximum credible earthquake is assumed to act along the source at the shortest distance from the study area. For avoiding a misleading interpretation of seismic hazard usually the DSHA approach modelled all the sources as point sources and the entire study area is divided into grids of size (approximately 1.0 × 1.0 km) then hazard estimation for each grid point was considered one by one. The source which gives the highest value of peak ground acceleration has the maximum earthquake potential and that *PGA* is considered for the particular grid point. This process is repeated for all grid points using the attenuation model and the corresponding acceleration spectrum has also been prepared.

A. *Attenuation Model*

Besides the source geometry and strength, regional properties also play major role in dictating the seismic hazard at any site. Hence it is a usual practice to utilize several empirical relations known as an attenuation model to estimate the probable ground motions at a site due to all competing potential fault ruptures. The attenuation model (Technical report of WCE constituted by the National Disaster Management Authority Govt. Of India, New Delhi) chosen for the study area is of the form

$$ln\left(\frac{S_a}{g}\right) = C_1 + C_2M + C_3M^2 + C_4r + C_5ln(r + C_6e^{C_7M}) + C_8log(r)f_0 + ln(\varepsilon)$$

$$f_0 = max(ln(r/100), 0)$$

In the above equation (S_a/g) is the ratio of spectral acceleration at bedrock level to acceleration due to gravity. *M* and *r* refer to moment magnitude and hypocentral distance in kilometers respectively. The coefficients of the above equation are obtained from the simulated database by a two-step stratified regression following Joyner and Boore (1981). The coefficients $C_1, C_2 \ldots\ldots C_8$ and the standard error are shown in the table given below as functions of period (1/frequency).

TABLE II
Coefficient as per Time Period

Period	C1	C2	C3	C4	C5	C6	C7	C8	σ(Ɛ)
0	-3.7671	1.2303	-0.0019	-0.0027	-1.4857	0.0385	0.8975	0.1301	0.394
0.01	-3.7649	1.2254	-0.0015	-0.0027	-1.4845	0.0379	0.8992	0.13	0.3926
0.015	-2.6575	1.1024	0.0068	-0.0028	-1.4778	0.0434	0.8804	0.1282	0.4602
0.02	-2.5364	1.1017	0.0064	-0.0028	-1.4555	0.0363	0.9	0.1257	0.4315
0.03	-2.5474	1.1146	0.005	-0.0028	-1.4276	0.0316	0.9131	0.1219	0.3966
0.04	-2.6973	1.1508	0.002	-0.0027	-1.4164	0.0314	0.9112	0.1213	0.3829
0.05	-2.8567	1.183	-0.0003	-0.0026	-1.412	0.0289	0.9212	0.1184	0.3773
0.06	-3.1317	1.2335	-0.0041	-0.0026	-1.3984	0.0274	0.9272	0.1161	0.3752
0.075	-3.5059	1.3089	-0.0101	-0.0026	-1.3831	0.0276	0.9225	0.1149	0.3721
0.09	-3.9446	1.4148	-0.0183	-0.0026	-1.3716	0.0273	0.9209	0.1152	0.3724
0.1	-4.2782	1.4909	-0.0242	-0.0026	-1.3652	288	0.9126	0.114	0.3718
0.15	-5.911	1.8819	-0.0535	-0.0025	-1.3352	0.0336	0.8876	0.1078	0.3753
0.2	-7.5046	2.2741	-0.0829	-0.0024	-1.3075	0.032	0.8878	0.1026	0.3787
0.3	10.4006	3.0324	-0.1384	-0.0023	-1.2968	0.0456	0.8386	0.1006	0.3886
0.4	-12.8011	3.6427	-0.1822	-0.0023	-1.2748	0.0494	0.8251	0.0985	0.3947
0.5	-14.6664	4.1214	-0.2156	-0.0022	-1.2735	0.0601	0.7992	0.0987	0.3979
0.6	-16.5796	4.575	-0.2469	-0.0022	-1.2498	0.0512	0.8157	0.0935	0.4001
0.7	-17.7618	4.8571	-0.2653	-0.0022	-1.2458	0.0539	0.8121	0.094	0.4001
0.75	-18.3078	4.9783	-0.273	-0.0021	-1.2414	0.0523	0.816	0.0933	0.4009
0.8	-18.8559	5.1126	-0.2811	-0.0021	-1.2515	0.0579	0.8068	0.0935	0.399
0.9	-19.9069	5.334	-0.2944	-0.0021	-1.2459	0.0531	0.8172	0.0919	0.3997
1	-20.3915	5.4297	-0.2996	-0.002	-1.2441	0.0512	0.8229	0.0932	0.3987
1.2	-21.5917	5.63	-0.3079	-0.002	-1.2435	0.0498	0.8342	0.0948	0.3931
1.5	-22.5895	5.7652	-0.31	-0.0018	-1.2601	0.0512	0.8393	0.0962	0.389
2	-23.5769	5.8344	-0.3034	-0.0017	-1.2867	0.0584	0.8352	0.1037	0.3877
2.5	-23.9621	5.7445	-0.2875	-0.0017	-1.2917	0.0491	0.8633	0.1067	0.3923
3	-24.0289	5.5676	-0.2637	-0.0016	-1.3173	0.0508	0.8699	0.1131	0.3962
4	-23.7515	5.2307	-0.2245	-0.0015	-1.3626	0.0644	0.8526	0.1198	0.4066

V. RESULTS AND DISCUSSIONS

The seismic hazard analysis of Bhubaneswar was done by dividing the entire area into grids of size 30˝x30˝. The total number of grid points considered in the analysis was 209 (Fig. 4). Using a code written in MATLAB, the peak ground acceleration and spectral acceleration (for periods 0.0 Sec to 4sec) values were calculated at bedrock level for each grid point.

The spectral acceleration contour maps for a period of 0.05sec are presented in Fig. 5. From the contour map it is observed that the seismic hazard is higher towards the north, northeast portion of Bhubaneswar covering ward number1(W-1), W-2, W-3, W-4 as per Bhubaneswar municipal corporation, whereas south,

south-west portion covering W-28, W-29, W-56, W-57, W-58, W-59, W-60 shows a comparatively low hazard. Fig. 6 represents the response spectra for the study area which clearly indicates the predominant period of the earthquake is 0.05sec with a maximum spectral acceleration of 0.0501g. From zero period acceleration *(ZPA)*, it has been found that the maximum expected *PGA* is 0.017g for the maximum credible earthquake of magnitude M_W=7.2, with a hypo-central distance of 373.61Km assuming an average focal depth of 18 Km. As per IS 1893-2002, Indian Seismic macro-zonation map, Bhubaneswar lies in seismic zone-III with the associated *MSK* intensity of VII and expected maximum *PGA* of 0.16g. It means the estimation of seismic force based on Indian seismic code overestimate the seismic demand, however the design will be on the conservative side.

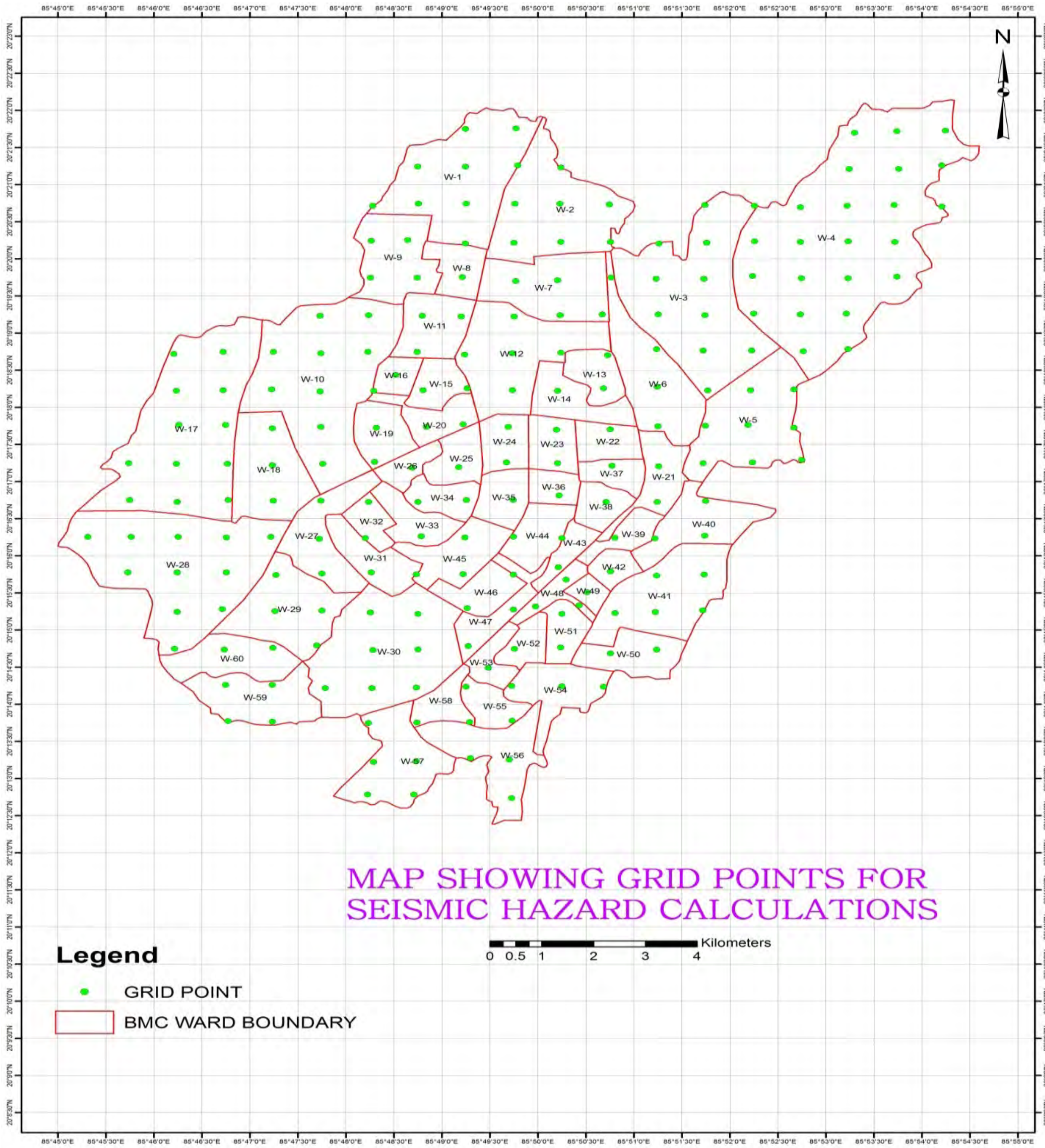

Fig. 4. Map showing grid points and Bhubaneswar ward boundary

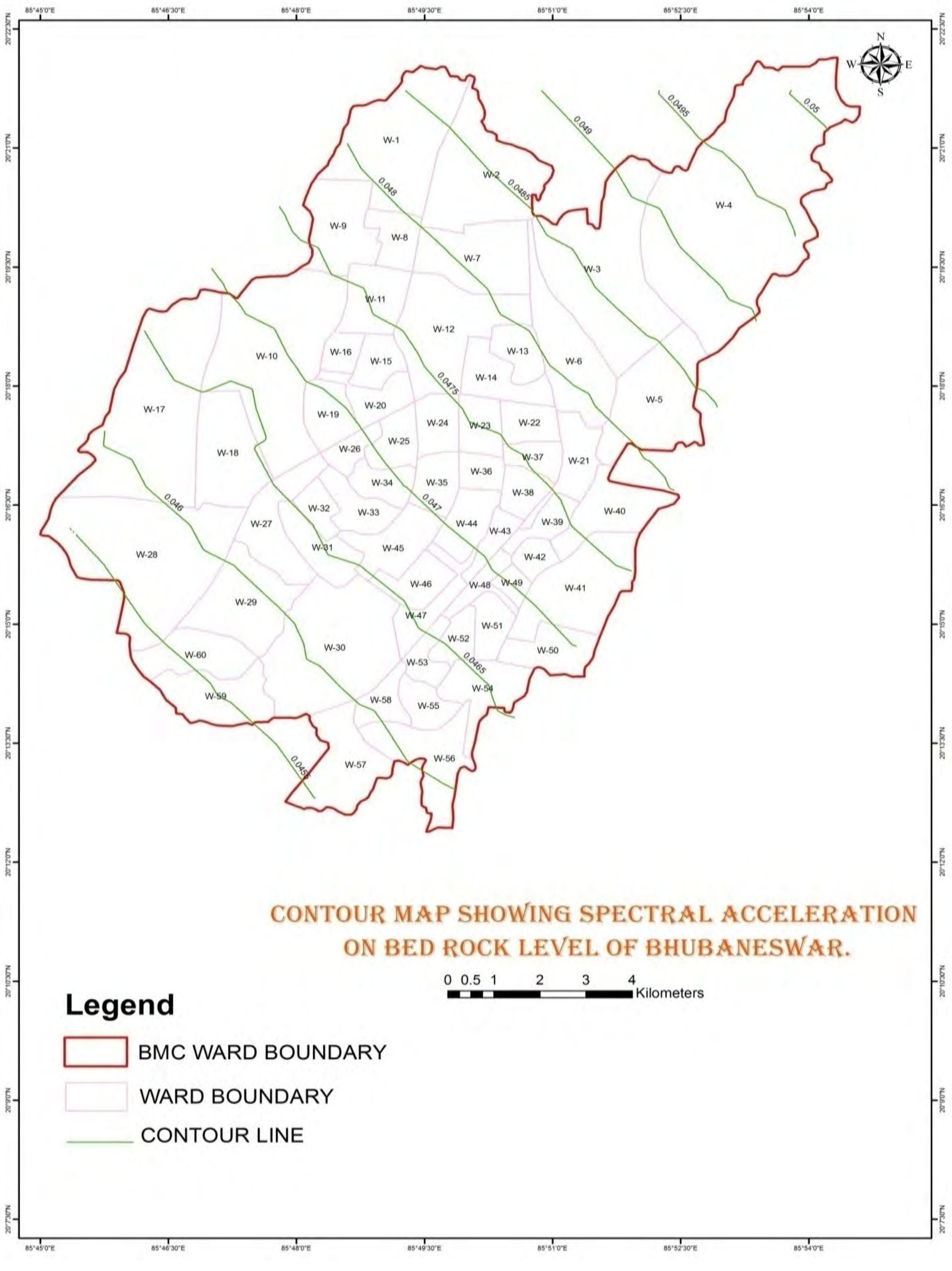

Fig. 5. Contour map showing spectral acceleration on bed rock level of Bhubaneswar for time period of 0.05sec.

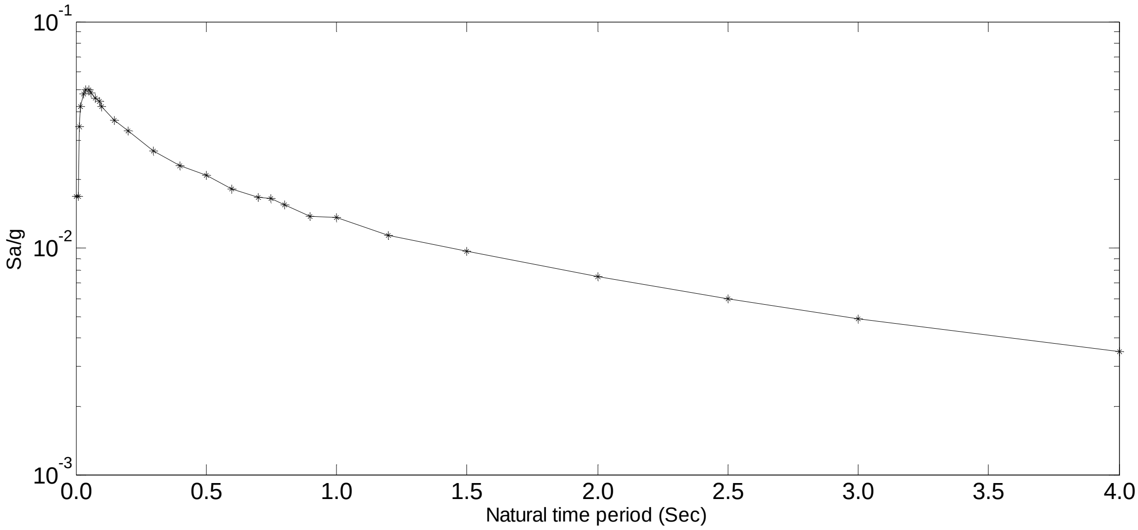

Fig. 6. Response spectra for an earthquake magnitude of 7.2 at rock level

VI. CONCLUSION

In this study a deterministic seismic hazard contour map of Bhubaneswar one of the major city of India with tourist importance, has been prepared in the form of spectral acceleration values considering the regional seismo-tectonic activity within 400 km radius around the city center. Analysis was carried out by dividing the entire area into grids of size 30˝x30˝, with a total of 209 numbers of grid points. Using a code written in MATLAB, the peak ground acceleration and spectral acceleration (for periods 0.0Sec to 4sec) values were calculated at bedrock level for each grid point. It is found that maximum credible earthquake found in terms of moment magnitude is 7.2. From the response spectra, it appears the predominant period of the earthquake is 0.05sec for maximum spectral acceleration of 0.0501g. From zero period acceleration *(ZPA)*, it has been found that the maximum expected *PGA* is 0.017g for the maximum credible earthquake of magnitude M_W=7. 2, with a hypocentral distance of 373.61Km assums an average focal depth of 18 Km. Result from this investigation is comparable to PGA values obtained in deterministic seismic hazard macrozonation of India by Sreevalsa Kolathayar et al. (2012) [18]. But as per IS 1893-2002, Indian Seismic macro-zonation map, Bhubaneswar lies in seismic zone-III with the associated MSK intensity of VII and expected maximum *PGA* of 0.16g which is on the conservative side.

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