

Seismic hazard estimation for Mumbai city

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This article presents an engineering approach to estimate the existing seismic hazard for Mumbai city. After assembling a catalogue of past earthquakes and analysing the database statistically, the recurrence relation for the control region is found out. This is used to compute the probability of ground motion that can be induced by each of the twenty-three known faults that exist around the city. Final results are presented in the form of peak ground acceleration and response spectra, for two different return periods. These results can be directly used by engineers as basic inputs in earthquake-resistant design of structures in and around Mumbai.

Keywords: Design spectrum, ground motion, Mumbai city, seismic hazard, site effects.

MUMBAI (Bombay), the financial capital of India, is a mega city with a population exceeding ten million. The city is located in Peninsular India (PI), which has experienced the devastating Koyna (1967, $M_w = 6.3$), Khillari (1993, $M_w = 6.1$), Jabalpur (1999, $M_w = 5.8$) and Bhuj (2001, $M_w = 7.7$) earthquakes. The hazard in this part of India is considered to be less severe than in the Himalayan plate boundary region. This perception is based on the relative occurrence of past tremors in the various regions. However, intra-plate earthquakes are rarer than plate boundary events but usually tend to be more harmful¹. Paucity of recorded ground motion data introduces uncertainties into the nature of future ground motion and the dynamic forces to be considered in the design of manmade structures. The behaviour of a building, dam or a power plant depends primarily on the local ground motion at the foundation level. A fairly accurate knowledge of such motion, due to all possible sources in the influence zone of about 300 km radius around the construction site, is the most sought after information in engineering practice. The existing Indian code IS-1893 does not provide quantified seismic hazard in the above fashion², but lumps large parts of the country into unstructured regions of equal hazard of doubtful accuracy. In contrast, the international building code IBC-2000, which can be used as a design code anywhere in the world³, requires the hazard to be specified in a more scientific manner, after factoring in all possible future events influencing the construction site on a probabilistic

basis. There are other reasons as to why probabilistic seismic hazard analysis (PSHA) should be adopted in India. Engineering design and construction cannot be viewed in isolation disjointed from socio-economic considerations. Since the economic lifetime of a structure can be envisioned at the planning stage, the uncertain seismic scenario can be tailored to match the expected life of the structure. This way a normal building with a shorter life period of about 100 years may be designed for a shorter return period spectrum, whereas a hospital or a monumental structure which has a longer social life could be designed for a longer return period scenario. Cities such as Mumbai would do well to understand their setting in the local seismo-tectonic province and adopt rational methods to map the prevailing hazard at the city level. Specification of seismic hazard in terms of response spectra valid for different local soil conditions is the information that a structural engineer can use in earthquake-resistant design. The present article develops such spectra specific to Mumbai city. Hazard estimates in the form of 5% damped response spectra are provided for 2 and 10% probability of exceedance in 50 years. These correspond to uniform hazard response spectra of nearly 2500 and 500-year return periods respectively.

Seismic status of the region

Mumbai, which lies along the west coast of India, is in the intra-plate stable continental region of PI. This land mass is far away from the Himalayan collision zone, which is a well-known boundary between the Indian and the Asian plates. Nonetheless, it is recognized that Cambay and Rann of Kutch in Gujarat are among the active regions of PI. The seismicity of PI from a seismological perspective has been discussed in the past, notably by Chandra⁴, and Rao and Rao⁵. Guha and Basu⁶ have compiled a catalogue of PI earthquakes of magnitude ≥ 3 . It is generally held that seismic activity is more at the intersections of the Dharwad, Aravali and Singhbhum proto-continents, which together constitute the PI. With data available up to 1984, Rao and Rao⁵ fitted a frequency–magnitude relationship for PI. They also demonstrated that the interval 1870–1920 had been a period of quiescence, whereas prior to and after this time window PI showed higher levels of seismic activity. Rajendran and Rajendran⁷ have investigated the geological and tectonic settings on the nature of seismicity in PI, with special reference to Khillari and Jabalpur events. They highlight the point that a Khillari-type event may

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occur unexpectedly on discrete faults in regions generally considered aseismic. Although the above studies are useful, there is lack of information on seismicity of PI, in so far as its application in engineering is concerned. For example, till recently there was no region-specific attenuation relationship for PI that engineers could use as being rational enough, for future earthquake events. It may not be out of place to note here that recently, the Code IS-1893 has eliminated the erstwhile low hazard region of PI (zone I) and revised it to a higher hazard status as zone-II. The scientific basis for this revision, if any, remains obscure. The most important historically known event to occur in the region surrounding Mumbai was the 11 December 1967 Koyna earthquake. Koyna is in the Dharwad proto-continent to which Mumbai belongs. According to Chandra⁴, Mumbai is in the Panvel zone, which is seismically active. This zone strikes in the north–northwest direction along the west coast. Its extent is from 16 to 21°N approximately, within which Mumbai is located. A large vertical fault with the same strike is exposed on the western slopes of the Western Ghats in the Belgaum–Vengurla region. Hence a system of N–NW striking faults is surmised to exist below the Deccan Traps in this zone. Nandy⁸ has again identified the N–S trending Panvel flexure as an active fault. He has highlighted the importance of the west coast fault zone running nearly N–S in the Koyna region. There are also a few NW–SE faults cutting across the shoreline and extending into the land mass. There is evidence, according to Wadia⁹, to conclude that the old land surface has subsided by some 10 m along the coast. This would be a signature of recent tectonic activity in the region under consideration. Studies show that there are basically four fault zones surrounding Mumbai¹⁰. These are the Cambay-structure, Narmada–Tapti tectonic zone, Kukdi–Ghod lineament zone and the Sahyadri mountain ranges. It is also observed that parallel to the Panvel fault, a number of short faults exist in the area. Subrahmanyam¹¹ has identified faults along Thane Creek, Panvel Creek and Dharmator Creek in and around Mumbai as being active. He pointed out that the tremor ($M = 3.6$) felt in Mumbai on 31 May 1998, had its epicentre in Panvel Creek.

Fault map

In seismic hazard estimation, the first step is to identify the source zones. Seeber *et al.*¹² (unpublished) have divided PI into nine broad seismic zones based on seismotectonic regimes and geology. According to them, Mumbai lies in the western passive margin. In the present study, since Mumbai city is selected as the target, a control region of radius 300 km around the city with centre at 19°N, 72.8°E is considered for further investigation. The fault map of this circular region prepared from the Seismo-tectonic Atlas of India¹³ is shown in Figure 1, superposed with known epicentres. Since earthquakes occurring at epicentral dis-

tances greater than 300 km do not generally cause structural damage, the current practice is to include only sources lying within this radius from the site in estimating hazard. From Figure 1, it is observed that in recent years seismic activity appears to be concentrated along Warna and Chiplun faults. A total of twenty-three major faults, which influence seismic hazard at Mumbai, can be identified from the above map. Some details of these faults are given in Table 1.

Database

After defining the seismic sources, the next step in seismic hazard estimation is to establish the magnitude–frequency recurrence relation of individual faults. This demands knowledge of slip rate of faults estimated from past data or from state-of-the-art palaeoseismic studies. In the present case, no information is available on slip rate of any of the faults influencing ground vibration at Mumbai. In the absence of these data, one has to heuristically estimate fault recurrence from regional recurrence relation. Thus first a catalogue of past earthquakes in the 300 km control region has to be assembled. There have been several efforts in the past to create an earthquake catalogue for PI. A list of earthquakes of magnitude ≥ 3 in PI, is available in the reports of Chandra⁴, Rao and Rao⁵, Guha and Basu⁶ and USGS (<http://neic.usgs.gov/>). A total of 1274 events have been collected from the above and other sources to prepare a fresh database specific to the region around Mumbai shown in Figure 1. This catalogue covering the period AD 1594–2002, is available in the thesis of the first author¹⁴. It may be mentioned here that aftershocks of the main event of 10 December 1967 at Koyna, have been excluded from

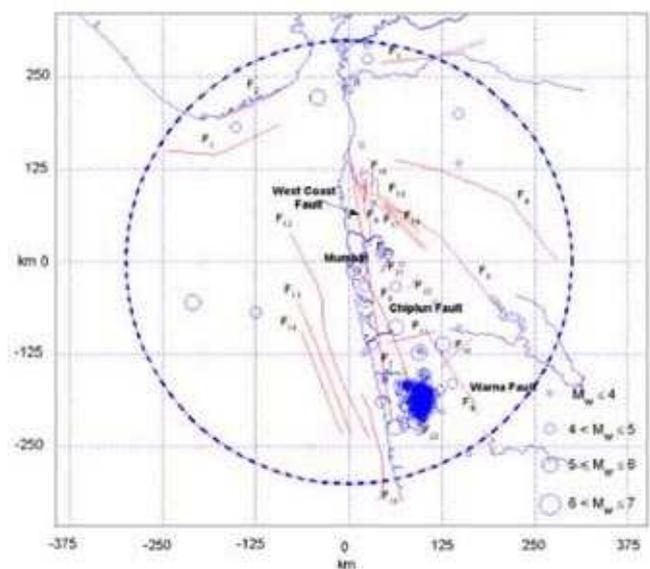


Figure 1. Seismotectonic map of Mumbai region.

Table 1. Fault characteristics

Fault no. (<i>i</i>)	m_u	Length (km)	Shortest hypocentral distance (km)	Weighting factors	
				α_i	χ_i
1	6.0	161	207	0.0518	0.0041
2	5.5	109	248	0.0352	0.0028
3	5.0	72	272	0.0231	0.0042
4	5.0	266	151	0.0856	0.0154
5	5.0	252	93	0.0810	0.0146
6	6.5	93	36	0.0299	0.0044
7	6.5	372	23	0.1195	0.0400
8	6.5	240	16	0.0773	0.0400
9	7.0	127	144	0.0408	0.3557
10	6.0	58	188	0.0182	0.0414
11	6.0	66	121	0.0212	0.0413
12	5.5	297	68	0.0955	0.0076
13	4.5	190	89	0.0612	0.0048
14	4.5	149	114	0.0480	0.0038
15	5.5	125	180	0.0403	0.0032
16	5.5	84	49	0.0269	0.0030
17	5.5	96	34	0.0310	0.0030
18	5.5	94	60	0.0303	0.0030
19	5.0	60	62	0.0193	0.0030
20	4.5	40	45	0.0129	0.0030
21	4.5	25	46	0.0081	0.0030
22	4.5	42	76	0.0135	0.0030
23	7.0	91	157	0.0293	0.3957

this catalogue. Also, whenever the magnitude of an event was not available in the previous reports, the approximate empirical relation $[m = (2/3) I_0 + 1]$ has been used to estimate it from the reported maximum MMI number. To avoid confusion associated with different magnitude scales, all magnitudes have been converted to moment magnitude M_w . Based on the nearness of epicentres to a particular fault, the maximum potential magnitude m_u of each fault has been fixed up as being 0.5 units higher than the magnitude reported in the past. It is observed from Figure 1, that the Koyna–Warna seismic belt strongly influences seismic hazard at Mumbai.

Regional recurrence

Seismic activity of a region is characterized in terms of the Gutenberg–Richter frequency–magnitude recurrence relationship $\log_{10} N = a - bM$, where N stands for the number of earthquakes greater than or equal to a particular magnitude M . Parameters (a , b) characterize the seismicity of the region. The simplest way to obtain (a , b) is through least square regression, but due to the incompleteness of the database, such an approach leads to erroneous results. It is generally known that large damage-causing events are rare but would not have gone unnoticed in past centuries. On the other hand, small events have been catalogued in recent decades owing to modern instrumentation and advances in seismology. Kijko and Sellevoll¹⁵ have proposed a reliable statistical

posed a reliable statistical method to address the issue of incompleteness of earthquake catalogues. They classify the database into two groups, called the extreme part and the complete part. The extreme part consists of a long time period where information on only large historical events is reliably available. The complete part represents the recent decades during which information on both large and small magnitude earthquakes is available. In hazard analysis, one would not be interested in events below a threshold level say, $m_0 = 4$. Again, there will be an upper limit on the potential of a fault, but this may not be precisely known from the catalogue. The above method, suited to engineering requirements, can estimate such doubly truncated Gutenberg–Richter relationship with statistical errors in past magnitude values. In the present study, the 410 years sample of earthquake data around Mumbai, was first evaluated for its degree of completeness, following the method of Stepp¹⁶. The analysis shows, that data are complete, in a statistical sense, in the following fashion: ($3 \leq m < 4$) is complete in 1952–2002; ($4 \leq m < 5$) is complete in 1942–2002; ($5 \leq m < 6$) is complete in 1932–2002; and ($6 \leq m < 7$) is complete in 1902–2002. In Table 2, cumulative number of events computed in the time interval in which the data are complete is reported. Based on the above grouping, the dataset can be divided into a complete part (1964–2002) and an extreme part (1594–1963). Now, following the maximum likelihood method of Kijko and Sellevoll¹⁵, the parameters of the Gutenberg and Richter equation are $a = 0.77 \pm 0.04$ and $b = 0.86 \pm 0.02$. The pooled data and

the curve fit of the recurrence relation are shown in Figure 2. Previously for PI, Rao and Rao⁵ reported $b = 0.85$, whereas Seeber *et al.*¹² (unpublished) estimated the b -value to be 0.89 for Maharashtra State. These values compare well with the present value of 0.86 for the control region around Mumbai.

Deaggregation

The recurrence relation derived above is for the entire region and is not specific to any particular fault. Fault-level recurrence is necessary to discriminate nearby sources from far-off sources and to differentiate activity rate among faults. Such fault-level recurrence relation is rarely known due to paucity of large-scale data accruing in historical times. An alternative is to empirically fix the b -value by measuring the slip rate of a fault. For the faults under consideration, no slip values are available. Moreover, PI earthquakes are associated with poor surface expressions of faults and hence reliable estimation of slip rates has not been yet possible¹⁷. Hence, one has to proceed on a heuristic basis invoking the principle of conservation of seismic activity. According to this, the regional seismicity measured in terms of the number of earthquakes per year with $m \geq m_0$, should be equal to the sum of such events occurring on individual faults. This amounts to $N(m_0) = \sum N_i(m_0)$ ($i = 1, 2, \dots, 23$), which is a fact. However, in finding $N_i(m_0)$ some assumptions are necessary. First, it is

argued that a longer fault can produce more number of small events of magnitude m_0 than a shorter fault. Hence, $N_i(m_0)$ may be taken as being proportional to the length of the fault, leading to a simple weight factor $\alpha_i = L_i/\sum L_i$. On the other hand, one may also argue that future activity will continue, at least in the short run, similar to past activity. Hence, irrespective of its length, seismic activity of a fault should be related to the number of past events associated with it in the catalogue. This way, one can arrive at another weight factor χ_i as the ratio of the past events associated with fault i to the total number of events in the region. Here, the average of α_i and χ_i is taken as the final weight to get

$$N_i(m_0) = 0.5(\alpha_i + \chi_i)N(m_0). \quad (1)$$

The above weight factors are included in Table 1. Since the control region is in a seismically homogenous region, it would be appropriate to use the regional b -value for individual faults also. This gives

$$N_i(m) = N_i(m_0) \left[1 - \frac{1 - e^{-\beta(m-m_0)}}{1 - e^{-\beta(m_u-m_0)}} \right], \quad (2)$$

where m_u is the maximum potential magnitude of the i th fault and $\beta = 2.303b$. The above arguments provide a basis for decomposing the regional hazard into fault-level recurrence relations. This final recurrence result is shown in Figure 3.

Table 2. Activity rate and completeness

Magnitude m	No. of events per year $\geq m$	Complete in interval (year)
3	15.481	50
4	0.792	60
5	0.125	70
6	0.013	100

Attenuation of strong motion

In engineering applications, the peak ground acceleration (PGA or zero period acceleration) and the response spectrum are needed at the site. These quantities depend primarily on the magnitude of the event and the distance of the site to the source. Thus, attenuation of spectral accel-

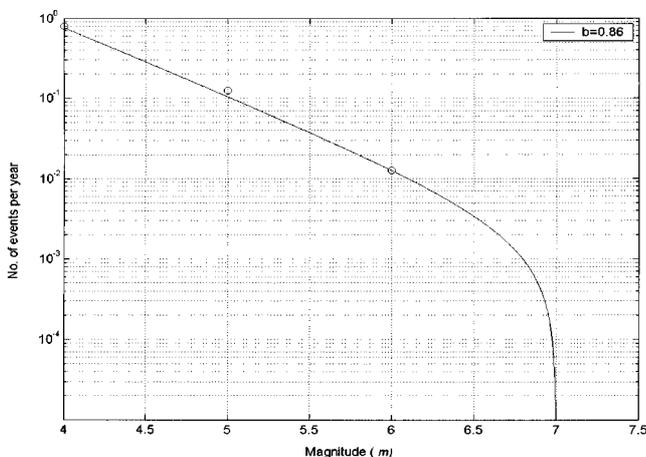


Figure 2. Regional magnitude–frequency relationship.

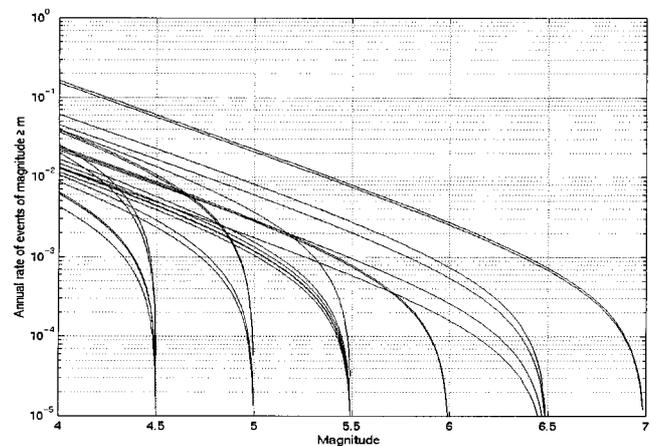


Figure 3. Fault-level recurrence relation.

eration as a function of magnitude and hypocentral distance is a key element in further seismic hazard analysis. Previously, the present authors^{18,19} have studied attenuation of PGA and S_a in PI from considerations of engineering seismology. The form of the attenuation equation proposed for bedrock (br) condition is

$$\ln(y_{br}) = c_1 + c_2(m - 6) + c_3(m - 6)^2 - c_4r - \ln r + \ln \epsilon_{br}. \tag{3}$$

This form is similar to the one used in other stable continental regions of the world. In this equation, y_{br} stands for the spectral acceleration (S_a/g); m and r refer to moment magnitude and hypocentral distance respectively. The coefficients in the equation have been obtained from extensive seismological modelling and simulation exercise. Here only results relevant to the present study are reported in Table 3. This relation is valid for bedrock sites with a shear wave velocity of 3.6 km/s. It is known that the surface-level spectral acceleration values can be different from bedrock values, depending on local soil conditions. To account for this effect, the average shear wave velocity in the top 30 m of a site (V_{30}) is universally adopted as the classifying parameter. This site classification according to NEHRP-USA (BSSC)²⁰ is shown in Table 4. Results of eq. (3) are modified for local site condition further as,

Table 3. Coefficients of attenuation eq. (3)

Period (s)	c_1	c_2	c_3	c_4	$\sigma(\ln \epsilon_{br})$
0.000	1.6858	0.9241	-0.0760	0.0057	0.4648
0.010	1.7510	0.9203	-0.0748	0.0056	0.4636
0.015	1.8602	0.9184	-0.0666	0.0053	0.4230
0.020	2.0999	0.9098	-0.0630	0.0056	0.4758
0.030	2.6310	0.8999	-0.0582	0.0060	0.5189
0.040	2.8084	0.9022	-0.0583	0.0059	0.4567
0.050	2.7800	0.9090	-0.0605	0.0055	0.4130
0.060	2.6986	0.9173	-0.0634	0.0052	0.4201
0.075	2.5703	0.9308	-0.0687	0.0049	0.4305
0.090	2.4565	0.9450	-0.0748	0.0046	0.4572
0.100	2.3890	0.9548	-0.0791	0.0044	0.4503
0.150	2.1200	1.0070	-0.1034	0.0038	0.4268
0.200	1.9192	1.0619	-0.1296	0.0034	0.3932
0.300	1.6138	1.1708	-0.1799	0.0028	0.3984
0.400	1.3720	1.2716	-0.2219	0.0024	0.3894
0.500	1.1638	1.3615	-0.2546	0.0021	0.3817
0.600	0.9770	1.4409	-0.2791	0.0019	0.3744
0.700	0.8061	1.5111	-0.2970	0.0017	0.3676
0.750	0.7254	1.5432	-0.3040	0.0016	0.3645
0.800	0.6476	1.5734	-0.3099	0.0016	0.3616
0.900	0.4996	1.6291	-0.3188	0.0015	0.3568
1.000	0.3604	1.6791	-0.3248	0.0014	0.3531
1.200	0.2904	1.7464	-0.3300	0.0013	0.3748
1.500	-0.2339	1.8695	-0.3290	0.0011	0.3479
2.000	-0.7096	1.9983	-0.3144	0.0011	0.3140
2.500	-1.1064	2.0919	-0.2945	0.0010	0.3222
3.000	-1.4468	2.1632	-0.2737	0.0011	0.3493
4.000	-2.0090	2.2644	-0.2350	0.0011	0.3182

$$y_s = y_{br} F_s \tag{4}$$

and

$$\ln F_s = a_1 y_{br} + a_2 + \ln \delta_s. \tag{5}$$

Here a_1 and a_2 are regression coefficients and δ_s is the error term corresponding to site classification $s = A, B, C, D$. These coefficients along with the standard deviation of the error $\sigma(\ln \delta_s)$ are presented in Table 5. With the help of these correction factors, the average 5% response spectrum can be found for any A, B, C and D-type site in PI, including Mumbai. The variation from the mean is characterized by the standard deviation expressed as

$$\sigma(\ln \epsilon_s) = \sqrt{\sigma(\ln \epsilon_{br})^2 + \sigma(\ln \delta_s)^2}. \tag{6}$$

Probabilistic seismic hazard analysis

Probabilistic seismic hazard analysis (PSHA) estimates the probability of exceedance of spectral acceleration S_a at a site due to all possible future earthquakes as visualized by the previous hazard scenario. The usefulness of PSHA in quantifying safety of man-made structures has been discussed extensively in the literature. PSHA has become a standard tool for estimating design basis ground motion²¹. The procedure for carrying out PSHA has been demonstrated for Delhi city by Iyengar and Ghosh²², and hence will not be repeated here. Assuming that the number of earthquakes occurring on a fault follows a stationary Poisson process, the probability that the control variable Y exceeds level y^* , in a time window of T years is given by

$$P(Y > y^* \text{ in } T \text{ years}) = 1 - \exp(-\mu_{y^*} T). \tag{7}$$

The rate of exceedance, μ_{y^*} is computed from the expression

$$\mu_{y^*} = \sum_{i=1}^K N_i(m_0) \int \int P(Y > y^* | m, r) p_{R|M}(r | m) p_M(m) dr dm. \tag{8}$$

Here K is the number of faults, $p_M(m)$ and $p_{R|M}(r/m)$ are the probability density functions of the magnitude and hypocentral distance respectively. $P(Y > y^* | m, r)$ is the condi-

Table 4. Definition of NEHRP site categories

Site class	Range of V_{30} (km/s)
A	$V_{30} > 1.5$
B	$0.76 < V_{30} \leq 1.5$
C	$0.36 < V_{30} \leq 0.76$
D	$0.18 < V_{30} \leq 0.36$
E, F	$V_{30} \leq 0.18$

Table 5. Site coefficients in eqs (5–6)

Period (s)	$F_A(a_1 = 0)$		$F_B(a_1 = 0)$		F_C			F_D		
	a_2	$\sigma(\ln\delta_s)$	a_2	$\sigma(\ln\delta_s)$	a_1	a_2	$\sigma(\ln\delta_s)$	a_1	a_2	$\sigma(\ln\delta_s)$
0.000	0.36	0.03	0.49	0.08	-0.89	0.66	0.23	-2.61	0.80	0.36
0.010	0.35	0.04	0.43	0.11	-0.89	0.66	0.23	-2.62	0.80	0.37
0.015	0.31	0.06	0.36	0.16	-0.89	0.54	0.23	-2.62	0.69	0.37
0.020	0.26	0.08	0.24	0.09	-0.91	0.32	0.19	-2.61	0.55	0.34
0.030	0.25	0.04	0.18	0.03	-0.94	-0.01	0.21	-2.54	0.42	0.31
0.040	0.31	0.01	0.29	0.01	-0.87	-0.05	0.21	-2.44	0.58	0.31
0.050	0.36	0.01	0.40	0.02	-0.83	0.11	0.18	-2.34	0.65	0.29
0.060	0.39	0.01	0.48	0.02	-0.83	0.27	0.18	-2.78	0.83	0.29
0.075	0.43	0.01	0.56	0.03	-0.81	0.50	0.19	-2.32	0.93	0.19
0.090	0.46	0.01	0.62	0.02	-0.83	0.68	0.18	-2.27	1.04	0.29
0.100	0.47	0.01	0.71	0.01	-0.84	0.79	0.15	-2.25	1.12	0.19
0.150	0.50	0.02	0.74	0.01	-0.93	1.11	0.16	-2.38	1.40	0.28
0.200	0.51	0.02	0.76	0.02	-0.78	1.16	0.18	-2.32	1.57	0.19
0.300	0.53	0.03	0.76	0.02	0.06	1.03	0.13	-1.86	1.51	0.16
0.400	0.52	0.03	0.74	0.01	-0.06	0.99	0.13	-1.28	1.43	0.16
0.500	0.51	0.06	0.72	0.02	-0.17	0.97	0.12	-0.69	1.34	0.21
0.600	0.49	0.01	0.69	0.02	-0.04	0.93	0.12	-0.56	1.32	0.21
0.700	0.49	0.01	0.68	0.02	-0.25	0.88	0.12	-0.42	1.29	0.21
0.750	0.48	0.02	0.66	0.02	0.36	0.86	0.09	-0.36	1.28	0.19
0.800	0.47	0.01	0.63	0.01	-0.34	0.84	0.12	-0.18	1.27	0.21
0.900	0.46	0.01	0.61	0.02	-0.29	0.81	0.12	0.17	1.25	0.21
1.000	0.45	0.02	0.62	0.11	0.24	0.78	0.10	0.53	1.23	0.15
1.200	0.43	0.01	0.57	0.03	-0.11	0.67	0.09	0.77	1.14	0.17
1.500	0.39	0.02	0.51	0.04	-0.10	0.62	0.09	1.13	1.01	0.17
2.000	0.36	0.03	0.44	0.06	-0.13	0.47	0.08	0.61	0.79	0.15
2.500	0.34	0.04	0.40	0.08	-0.15	0.39	0.08	0.37	0.68	0.15
3.000	0.32	0.04	0.38	0.10	-0.17	0.32	0.09	0.13	0.60	0.13
4.000	0.31	0.05	0.36	0.11	-0.19	0.35	0.08	0.12	0.44	0.15

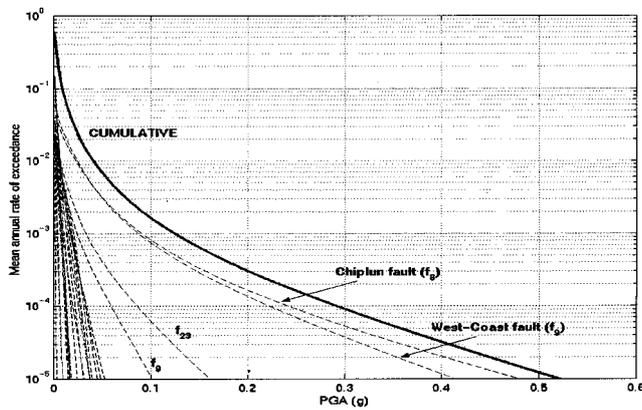


Figure 4. Seismic hazard in Mumbai at bedrock condition.

tional probability of exceedance of the ground motion parameter Y . The reciprocal of the annual probability of exceedance gives the return period for the corresponding ground motion value.

Seismic hazard curves

Seismic hazard curves can be obtained by computing the mean annual rate of exceedance μ_{y^*} , for different specified

ground motion values y^* . These curves are first obtained individually for all the twenty-three faults and combined to estimate the aggregate hazard at the site. The seismic hazard curve for PGA at bedrock obtained by the above procedure is shown in Figure 4 along with individual contributions from the twenty-three faults. It is observed that seismic hazard at Mumbai is mainly controlled by Chiplun and west coast faults. The local soil at a specific site in Mumbai city will be different from bedrock and in fact may vary from A-type to F-type soil. Ideally, with the help of detailed shear-wave velocity profiles, covering all parts of the city, precise estimation of site-specific hazard will be possible. Even in the absence of this, the design response spectrum can be standardized for sites of type A, B, C and D. Seismic hazard curves for PGA computed separately for these sites in Mumbai are shown in Figure 5. It is observed that at shorter return periods, PGA value of C and D-type sites is higher than that of A and B-type sites. On the other hand, for longer return periods, PGA obtained for C and D-type sites is less than the B-type site value. This is attributable to the disposition of faults vis-à-vis Mumbai, the differing probability of large magnitude events on the faults and finally the nonlinear behaviour of C and D-type sites. For E and F-type sites, rigorous nonlinear site response analysis would be needed, with

specific local parameters and is outside the scope of the present study.

Uniform hazard response spectra

Traditionally, PGA has been used to characterize ground motion. However, in recent times, the preferred parameter has been the spectral acceleration (S_a). It may be pointed out that the old practice of scaling a normalized response spectral shape to the design PGA level leads to different probability of exceedance over the frequency range of civil engineering structures. The present approach in engineering practice is to use design response spectra, with equal probability of exceedance over the entire frequency range of interest. Such design spectra are known as uniform hazard response spectra (UHRS). For finding UHRS, seismic hazard curves of S_a are computed for a range of frequency values. From these hazard curves, response spectra for a specified probability of exceedance over the entire frequency range of interest are obtained. Here, UHRS for Mumbai have been derived by performing PSHA on spectral acceleration using the coefficients reported in Tables

3 and 5. As an example, in Figure 6, S_a corresponding to 1 s. natural period, known as the long period seismic coefficient, is shown. It is observed that, at the same risk level, spectral acceleration is high on soft soil sites. The international code IBC³ prescribes design forces based on S_a corresponding to 10 and 2% exceedance probability in 50 years. These correspond to 475 (~ 500) and 2475 (~ 2500) year return periods respectively. In Figure 7 a and b, UHRS for Mumbai corresponding to the above two standard return periods are presented. The corresponding PGA values are also shown.

Discussion

There are no previous engineering studies in the open literature on probabilistic seismic hazard analysis covering PI. The work of Seeber *et al.* (unpublished) appears to be the only one in recent years to have addressed this question. They have reported the b -value to be 0.89 for Maharashtra region. This value is nearly same as that obtained here for

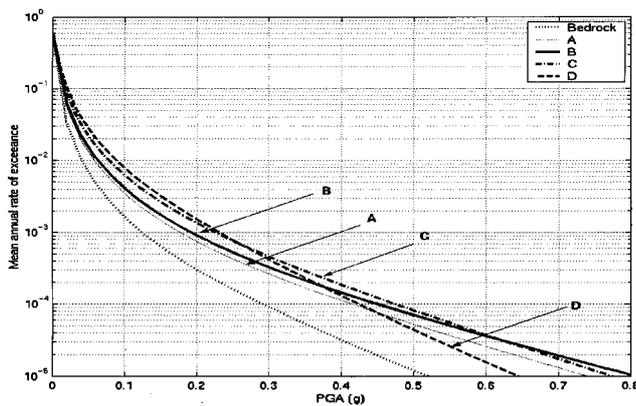


Figure 5. Effect of local site condition on seismic hazard in Mumbai.

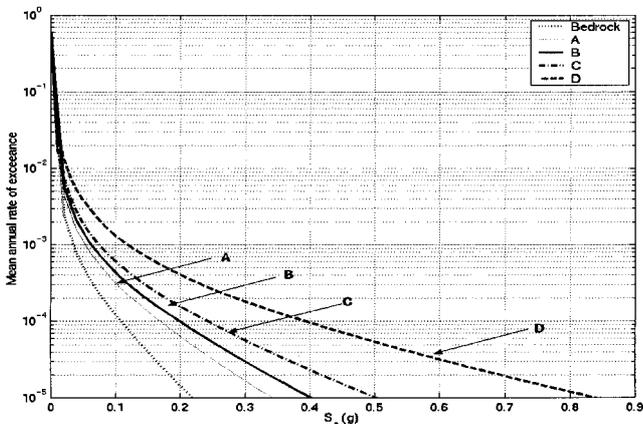


Figure 6. Spectral acceleration at period of 1 s and 5% damping for Mumbai.

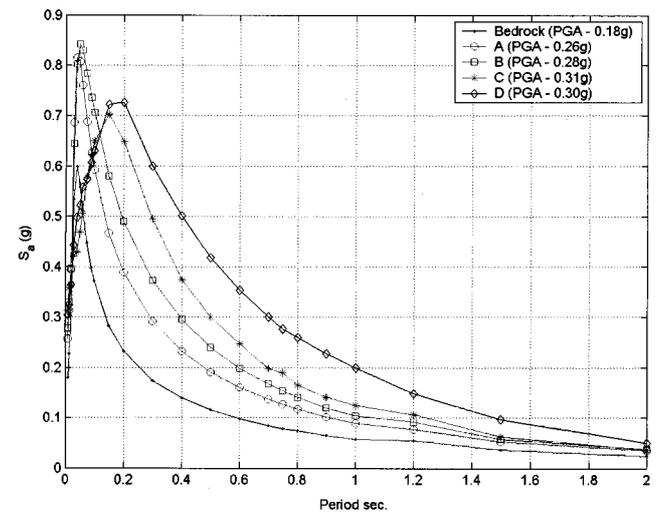
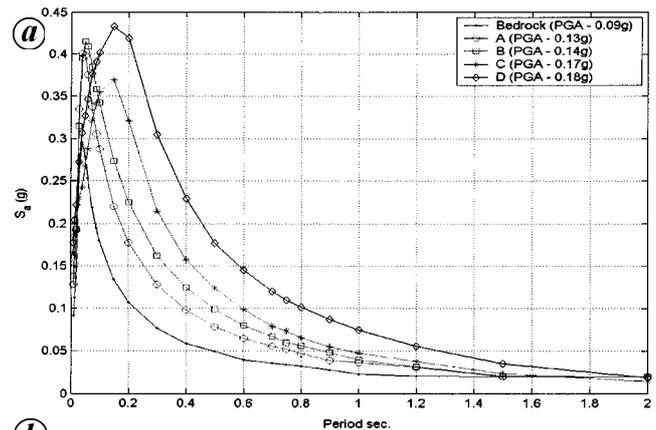


Figure 7. UHRS with (a) 10% probability of exceedance in 50 years (5% damping) and (b) 2% probability of exceedance in 50 years (5% damping) for Mumbai.

Table 6. Hazard estimates for Mumbai

Ground motion parameter	Return period (475 yrs)		Return period (2475 yrs)	
	Seeber <i>et al.</i> B–C type site	Authors B-type site	Seeber <i>et al.</i> B–C type site	Authors B-type site
PGA (g)	0.15	0.14	0.33	0.28
$S_a(g)$, 0.2 s	0.25	0.23	0.55	0.49
$S_a(g)$, 1.0 s	0.06	0.04	0.13	0.10

the control region around Mumbai. Seeber *et al.* have shown some results as applicable to Mumbai in terms of 2 and 10% probability of exceedance in 50 years. They used an aerial source model for past activity and an attenuation relation valid for eastern USA. Their estimation of hazard was for a site between B- and C-type conditions. In Table 6, their results are compared with the present results for B-type site condition. Since these authors used a site condition between B and C-type, their values are slightly higher than the present values obtained for B-type site. It is noted that overall comparison between the two estimates is good. The present analysis indicates that earthquake hazard at Mumbai is controlled predominantly by West Coast and Chiplun faults, which are at about 30 km from the city. In this article, Mumbai city has been represented as a single point. This is not a major limitation in estimating seismic hazard. Previous work on microzonation of Delhi²² shows that surface-level spatial variation of hazard, on a city size region, depends more on local soil conditions rather than on the disposition of seismic sources. Hence at bedrock condition, spatial variation within city limits is expected to be minimal. However, different sites in a city will have different V_{30} values and belong to one of A, B, C and D-types. With this in view, in the present study, design response spectra have been derived for these four types of sites.

Limitations

There are several limitations in the above approach, even though this is among the best possible as of now. First, the past database is of short duration and hence the seismic character of the region would not have been captured accurately. Secondly, even with the available data, inaccuracies arise as one moves from periods of poor (prior to 1950) to better instrumentation. This aspect has been handled here using a statistical method. However, other approaches may lead to slightly different b -values. Rigorous estimation of maximum potential magnitude and fault-recurrence relation requires reliable slip rate values for the faults that are not available. Even palaeoseismological studies are unlikely to give realistic results for the recurrence of earthquakes in PI¹⁷. In the absence of this information, recurrence of events on individual faults has been computed by a simple approach in the present study. Two weights

based on length of the fault and seismic activity, have been computed and the average weight has been used in further analysis. The individual fault recurrence relation has been obtained by multiplying the regional recurrence with its corresponding relative weight. This is under the assumption that the faults are as active as the region itself. Alternative methods based on better seismological reasoning could lead to more realistic results.

Summary and conclusion

The present article investigates seismic hazard at Mumbai city using state-of-the-art probabilistic analysis. Twenty-three faults that can induce ground motion at Mumbai have been identified from the seismo-tectonic map of the region. Since slip rates of individual faults are not available, the recurrence relation of these faults has been estimated from the regional recurrence relation. The attenuation relations developed previously^{14,18} specifically for PI are used for computing spectral acceleration hazard curves. From these results, uniform hazard response spectra have been derived for 2 and 10% probability of exceedance in 50 years. Results obtained here compare well with those reported by Seeber *et al.*¹². The design spectra developed here incorporate uncertainties in location, magnitude and recurrence of earthquakes. Hence, these are superior to spectra recommended by IS-1893. Influence of local site condition has been accounted by providing design spectra for A, B, C and D-type sites separately. The results show that frequency content of the UHRS varies with the local site condition. The present work has been motivated by the needs faced by engineers. Hence in this study Mumbai is represented as a point. This is not a limitation since at bedrock level the hazard does not show strong spatial variation on city-scale distances. The results presented here can be directly used to create a microzonation map for Mumbai. However, for this to be credible, detailed shear-wave velocity profiles of the upper layers of the city are to be obtained. A seismic hazard map covering Mumbai and its environs on a finer grid will cater to the needs of city-level disaster management.

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