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Research Article

Seismic Hazard Assessment for Indira Sagar Dam

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Abstract Indira Sagar Project is a multipurpose project in the state of Madhya Pradesh (India). In this study, seismic hazard has been assessed for Indira Sagar Dam site. The probabilistic Seismic Hazard analysis has been used. Effects of all the faults, who can produce earthquake equal to or more than 3.5 Magnitude and those within a radius of 300 Km from the centre of the Concrete Gravity Dam have been considered. The past history of earthquakes indicated that a total 66 earthquakes of magnitude 3.5 or more have been occurred in last 172 years. The maximum magnitude reported within the region of consideration is 6.2 in 1938 in Satpura range. Probabilistic approach used these data for hazard Analysis. Results are presented in the form of peak ground acceleration and seismic hazard curves.
Keywords *Ground motion; Indira Sagar Dam; Peak ground acceleration; PSHA; Seismic hazard*

1. Introduction

Large food grain requirements and shortage of electrical energy, forced India to go for different multipurpose schemes for water reservoirs so that sufficient water may be available for irrigation purpose and surplus water may be used for electrical energy generation. A large number of major dams (multipurpose) were constructed in the past. At that time, consideration for seismic activity was not that sensitive for designing and construction of these dams. In the present study the Indira Sagar Multipurpose Project (22°17'05”N, 76°28'15”E) popularly known as Indira Sagar Dam or Narmada Sagar Dam, site is considered for analysis. This dam is situated in the state of Madhya Pradesh (India) was constructed about 20 years ago. Occurrence of various earthquakes in recent past in the intra-plate region of peninsular India has clearly warned about the safety aspects of structures in the region.

Indira Sagar Dam has been constructed across the River Narmada, near village Punasa in Khandwa District. Indira Sagar Dam site is situated in Central Indian tectonic zone and come under seismic zone III (BIS-1893-2002, Part I). It is surrounded by number of faults; Son Narmada South Fault, Son Narmada North Fault and Tapti North Fault are some of them and many unnamed faults. Indira Sagar Dam is situated within the range of famous 1938 Satpura (epicentre, 21.13^{0}N, 75.75^{0}E) Earthquake of Magnitude 6.2. Also Jabalpur earthquake of magnitude 6.0 on 22 May 1997 (epicenter, 23.07^{0}N, 80.02^{0}E) centered about 300 km North-East side of the dam site; depth of focus is at 33 km. The Dam site is located in Peninsular India (PI), which has experienced the devastating

Koyna (1967, Mw = 6.3), Killari (1993, Mw = 6.1), Jabalpur (1997, Mw=6.0) and Bhuj (2001, Mw = 7.7) earthquakes. The hazard in this part of India is considered to be less severe than in the Himalayan plate boundary region. However, intra-plate earthquakes are rarer than plate boundary events but usually tend to be more harmful.

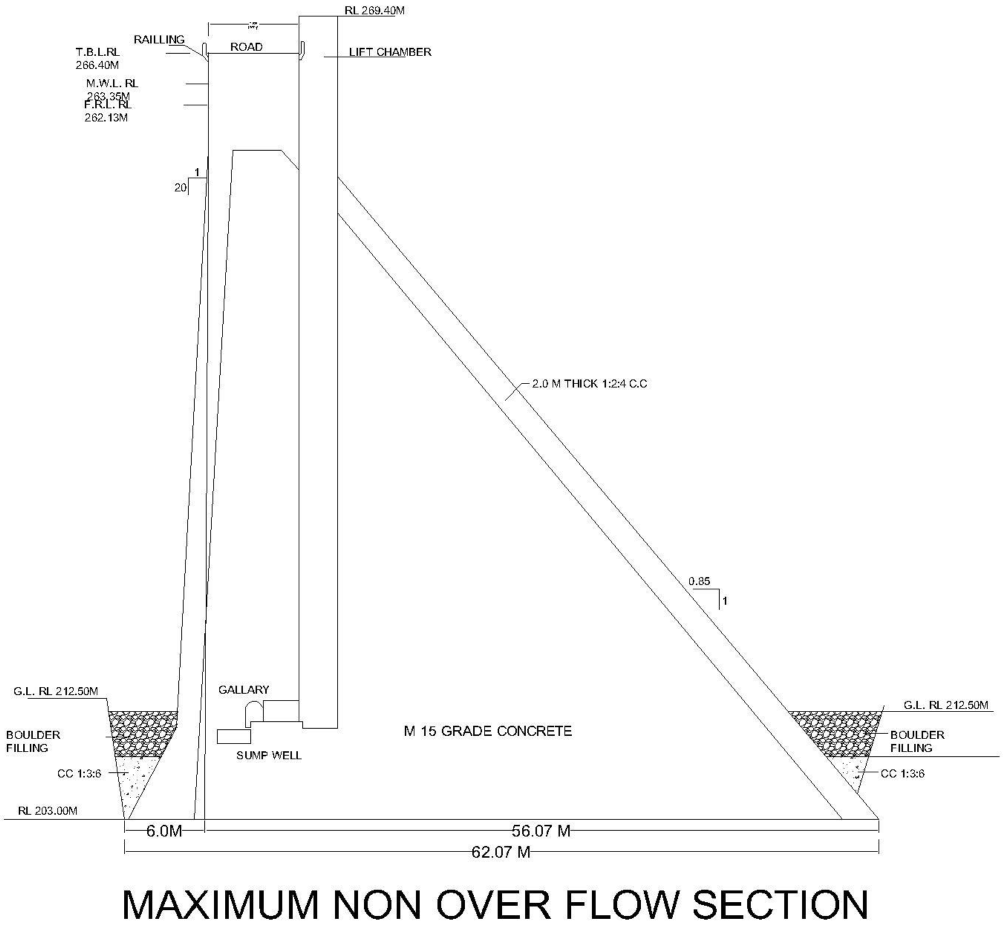

Figure 1: *Cross section of Indira Sagar Dam from DPR*

It is well established fact that past historical data plays very important role for any seismic hazard study. Age of earth is approximately 800 billion years. Seismic activities were there since very long period. As compared to this the available data for seismic activity is very small. Still earthquake engineers are trying to estimate the seismic hazard with these small numbers of recorded ground motion data. Ground motion introduces uncertainties into the nature of future and the dynamic forces to be considered in the design of dam structures. The response of any civil engineering structure depends primarily on the local ground motion at the foundation level. Accurate knowledge of such motion, due to all possible sources in the influence zone is the most sought information in engineering practice. The existing Indian code IS-1893 does not provide quantified seismic hazard, but lumps large parts of the India into unstructured regions of equal hazard of doubtful accuracy. There are other reasons also as to why probabilistic seismic hazard analysis (PSHA) should be adopted in India. 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 dam structure which has a longer social life could be designed for a longer return period scenario. In this work probabilistic seismic hazard has been estimated for Indira Sagar dam.

Indira Sagar dam is 654 meter long and 91.4 meter high (above deepest foundation level) concrete gravity dam with gross storage of 12200 MCM and a live storage of 9750 MCM corresponding to an FRL of +262.13 meter. There will also be a small saddle dam on the right side of reservoir. Central spillway, 495 meter long, to pass a design flood (SPF) of 83534 cumecs and PMF of 1.15Lakh cumecs through 20 numbers of radial crest gates of site 20x17 meter. A surface power house on the right bank to house 8 units of 125MW each, with conventional turbines installed. Cross section of Non Over flow section of Indira Sagar dam at deepest foundation level is shown in Figure 1 from Chief Engineer (1982), Detailed Project Report of Indira Sagar Dam.

2. Seismicity of the Region

Considered dam i.e. Indira Sagar Project (22°17'05"N, 76°28'15"E) is situated in Son Narmada Lineament Zone, which is ENE-WSW trending Lineament belongs to Central Indian tectonic zone(CITZ) extends roughly between 20^0N -24^0N latitude and 77^0E -83^0E longitudes (Consists of Son Narmada North Fault, Son Narmada South Fault, Govilgarh Fault, Tapti North Fault, Purna Fault, Kaddam Fault etc. and number of Unnamed Faults.) which is a part of Peninsular India. The major prominent rifts are the Narmada Son Lineament and the Tapti Lineament together called SONATA (Son-Narmada-Tapti Lineament) zone separating the northern and the southern blocks of the shield.

The most significant earthquakes have been Satpura-valley earthquake of 14 March, 1938, which had a magnitude of 6.2. This earthquake was located in Madhya Pradesh's Barwani District (21.13^0N, 75.75^0E) and was felt at many places of Madhya Bharat and Jabalpur Earthquake of magnitude 6.0 on 22 may 1997 (23.07^0N,80.02^0E), both were a deep-seated events, Rajendran et. al. (1998, 1999).

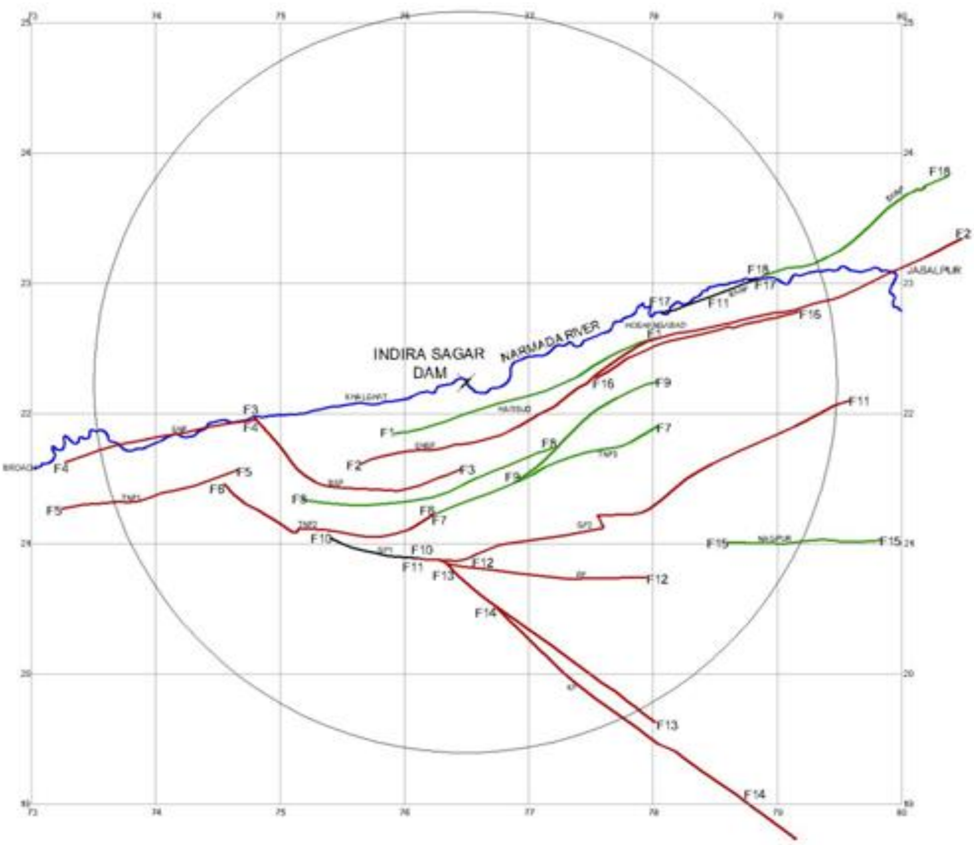

Figure 2: *Fault map for SHA prepared from Seismotectonic Atlas of India for Indira Sagar Dam*

According to Jain et al. (1995 CRUMSONATA) the western part of Son Narmada Tapti lineament (SONATA) zone, starting from Surat to east of Jabalpur, is covered mostly by Deccan basalt lava. The thickness of the lava pile varies in different parts. A huge thickness of 1450 m of basalts is preserved in the Western Ghats and in Satpura area while the Deccan basalts are very thin along the eastern margin of the main exposure. In Amarkantak (Origin of Narmada River), lava pile is about 150m thick. A series of N-S traverses were taken using deep seismic sounding (DSS) across the lineament zone to study the nature of Deccan volcanics, disposition pattern of the flows in the various physiographic segments, their correlation if any, it shows that Near Jabalpur, Narmada river the Lameta-Deeccan basalt is exposed at elevation of 410m msl while south wards lowest exposed flow occurs below 385m msl. This indicates reverse faulting at the Lameta contact.

The Deccan Basalts in the Narmada valleys and the Gondwana sediments in the area cut by numerous dykes trending NW-SE, ENE-WSW to NE-SW. The ENE-WSW trending dykes continuous further to the east of Seoni district (Dyke is a sheet of Rock that formed in a fracture in a pre-existing rock body) North of the Narmada valley, dyke are found only up to the foothills of the Malwa Plateau and its scrap. Here also it is in the area south of the Narmada river course that dykes are very predominant. The river bed is highly fractured and the fractures carry dykes in the vicinity of the Narmada river ENE-WSW trend is more prevalent.

According to Pimpricar S.D. (2009), the increase in the seismicity level during the recent years in the central Indian shield, this keeping in view that the lithospheric environment beneath this zone may be wet, thus accounting for higher rates of magmatic activity. Evidences indicate that CITZ has a major zone of differential crustal movement since Neo-archaean time. As per SEISAT (2000) a series seven number of very small faults on the western side (downstream side) of the Indira Sagar Dam.

There is lack of information on seismicity of PI, in so far as its application in engineering is concerned. For example, till some years back there was no region-specific attenuation relationship for PI that engineers could use as being rational enough, for future earthquake events, then Iyengar and Raghukant (2004) given an attenuation relationship for PI and Jaiswal and Sinha (2008) computed seismic Hazard parameters of PI. It may not be out of place to note here in 2002, 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.

3. Fault Map

Identifications of different faults and their characteristics, around any site, are first and major step for any seismic hazard estimation. In the present study, Indira Sagar Dam has been selected as the target, a control region of radius 300 km around the Dam (22°17'05"N, 76°28'15"E) considered for further investigation. The fault map of this circular region prepared from the Seismo-tectonic Atlas of India (2000). Some researchers i.e. Raghukanth (2006) have taken 300 Km. Radius around the site and some researchers Sitharam (2012) mentioned the range 300 km to 400 km radius centered from site. Hence, 300 km. radius has been considered for this study. It is well established fact that earthquakes occurring at epicentral distances greater than 300 km do not generally cause structural damage. Hence, the faults lying within this radius from the site have been considered in estimating hazard. Fault map seismic hazard analysis is prepared from Seimotectonic atlas of India; GSI (2000) for Indira Sagar Dam is shown in Figure 2. A total of eighteen faults, influence seismic hazard at Indira Sagar Dam, can be identified from the above map. Details of considered faults are given in Table 1.

Table 1: *Details of faults considered*

Fault no.	Name of fault	M_{max} associated	Mu	Length of fault in Km	Shortage epicentral distance in Km	Average weightage factor
F1	-	4.0	4.5	188.6	19.4	0.0501
F2	SNSF	6.5	7.0	531.6	44.5	0.1136
F3	BSF	5.7	6.2	174.0	67.8	0.0578
F4	SNF	5.5	6.0	178.1	159.5	0.0545
F5	TNF-1	4.0	5.5	146.4	204.1	0.044
F6	TNF-2	4.0	4.5	165.5	107.7	0.0468
F7	TNF-3	4.8	5.3	261.4	86.6	0.0633
F8	-	4.0	4.5	138.8	71.8	0.0428
F9	-	4.5	5.0	139.4	86.0	0.0459
F10	GGF(SubS)	6.2	6.7	72.5	144.1	0.0461
F11	GGF	6.2	4.5	318.0	129.5	0.0813
F12	Purna F	4.0	4.5	112.0	146.7	0.0392
F13	-	4.0	6.7	170.6	206.0	0.0475
F14	Kaddam F	4.0	4.5	352.0	185.0	0.0486
F15	Nagpur	5.6	6.1	118.0	256.3	0.0492
F16	-	5.2	5.7	185.3	101.8	0.0565
F17	SNNF(sub)	4.0	4.5	85.8	174.8	0.0353
F18	SNNF	4.7	5.2	352.1	260.7	0.0776

4. Past Earthquake Records

Establishment of magnitude-frequency recurrence relation of individual fault is next step for seismic Hazard estimation. Fault recurrence estimate has been developed from regional recurrence relationship. Hence a catalogue of past earthquakes in the 300 km radial region has been developed. There have been several efforts made in the past to create an earthquake catalogue for India. A list of earthquakes of magnitude 3.5 and above is prepared using catalogue of Oldham, Raghukant (2004), Pimparikar (2009), CGS, USGS, IMD, GSI. Total 66 events from 172 years (1846-2016) are chosen for seismic hazard analysis, 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 Mw.

Some of the major earthquakes reported within 300 km radius of Indira Sagar Project are : 27th May 1846 (23.5^{O}N,79.5^{O}E) of Mw 6.5, near Fault F2, 31st March 1852 (22.1^{O}N,77.5^{O}E) of Magnitude 6, 31st December 1858 (21^{O}N,75^{O}E) of Magnitude 5.5, 18th November 1863 (21.8^{O}N,75.3^{O}E) of magnitude 5.7 Near Barwani Sukta fault, 14th March 1938 (21.13^{O}N,75.75^{O}E) of magnitude 6.2 and 25th August 1957 (22^{O}N,80^{O}E) of magnitude 5.6 Near Govil Garh fault.

Also recent earthquake events are 22nd May 1997 (23.07^{O}N, 80.02^{O}E) of magnitude 6.0 near Jabalpur SNS Fault F2, 18th October 2012 (23.5^{O}N, 79.5^{O}E) of magnitude 5.0 near Son Narmada south fault F2 and series of very small magnitude earthquakes in Khandwa District.

5. Regional Recurrence

In this work regional seismic activity has been characterized by 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 as shown in Figure 3.

In the present study, the 172 (1846-2016) years sample of earthquake data around Indira Sagar Dam site was evaluated and obtained values of a is 1.884 and b value is 0.567 for the region around Indira Sagar Dam.

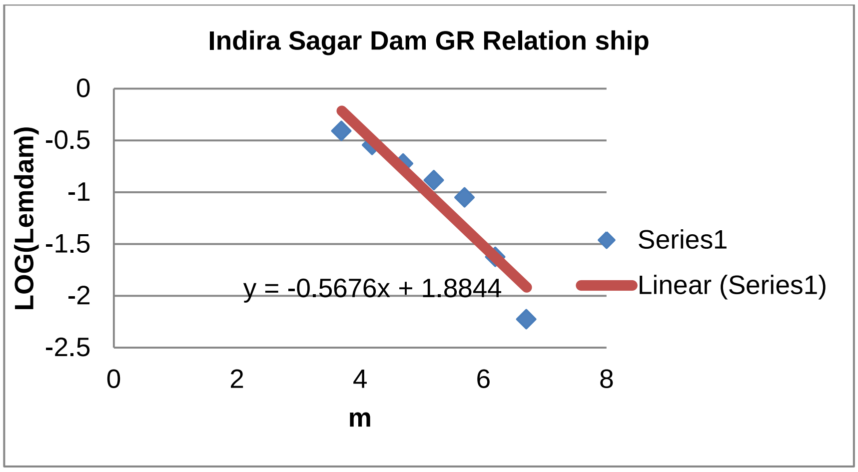

Figure 3: *Gutenberg Richter relationship*

6. Deaggregation

The fault level recurrence is required for differentiating the nearby sources or far off sources from the Indira Sagar Dam site. Fault level recurrence is rarely known due to meager amount of recorded earthquakes, because only recent data is available, old data are of lower magnitude earthquake are not available. The recurrence relation computed above for the 300 km radius region around Indira Sagar Dam is for whole region and is specific to any particular fault. Hence this problem can be tackled using the principle of conservation of seismic activity. According to this the region measured in terms of number of earthquakes per year with $m \geq m_o$, should be equal to the sum of such earthquakes occurring on individual faults. Considering that longer fault can produce more number of small events of magnitude m_o than a shorter fault. Hence, $Ni(m_0)$ may be taken as being proportional to the length of the fault, leading to a simple weight factor $p_i = L_i/\sum L_i$, Where L_i is length of individual ith fault in Kms. It is now well established fact that future activity will continue, at least in the short run, similar to past activity. Hence, seismic activity of a fault should be related to the number of past events associated with it in the catalogue. Hence, one can arrive at another weight factor q_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 pi and qi is taken as the final weight to get

$$N_i\,(m_0) = 0.5(p_i + q_i)\,N\,(m_0) \ldots (1)$$

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 give:

$$Ni(m) = Ni(m_0)\vee\left[\frac{e^{-\beta(m-m_0)} - e^{-\beta(m_u-m_0)}}{1-e^{-\beta(m_u-m_0)}}\right] \ldots (2)$$

Where m_u is the maximum potential magnitude of the ith fault and β= 2.303b and v $=e^{\alpha-\beta mo}$. The above arguments provide a basis for decomposing the regional hazard into fault-level recurrence relations is shown in Figure 4 for Indira Sagar Dam.

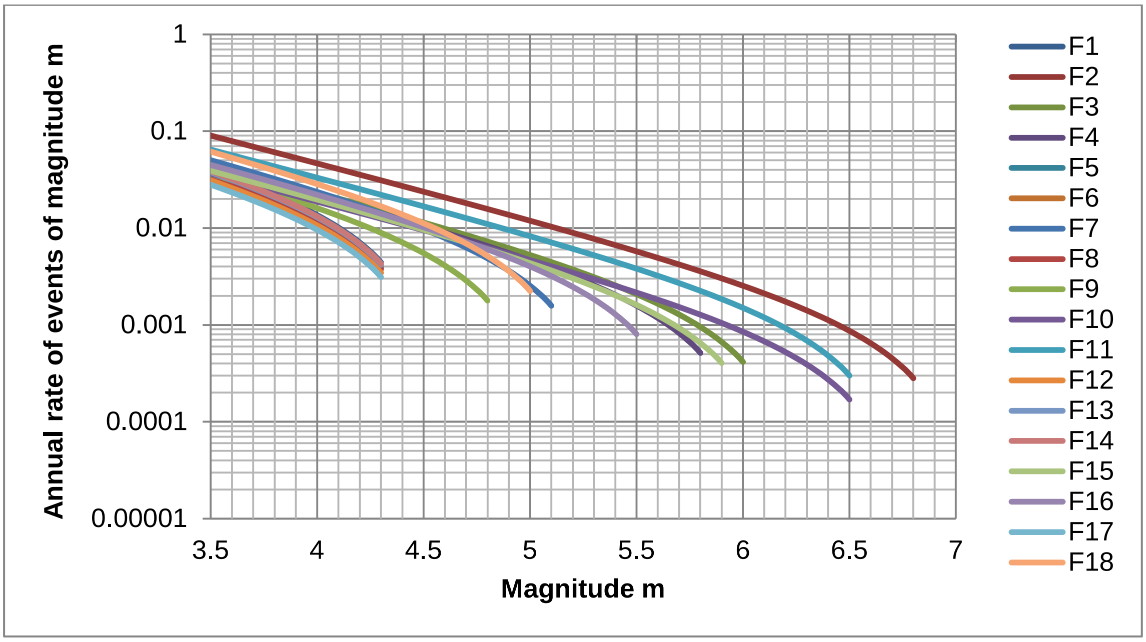

Figure 4: *Fault level recurrence relation*

7. 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 acceleration as a function of magnitude and hypo-central distance is a key element in further seismic hazard analysis. Attenuation relationship developed by Iyenger and Raghukanth (2004, 2007) considered for the analysis and PGA has been calculated. The form of the attenuation equation proposed for bedrock (*br*) condition is:

$$\ln(y_{br}) = C1 + C2(m-6) + C3(m-6)^2 - C4\,r - \ln r + \ln \varepsilon_{br} \ldots \text{(3)}$$

In this equation, y_{br} stands for the spectral acceleration (S_a/g); m and r refers to moment magnitude and hypocentral distance respectively. The coefficients of the above equation taken from Raghukanth and Iyengar (2006). The average of the error term ln(ε_{br}) is zero, but the standard deviation is of importance in probabilistic hazard analysis. This relation is valid for bedrock sites with a shear wave velocity more than 1.5 km/s. The coefficients for zero period were used for the calculation which are C1=1.6858, C2=0.9241, C3=-0.0760, C4=0.0057 and standard deviation of ε_{br}=0.4648. The normal cumulative distribution function has a value which is most efficiently expressed in terms of the standard normal variables (z), which can be computed for any random variables using transformation as given below (Kramer, 1996):

$$z = \frac{lnPHA - lnPHA}{\sigma lnPHA} \ldots \text{(4)}$$

Where, PHA is the various targeted peak acceleration levels, which will be exceeded. ln PHA(bar) the value is calculated using attenuation relationship equation and ln PHA is the uncertainty in the attenuation relation expressed by the standard deviation.

8. 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. In reality, the seismic hazard at a site is influenced by all the earthquakes with different magnitudes and different distances. PSHA considers the contribution of all earthquakes in that region. PSHA also considers the uncertainties associated with time of occurrences of earthquakes and its location. 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 motion. It also provides a framework where these uncertainties can be combined rationally to provide more complete picture of seismic hazard (Kramer, 1996). Following Raghukanth and Iyengar (2006), 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:

$$P(Y > y^* \text{ in T years}) = 1 - \exp(-\mu_{y^*} T) \dots (5)$$

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

$$\mu_y^* = \sum_{j=1}^{Nm} \sum_{k=1}^{Nr} vi\, P(Y > y^*|mj, rk)\, P[M=mj]\, P[R=rk] \quad \dots (6)$$

Here P[M=m] and P[R=r] are the probability density functions of the magnitude and hypocentral distance respectively. P(Y >y*|m, r) is the conditional 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.

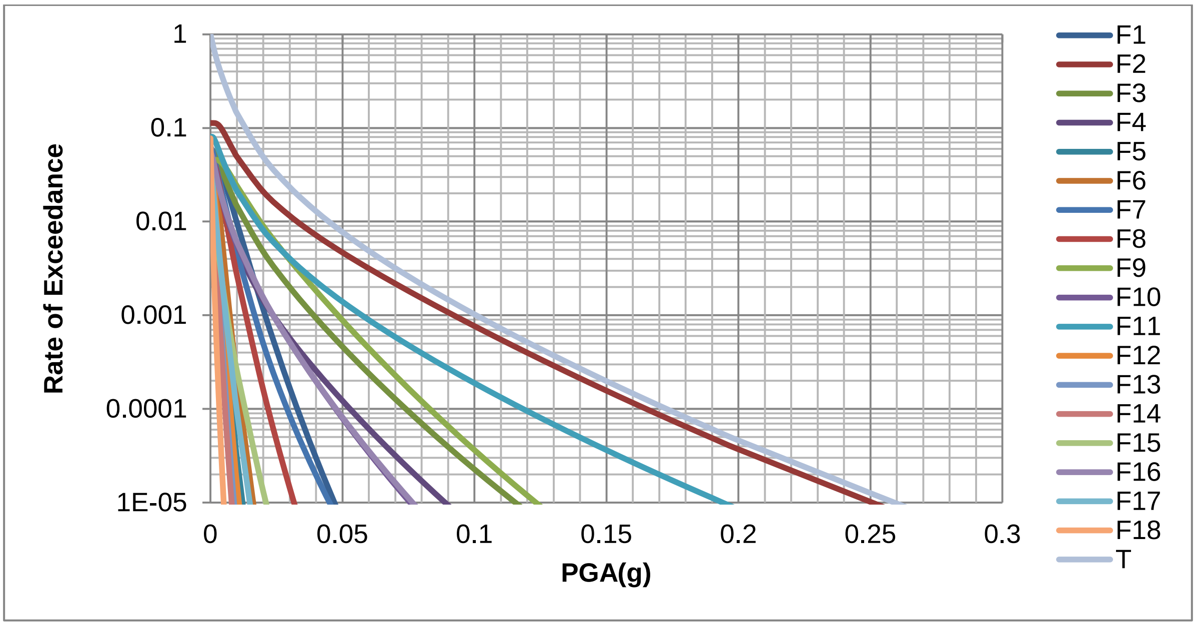

Figure 5: *Seismic hazard curves for Indira Sagar Dam site*

9. 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 obtained individually for all the sixteen capable faults around Dam site and considering the individual effect of all eighteen faults and combined them to estimate the aggregate hazard at the site. The seismic hazard curve for PGA at bed rock (foundation level of Dam) obtained by above procedure is shown in Figure 5 for Indira Sagar Dam Site. It is observed that seismic hazard at Indira Sagar dam is mainly influenced by Fault F2-Son Narmada South Fault, F11-Govilgarh Fault, F3-Barwani-Sukta Fault and F4-Son Narmad Fault.

10. Conclusions

The present article investigates seismic hazard of Indira Sagar Dam near Punasa village of Khandwa District of Madhya Pradesh state of India using state-of-the-art probabilistic analysis. Eighteen faults and Nine Lineaments Identified from Seismotectonic atlas of India and its environ, 2000, considered all the Eighteen Faults that can induce ground motion at Dam site have been identified from the seismo-tectonic map of the region and from old and recorded events of earthquake. 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 specifically for PI are used for computing spectral acceleration hazard curves. Probability that an acceleration of 0.1g would be exceeded in 50 years may be p[YT>y*] = 5.0%. The PGA that has a 10% Probability of exceedance in 50 year period (For return period of 475 years) is 0.12g and the PGA that has a 2% probability of exceedance in 50 year period (For return period of 2475 years) is 0.16g which is within limits of BIS-1893-2002, Part I coefficients for zone III.

The maximum regional magnitude for Indira Sagar Dam is also estimated. With the help of these data we can check the stability of Dam considering seismic activity in area.

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