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A comparative attenuation study of seismic waves in terms of seismic Albedo for Chamoli, Kachchh and Koyna regions of India

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ABSTRACT :*A comparative study of attenuation of seismic waves for Chamoli, Kachchh and Koyna regions of India has been evaluated. For this purpose seismic albedo (B_0) & extinction length (L_e) are computed using Q_α, Q_β & Q_c values for Chamoli, Kachchh and Koyna regions. In order to estimate B_0 and L_e we have used already published attenuation parameters for these regions except Q_c for Chamoli region which is estimated in the present study. As a result we found B_0 > 0.5 for Chamoli while B_0 < 0.5 for Kachchh regions. This represents that scattering attenuation is predominant over intrinsic attenuation for Chamoli while L_e varies from 20 to 66 km. The Chamoli area falls in the interplate seismicity regime and highly heterogeneous in nature. For Kachchh region intrinsic attenuation is predominant over scattering attenuation and L_e varies from 40 to 70 km. Kachchh area falls in intraplate region corresponding to the higher intrinsic attenuation as compared to scattering attenuation. On the other hand in Koyna region for central frequency 1.5 Hz scattering attenuation is dominant over intrinsic attenuation while for frequency range of 3 to 18 Hz only intrinsic attenuation is responsible for the attenuation of seismic waves. The values obtained in the present study are consistent with geology and tectonic set up of three regions. Due to socio-economic importance of these regions the seismic hazard is very much essential for the structural engineering practices. So these values can be used to estimate the seismic hazard of these regions.*

KEYWORDS: *Albedo, extinction length, seismicity, attenuation, intrinsic, scattering.*

I. INTRODUCTION

The frequency-dependent scattering attenuation has been investigated using statistical models of the seismic velocity fluctuation, represented by its spatial autocorrelation function, and characterized usually as exponential, self-similar or Gaussian. Attenuation estimated from direct S waves (Aki, 1980; Rautian and Khalturin, 1978; Taylor et al., 1986) contains the combined effects of scattering and intrinsic loss. Attenuation inferred from the decay rate of the coda (Aki and Chouet, 1975; Rautian and Khalturin, 1978; Singh and Herrmann, 1983; Sato, 1988) is also a combination of scattering and intrinsic attenuation; however, both of these methods are incapable of separating these effects. The relative contributions to the apparent attenuation have been the subject of much interest (Aki, 1980; Frankel and Wennerberg, 1989). This is also evident due to the low Q values in these areas is achieved by so many researchers in these areas (Mandal and Rastogi, 1998; Sharma et al, 2007, 2008 & 2009). There is literature available where the separation of Qi and Qs are done for many regions worldwide (Del Pezzo et al, 2006; Ugalde et al, 2006; Sharma et al, 2008; Woong, 2014).Wu, 1985 gave a method, based on the radiative transfer theory (Ishimaru, 1978), allows an estimation of the relative amounts of scattering and intrinsic attenuation from the dependence of the entire S wave energy on hypocentral distance (Wu and Aki, 1988; Mayeda et al., 1991; Tokstz et al., 1988). Hoshiba et al. (1991) have developed a more reliable method, called to estimate the scattering and intrinsic Q by considering energy for different time windows as a function of hypocentral distance (Fehler et al., 1992). The seismic albedo, B_0 is defined as the relative amount of scattering attenuation to total attenuation and the total attenuation coefficient as Le is the extinction distance over which the primary S wave energy is decreased by e^{-1}. When B_0 >0.5, scattering attenuation is dominant, and when B_0 < 0.5, intrinsic loss is dominant. The shapes of the three energy curves as a function of source-receiver distance are simultaneously fit to Monte Carlo simulations using homogeneously distributed scatterers in a full space with uniform intrinsic attenuation under the assumption of isotropic multiple scattering for various B_0 and Le (Hoshiba et al., 1991).

In the present study the comparative attenuation study is carried out for Chamoli, Kachchh and Koyna regions of India. For this purpose resultant scattering and intrinsic quality factors are computed and then utilised to obtain B_0 and Le for these three Indian regions. For Kachchh & Koyna regions the quality factors of P, S & coda (Q_α, Q_β and Q_c) waves computed by Sharma et al, 2007 & 2008, have been used. For Chamoli the quality factors Q_α and Q_β estimated by Sharma et al, 2009, have been used. Present study also include the estimation of Quality factor (Q_c) using coda waves for Chamoli region using single backscattering model of Aki and Chouet,

1975. Wennerberg (1993) formulations have been used to estimate Q_i (Intinsic quality factor) and Q_s (Scattering quality factor) for Koyna and Chamoli regions while the Q_i and Q_s estimated for Kachchh by Sharma et al, 2008 are used to estimate B_0 and L_e for Kachchh.

II. STUDY REGIONS AND DATA

Three different Indian regions i.e. Chamoli, Kachchh and Koyna have been considered to compare the attenuation characteristics of these regions. This study gives an overview to observe the patterns of attenuation in these three regions which intern makes it an important to assess the seismic hazard in regions. The Chamoli area falls in the foothills of Himalayan Mountains which is comprised with the interplate seismicity in this region. The Himalaya is the product of continent-continent collision between India and Tibet along the Indus-Tsangpo suture (Ni and Barazangi, 1984; Molnar, 1990). The region is characterized by the presence of many tectonic features that includes Main Central Thrust (MCT) and Main Boundary Thrust (MBT). These two thrusts exist through the entire length of the Himalaya. The MBT separates the lesser Himalaya from the sub-Himalaya belt while MCT separates the high Himalaya from the lesser Himalaya. From the analysis of space-time patterns of seismicity of the region, Khattri and Tyagi (1983) and Khattri (1987) established the existence of three seismic gaps in the Himalaya plate boundary. The 1991 Uttarkashi (Mw 6.8) and 1999 Chamoli (Mw 6.5) earthquakes occurred in the central seismic gap of the Himalayan plate boundary. Thus a serious seismic hazard scenario exists in this region.

The Kachchh region exhibits the intraplate seismicity and rift marks the earliest phase of the breakup of the Gondwana supercontinent in the early Jurassic and is the largest Indian intracontinental rift zone situated at the western border of India and few hundred kilometers away from the Indian plate boundary. The rifting process in the Kachchh region ended with the change of stress direction due to rotation of the Indian plate (Biswas, 1987). Geologically, the Kachchh region is characterized by Quaternary/ Tertiary sediments, Deccan volcanic rocks, and Jurassic sandstone overlying an Archean basement (Gupta et al., 2001). The basin formed between Nagar Parkar fault and the North Kathiawar fault, the later being the master fault. There are three uplifts formed along primordial faults of Aravali belt:Island Belt (south of Island Belt fault), Wagad, and Kachchh Mainland (south of Kachchh Mainland fault) with intervening graben sand half grabens (Biswas,1987). Biswas (1987) suggested that a subsurface north–south basement ridge, Median High, crosses the basin. Acting as a hinge, it divides the basin into a deeper western part and a shallower and more tectonized eastern part. The Kachchh rift region is characterized by a high level of seismic hazard. It is inferred to have large compressive stresses due to upward buckling of the region that started after the major continent collision process had almost stopped along the Himalayas 10 m.y.a. (Rastogi, 2004). The Kachchh region has experienced two great earthquakes, one in 1819 (Mw 7.7) and the other in 2001 (Mw 7.7), and some other devastating earthquakes in 1845 (Mw 6)and in 1956 (Mw 6).The potential for a catastrophic earthquake in the Kachchh region is the highest among the stable continental regions of the world. Another fault, named Gedi fault, 60 km northeast of the 2001 mainshock epicenter has become active since 2006. Moreover, in the 2001 epicentral zone, seismicity at an increased level is still occurring with one or two M 5–6 earthquakes every year.

Koyna region on the other hand shows a reservoir induced seismicity which started in the region after the impoundment of the Koyan Dam. In this region, rocks are all Deccan traps. The basement under the traps consists of metasedimentary gneisses, schist, and granite of Dhawarian and Cuddapah age. Crude columnar joints and extensive curved fractures are common to these homogeneous, hard brittle rocks (Krishnan 1960). The Koyna–Warna region of the Indian peninsula is a seismically active region. Seismicity of this zone started after the impoundment of Shivajisagar Lake in 1963 by the construction of the Koyna Dam. The Koyna earthquake sequence is considered as one of the most outstanding example of the reservoir-induced seismicity (Rastogi et al. 1992). Earthquakes of small magnitude are still continuing in the vicinity of Koyna. The seismicity in this region was increased during 1973 when an earthquake of NW trend with NE appear to be more seismically active, and relocated depths are within 12 km of this region (Rastogi and Talwani 1980). The 30-km long NS seismic zone extending southward from the Koyna Dam has been active all the time from 1967 onwards (Rastogi et al. 1997). Talwani (1997) relocated the seismicity between 1963 and 1995 for the Koyna region and concluded that the area lying between Koyna and Warna Rivers can be divided into several seismogenic crustal blocks.Figure 1 shows the tectonic features of three Indian regions Chamoli, Kachchh and Koyna considered for the present study along with the stations, events and major faults in these areas. Attenuation parameters of these three Indian regions have been used to estimate the seismic albedo B_0 and extinction length L_e for these areas. For Chamoli region total 25 earthquakes recorded from 06/04/99 to 14/05/99 (Magnitude range from 1.8 to 4.6) at five stations (Pakhi (PAK), Joshimath (JSM), Okhimath (OKI), Nandprayag (NPG)) and

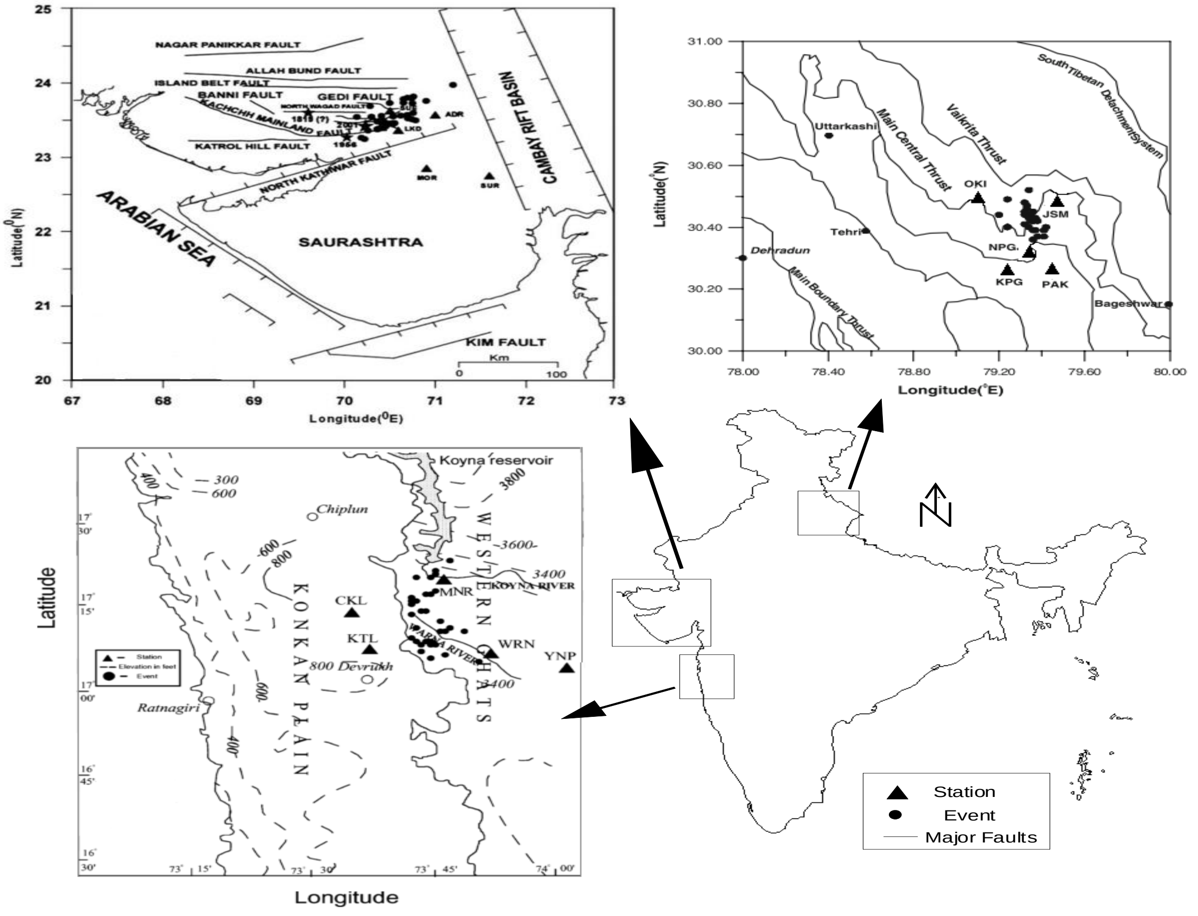

Figure 1: Tectonic features of three Indian regions Chamoli, Kachchh and Koyna considered for the present study along with the stations, events and major faults.

Karanprayag (KPG) have been used to estimate Q_c under present study. Q_α and Q_β for Chamoli region are used from study of Sharma et al, 2009. For Kachchh region the attenuation parameters of three stations (Adesar (ADR), Suvai (SUV) and Lakadia (LKD)) estimated by Sharma et al, 2008 and for Koyna region attenuation parameter of five stations (MNR, CKL, WRN, KTL and YNP) estimated by Sharma et al, 2007 have been used to estimate B_0 and L_e.

III. METHODOLOGY

Quality factor of coda waves for Chamoli region have been estimated using single backscattering model of Aki and Chouet (1975) which is explained by following equation.

$$Ac(f,t) = S(f)t^{-a} exp\frac{(-\pi f t)}{Qc} \tag{1}$$

where *S(f)* represents the source function at frequency *f*, and is considered a constant as it is independent of time and radiation pattern, and therefore, not a function of factors influencing energy loss in the medium; a is the geometrical spreading factor, and taken as 1 for body waves, and Q_c is the apparent quality factor of coda waves representing the attenuation in a medium. The above equation can be rewritten as

$$ln\big(Ac(f,t)\big) = ln\big(S(f)\big) - \frac{(\pi f)}{Qc}t \tag{2}$$

It is a linear equation with the slope - $\frac{(\pi f)}{Qc}$ from which Q_c is estimated.

Wennerberg (1993) provided the formulation based on Zeng et al. (1991) model to estimate Q_i and Q_s. According to Zeng et al. (1991), we can write the observed value of Q_c in terms of Q_i and Q_s as below:

$$\frac{1}{Qc} = \frac{1}{Qi} + \frac{(1-2\delta(\tau))}{Qs} \quad (3)$$

where, $\delta(\tau)$ is $-\frac{1}{(4.44+0.738)}$, $\tau=\frac{\omega t}{Qs}$, ω is the angular frequency and t is the lapse time. Assuming Q_d as the quality factor of direct wave evaluated in the earth volume equivalent to the volume sampled by coda waves, it can be written as (Wennerberg, 1993):

$$\frac{1}{Qs} = \frac{1}{2\delta(\tau)}\left(\frac{1}{Qd} - \frac{1}{Qc(\tau)}\right) \quad (4)$$

$$\frac{1}{Qi} = \frac{1}{2\delta(\tau)}\left(\frac{1}{Qc(\tau)} + \frac{(2\delta(\tau)-1)}{Qd}\right) \quad (5)$$

If Q_c is measured as a function of lapse time t, Q_i and Q_s can be estimated using equations (3), (4) and (5), where Q_d is measured as a function of distance.

The method described above by Wennerberg (1993) formulations have been used to estimate Q_i (Intinsic quality factor) and Q_s (Scattering quality factor) for Koyna and Chamoli regions while the Q_i and Q_s estimated for Kachchh by Sharma et al, 2008 are used to estimate B_0 and L_e for Kachchh. Since the determination of B_0 and L_e depends critically on the shape of the energy curves as a function of source-receiver distance (Mayeda et al., 1992), to find the distribution of coda energy in space. Seismic albedo and extinction lengths are estimated by following equations.

$$B_0 = \eta_s L_{e,} \quad (6)$$

where Q_s is the scattering attenuation coefficient.

$$L_e^{-1} = \eta_e = (\eta_i + \eta_s) \quad (7)$$

where η_i is the intrinsic attenuation coefficient, η_e is the total attenuation coefficient and η_s is the scattering attenuation coefficient. Attenuation was determined by:

$$Q_s^{-1} = \eta_s k^{-1} \quad (8)$$

$$Q_i^{-1} = \eta_i k^{-1} \quad (9)$$

$$Q_t^{-1} = \eta_e k^{-1} \quad (10)$$

where $k = 2\pi f/\beta$ and β = velocity of S-wave (Mayeda et al., 1992).

IV. RESULTS AND DISCUSSIONS

It is known about Chamoli, Kachchh ang Koyna regions that these three regions are seismically active as all these three regions have experienced considerable amount of seismicity in past. Table 1 shows the results of present study in terms of all Q's estimated, L_e and B_0. Here Q_c values are computed under present study for Chamoli region using Single backscattering model of Aki & Chouet, 1975. The values of Q_α and Q_β for Chamoli are taken from Sharma et al (2009). With the help of Q_β and Q_c the values of Q_i and Q_s are estimated using Wennerberg (1993) formulation which are intern used to estimate B_0 and L_e for Chamoli. For Kachchh region Q_i, Q_s, Q_c and Q_β are taken from Babita Sharma et al, 2008. With the help of these values B_0 and L_e are estimated for Kachchh. For Koyna region using values of Q_β and Q_c from Sharma et al (2007), total attenuation is separated in terms of Qi and Qs using Wennerberg (1993) formulation and then these values are used to estimate B_0 and L_e for Koyna.

It is clear from Table 1 that all Q's are frequency dependent. As the frequency increases all Q's also increase. In table 1, we found $B_0 > 0.5$ for Chamoli which represents that scattering attenuation is predominant over intrinsic attenuation in Chamoli while L_e varies from 20 to 66 km. The Chamoli area falls in the interplate

C.F.	Q_α	Q_β	Q_c	Q_s	Q_i	$B_0 \pm \delta$	$Le \pm \delta$
CHAMOLI REGION							
1.5	68	126	389	239	265	0.52 ± 0.03	48 ± 05
3	96	175	548	327	376	0.53 ± 0.02	33 ± 04
6	173	299	1026	533	681	0.56 ± 0.04	28 ± 03
12	382	502	1412	980	1029	0.53 ± 0.02	21 ± 02
24	588	868	2489	1665	1813	0.51 ± 0.03	20 ± 03
KACHCHH REGION							
1.5	89	136	204	529	183	0.29 ± 0.05	70 ± 06
3	239	237	459	628	380	0.22 ± 0.06	62 ± 06
6	458	615	1093	1819	928	0.35 ± 0.03	53 ± 04
12	781	881	1680	2370	1402	0.37 ± 0.02	50 ± 05
24	1044	1424	3454	3053	2668	0.47 ± 0.02	42 ± 04
KOYNA REGION							
1.5	81	102	150	414	135	0.24 ± 0.05	38 ± 04
3	228	379	373	-	374	-	-
6	399	798	847	-	834	-	-
12	760	1850	1318	-	1421	-	-
18	1248	2831	1776	-	1964	-	-

Table 1: Range of Model Parameters and Corresponding Average Scattering, Intrinsic, and Total Attenuation, where C.F.- Central Frequency, Q_α – Quality factor using P-waves, Q_β – Quality factor using S waves, Q_c – Quality factor using Coda waves, Q_s- Scattering Q, Q_i – Intrinsic Q, B_o – Seismic Albedo an L_e – Extinction Length.

seismicity regime which intern is highly heterogeneous in nature. This heterogeneity is dominant in the area which is also reflected in the present outcome. These results are comparable with the similar type of study in this region by Kumar et al, 2010 for Garhwal Kumaun, Himalaya. In table 1 it is observed $B_0 < 0.5$ for Kachchh region which shows the intrinsic attenuation is predominant over scattering attenuation and L_e varies from 40 to 70 km. Kachchh area falls in intraplate region corresponding to the higher intrinsic attenuation as compared to scattering attenuation. This area shows intrinsic loss more dominant over scattering. On the other hand in Koyna region for central frequency 1.5 Hz scattering attenuation is dominant over intrinsic attenuation while for frequency range of 3 to 18 Hz only intrinsic attenuation is responsible for the attenuation of seismic waves. This may be due to the entirely different seismicity of the area which is the reservoir induced seismicity. In this case at higher frequencies the attenuation is controlled only by intrinsic attenuation parameter. This outcome is also supported by Mandal and Rastogi, 1998 for the Koyna region. Figure 2 shows the comparison of Q_α, Q_β and Q_c values for Chamoli, Kachchh and Koyna regions. This figure shows the frequency dependence of Q_α, Q_β and Q_c. Figure 3 shows the comparison of intrinsic and scattering Q for Koyna, Kachchh and Chamoli regions. Figure 4 represents the variation of seismic albedo (B_0) and Extinction length (L_e) for Koyna, Kachchh and Chamoli regions.

The frequency-dependent Q_i and Q_s observed for all three regions is consistent with theoretical results (Wu, 1982; Sato, 1982) which predict that scattering Q_s increases with increasing frequency beyond the critical value corresponding to the dominant scale length of heterogeneity. In general, for frequencies less than or equal to 6.0 Hz, scattering Q_s is lower than intrinsic Q_i, whereas above 6.0 Hz the opposite is true. We found that in all three regions the scattering attenuation is strongly frequency dependent whereas intrinsic Q_i is considerably less frequency dependent. If scattering Q_s increases faster than frequency, this is consistent with theoretical results for a medium characterized by Gaussian correlation function (Wu, 1982). Alternatively, if the dependence of scattering Q_s on frequency is roughly inverse of frequency then this corresponds to a medium with exponential autocorrelation function.

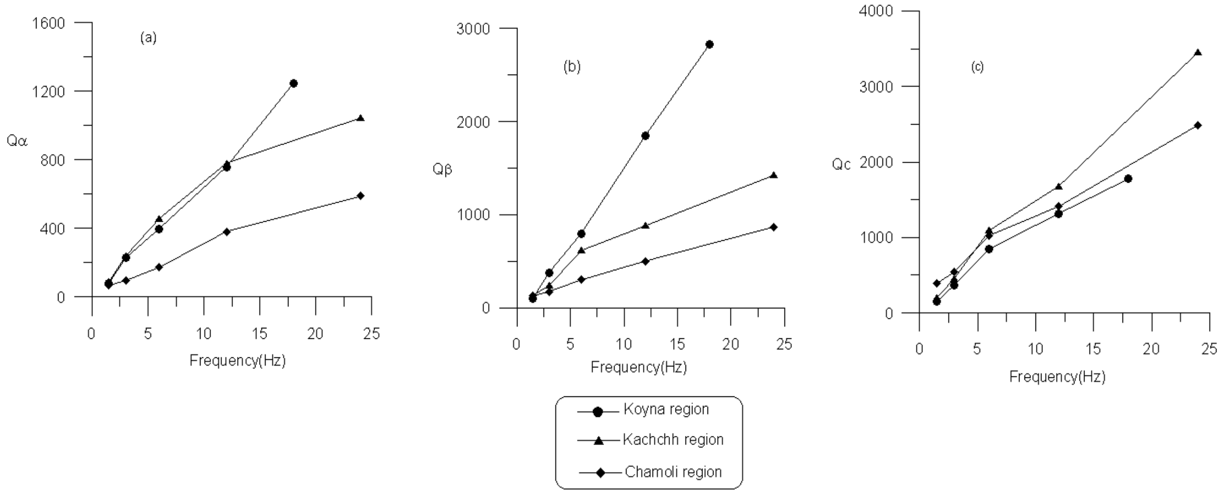

Figure 2: Comparison of Q_α, Q_β and Q_c values for Koyna (a), Kachchh (b) and Chamoli (c) regions.

At high frequencies where the wavelength is much smaller than the dominant scale length of heterogeneity, forward scattering becomes important and thus applying an isotropic scattering model to a medium with relatively large forward scattering lead to an underestimation of B_0 since less energy will be scattered into the backward direction which affects energy in later time windows (Fehler et al., 1992). Likewise, if the medium has stronger backscattering, B_0 will be overestimated. Though the fitting is generally poor at low frequency, the smaller separation of the three time windows, as compared with those greater than 3.0 Hz, also support that B_0 is higher than 0.5. Measurements of coda Q in Hawaii and Long Valley become independent of station site for lapse times after roughly 30 s (Mayeda et al., 1992). Therefore, we used a lapse time window of 30 s for our coda Q analysis and averaged over all sites. As found in previous studies for these regions (Phillips et al., 1988; Peng et al., 1987), coda Q depends strongly on frequency and is remarkably unique to a particular

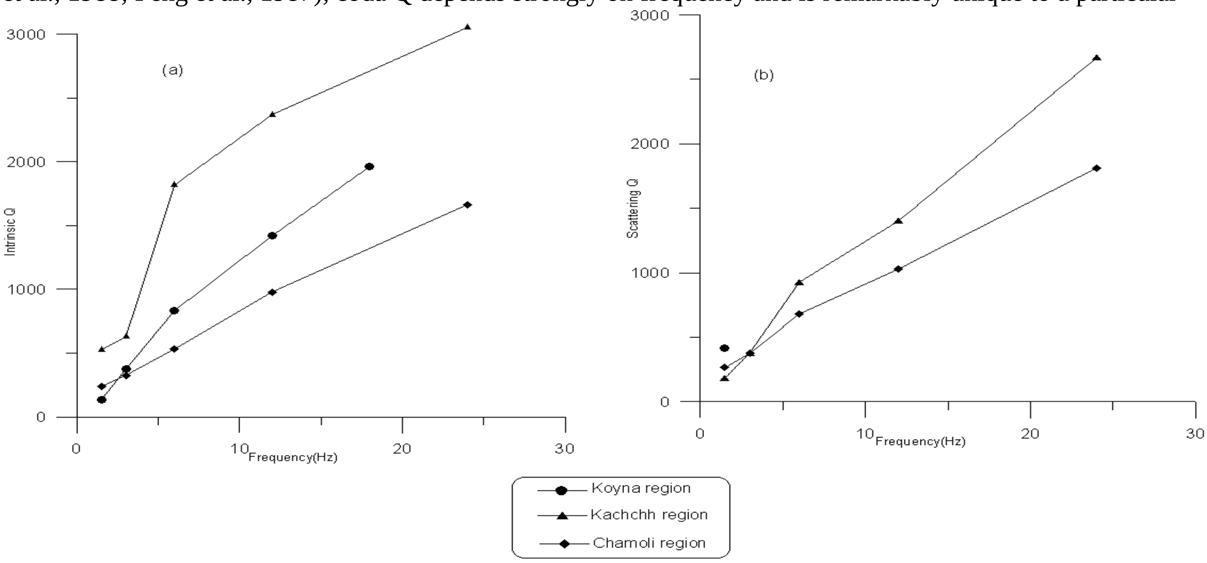

Figure 3: Comparison of intrinsic (a) and scattering (b) Q for Koyna, Kachchh and Chamoli regions.

region. Zeng et aI. (1991) have formulated an integral equation which gives the seismic energy density from a point source as a function of position and time for an unbounded medium characterized by constant velocity with uniform intrinsic and scattering Q. We have determined the expected coda Q by fitting the single-scattering formula of Aki and Chouet (1975). From the analytic results of Shang and Gao (1988), we know that the coda Q is identical to the intrinsic Q_i for the two-dimensional case when scatterers are randomly distributed and intrinsic Q_i is uniform and closer to the intrinsic Q_i for the three-dimensional case (Gusev and Abubakirov, 1987). Zeng (1991) has suggested that a depth-dependent intrinsic Q_i which increases with depth can explain the discrepancy between theoretical predictions and observations.

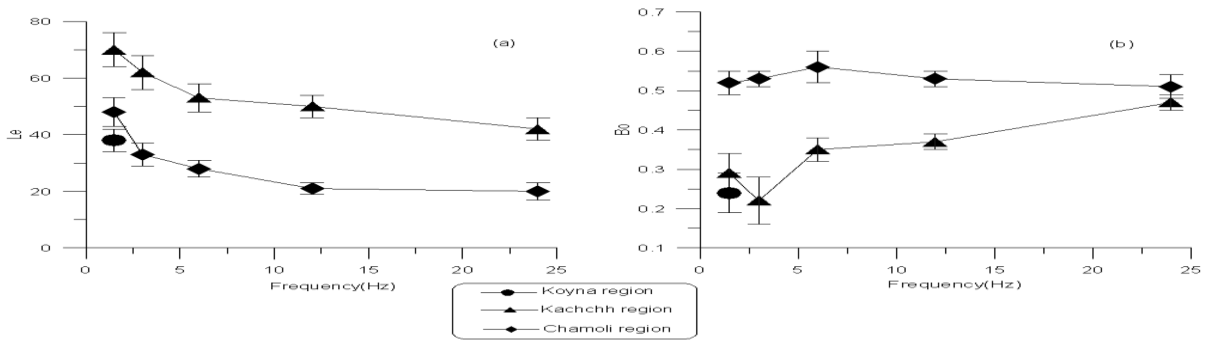

Figure 4: Comparison of seismic albedo (B_0) and Extinction length (L_e) (a and b respectively) for Koyna, Kachchh and Chamoli regions.

He found that the observed coda Q is closer to the total Q_t (rather than intrinsic Q_i) when the intrinsic Q_i decreases with depth, even in strong scattering environments. In addition to the depth-dependent intrinsic Q_i, the horizontal layering of crustal rocks may result in an anisotropic scattering. The integral solution of Zeng et al. (1991) may provide the starting point for more realistic models, especially if nonisotropic scattering and heterogeneous distribution of scatterers and non uniform absorption can be included. It is important to estimate separation of attenuation in terms of intrinsic and scattering loss as these values show the actual picture of the sub surface strata. B_0 and L_e represent actual hazard parameters. So they are more important than just to estimate quality factor of coda waves. Comparative attenuation study presented here is very important as these Kachchh, Koyna and Chamoli regions of India are very much important as lot of construction practices are going on in these regions. Due to socio-economic importance of these regions the seismic hazard is very much essential for the structural engineering practices. So these values can be used to estimate the seismic hazard of these regions.

V. CONCLUSION

The comparative study of attenuation of seismic waves for Chamoli, Kachchh and Koyna regions of India has been evaluated here. Seismic albedo (B_0) and extinction length (L_e) are computed and for this purpose the Q_β and Q_c values are used for Chamoli, Kachchh and Koyna regions. As a result we found $B_0 > 0.5$ for Chamoli while $B_0 < 0.5$ for Kachchh. This represents that scattering attenuation is predominant over intrinsic attenuation in Chamoli while L_e varies from 20 to 66 km. For Kachchh region intrinsic attenuation is predominant over scattering attenuation and L_e varies from 40 to 70 km. The Chamoli area falls in the interplate seismicity regime which intern is highly heterogeneous in nature. Kachchh area falls in intraplate region corresponding to the higher intrinsic attenuation as compared to scattering attenuation. On the other hand in Koyna region for central frequency 1.5 Hz scattering attenuation is dominant over intrinsic attenuation while for frequency range of 3 to 18 Hz only intrinsic attenuation is responsible for the attenuation of seismic waves. The values obtained in the present study are consistent with geology and tectonic set up of the three regions. These values can be intern used to estimate the seismic hazard in these regions.

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