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DETERMINATION OF GEOPHYSICAL PARAMETERS OF HIMALAYAN REGION

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Abstract

Earthquake resistant design of structures requires the knowledge of quantified seismic hazard. To quantify the seismic hazard, Peak Ground Acceleration (PGA) is used for design procedures. The maximum possible PGA of a particular region depends on seismic parameters like magnitude, hypocentral distance, type of soil etc. Though it can be obtained by observing the past seismic events, it is more realistic to relate it with the parameters that influence it.

Due to high seismic activity at the Himalayan region, this paper is aimed at developing a Ground Motion Prediction Equation (GMPE) for this region. For this purpose, two sets of 168 earthquakes (2.5 - 7.2 M_w) have been selected that are recorded at different stations within 500 km radius along the Himalayan belt. A statistical analysis is carried out on both sets separately based on the relation of PGA with magnitude, hypocentral distance and the type of soil. New GMPE equations have been proposed. The same are compared with the existing GMPE for the same region and seismically similar regions.

Keywords: Peak ground acceleration (PGA); Ground motion prediction equation (GMPE); Seismic hazard

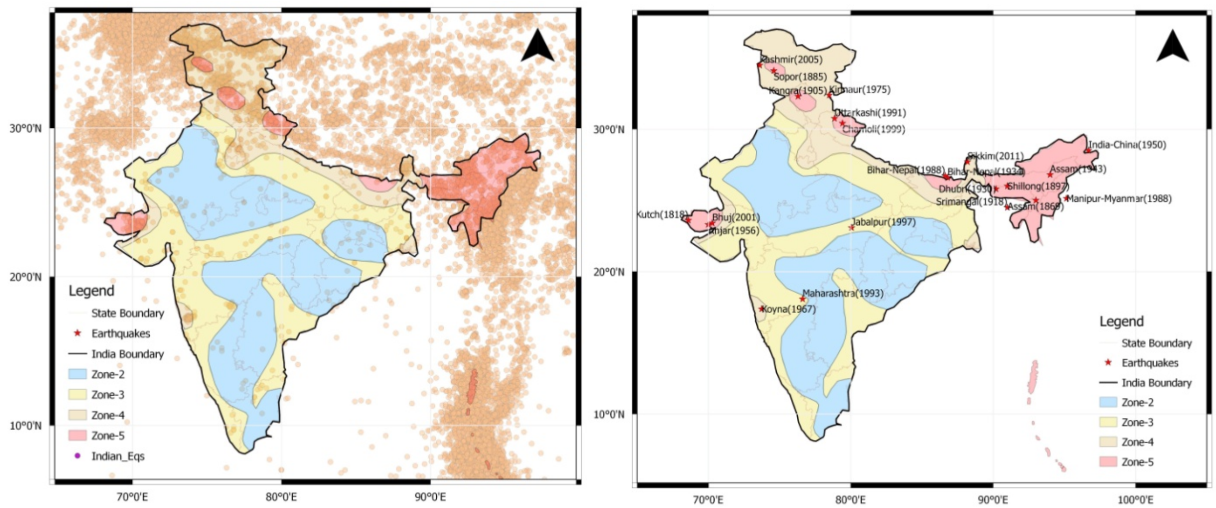
1. Introduction

India is divided into four seismic zones (II, III, IV, V), according to Indian Standard code for earthquake resistant design (IS: 1893(part I) - 2002). Each seismic zone is assigned with quantified hazard in terms of spectral acceleration that denotes the maximum value that can occur. For a realistic estimation of Peak Ground Acceleration (PGA), the past seismicity of the region has to be studied that requires lot of known earthquake parameters. Inspite of observing the past seismicity, it is convenient to derive an equation from the influencing parameters. The parameters that influence the hazard can be divided into three; the source, the path and the site effects such as magnitude, epicentral distance and type of soil.

The design spectrum suggested by the IS: 1893 (part I) – 2002 is applicable to ordinary buildings but not for important structures like power plants, etc. For important buildings, site specific response spectrum should be developed for design. Such a spectrum with a constant level of probability of occurrence is called uniform hazard spectrum. In developing uniform hazard spectrum for a region, the seismic attenuation is required. Ground motion prediction equation is required to know the effect of different parameters on seismic attenuation.

India can be divided into three geological units; the Himalayan arc, the Indo-Gangetic plain, and the Indian shield (Bilham, 2004). The Himalayas were formed as a result of collision between the Indian and the Eurasian plates for 50-60 million years ago. The current subduction rate of the Indian plate into the Eurasian plate is estimated to be 4.5 cm/year (Bilham, 2004). Due to the interaction between the Indian and the Eurasian plate, more stresses accumulate in the Himalaya regions. This makes the

Himalayas seismically very active and increases possible occurrence of great and major earthquakes in the future (Bilham, 2004). Figure 1 represents major earthquakes that have occurred along the Himalayan region and other parts of India (1842-Jalalabad, 2005-Kashmir, 1885-Kashmir, and 1905-Kangra, 1833-Nepal, 1934-Bihar-Nepal, 1950-Assam, 1897-Assam, 1762-Chittagong, 2004-Sumatra, and 2001-Bhuj). Amongst all the earthquakes, except the 2005 Kashmir earthquake, none of the earthquakes produced surface rupture on the Himalayan Frontal Thrust (HFT). Hence a seismic gap exists at this region that needs accurate estimation of seismic hazard.



(a) (b)

Fig. 1 - (a) Seismicity of India (b) Major earthquakes since 1800 (Data Source: IMD, Raghukanth et al., 2010)

The present study is focused on developing a ground motion prediction equation using 167 earthquakes recorded by National Geophysical Research Institute (NGRI) and Programme for Excellence in Strong Motion Studies (PESMOS).

2. Review of Existing GMPE

Singh *et al.*, (1996) proposed a ground motion prediction equation for acceleration and velocity for Himalayan region. The equation is developed from the data of earthquakes with magnitude range 5.7 - 7.2. The five major earthquakes (Dharmasala, 1986; Meghalaya, 1986; Burma-India, 1987; Tripura-Assam, 1988; Guwahati, 1988) that occurred in the region are considered. The attenuation model proposed by Kanai (1961) that uses Intensity as a dependent parameter, is used for developing the equation. The developed equation is applicable for earthquakes occuring within a radius of 200km from the hypocenter. This equation is one of the oldest and was developed when not much earthquake records are available in the himalayan region. The effect of magnitude and epicentral distance on acceleration is only studied which needs further investigation. The effect of geometrical spreading and the inelasticity of earth are disaccounted for in the proposed equation.

Iyengar *et al.*, (2004) in carrying out probabilistic seismic hazard analysis for Delhi city, developed an attenation relation from the combination of 23 samples with the 38 ssmples of data available in Sharma (1998). The equation is applicable for rock sites in North India. Himalayan region is the most seismically active when compared with the remaining part of the north India, that needs a separate study to be carried out. In order to get a reliable estimate of the attenuation, Anbazhagan *et al.*, (2013) proposed an equation depending on a combination of existing and simulation ground motions for himalayan region.

FINSIM(finite fault simulation) is used for simulating the ground motion. This relation is the first relation for the region, which is valid for all ranges of magnitudes of engineering interast and upto hypocenter distance of 300km.

As discussed in the previous section, ground motion parameter is highly influenced by many variables. In order to consolidate the effect of each variable, a functional form is required. Boore *et al.*, (1982) suggested a functional form for developing the GMPE keeping in view the major influencing parameters. This study forms the basic underlying principle of developing prediction equation.

Atkinson et al., (1995) developed a stochastic model for Eastern North America (ENA) using the latest earthquakes recorded after 1987 and it is used to develop a ground motion attenuation relation. The method to develpe the ground motion relations is briefly reviewed, with emphasis on the data defining each of the input parameters. Predictive relations are developed for peak ground motion and response spectra for rock sites and compared to available ground motion data. In this study, the ground motion is modeled as bandlimited Gaussian noise; the radiated energy is assumed to be evenly distributed over a specified duration.The prediction equation provides a good description of peak ground motions for ENA earthquakes of small-to-moderate magnitude.

Kanno et al., (2006) using 11,542 records from 184 earthquake events developed a ground motion prediction equation for Japan. Two regression models were adopted for shallow and deep focus earthquakes. Correction factors for site effects were introduced as a function of average shear wave velocity from ground surface to 30m in depth.

3. Attenuation Model

Due to anelasticity of earth medium, the seismic energy measured at the site differs from the seismic energy released at the focus of the earthquake. Each seismic parameter effects the attenuation differently. For example, the seismic energy increases with increase in magnitude of earthquake whereas it decreases with increase in epicentral distance. Another cause for seismic attenuation is the geometrical spreading. In practice, various parameters influence the attenuation process. Different researchers proposed various attenuation functional forms/models that consider some of those important parameters that affect the attenuation mechanism. These functional forms are usually selected to reflect the mechanical properties of the ground motion as close as possible.

In general, ground motion prediction equations require the knowledge of two variables; dependent variable and independent variable. As a common practice, Peak Ground Acceleration (PGA) is considered as dependent variable. Out of the three components of PGA, the vertical component is of less importance from the structural engineering perspective. This is because the buildings designed for gravity loads usually have a factor of safety more than 2 that is sufficient for resisting the vertical ground motion. Out of the two horizontal components of ground motion; either any one or the resultant of the two can be considered (Joyner and Boore, 1981). In this study, the resultant of the two horizontal components is considered for the deriving the relation.

Though, many functional forms are available, the present study adopts the standard functional form proposed by Joyner and Boore, 1981 which relates PGA with the magnitude, epicentral distance and type of soil. As the rate of occurrence of earthquakes with different moment magnitudes can be related directly to slip rates on faults moment magnitude is considered as an independent variable (Joyner and Boore, 1982). Another independent variable is the distance from the source to the station. Depending on the availability of data, geologic material can also be an independent variable. The functional form of the predictive equation looks like

$$Y = b_1 e^{b_2 M} [e^{b_3 D} / D^{b_4}] e^{b_5 S} e^{b_6 P} \tag{1}$$

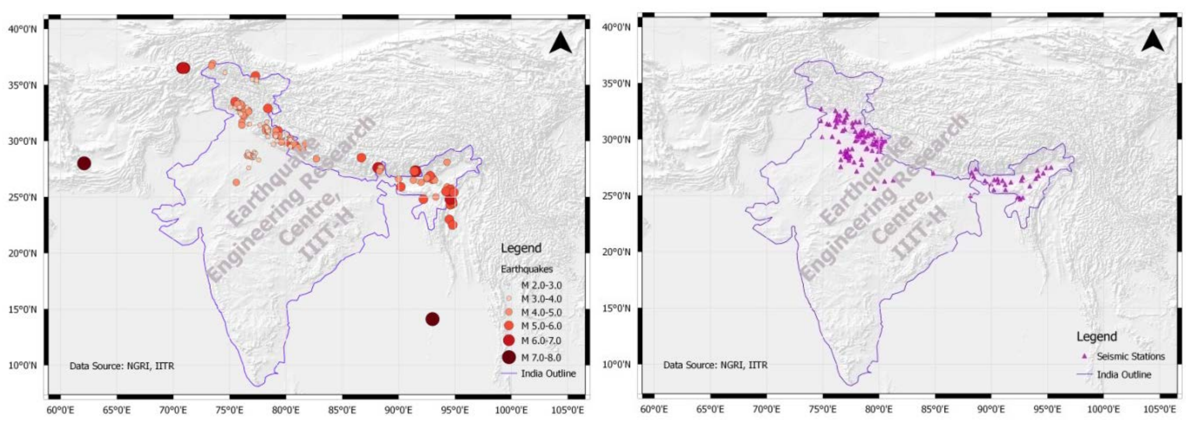
Where Y is the dependent variable (i.e., PGA), M is moment magnitude (to maintain homogeneity), D a function of the distance measure, S a binary variable representing local site geology (0 if rock, 1 if soil, 2 if sand) and P the uncertainity in the prediction. In the context of this paper, "sand" indicates those that are highly susceptible to ground amplification such as soft soil, soft clay etc whereas "soils" indicate those that are relatively less sensitive to ground motion amplification such as medium stiff clay, dense and stiff soils etc. In this analysis, epicentral distance is considered to maintain homogeneity as the depth of focus is not known for few earthquakes.

The exponential dependence on magnitude stems from the basic definition of magnitude as a logarithm of a measure of ground motion; the distance dependence in brackets accounts for anelastic attenuation (b_3) and geometrical spreading (b_4); the soil term is arbitrary, but agrees with the notion that site effects should be multiplicative; finally, the uncertainity follows from the assumption of a log-normal distribution of the observations about the regression line (Joyner and Boore, 1981).

4. Ground Motion Prediction Equation

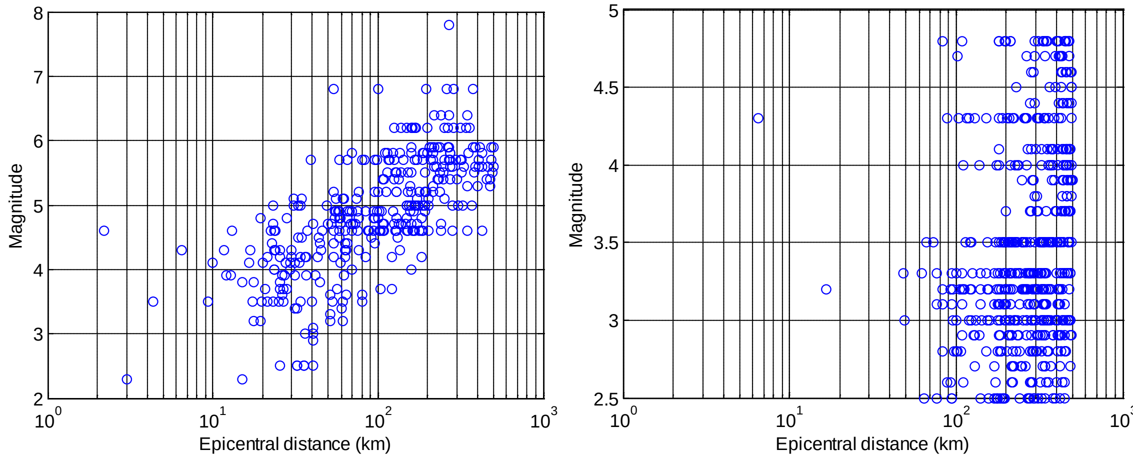
The present study considers a set of 167 earthquakes of magnitude ranges M2.8-7.8 recorded at 130 seismic stations. The dataset is collected from National Geophysical Research Institute (NGRI), Hyderabad and Programme for Excellence in Strong Motion Studies (PESMOS) organized by Indian Institute of Technology (IITR), Roorkee. The NGRI dataset consists of 3000 ground motions and valid M2.5-4.8, whereas PESMOS dataset has 1401 ground motions and valid M2.5-7.8. It means PESMOS dataset has sparsely distributed with an epicentral distance of 500 km and the ground motions are recorded at site class A, B and C. The V_{30} for site class A, B and C are 700-1400 m/s, 375-700 m/s and 200-375 m/s.

Figure 2 shows the location of earthquakes and stations. Figure 3 shows the distribution of magnitude of earthquake with the epicentral distance. Though the data contains earthquakes at distance more than 1000km, we considered earthquakes within 500 km radius. Figure 4 represents relation between epicentral distance and PGA. Figure 5 represents relation between magnitude and PGA.



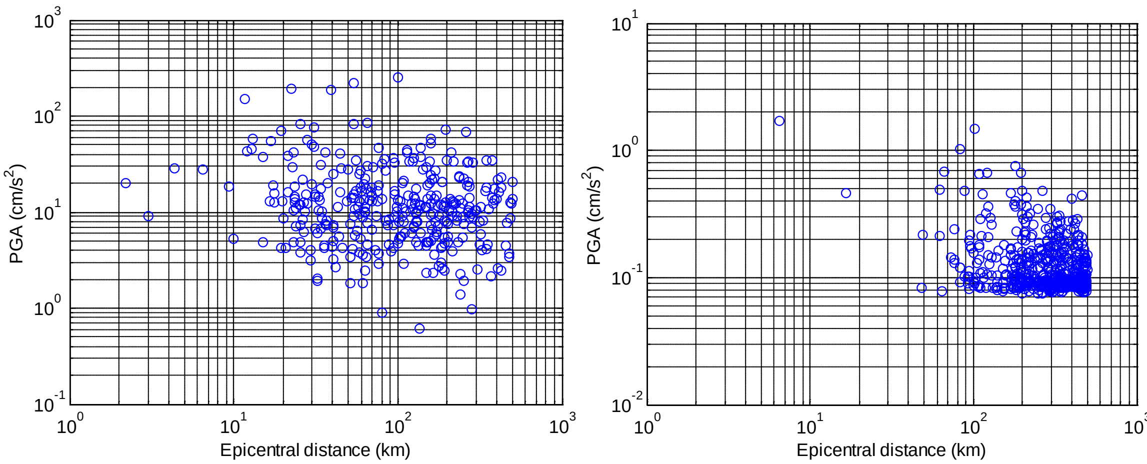
(a) (b)

Fig. 2 - Map showing location of (a) Earthquakes (b) Recorded stations



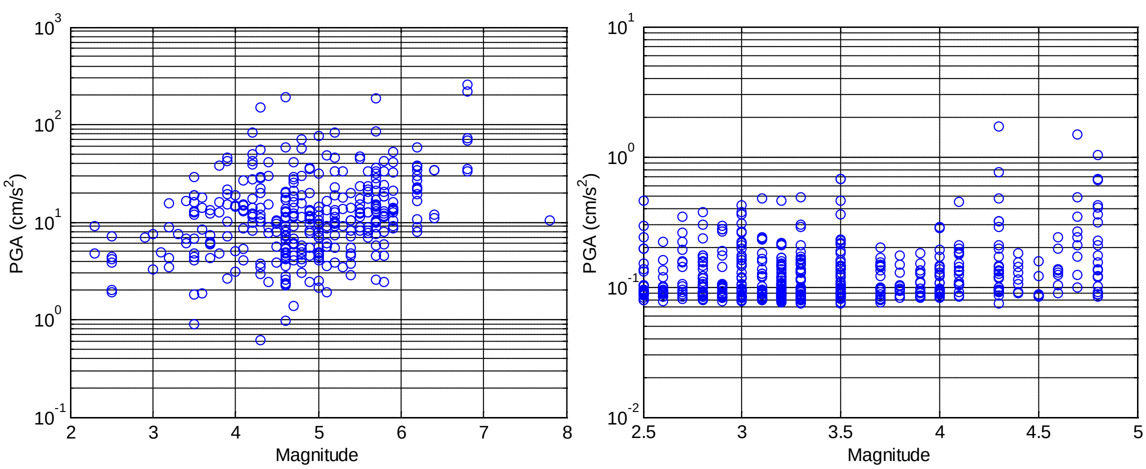
(a) (b)

Fig. 3 - Distribution of earthquake magnitude (a) Data from PESMOS (b) Data from NGRI



(a) (b)

Fig. 4 - Distribution of PGA with earthquake magnitude (a) Data from PESMOS (b) Data from NGRI



(a) (b)

Fig. 5 - Distribution of PGA with earthquake magnitude (a) Data from PESMOS (b) Data from NGRI

Since earthquake is a strain built up process, it follows lognormal distribution for the prediction of future occurrence. Hence, in the estimation of seismic attenuation, the influencing parameters are related to logarithm of PGA. The amplitude of body waves is inversely proportional to the distance and amplitude of surface waves is inversely proportional to the square root of the distance. The functional form used in this study considering the geometrical spreading only is expressed as

$$log_{10}PGA = a + f_1(M) + f_2(R) + f_3(S) + \delta_e \quad (2)$$

Where $f_1(M)$ is a function of magnitude, $f_2(R)$ is a function of epicentral distance $f_3(S)$ is a function of site category and δ_e is the uncertainity in the predicted relation.

It is necessary to consider the variable separation in the relationship. First, it is reasonable to assume that function f_1 depends only on M. In this model, the seismic variables are considered independently; no coupled terms of these variables are taken into account. The forms of $f(Y)$ and $f_1(M)$ are selected as

$$f(Y) = log_{10}(Y) \quad (3)$$

$$f_1(M) = bM \quad (4)$$

Considering the attenuation resulting from geometric spreading, material anelasticity, and scattering effect, $g_2(R)$ can be expressed

$$f_2(R) = clog_{10}(R^2 + h^2) + dR \quad (5)$$

The first term represents the geometric spreading and the second term represents the anelastic attenuation.

It is generally inappropriate to assume that the function f_2 depends only on R. The parameter h is called fictitious depth and is determined by regression and incorporates all of the factors that tend to limit motions near the source. The parameter h is introduced to allow for the fact that the source of the peak motion values may not be the closest point on the rupture. If the source of the peak motion were directly below the nearest point on the surface projection of the rupture, the value of h would simply represent the depth of that source. Theoretical study showed that the seismic wave amplitudes decrease approximately as $1/R$ at far distances and converge to a finite value as distance goes to *zero*. This is due to one of the effects from the near field term of the seismic radiations, and it is noted that this holds true even when the distance is *zero*, that is when station is located on the fault plane. Thus, it is more appropriate and natural to introduce the form $f2 \sim (1/(R+h))\ of\ 1/\sqrt{(R2+h2)}$ than to keep $1/R$. One important point in this form is that the variable h depends on the magnitude M, since the near field territory depends on the fault size of the earthquake, and on M. The variable h is a function of M, and therefore, the function f_2 depends on M as well as on R.

The function $f_2(S)$, is not free from the non-linear response of the ground surface at the station is covered with soft soil, which means that the function depends both on the site categories S and on the amplitude that comes into the surface layers, which in turn depends on M and R. The function form for $f_3(S)$, relating to the site category, can be taken as

$$f_3(S) = eS \quad (6)$$

Where e is the coefficient for regression and S represents the site category; 2 for sand, 1 for soil and 0 for rock site. The final function form for modeling the ground motion attenuation can be represented as follows

$$log_{10}(Y) = a + bM + clog_{10}\sqrt{R^2 + h^2} + eS + \delta_e \quad (7)$$

Where δ_e is the standard deviation of the logarithm of *Y*, *M* is the magnitude, *R* is the epicentral distance.

4. Results

By carrying out the multi linear regression analysis, the obtained ground motion prediction equation is as follows

From PESMOS data

$$log_{10}(PGA) = 1.168 + 0.288M - 0.65log_{10}\sqrt{R^2 + h^2} + 0.009S + 0.4432 \quad (8)$$

From NGRI data

$$log_{10}(PGA) = 1.525 + 0.2M - 1.55log_{10}\sqrt{R^2 + h^2} + 0.532 \quad (9)$$

Where M is the magnitude of earthquake, *R* is the epicentral distance, *h* is the depth of focus, S is the type of soil. A standard deviation of 0.4432 is obtained for the proposed GMPE.

For validating the proposed study, a comparative study is carried out with the exiting attenuation equations available. Table 1 shows the available equation and figure 6 shows the comparison. From figure 6, it is observed that IITR-PESMOS GMPE gives higher values compared to other GMPE equations. Equation 8 gives higher PGA values, whereas, equation 9 gives lower values. Because, it is applicable for lower magnitudes (M2.5-4.5).

Table 1 - Available GMPE from literature

S.No	Proposer	Proposed equation
1	R P Singh, 1996 *(cm/s²)*	$log_{10}(A) = 1.14 + 0.31M - 0.615log_{10}R$
2	Sharma, 1998 *(g)*	$log_{10}(A) = -1.072 + 0.3903M - 1.21log_{10}(R + e^{0.5873M})$
3	Atkinson & Boore, 1995 *(cm/s²)*	$log_{10}(A) = 3.79 + 0.298(M - 6) - 0.536(M - 6)^2 - logR - 0.00135R$
4	Kanno *et al.*, 2006 *(cm/s²)*	$log_{10}(A) = 0.41M - 0.0039R - log_{10}R + 1.96$
5	Iyengar & Ghosh, 2004 *(g)*	$log_{10}(A) = -1.5232 + 0.3677M - 1.004log_{10}(R + e^{0.41M}) + 0.263$
6	Anbazhagan *et al.*, 2013 *(g)*	$log_{10}(A) = -1.283 + 0.544M - 1.792log_{10}(R + e^{0.381M}) + 0.283$

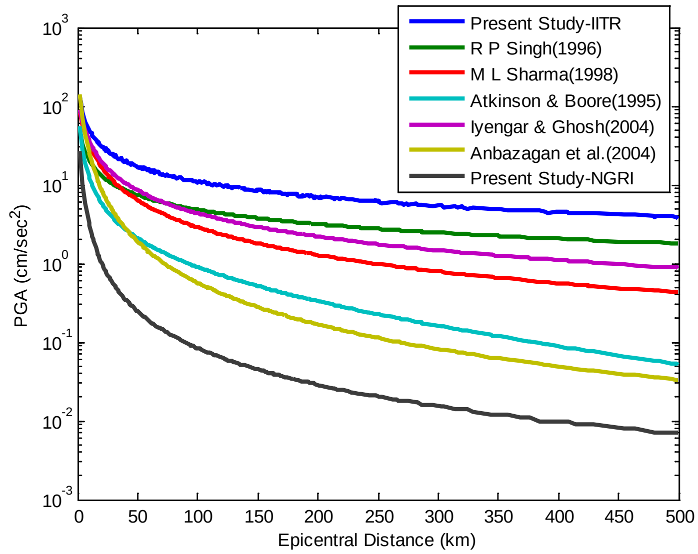


Fig. 6 - Comparison of proposed ground motion prediction equation with the existing equations

5. Conclusions

The paper is aimed to develop a GMPE for Himalayan region. For this purpose of study, two sets of 168 earthquakes (2.5 - 7.2 M_w) have been selected that are recorded at different stations within 500 km radius along the Himalayan belt. A statistical analysis is carried out on NGRI and PESMOS datasets separately based on the relation of PGA with magnitude, hypocentral distance and the type of soil. The conclusions of the study are as follows:

- From PESMOS data

$$log_{10}(PGA) = 1.168 + 0.288M - 0.65 log_{10}\sqrt{R^2 + h^2} + 0.009S + 0.4432$$

- From NGRI data

$$log_{10}(PGA) = 1.525 + 0.2M - 1.55 log_{10}\sqrt{R^2 + h^2} + 0.532$$

- GMPE obtained from PESMOS, is similar to Japanese GMPE obtained by Kanno.

From the figure 6, the proposed GMPE based on PESMOS (IITR) data clearly shows the huge variation in the PGA values due to soil when compared to the proposed GMPE based on NGRI data. The huge variation of the PGA values in the proposed GMPE based on NGRI data can be attributed to the small data set considered. Though the Himalayan region has the potential to cause earthquakes of larger magnitudes $M_w > 6$, the considered magnitude window is less than 6. This clearly shows the insufficiency of recorded data in the literature. On the other hand, the GMPE obtained from the recorded data of IIT R is sufficiently in agreement with the existing literature. The notable feature in this prediction equation is that the variation of PGA with type of soil is captured to a sufficient accuracy.

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