Strong Ground Motion Prediction Equation for low Magnitude and Near-field Earthquake data for Shield region in India

C. Srinivasan & Y.A. Willy
National Institute of Rock Mechanics, Champion Reefs, KGF-563117

A. Harbindu & M.L. Sharma
Department of Earthquake Engineering, Indian Institute of Technology Roorkee

SUMMARY:
A common way to evaluate seismic hazard related to ground shaking is to make use of predictive models commonly known as attenuation relations, which in general expressed as mathematical function relating to strong-motion parameter to parameters characterizing the earthquake, propagation medium and the local site geology. Many predictive relations are nowadays available for different regions of the world for peak ground acceleration (PGA) and these are mostly derived from strong motion records. There are a few studies that derived the attenuation of PGA from weak motion recordings, although several small magnitude earthquakes have produced PGA values of engineering interest.
This study derives ground-motion predictive equation for PGA for short distances and low magnitudes for Kolar Gold Field mines region of India. The dataset is covering a magnitude range between 1.5 to 3.2 and a hypocentral distance up to 30 km. The data base suffers a lack of near-field recordings for distances greater than 5 km, however which is compensated by including additional data for distances less than 30 km from Campania-Luciana region of Southern Italy. The attenuation of PGA is found to be logarithmically distributed with a strong attenuation for low distances and low magnitude values.
The resulting equation is

$$\log(PGA) = -1.664 + 0.36075\,M - 1.477\log(R) \pm 0.338$$

where PGA is expressed in ms^{-2}, M is the magnitude, R is the hypocentral distance. The sensitivity analysis of the model is performed by estimating residuals. The residual trend show that predicted PGA are quite stable with respect to reasonable variation of the model.

Keywords: Ground-motion prediction equation, PGA attenuation, Low magnitude, shield region

1. INTRODUCTION

India has faced several devastating earthquakes in the past. The largest of these have originated in the Himalayan plate boundary region, which has remained a region of great scientific and engineering interest. Not surprisingly, considerable data and earthquake related literature are available about the northern part of India. On the other hand very little seismological information is available about Peninsular India (PI), which is taken here as south of 24^0 N latitude. This situation is changing, in response to the three recent devastating events: the Khillari (30.9.1993), Jabalpur (22.5.1997), and Kutch (26.1.2001) shocks. But the available quantified information is so sparse, engineers presently face a daunting problem in estimating ground motion levels for future events in PI. The present paper is motivated by this need, to have a simple approach to understand attenuation in PI from the engineering point of view. The paper consists of the data base from Kolar Gold Field mining region and the development of the attenuation relationship. Finally, attenuation relationship for low magnitude and shorter distances is proposed for the region.

2. GEOLOGY OF THE STUDY AREA

The region of the Indian subcontinent south of 24^0 N latitude is taken here as Peninsular India (PI).

This landmass 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 very active regions of India. Leaving this region and the Andaman-Nicobar Islands, the remaining part of continental PI has reliably experienced some 400 earthquakes in a period of 600 years. This number will be much larger if all instrumentally recorded shocks of small magnitudes were also included. The seismicity of PI, from a seismological perspective has been discussed in the past notably by Chandra (1977), and Rao (1984). A catalogue of earthquakes of magnitude ≥ 3 for PI has been compiled by Guha and Basu (1993). Seeber et al (1999) have studied the seismicity of PI with particular reference to Maharashtra. They concluded that between 1960 and 1990 the seismicity of PI showed a threefold increase. This was the period during which industrial development also increased several fold in PI. Thus, engineers have to recognize that the looming seismic risk to man-made structures in PI is more than what was previously believed.

In regions lacking strong motion data, seismological models (Boore 1983) are viable alternatives and are used worldwide for deriving attenuation relationships (Atkinson and Boore 1995, Hwang and Huo 1997, Toro et al 1997). Singh et al (1999) have used a seismological model for estimating ground motion in parts of PI, but no specific attenuation equation has been proposed by them. The theory and application of seismological models for estimating ground motion has been discussed in detail by Boore (1983; 2003).

Fig. 1 display the geology of Kolar Gold Field mining region. KGF Gold Mines are situated in a belt of highly.

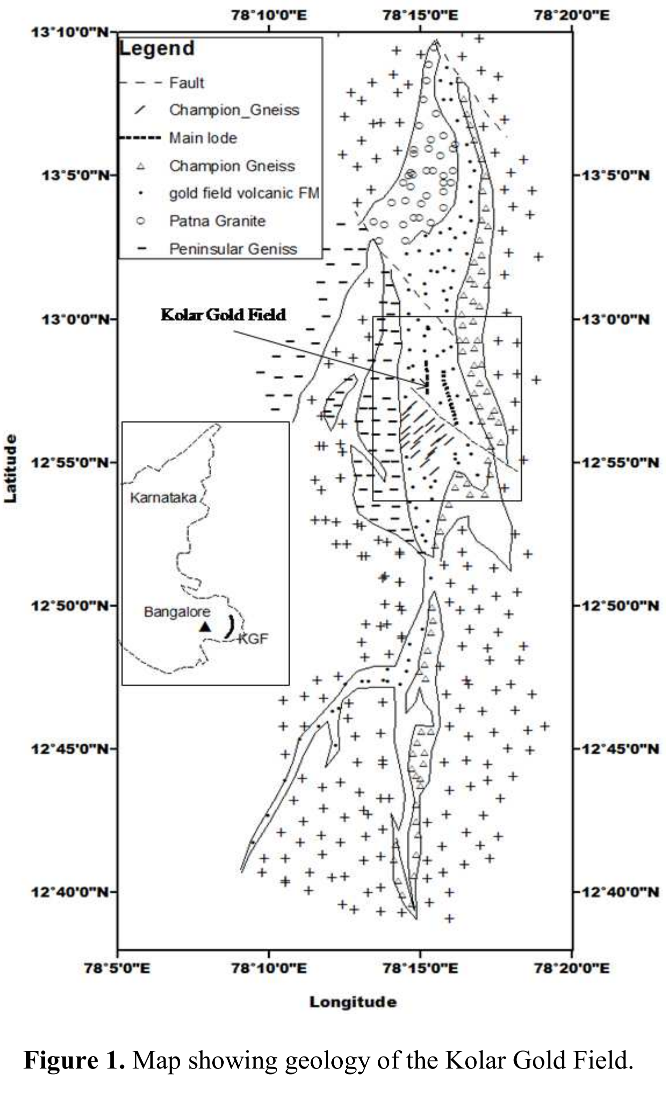

Figure 1. Map showing geology of the Kolar Gold Field.

metamorphosed schists which runs 80 km North –South and 4 km East-West, the major rock types are schist of lower Dharwar age which are surrounded by Granites and Gneisses of Achaean Age, the schists is popularly known as Kolar Schists Belt. At the southern tip of the 80 km, KGF mines are situated, there are about 26 known lodes and out of which champion lode is gold bearing schist and it is of economic importance. The schists are folded and faulted with intrusion of Dolerite dykes and pegmatites. The fold dips westward from 30^{o} near the surface to 85^{o} in the deeper working mines. Each side of reef calcite, beds of pale green augite and micaceous and chlorite are seen. Figure-1 shows the geology of Kolar Gold Fields.

3. DATA SET

Rockburst is a common phenomenon since the beginning of 20^{th} century in the mines of Kolar Gold Fields which is situated in Karnataka. Rockbursts have caused severe damages to buildings on surface and underground mine workings in several instances. The rockbursts were monitored using seismic monitoring system from 1979. Department of Science and Technology under World Bank assisted project installed one Broad Band Seismic Monitoring station during 1999 and one Strong Motion Accelerographs during 2005. The Strong Motion Accelerographs has recorded several rockbursts as it is in the close vicinity of the mines of Kolar Gold Fields. The Strong-motion accelerogram generated due to rockburst were used to obtain Wood-Anderson synthetic seismogram which provided useful basis for getting accurate and reliable values of local magnitudes. The three components of a total of 711 strong motion records obtained from seismic events in different zones of the mines before and after the major rockburst which occurred between Jan 2006 to July 2011 were used. The local magnitudes of these seismic events were in the range from 0.5 to 3.0 at a distance of radius 4.76 km. These accelerograms have been recorded by strong-motion Accelerographs installed in the campus of National Institute of Rock Mechanics. Data having hypocentral distance less than one is removed since there was a drastic change in PGA values for the recording having less than one kilometer hypocenter distance. The Kolar Gold Field data base suffers a lack of near-field recordings for distances greater than 5 km, however which is compensated by including additional data for distances less than 30 km from Campania-Luciana region of Southern Italy. Emolo et al. (2011) presented observed data of this region for Tertiary and Mesozoic soil classes. Using corrective coefficients presented by Cantore et al. (2010), the PGA is estimated for the hard rock site class for present study. The Fig. 2. display the distribution of earthquakes with respect to distance.

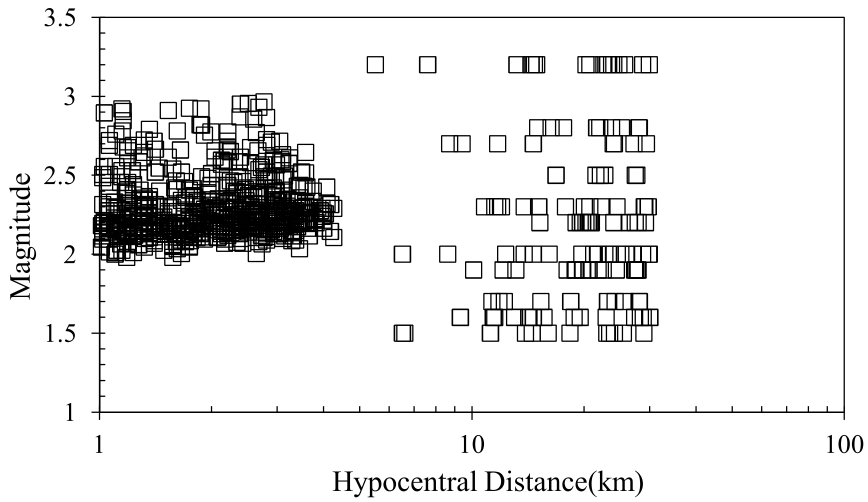

Figure 2. Plot of all seismic events PGA versus Distance

4. DEVELOPMENT OF ATTENUATION RELATIONSHIP

The general functional form for modeling the attenuation of ground motion, adopted in this paper, is represented by the expression

$$f(Y) = a + f_1(M) + f_2(R) \pm \sigma \tag{4.1}$$

where Y is the ground motion parameter to be predicted, $f_1(M)$ is the function of the magnitude and $f_2(R)$is a function of the distance, and σ is the standard deviation of the random variable Y. In this study, we assume PGAs are expressed in m/s^2 and distance in km. Since the distribution of Y is well approximated by a log-normal distribution, we set the independent variable $f(Y)$ as $f(Y) = logY$ in Eqn. 4.1.
we tested different functional forms of $f_1(M)$ and $f_2(R)$ in Eqn. 4.1. The function $f_1(M)$ depending on the magnitude, can be formulated as:

$$f_1(M) = bM + cM^2 \tag{4.2}$$

The function form of $f_1(M)$ has been used in different form by several authors. Some authors have used the linear dependence of magnitude (Sabetta and Puliese, 1996; Emolo et al.2010; Massa et al. 2007) and a few have introduced the quadratic term, $b'M^2$ (e.g. Akkar and Bommer, 2007) that dominates at large magnitude values. We investigated the quadratic function form, equation (2) on our observed dataset and found that the coefficient *c* does improve the uncertainties in the regression. Therefore we adopted linear dependency on magnitude by taking dY/dM equal to *c* for regression of ground motion prediction equation.
In order to investigate the path attenuation due to the geometrical spreading anelastic attenuation, we formulate the propagation function $f_2(R)$ as follows:

$$f_2(R) = c\log(R) + dR \tag{4.3}$$

where $c\log(R)$ represent the geometarical attenuation and dR represent the anelastic attenuation. The regression performed on assumed functional form of $f_2(R)$ on the observed dataset and found the anelastic coefficient close to zero value. Similar observations have been found in other weak-motion attenuation studies also (e.g. Atkinson and Morrison, 2009; Frisenda, 2008). This implies the attenuation of PGA for low magnitude earthquakes are mainly affected by the geometrical spreading in comparison to anelastic attenuation. Therefore we removed the dR in Eqn. 4.3. and formulated it as $f_2(R) = c\log(R)$.The proposed model for ground motion estimation considered as follows:

$$log(Y) = a + bM + clog(R) \pm \sigma_{logY} \tag{4.4}$$

where *Y* correspond to PGA in m/s^2 and *M* is local magnitude and *R* is the hypocentral distance. Here using hypocentral distance in deriving GMPEs will not introduce any bias in relation as the dimension of the rupture surface of smaller events are usually is smaller than the distances to the recording stations. σ_{logY} is the standard error associated with the distribution of random variable $log(Y)$.
The regression of Eqn. 4.4. has been performed using the nonlinear least-square Marquardt-Levenberg algorithm (Press et al. 1992) and the coefficients a, b, and c are determined.

5. RESULTS

The Eqn. 4.4. was fitted to the data to determine the peak ground acceleration and the equation that best fits the dataset was found to be:

$$\log(PGA) = -1.664 + 0.36075\,M - 1.477\log(R) \pm 0.338 \tag{4.5}$$

with errors for parameters *a*, *b*, and *c* are ±0.002, ±0.001, and ±0.02 respectively. The prediction equation is considered appropriate for low magnitude earthquake (M< 3.2) at shorter distances (*R*< 30 km) for rock sites.

Fig. 3. shows the attenuation of PGA values versus the distance for different magnitude bins. The two curves (solid lines) represent the attenuation of PGA values of upper and lower magnitude values of bin. The distribution of PGA values with respect to distance show that attenuation is higher in low magnitudes bins ($1.5 \leq M \leq 2.0$) when compare to higher magnitude bins ($2.5 \leq M \leq 3.2$). This confirm that the low magnitude earthquakes are characterized by the low frequency contents.

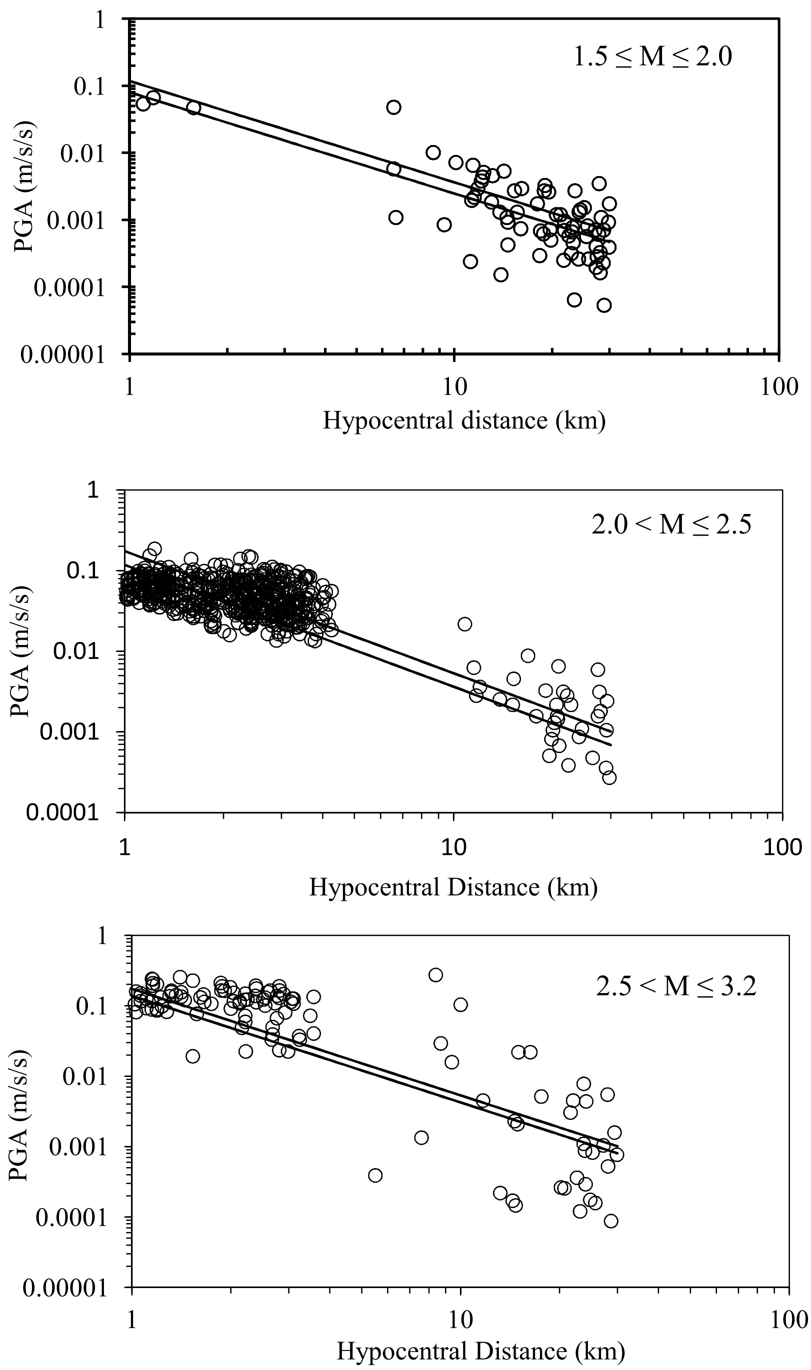

Figure 3. Plots of attenuation curves (solid lines). The two solid lines represent the attenuation curve for magnitudes mentioned in graph panel. Circles represent the observed PGA data of all events used in this study.

Another important observation in Fig. 3. is the attenuation curves is characteristic geometrical spreading rate , *c* estimated as $R^{-1.4}$ for low magnitude and shorter distance earthquakes. Similar decay geometrical spreading decay rate ($R^{-1.3}$) have be reported by Atkinson (2004) for ENA earthquakes at small magnitudes at distances lesser than 70 km.

In order to check goodness-of-fit to observed data, we computed residuals as follows:

$$residuals = \log Y_{obs} - \log Y_{pred} \tag{5.4}$$

where Y_{obs} and Y_{pred} represent the observed and predicted peak ground-motion values, respectively. The predicted values are computed using the derived GMPE as Eqn. 4.5.We have also estimated the bias between the observed and predicted values as the mean value of the residual distribution. The Fig. 4a and 4b. show the distribution of residuals with respect to distance and magnitude and no systematic trend is observed in distribution of residuals. The low values of model bias show the goodness-of-fit of the observed data.

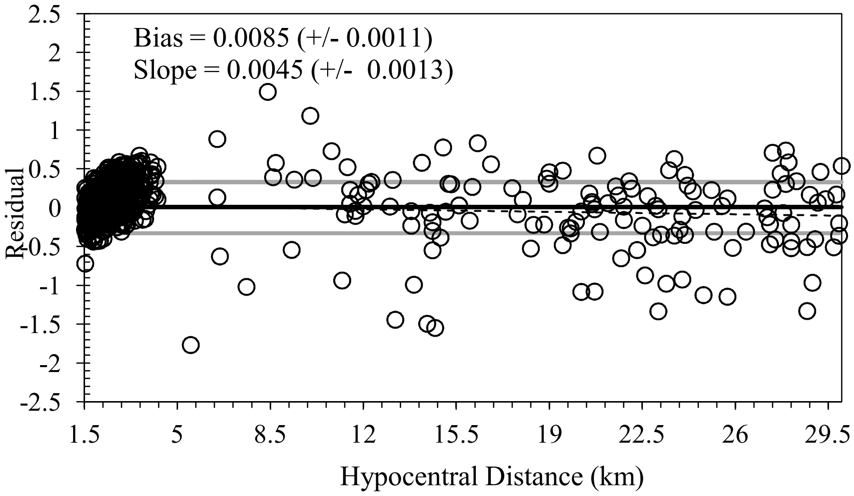

Figure 4a. The residuals for PGA (logarithm of observations minus logarithm of predictions) estimated by the regression performed considering Eq. and calculated versus both hypocentral distance and magnitude. Thick solid line represent bias, light grey solid line and dashed line represent the standard deviations and the residuals best fit.

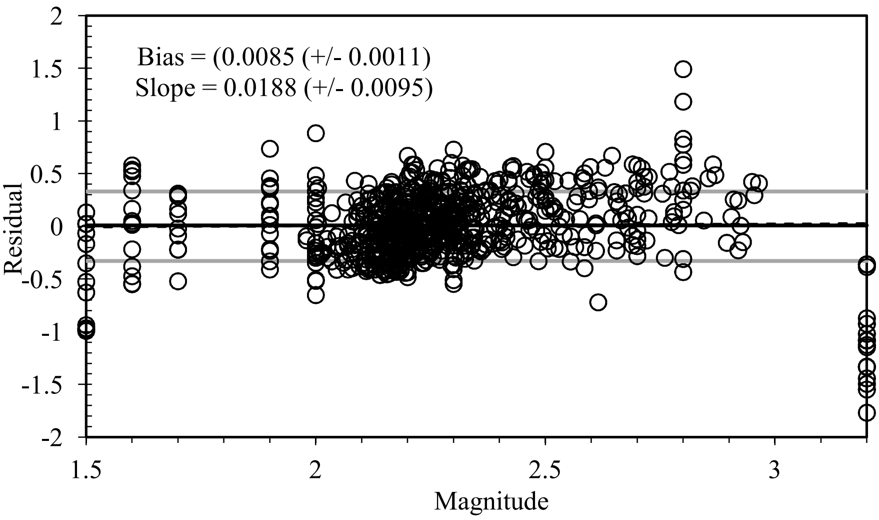

Figure 4b. Continues for residuals versus magnitude

Furthermore, in order to check the reliability of derived GMPE, we compared it with other available GMPEs derived for low magnitude and shorter distances (e.g. Emolo et al., 2010; Massa et al. 2007). The two models have been derived for Lucia-Campania area of southern Italy and Central-Northern Italy. Both models have been compared for rock site conditions because available observed dataset is collected from rock-site. Referring to Fig. 5. , we observed attenuation present estimated have slower attenuation characteristic than the Massa et al. (2007). This may be due to range of distance of observed data set used. Our study is limited to 30 km distance while Mass et al (2007) used most of the observed data in range of 30 to 300 km. This study shows similar attenuation characteristic as by Emolo et al. (2011). This attributed to the similar distance range considered to retrieved the GMPE from observed PGA. This may lead to the conclusion that attenuation characteristics of low magnitude earthquakes strongly dependent on distance range considered irrespective of region/site considered.

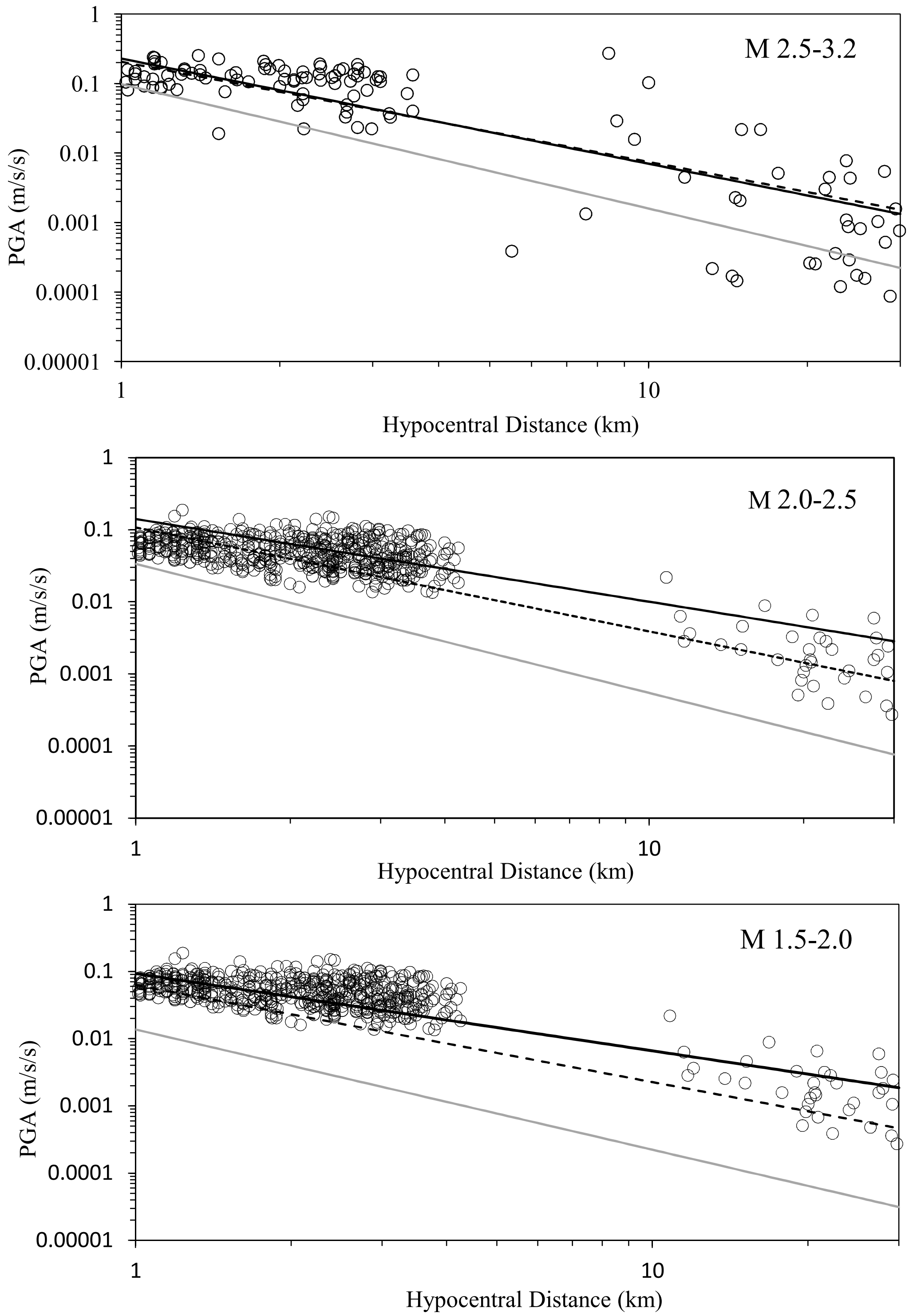

Figure 5. The observed PGA values (circles), as function of hypocentral distance, compared with respect to the GMPE obtained in this study (black solid line), Emolo et al. 2011(dashed line) and Mass et al. 2007(grey solid line)

6. CONCLUSIONS

Rockbursts are minor earthquakes which are induced due to mining operations. These events have been used to look into the attenuation behavior of strong ground motion. Attenuation relationships for peak horizontal ground acceleration for short distances and low magnitudes have been developed for Kolar Gold Fields mines region in South India. The dataset is covering a magnitude range between 1.5 to 3.2 and a hypocentral distance up to 30 km. The data base suffers a lack of near-field recordings for distances greater than 5 km, however which is compensated by including additional data for distances less than 30 km from Campania-Luciana region of Southern Italy. The recommended attenuation relationship has been shown to be representing the attenuation with distance. Since no such attenuation relationship have been found to exist derived for Indian region. We compared derived GMPE with global GMPEs derived for low magnitude and shorter distances. The general comparison with the higher magnitude and larger distance attenuation relationships shows lesser strong ground motion at shorter distance which could be attributed to the low strain levels at which the earthquakes are generated.

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