of the models for operational use may be further improved from time to time as more and more data becomes available.

5. Conclusions

Empirical formulae relating earthquake magnitude with coda duration and epicentral distance have been developed using the data from WWSSN, SRO and Helicorder systems of New Delhi, Shillong and Bombay observatories. Three models have been fitted with four data sets using regression analysis. It is concluded that Model III, which accounts for a possible increase in slope M_L *versus* $\log_{10} D$ plot arising due to systematic errors in the measurement, yields better results over Models I and II for all the data sets analysed. It has, however, been observed that Models II and III do not show much difference. The coda durations measured from SRO system could be made use of for calibrating the coda duration with Richter's magnitude. To further improve upon the results, the data has been passed through a 1-S.D. filter and the parameters of the models re-determined. The results show remarkable improvement as evidenced by higher correlation coefficient of 98% and a very low standard error of estimate of 0.15 for the data of WWSSN system of Shillong. The empirical relations developed in the present study will be of great operational utility in improving the assignment of local magnitudes in day to day analysis work.

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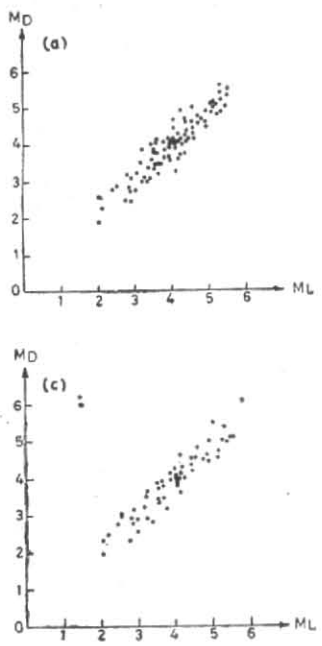
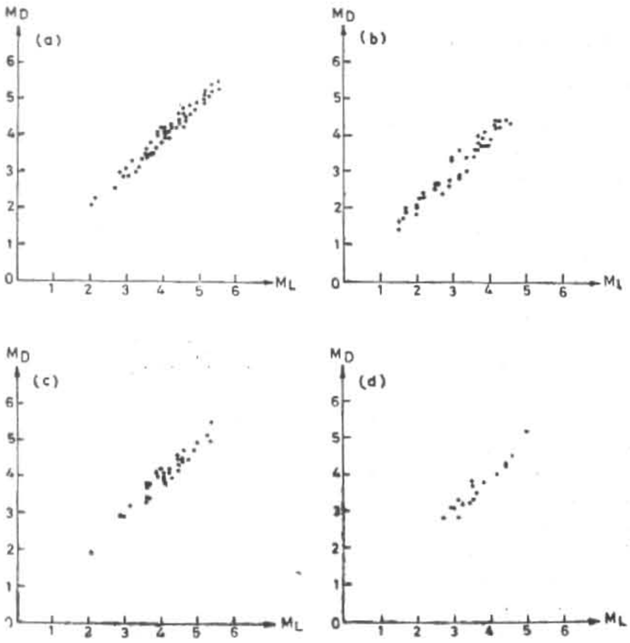


Figs. 5 (a-d). Fit between M_L and M_D using the results of Model III for **four** data sets



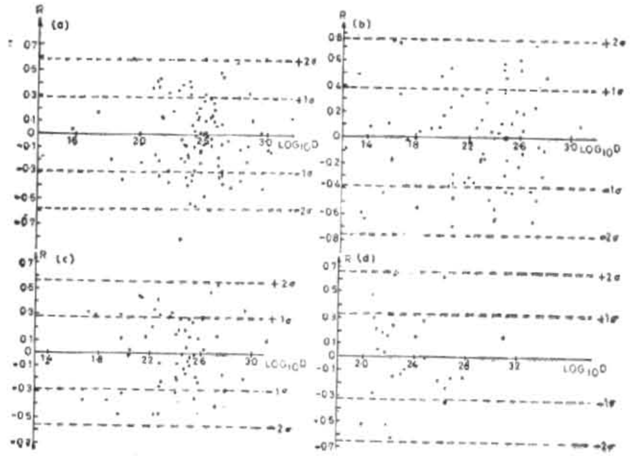
Figs. 6 (a-d). Plots of M_L *versus* M_D obtained for Model III using the filtered data

TABLE 3

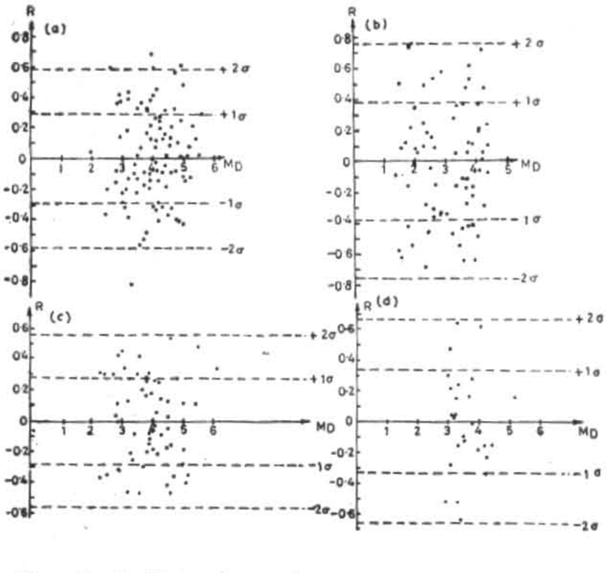
Results

Model	No. of events	a_0	a_1	a_2	$R(\%)$	S.E.
		(a) WWSSN (Shillong)				
II	63	—0.6066	1.6265	0.0038	97.9	0.156
III	63	1.2946	0.3396	0.0039	98.1	0.148
		(b) WWSSN (New Delhi)				
II	46	—0.5670	1.3831	0.0026	97.4	0.209
III	46	0.8641	0.3220	0.0026	97.6	0.204
		(c) SRO (Shillong)				
II	37	—1.1525	1.9436	0.0023	96.9	0.174
III	37	1.0396	0.4194	0.0024	97.6	0.156
		(d) Helicorder (Bombay)				
II	19	—1.6634	1.9835	0.0031	96.3	0.167
III	19	0.7486	0.3891	0.0035	96.1	0.171

and M_D plotted using the results of Model III (Table 2) for the four data sets. To further improve upon the applicability of the models for operational use, the original data has been passed through a 1-S.D. filter and the parameters of the models re-determined. The results tabulated in Table 3 clearly show considerable improvement as evidenced by very low standard errors and high correlation coefficients. Figs. 6 (a-d) are the plots of M_L *versus* M_D obtained for Model III using the filtered data (Table 3). The data set from WWSSN system at Shillong yields the lowest standard error of estimate of 0.148 with a correlation coefficient of 98.1 per cent for Model III. However, it may be seen from Table 2 that, the data from SRO system gives better estimates of duration magnitudes over the data set of WWSSN system of Shillong, when 1-S.D. filter is not used. The efficacy



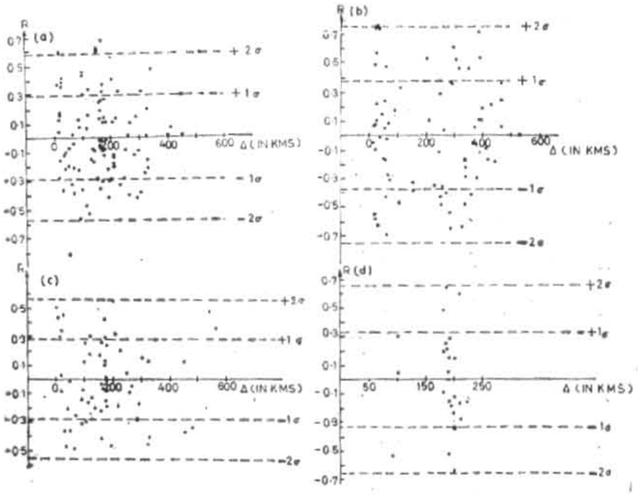
Figs. 2 (a-d). Plots of magnitude residuals against common logarithm of duration



Figs. 4(a-d). Plots of magnitude residuals against duration magnitude (M_D)

estimates have any effect on a possible increase in the slope arising due to errors involved in the measurement of duration. Hence, Model III, which accounts for this non-linearity, has been fitted with the data. A comparison of the results obtained for Models II and III indicates that the difference is not significant but Model III is marginally superior to Model II. The results also show good agreement with a similar study attempted by Rao and Gupta (1982) who had derived an expression of the form :

$$M = -0.74+1.67\log D+0.0009\,\triangle$$



Figs. 3 (a-d). Plots of magnitude residuals against epicentral distance (km)

with an uncertainity of 0.28 (S.D.). Dube *et al.* (1986) while working on the seismicity of northeast India have also derived an expression of the form :

$$M_D = 1.3622\log D+1.17$$

Further analysis by them has indicated that a term of $0.0001\,\triangle$ could be added to the model to suggest marginal dependence upon the epicentral distance (unpublished).

A close examination of Table 2 clearly indicates that Model III in general yields better results in comparison to Models I and II for all the data sets. However, the data set for Bombay region does not practically show any difference between the models. This may be attributed to the fact that the events recorded by the Bombay observatory have more uniform magnitudes ranging from 2.6 to 4.6 (except for one event with $M = 5.0$) with their epicentral distances varying between 90 & 220 km. From the foregoing discussion, it is evident that Model I yields equally better results as long as the data set consist of events recorded within limited range in magnitudes and epicentral distances. As the range of magnitudes and epicentral distance increases, it becomes necessary to account for the distance term and hence Models II and III yield better results over Model I.

In order to ensure that the empirical relations so developed are consistent over the entire range of variables, it is necessary to examine whether the magnitude residuals ($R=M_D-M_L$) show any systematic variation with epicentral distance, coda duration and duration magnitude. The plots of magnitude residuals against epicentral distance, common logarithm of duration and duration magnitude are shown in Figs. 2-4 for all the data sets. As may be seen from the diagrams, no clear trends are evident. Also, it may be seen that most of the events have residuals within ± 1 S.D. range. Figs. 5 (a-d) demonstrate an excellent fit between M_L

TABLE 2

Results

Model	a_0	a_1	a_2	$R(\%)$	S.E.
		(a) WWSSN (Shillong)			
I	—1.9502	2.4153	—	83.7	0.444
II	—0.7645	1.6783	0.0038	93.2	0.295
III	1.2305	0.3453	0.0039	93.3	0.293
		(b) WWSSN (New Delhi)			
I	—1.5612	2.0791	—	88.5	0.464
II	—0.4425	1.3203	0.0027	92.3	0.384
III	0.8879	0.3146	0.0026	92.4	0.382
		(c) SRO (Shillong)			
I	—2.1985	2.5542	—	89.5	0.407
II	—0.9280	1.8084	0.0029	95.0	0.285
III	1.0915	0.3969	0.0029	95.3	0.277
		(d) Helicorder (Bombay)			
I	—1.0984	1.9904	—	85.2	0.327
II	—1.1120	1.9507	0.0006	85.3	0.326
III	1.2157	0.3874	0.0011	85.3	0.326

$$R = \frac{\overline{M_L M_D} - \overline{M}_L \,.\, \overline{M}_D}{\sqrt{\left(\overline{M^2_L} - \overline{M}^2_L\right).\left(\overline{M^2_D} - \overline{M}^2_D\right)}} ,$$

$$\text{S. E.} = \sqrt{\frac{\Sigma\,(M_L - M_D)^2}{N}}$$

4. Analysis and discussion

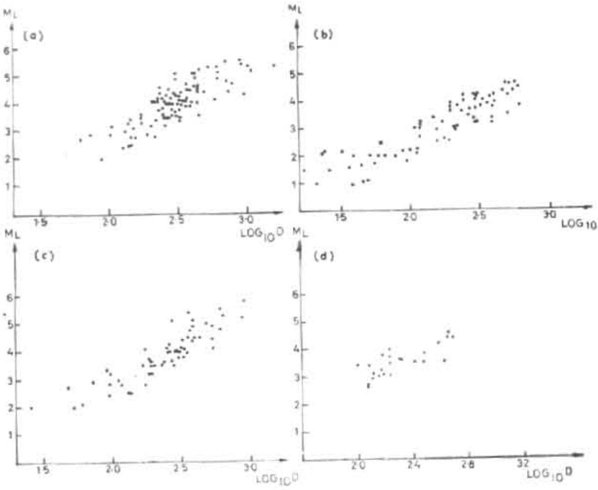
The following three models have been tested on the data sets referred in the previous section :

Model I : $M_D = a_0 + a_1 \log_{10} D$

Model II : $M_D = a_0 + a_1 \log_{10} D + a_2 \triangle$

Model III : $M_D = a_0 + a_1 (\log_{10} D)^2 + a_2 \triangle$

where M_D is the duration magnitude, D is the signal duration in seconds, $\triangle$ is the epicentral distance in kilometres and a_0, a_1 and a_2 are the constants to be determined through regression analysis. The results obtained using the S.E./models are tabulated in Table 2 for all the four data sets. In Table 2, R denotes the correlation coefficient between M_L and M_D and S.E- the standard error of estimate. Figs. 1 (a-d) depict the common logarithm of signal duration plotted against local Richter magnitude (M_L) for all the events used in the analysis. Assuming a linear relationship between magnitude and log D, Model I has been fiited with the data, the results of which are tabulated in Table 2. Studies by Tsumura (1967) and Gupta *et al.* (1980) indicated that there is little dependency of epicentral distance on coda duration magnitudes. This is also reflected by the small coefficients obtained for the distance term in the models. Gupta *et al.* (1980) while working on the data of Koyna network have found that the effect of epicentral distance in estimating the magnitude from coda duration is very small especially for smaller epicentral distances. Accordingly, they have adopted a model of Type I wherein the surface wave magnitude (M_S) determined from the records of HYB is linearly related with the common logarithm of duration. The parameters of the model obtained by them for the Koyna network are :



Figs. 1 (a-d). Relation between $\log_{10} D$ and M_L

$$a_0 = -2.44 \quad \text{and} \quad a_1 = 2.61$$

It is necessary to account for the distance term in these models when the events analysed have comparatively larger range of epicentral distances. As the events analysed in the present study have epicentral distances as large as 555 km, the distance term has been incorporated in Model II and the results when compared with that of Model I indicate that Model II yields better results over Model I as evidenced by higher correlation coefficients and lower standard errors of estimate.

Charles and Teng (1973) while applying coda duration method for the data of California region network have observed that there is a slight increase in the slope of log D *vs* M_L plot for higher magnitude levels ($M > 3.8$). To account for this increase in the slope, they have adopted a quadratic form of equation by adding another variable $(\log_{10} D)^2$. Two possible explanations have been offered for this observed non-linearity namely, systematic errors in measurement of duration or systematic difference between the Richter magnitude and other magnitude scales. The events analysed in the present study have a very wide range of magnitudes (M_L) ranging from 1.0 to 5.8. An attempt has, there fore, been made to examine whether the magnitude