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SIZE BASED CHARACTERIZATION OF SEISMIC MAGNITUDES

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ABSTRACT
Seismic magnitude is the quantitative measurement of amount of energy released by an earthquake. The size of the earthquakes is independent of the density of population and type of construction. Earthquakes may be characterized as minor or great, depending on their magnitude. Different magnitude scales used to measure the magnitude of an earthquake are Richter scale, Body-wave magnitude scale, Surface-wave magnitude scale and Moment-magnitude scale. Seismograms recorded at different epicentral distances are employed to determine origin time, epicenter focal depth and type of faulting as well as to estimate the energy released during an earthquake. Selection of the scale depends upon the earthquake size. In this paper, we discuss the different magnitude scales, the relevance of each scale and their conversion equations.

KEYWORDS: Seismic waves, magnitude, delta, Richter, Scale.

I. INTRODUCTION
Earthquake size is expressed and measured in several ways: Qualitative or non instrumental and quantitative or instrumental. The latter can be either based on regional calibrations or applicable worldwide. Non-instrumental measurements are of great importance for pre-instrumental and are hence essential in the compilation of historical earthquake catalogues for purpose of hazard analysis. For earthquake that have seen instrumentally recorded, qualitative scales are complementary to the instrumental data. The assessment and use of historical records is not straight forward and may lead to incorrect results due to inevitable biases.

Seismograms recorded at different epicentral distances are employed to determine origin time, epicenter focal depth and type of faulting as well as to estimate the energy released during an earthquake. Descriptive methods can also be used to establish earthquake-induced damage and its spatial distribution.

The standard interpretation of a seismogram involves measurement of the arrival of the wave groups or phases which are identified by wave type and path through the earth. The seismograms are interpreted with the aid of travel time charts/table. Travel time of a phase at an epicentral distance Δ (Delta) is the time required by the phase to travel from the hypocenter (or focus) to arrive at a station with the epicentral distance Δ. The distance between two points on surface is measured along the shortest path between these points. This path is part of great circle on the earth. If this path subtends an angle Δ° at the centre of the earth, distance is also indicated by this angle. The perimeter of the earth is about 40,000 km and this perimeter subtends 360° at the centre of the earth. Thus distance 9° between two points means distance is equal to 1000 km, thus 1° =111.1 km.

Earthquakes are quantified either in terms of magnitude or intensity. The strength of an earthquake, or strain energy released by it is usually measured by a parameter called "Magnitude" determined from the instrumental (Seismograph) records. Magnitude for an earth quake remains the same, irrespective of the place, where it is measured. It can be measured by the amount of strain energy released.

Intensity of an earthquake is a subjective measure of the force of an earthquake at a particular place as determined by its effects on persons, structures and earth materials. The intensity at a point depends not only upon the strength of the earthquake (i.e. magnitude) but also upon the distance from the earthquake to the point and the local geology at that point. The intensity decreases with the distance from the epicenter. An earthquake at different locations is experienced with different levels of intensity.

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The earthquake magnitude has statistical and other uses independent of the relation between magnitude and energy. Based upon the epicentral distance and the characteristics of the seismographs, five magnitude scales are in use for earthquakes:

(1) Magnitude from coda duration (M_d)

(2) Local magnitude or Richter magnitude (M_L)

(3) Body-wave magnitude (M_b)

(4) Surface-wave magnitude (M_s)

(5) Moment magnitude (M_w)

M_L was identified for local events in South California by Woods Anderson in torsion seismographs by Richter [-]. The development of Richter scale and its use for determining earthquake source parameters has been explained by Boore [-]. Later, Gutenberg and Richter [-] modified the tables for determining M_b, due to the discrepancies arising among magnitudes from local earthquake data M_L, body waves M_b and surface waves M_s. Kanamori [-] examined the relation between different magnitude scales and introduced the concept of moment magnitude M_w. Bormann and Giacomo [-] have discussed the modern scales for moment magnitude M_w and energy magnitude M_e and provided a parameter linking the two magnitudes.

In the present paper, we discuss the methods of determining different magnitude scales of earthquakes, and explain the techniques of their measurement employed in India.

II. EARTHQUAKES CHARACTERIZATION METHODS

The various methods used to determine the magnitude of earthquakes are discussed below:

(1) Magnitude from coda duration (M_d)

If earthquake is having epicenter very close to recording station i.e. Δ upto 1°, then the magnitude is calculated using total duration of the earthquake in recorded waveform (Fig. 1)

$$M_d = 0.567 + 1.3831 \times \log_{10} D + 0.0026 \times \Delta \quad (1)$$

where D is the total duration of the earthquake on seismogram in seconds, which starts from beginning of Primary (P) wave to end of Secondary (S) wave. In Eq. (1) value of Δ (i.e. S-P) is taken from travel-time table (Table 1).

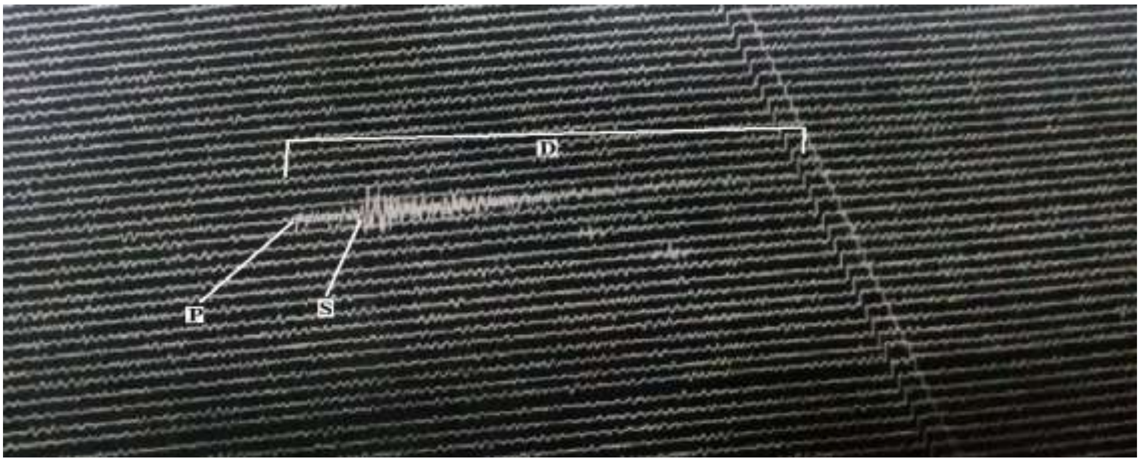

Fig. 1: Pattern of earthquake waveform recorded by Micro Earthquake Recorder for M_d

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Table 1: Travel-time difference table of local earthquakes for determining Δ°

Δ°	$S_g - P_g$ (Sec.)	$S^* - P^*$ (Sec.)	$S_n - P_n$ (Sec.)	$S_g - P_n$ (Sec.)		Δ°	$S_g - P_g$ (Sec.)	$S^* - P^*$ (Sec.)	$S_n - P_n$ (Sec.)	$S_g - P_n$ (Sec.)
0.1	1.3					2.1	27.5	27.6	27.2	32.6
0.2	2.6					2.2	28.8	28.8	28.3	34.4
0.3	3.9					2.3	30.1	30.1	29.4	36.2
0.4	5.2					2.4	31.4	31.4	30.5	38.1
0.5	6.5					2.5	32.7	32.6	31.6	40.0
0.6	7.8	8.6				2.6	34.0	33.8	32.7	41.9
0.7	9.1	9.9				2.7	35.3	35.1	33.8	43.7
0.8	10.4	11.2	12.7	8.1		2.8	36.6	36.4	34.9	45.6
0.9	11.7	12.5	14.0	10.0		2.9	37.9	37.7	36.0	47.5
1.0	13.0	13.7	15.0	11.9		3.0	39.3	38.9	37.2	49.4
1.1	14.3	15.0	16.2	13.8		3.1	40.6	40.1	38.4	51.2
1.2	15.7	16.2	17.3	15.7		3.2	41.9	41.4	39.5	53.2
1.3	17.0	17.5	18.4	17.6		3.3	43.2	42.7	40.6	55.1
1.4	18.4	18.8	19.5	19.5		3.4	44.5	44.0	41.7	56.9
1.5	19.7	20.0	20.6	21.4		3.5	45.8	45.2	42.8	58.8
1.6	21.0	21.2	21.7	23.3		3.6	47.1	46.4	43.9	60.7
1.7	22.3	22.5	22.8	25.2		3.7	48.4	47.7	45.0	62.6
1.8	23.6	23.8	23.9	27.0		3.8	49.8	49.0	46.1	64.5
1.9	24.9	24.1	25.0	28.9		3.9	50.0	50.3	47.2	65.4
2.0	26.2	26.3	26.1	30.7		4.0	52.4	51.5	48.3	68.3

(2) Local magnitude or Richter magnitude (M_L **)**

The magnitude of most earthquakes is measured on the Richter scale and it is used for earthquake which occur at $\Delta < 9^{\circ}$. At a particular observatory, seismograms of larger earthquakes show bigger wave amplitudes than those of smaller earthquakes. Where seismograms recorded at farther distances show smaller wave amplitudes than those at closer distances. The Richter magnitude is calculated from the amplitude of largest seismic wave recorded for the earthquake, irrespective of the type of wave. This scale is also called local magnitude scale. This magnitude is based on a logarithmic scale (base 10), this means that for each whole number we go up on

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the Richter scale, the amplitude of the ground motion recorded by a seismograph goes up ten times. Photographic papers used in Wood Anderson (W.A.) seismograph.

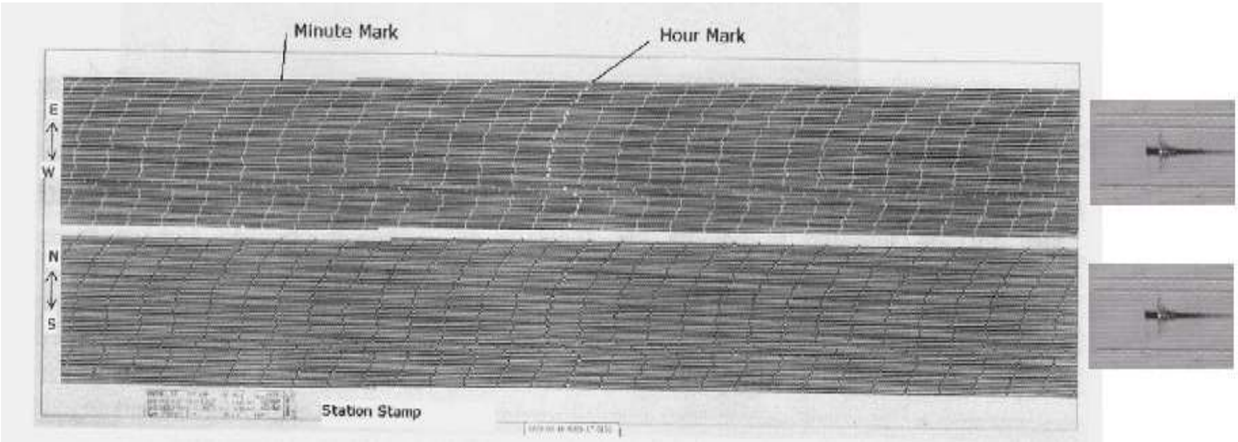

Fig. 2: Pattern of earthquake waveform recorded by Wood Anderson Recorder for M_L

Procedure of M_L ***determination:*** Measure maximum trace amplitudes of the earthquake in N-S and E-W component A_e and A_n in mm at the same time. Subtract thickness of the normal trace line. Add final values of both components and multiply the result by 0.7.

$$(A_e + A_n) \times 0.7 = B \quad (2)$$

Match the value of B given by Eq.(2) with delta (km/degree) on the monogram in Fig. 3. The value of M on the central scale of the monogram is the magnitude (M_L) of the earthquake on Richter scale.

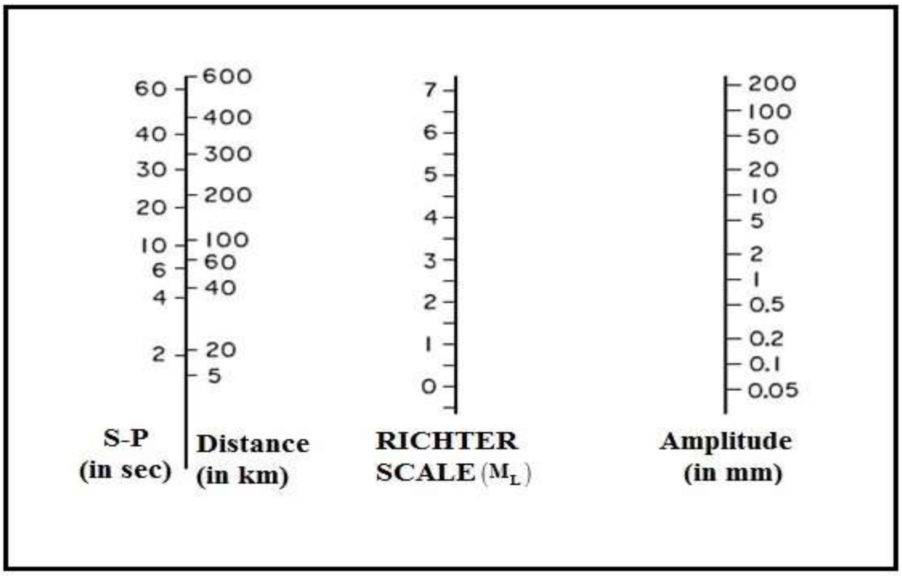

Fig. 3: Monogram for M_L *calculation*

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(3) Body-wave magnitude (M_b)

M_L is very useful when earthquakes occur near from the recording station, but it is convenient to define a magnitude based on the amplitude of few cycles of P-wave. This is termed as M_b and is given by,

$$M_b = Q + \mathrm{Log}_{10}\left(\frac{A}{T}\right), \tag{3}$$

where, Q is the depth-distance factor which depends on both Δ° and focal depth and is obtained from Travel time table Table 3, A is the maximum ground amplitude of P-wave (P_Z, P_H, PP_Z, PP_H phases) and S_H phase of S-wave of the first few cycles of the wave recorded in a short period seismograph, T is the corresponding period of the wave in seconds. Here, A is in micron (1 micron=0.001 mm). To obtain A in mm, the recorded amplitude is divided by the magnification (K) of the seismograph at the period T. Where, K is the magnification factor in thousands at period T, given by Table 4. Eqn. (3) can be written as,

$$M_b = Q + \mathrm{Log}_{10}\left(\frac{A}{KT}\right) \tag{4}$$

Table 2: Travel-time table of surface focus earthquakes

Δ°	S-P			Δ°	S-P			Δ°	S-P			Δ°	S-P	
	Min	Sec			Min	Sec			Min	Sec			Min	Sec
1	0	21		27	5	45		53	9	21		79	12	7
2	0	35		28	5	55		54	9	28		80	12	13
3	0	50		29	6	4		55	9	35		81	12	18
4	1	4		30	6	13		56	9	43		82	12	23
5	1	18		31	6	21		57	9	50		83	12	28
6	1	32		32	6	30		58	9	57		84	12	34
7	1	46		33	6	39		59	10	4		85	12	39
8	2	0		34	6	48		60	10	11		86	12	44
9	2	14		35	6	56		61	10	18		87	12	48
10	2	28		36	7	5		62	10	24		88	12	53
11	2	42		37	7	13		63	10	31		89	12	58
12	2	55		38	7	21		64	10	38		90	13	3
13	3	9		39	7	30		65	10	14		91	13	7
14	3	22		40	7	38		66	10	50		92	13	12
15	3	35		41	7	46		67	10	57		93	13	17
16	3	48		42	7	55		68	11	3		94	13	21
17	4	1		43	8	3		69	11	9		95	13	26
18	4	13		44	8	11		70	11	15		96	13	30
19	4	26		45	8	19		71	11	22		97	13	35
20	4	37		46	8	27		72	11	28		98	13	39
21	4	47		47	8	35		73	11	33		99	13	41
22	4	58		48	8	43		74	11	39		100	13	48
23	5	7		49	8	50		75	11	45		101	13	53
24	5	17		50	8	58		76	11	51		102	13	57
25	5	27		51	9	6		77	11	56		103	14	2
26	5	36		52	9	13		78	12	2				

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Δ°	PP-PKP		Δ°	PP-PKP		Δ°	PP-PKP		Δ°	PP-PKP	
	Min	Sec		Min	Sec		Min	Sec		Min	Sec
110	0	37.8	122	1	38.4	134	2	34.5	146	3	26.1
111	0	43.8	123	1	43.5	135	2	38.6	147	3	30.4
112	0	47.9	124	1	48.5	136	2	42.8	148	3	34.8
113	0	53.9	125	1	52.6	137	2	47.0	149	3	38.2
114	0	58.9	126	1	57.5	138	2	52.1	150	3	43.0
115	1	4.0	127	2	1.8	139	2	56.3	151	3	47.1
116	1	9.0	128	2	6.8	140	3	0.5	152	3	50.6
117	1	14.1	129	2	11.9	141	3	4.7	153	3	55.2
118	1	19.2	130	2	16.0	142	3	9.0	154	3	59.8
119	1	24.2	131	2	21.1	143	3	13.3	155	4	3.45
120	1	28.3	132	2	25.2	144	3	17.6	156	4	8.2
121	1	33.3	133	2	29.3	145	3	21.8			

Table 3: Depth-distance factor (Q) at surface for M_b

Δ°	Q	Δ°	Q	Δ°	Q	Δ°	Q
1	--	13	6.7	25	6.2	37	6.2
2	5.3	14	6.3	26	6.1	38	6.2
3	5.5	15	6.0	27	6.2	39	6.1
4	5.8	16	5.6	28	6.3	40	6.1
5	6.1	17	5.6	29	6.3	41	6.2
6	6.3	18	5.6	30	6.3	42	6.2
7	6.5	19	5.7	31	6.4	43	6.2
8	6.7	20	5.7	32	6.4	44	6.2
9	6.0	21	5.8	33	6.4	45	6.4
10	7.0	22	5.9	34	6.4	46	6.5
11	6.9	23	6.0	35	6.4	47	6.5
12	6.8	24	6.0	36	6.3	48	6.5

Table 4: K factor of Magnification

Wave Period	Magnification	A in micron
0.2	40000	$\text{Log}\left(\dfrac{\text{single amplitude}\times 1000}{8}\right)$
0.4	60000	$\text{Log}\left(\dfrac{\text{single amplitude}\times 1000}{24}\right)$
0.5	70000	$\text{Log}\left(\dfrac{\text{single amplitude}\times 1000}{35}\right)$
0.6	75000	$\text{Log}\left(\dfrac{\text{single amplitude}\times 1000}{45}\right)$
0.7	72000	$\text{Log}\left(\dfrac{\text{single amplitude}\times 10000}{504}\right)$

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0.8	66000	$\text{Log}\left(\frac{\text{single amplitude}\times 10000}{528}\right)$
0.9	60000	$\text{Log}\left(\frac{\text{single amplitude}\times 1000}{54}\right)$
1.0	50000	$\text{Log}\left(\text{single amplitude}\times 20\right)$
1.1	32000	$\text{Log}\left(\frac{\text{single amplitude}\times 10000}{352}\right)$
1.2	22000	$\text{Log}\left(\frac{\text{single amplitude}\times 10000}{264}\right)$
1.3	18000	$\text{Log}\left(\frac{\text{single amplitude}\times 10000}{234}\right)$
1.4	16000	$\text{Log}\left(\frac{\text{single amplitude}\times 10000}{224}\right)$
1.5	14000	$\text{Log}\left(\frac{\text{single amplitude}\times 1000}{21}\right)$
1.6	12000	$\text{Log}\left(\frac{\text{single amplitude}\times 10000}{192}\right)$
1.7	12000	$\text{Log}\left(\frac{\text{single amplitude}\times 10000}{204}\right)$
1.8	12000	$\text{Log}\left(\frac{\text{single amplitude}\times 10000}{216}\right)$
1.9	12000	$\text{Log}\left(\frac{\text{single amplitude}\times 10000}{228}\right)$
2.0	9000	$\text{Log}\left(\frac{\text{single amplitude}\times 1000}{18}\right)$

(4) Surface-wave magnitude (M_S)

Due to limitation of epicentral distance and instrument characteristics and in the calculation of magnitude, it necessary to use an alternate magnitude scale. For larger epicentral distances, i.e. $\Delta > 9^{\circ}$, the seismogram usually show surface waves with longer periods (Fig. 4).

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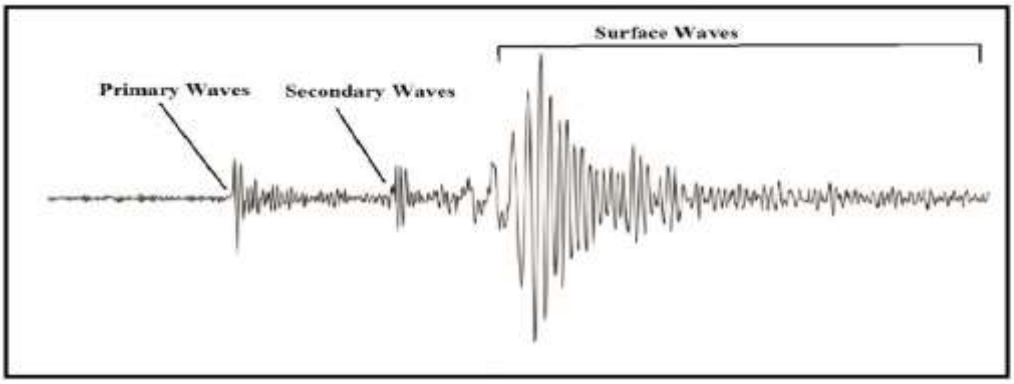

Fig. 4: Earthquake with surface wave pattern

Surface waves contain the largest energy content of the whole wave front. Thus, it is possible to estimate the energy released by an earthquake from the amplitude and periods of surface wave. Surface wave magnitude, M_S is obtained from the relation

$$M_S = \text{Log}\left(\frac{A}{T}\right)_{max} + 1.66(\text{Log}\,\Delta) + 3.3 \qquad (5)$$

Here again A is ground amplitude in micron, $\left(\frac{A}{T}\right)_{max}$ is the maximum values of all A/T values of the surface wave group either in vertical or in horizontal component. It is recommended to use horizontal component of Rayleigh surface wave in the long period range of 10 to 30 second. If A_N and A_E are double amplitudes in north and south components then

$$\frac{A}{T} = \frac{1}{1000\,KT}\sqrt{\left(\frac{A_N}{2}\right)^2 + \left(\frac{A_E}{2}\right)^2}$$

where K is the magnification at the period T of surface wave (Table 4).

(5) Moment magnitude (M_W)

It is seen that for large earthquakes, M_b becomes saturated at about 6.5 and M_S is saturated at about 8.0 magnitudes. To avoid this saturation effect and standardize the magnitude scales, a magnitude scale based on seismic moment (M_o) was proposed by Kanamori (1977). The seismic is the measure of size of an earthquake based on the area of fault rupture, the average amount of slip and the force that is required to overcome the friction sticking the rocks together that become offset by faulting. The moment magnitude (M_W **)** scale is estimated using the formula given below

$$M_W = \frac{2}{3}\text{Log}\,M_o - 6.06 \qquad (6)$$

M_o is the seismic moment in dyne-cm, given by

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$$M_o = (\text{Rock rigidity}) \times (\text{Fault area}) \times (\text{Slip distance}) = \mu\ A\ D$$

μ = Rigidity or shear modulus of the crust (approx. $3\times10^{10}\ N/m^2$)

Since the seismic moment is a measure of strain energy released from the entire rupture surfaces, a magnitude scale based on the seismic most accurately describes the size of large earthquakes. So, the moment magnitude scale is the most preferred magnitude scale in case of large earthquakes.

The three magnitudes M_d, M_b and M_s for same earthquake may not agree with each other and relations exist among them. The relation between M_b and M_s is

$$M_b = 0.56\,M_s + 2.9$$

The relation between M_L and M_b may vary with regions. A favourable relation between them is given by

$$M_b = 1.7 + 0.8\,M_L - 0.01(M_L)^2$$

III. CONCLUSION

Seismic magnitude scales are used to describe the overall strength or 'size' of an earthquake. Magnitudes are determined from measurements of an earthquake's seismic waves as recorded on seismogram. Different magnitude scales are necessary because of differences in earthquakes, and in the purposes for which magnitudes are used. All magnitude scales retain the logarithmic scale as devised by Charles Richter. The magnitude of an earthquake is complexly related to the parameters which control the level and duration of the strong ground motion. In conclusion, we can say that the Richter Scale is mostly effective for regional earthquakes, while the Moment magnitude is more effective for large earthquakes.

IV. ACKNOWLEDGEMENTS

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