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A Seismic Moment Magnitude Scale

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Abstract The aim of obtaining a single scale for earthquake magnitudes has led many studies in the past to either develop relationships among various existing scales or develop an altogether new scale to represent a wide range of magnitudes on a single scale. Although a reliable and standardized estimation of earthquake size is a basic requirement for all tectonophysical and engineering applications, different magnitude scales estimate different values for the same earthquake, thereby making such studies inadequate. The moment magnitude (M_w) scale has been referred to by various researchers as the best scale, one that matches well with the observed surface-wave magnitudes with $M_s \geq 7.5$ at a global level. The formulation and validation of the M_w scale were carried out considering the southern California region for lower and intermediate earthquakes.

In this study, an endeavor has been made to extend the moment magnitude scale to include lower and intermediate magnitudes in a global context emphasizing the use of body waves, particularly *P* waves, in which data are abundant. We first investigate the degree of closeness of M_w values with other observed magnitudes (e.g., M_s and m_b) for smaller and intermediate magnitude ranges considering global International Seismological Centre (ISC) and Global Centroid Moment Tensor (CMT) databases. To improve upon the consistency of the M_w scale for a wider range, a uniform generalized seismic moment magnitude scale $M_{wg} = \log M_0/1.36 - 12.68$, for magnitudes ≥ 4.5, has been developed, considering 25,708 global earthquake events having m_b and M_0 values from ISC and Global CMT databases, respectively, during the period 1976–2006. The M_{wg} scale is also valid for $3.5 \leq m_b \leq 7.0$ because the relations between seismic moment and the magnitudes m_b and M_{wg} are same.

The greater accuracy of the M_{wg} scale over the M_w scale at different magnitudes (i.e., m_b or M_s) is found to be statistically significant in the range including smaller and intermediate events. The similarity of the M_{wg} scale is also tested on 394 global seismic radiated energy values collected from Choy and Boatwright (1995). It is observed that 76% of estimated radiated energy values obtained through the M_{wg} scale show closer agreement (than with M_w) to the observed radiated energy values. M_{wg} is computed from low- and high-frequency spectra, and because it is consistent for small, intermediate, and large earthquake events, it will play a useful role as an earthquake magnitude estimator for all earthquake related studies.

Introduction

The magnitude is generally the first source parameter that is calculated quantitatively to determine the strength of an earthquake. Richter (1935) derived the first magnitude scale based on records of local shocks in southern California. Several other magnitude scales then came into practice for estimating the size of an earthquake while accounting for the variations in the earthquake source and the wave type used. However, even after careful assessment of earthquake magnitude size for a given event, actual earthquake magnitude values remain mostly elusive for many obvious reasons. However, the seismic moment has been considered the most useful measure by representing the size of an earthquake in terms of the dislocation phenomenon. Hence, out of all the contemporary magnitudes scales (i.e., body-wave magnitude m_b, surface-wave magnitude M_s, local magnitude M_L, duration magnitude M_D, energy magnitude M_e, and moment

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magnitude M_w), the seismic moment-based magnitude scale M_w is the most widely used unsaturated magnitude scale. One may estimate M_w for magnitude ≥ 3 using equation (7) of Hanks and Kanamori (1979), but it is important to note that the basic idea behind the development of M_w applicable for magnitude ≥ 3 was only based upon and validated with the southern California region. Despite the popularity of M_w, it provides limited information about the earthquake source. This is particularly true regarding its high-frequency content (e.g., Beresnev, 2009), which is more relevant for the evaluation of an earthquake's shaking potential. It has been observed by many authors that using only one scale (i.e., the M_w scale) does not serve the purpose of measuring the actual size of earthquakes due to its inherent limitations (Kanamori, 1977, 1983; Choy and Boatwright, 1995; Kanamori and Brodsky, 2004; Bormann *et al.*, 2009; Das *et al.*, 2011, 2012, 2013, 2014, 2018; Wason *et al.*, 2012). Hence, there is a need to revisit the seismic moment-based M_w magnitude scale in a global context.

Moment Magnitude Scale

To revisit the magnitude scale, we start with the work of Hanks and Kanamori (1979) in which they derived the moment magnitude scale substituting the ratio of energy (E) and the seismic moment (M_0) (i.e., $E/M_0 = (\Delta\sigma/2\mu) = 5 \times 10^{-5}$, in which σ is the earthquake stress drop and μ is the shear modulus) into the Gutenberg–Richter energy magnitude equation:

$$\log E = 1.5M_s + 11.8. \tag{1}$$

This equation is obtained by substituting $m = 2.5 + 0.63M$ in the energy equation $\log E = 5.8 + 2.4m$ (Richter, 1958), in which m is the Gutenberg-unified magnitude and M is a least-squares approximation of the magnitude determined from surface-wave values. Furthermore, the resultant equation

$$\log M_0 = 1.5M_s + 16.1 \tag{2}$$

has been compared to equation (1) of Purcaru and Berckhemer (1978) for the magnitude range $5.0 \le M_s \le 7.5$ (Hanks and Kanamori, 1979). The equation (1) of Purcaru and Berckhemer (1978) for the magnitude range $5.0 \le M_s \le 7.5$ is not reliable due to the inconsistency of the defined magnitude range (moderate-to-large earthquakes defined as $M_s \le 7.0$ and $M_s = 7$–7.5) and to scarce data that rarely represent the global seismicity (e.g., see figs. 1a,b, 4 and table 2 of Purcaru and Berckhemer, 1978). To validate the M_w scale for the lower magnitude range, equation (2) is compared to the southern California local magnitude scale for the magnitude range $3.0 \le M_L \le 7.0$. However, it has been observed from different studies that there are significant spatial variations in the local magnitude (e.g., Hutton and Boore, 1987; Choy and Boatwright, 1995; Ristau *et al.*, 2003; Keir *et al.*, 2006). Finally, Hanks and Kanamori (1979) defined an unsaturated moment magnitude scale in the form:

$$M_w = \frac{2}{3}\log M_0 - 10.7. \tag{3}$$

To check the authenticity of the M_w scale, a comparison was performed between estimated M_w (using equation 3) and other magnitude scales (i.e., M_L and M_s of southern California; see tables 1 and 2 of Hanks and Kanamori, 1979). Because the developed M_w scale (equation 3) was based on equations (1) and (2), Hanks and Kanamori (1979) inferred that the M_w scale was uniformly valid for magnitude ≥ 7.5. However, the moment magnitude scale ($M_w = 2/3 \log M_0 - 10.7$) was also based on the relationship between the local magnitude and the seismic moment for the southern California region as well as the surface-wave magnitude and the seismic moment. Thus, the usability of the M_w scale at global level, specifically for magnitude < 7.5, is not appropriate. This is because the lower range of magnitudes was only calibrated using southern California data and very few surface-wave magnitudes represent global seismicity in equation (1) of Purcaru and Berckhemer (1978).

In this study, we analyze the use of the M_w scale for globally distributed data, particularly within the range including smaller and intermediate events. We first compare the estimates of M_w to other estimates of earthquake size, namely m_b and M_s, for 18,521 events in a global dataset. These comparisons show that the M_w estimates are in reasonable agreement in the high-magnitude range for which it was developed. The primary objective of this study is to provide a consistent generalized seismic moment magnitude scale (M_{wg}) for global level use based on the seismic moment for magnitudes ≥ 4.5, with unsaturated property, and that closely matches other instrumentally measured earthquake magnitudes (i.e., m_b, M_s). Because the proposed scale is developed relating m_b (the first few cycles of P waves) and the seismic moment (low-frequency amplitude spectra) and closely matches with m_b, M_s, M_e, and seismic radiated energy E_s at global level, therefore, this magnitude scale can serve as a useful earthquake size estimator for all earthquake related studies.

Measure of Earthquake Size from Global Seismicity

The applicable range being on the high side for assigning M_w, its equivalence for the range including small and intermediate events is not straightforward and leads to severe bias in size estimation for small and intermediate earthquake events. This is evident from the plot of global seismicity for surface- and body-wave magnitudes shown in Figure 1a,b. Figure 1a reveals that M_w is in reasonably good agreement with higher magnitudes (i.e., around 7.5 and above, within the range for which it was mainly developed from a global database), but fails to represent the trend toward the observed m_b and M_s data for lower and intermediate earthquake events (see Fig. 1a,b). Therefore, Hanks and Kanamori (1979) inferred that M_w is uniform for magnitude ≥ 7.5. Equation (2) drastically underestimates seismic moment values for M_s less than 6.5 and for all ranges of m_b (see Fig. 2a,b). According to equation (3), the

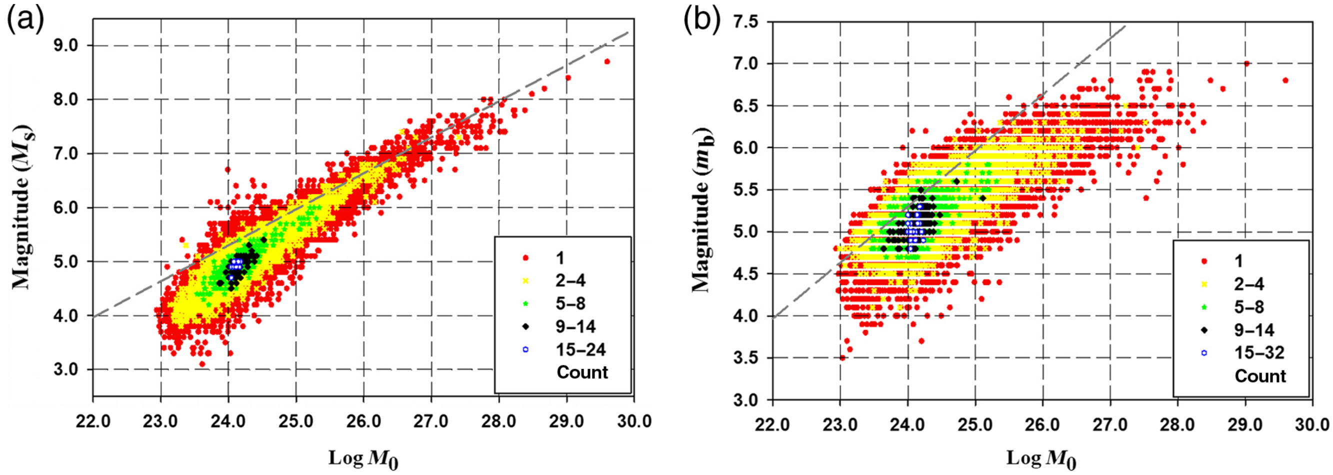

Figure 1. Fitting of Hanks and Kanamori (1979) moment magnitude scaling relation (equation 3) (gray dashed line) using global seismicity for (a) surface-wave magnitudes and (b) body-wave magnitudes. The color version of this figure is available only in the electronic edition.

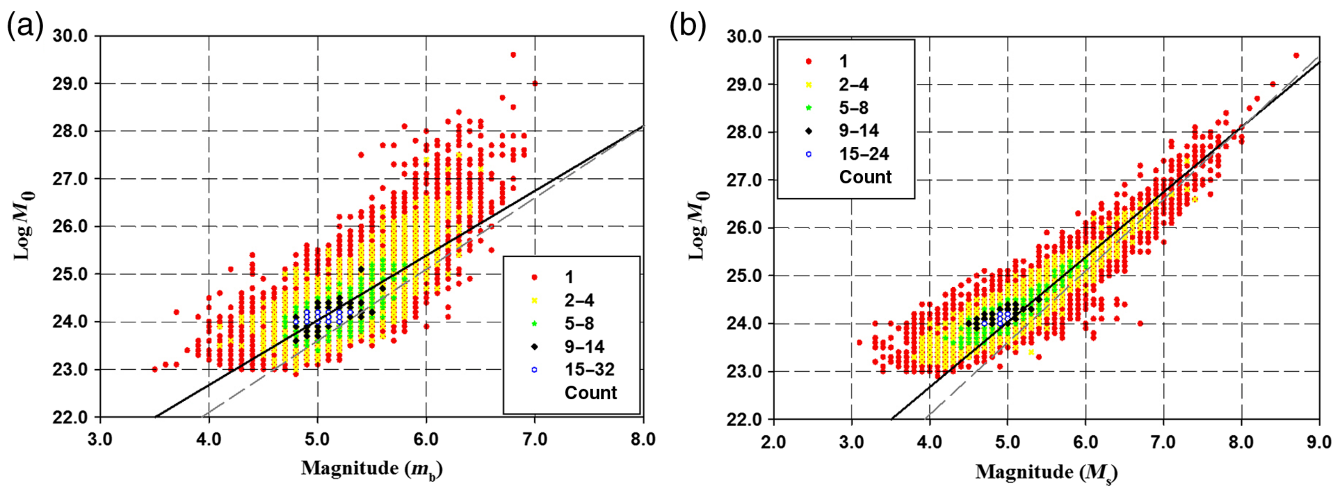

Figure 2. Comparisons of observed seismic moment with estimated ones considering equation (2) based on Hanks and Kanamori (1979) (gray dashed line) and proposed equation (4) (black solid line) using global events with (a) body-wave magnitudes and (b) surface-wave magnitudes. The color version of this figure is available only in the electronic edition.

average difference between observed m_b and estimated M_w is -0.31 ± 0.30, whereas using equation (5), the average difference between observed m_b and estimated M_{wg} is 0.008 ± 0.33. According to equation (3), the average difference between observed M_s and estimated M_w is -0.43 ± 0.28, whereas using equation (5), the average difference between observed M_s and estimated M_{wg} is -0.12 ± 0.26. The moment magnitude scale M_w was developed, in principle, to provide equal magnitude values for earthquakes that radiate equal amounts of energy. However, a systematic bias exists between the developed scale (M_w) and the reference magnitude scales (e.g., m_b, M_s, etc.). The reasons for this disagreement may be attributed to: (1) consideration of a particular regional local magnitude scale (M_L) for validation of lower and intermediate range on the M_w scale (Hutton and Boore, 1987; Choy and Boatwright, 1995; Ristau *et al.*, 2003; Keir *et al.*, 2006); (2) use of the same apparent stress-drop value for earthquakes of different seismotectonic environments; (3) the M_w scale has been validated for the range $5.0 \le M_s \le 7.5$ with equation (1) of Purcaru and Berckhemer (1978), which had limited events representing global seismicity (see figs. 1a,b, 4, and table 2 of Purcaru and Berckhemer, 1978); and (4) consideration of unified magnitude and the two-step method for regression in development of the Gutenberg energy–magnitude ($\log E_s - M$) relationship, in which E_s denotes radiated energy and M denotes an approximation to the magnitude determined from surface waves of shallow teleseisms (Richter, 1958; Geller and Kanamori, 1977; Abe, 1981; Ambraseys *et al.*, 1996).

Our objective is to provide an unsaturated seismic moment–based magnitude scale that is in close agreement with the most used instrumentally measured earthquake sizes

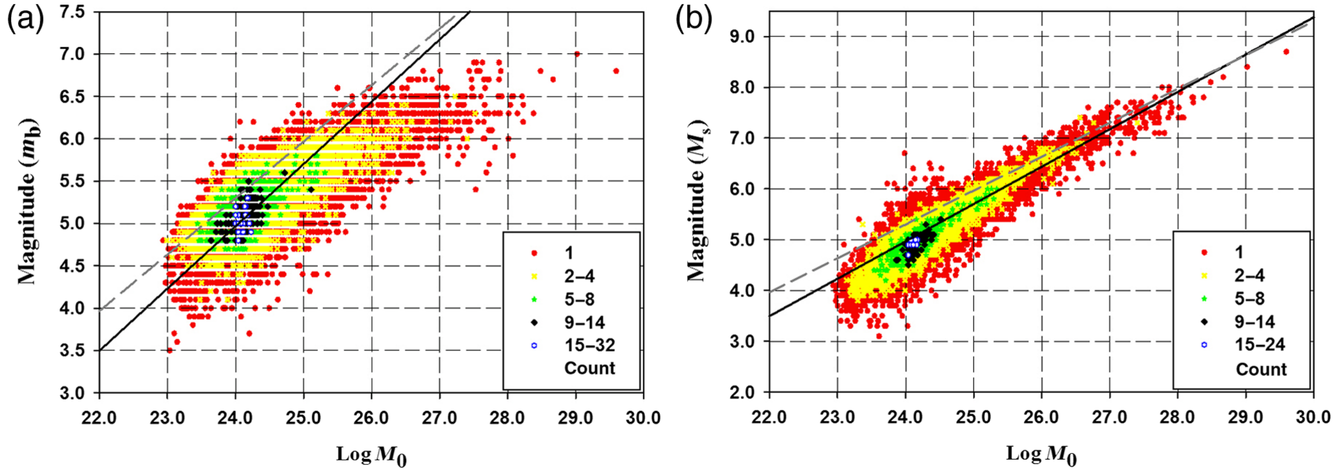

Figure 3. Comparisons of equation (3) for moment magnitude scaling relation (shown in gray dashed line) and equation (5) for generalized moment magnitude scale M_{wg} (shown in solid black line) on (a) body-wave magnitudes and (b) surface-wave magnitudes using global seismicity. The color version of this figure is available only in the electronic edition.

(i.e., m_b and M_s) for lower, intermediate, and higher magnitude ranges irrespective of the regional effects.

To develop an unsaturated and consistent magnitude scale, a total of 25,708 directly observed seismic moment values, along with m_b magnitudes representing global seismicity, have been compiled from Global Centroid Moment Tensor (CMT) and International Seismological Centre (ISC) databases, respectively, for the time period 1976–2006. To be consistent with the fitting techniques of Hanks and Kanamori (1979) and earlier works, a simple least-squares fitting relationship between M_0 and m_b has been derived using 25,708 events over the magnitude range 3.5–7.0, which is given as follows:

$$\log M_0 = 1.36 m_b + 17.24. \tag{4}$$

Our main aim is not to provide the best-fitting line between m_b and M_0 for a certain magnitude range considering the saturation effect, but to provide an unsaturated magnitude scale that matches closely with the observed body, as well as surface-wave magnitudes in low-, intermediate-, and high-magnitude ranges, so that a single magnitude scale could represent the entire range of magnitudes. The line obtained from equation (4) fits statistically better with the (m_b, $\log M_0$) and (M_s, $\log M_0$) datasets of global seismicity (Fig. 2a,b) than with the estimates yielded by equation (2) of Hanks and Kanamori (1979).

Figure 2 shows that the estimated M_0 (using equation 4) is closer to the observed M_0 than that using equation (2). The differences between observed M_0 and the estimated M_0 obtained using equations (4) and (2) are statistically significant for the entire m_b magnitude range (Fig. 2a); however, in the case of Figure 2b, the differences in the estimates obtained by equations (4) and (2) are negligible for higher magnitudes (e.g., from magnitude 7.5–8.5). Comparisons of the estimates using equations (4) and (2), shown in Figure 2, revealed that equation (2) systematically underestimates the seismic moment values up to magnitude 7.8 (Fig. 2b). Thus, the estimates obtained using equation (4) are found to be closer to the observed seismic moments in cases of body- and surface-wave magnitudes for global levels than are those using equation (2).

In deriving M_{wg}, we follow the same procedure adopted by Hanks and Kanamori (1979). The idea is that if m_b is bounded in equation (4), so should M_0 be. Given that M_0 is considered independently, it can therefore be used on the left side of equation (4) in the form $m_b = (\log M_0/1.36) - 12.68$ to determine a magnitude that will not saturate, and it is denoted by M_{wg}. Therefore, M_{wg} can be defined in terms of M_0 as

$$M_{wg} = \frac{\log M_0}{1.36} - 12.68. \tag{5}$$

It has been observed that M_w estimates obtained using equation (3) are significantly overestimated compared with those of M_{wg} using equation (5) up to the value $\log M_0 = 27.38$ (see equations 3 and 5 with Fig. 3), that is, up to a magnitude of 7.5. A null hypothesis test has been performed to quantify the overestimations. We assume that there is no significant difference between both estimations (M_w and M_{wg}) and this null hypothesis has been rejected at confidence intervals 0.05 and 0.025 (Table 1). Although the proposed M_{wg} (equation 5) approaches M_w (equation 3) for the higher magnitudes (i.e., $7.5 \le$ magnitude ≤ 9.0), M_{wg} closely encompasses the energy released for low-, intermediate-, and high-magnitude events. Most of the studies pertaining to seismic microzonation for areas of low and intermediate seismicity involving magnitudes in the range 3–6.5 will find that using M_{wg} as proposed in this study will have significant bearing on hazard values.

Validation of the Generalized Seismic Moment Magnitude M_{wg}

To demonstrate the applicability of the M_{wg} scale for determining consistent earthquake size among small, intermediate, and large events, a total of 18,521 ISC surface-wave magnitudes in the range 3.1–8.7, and 25,708 body-wave

Table 1
Null Hypothesis Test Results for Log M_0 (up to 27.38), m_b in the Range 4.5–5.5, and M_s in the Range 5.5–7.5

	Log M_0		m_b		M_s	
	M_w	M_{wg}	M_w	M_{wg}	M_w	M_{wg}
Mean	5.520507	5.210265	5.38609	5.062011	5.11642	4.764581
Variance	0.202144	0.245904	0.098087	0.119321	0.07508	0.091333
Observations	17,781	17,781	14,193	14,193	1,492	1,492
Df	35,560		28,384		2,982	
t Stat	61.8039		82.80379		33.31456	
$P(T \le t)$ one tail	0		0		0	
t critical one tail	1.644896		1.644907		1.645365	
$P(T \le t)$ two tail	0		0		0	
t critical two tail	1.960031		1.960048		1.96076	

Df, degree of freedom; $P(T \le t)$, probability of test statistics; t Stat, test statistics.

magnitudes in the range 3.5–7.0, have been considered (Figs. 2 and 3). It has been observed from Figure 3 that compared with M_w, M_{wg} estimates exhibit significantly better agreement with respect to observed m_b as well as M_s. It has also been observed that both of the magnitude scales (M_{wg} and M_w) provide nearly the same value for magnitudes in the range 7.5 ≤ magnitude ≤ 9.0 (see Fig. 3b). To validate the significance of the differences between the two estimates (M_w and M_{wg}), a null hypothesis has been created and tested for the two sets of estimates (null hypothesis [Ho]: both data sets have the same mean and variances; the Ho has been rejected at the confidence levels 0.05 and 0.025 for the range 4.5–5.5 for m_b and the range 5.5–7.5 for M_s; see Table 1). Therefore, the differences in the aforementioned ranges have statistical significance. Thus, the single magnitude scale M_{wg} is uniformly valid for magnitude $M_{wg} \ge 4.5$ (see Fig. 3a,b). The moment magnitude estimated by equation (3) instead of equation (5) will produce an average error of 0.31, which is quite significant.

Furthermore, to validate the M_{wg} scale with other observed magnitude scales (e.g., m_b, M_s), a comparison has been performed using 18,521 events that have M_0, m_b, and M_s values. We split the data sets into two parts: shallow focal depth (≤40 km) and deeper focal depth (>40 km) earthquakes. For earthquakes with shallow focal depths, 70% of the observed m_b and 85% of the observed M_s are found to be closer to the estimated M_{wg} than to the corresponding values of M_w. In cases of deeper earthquakes, it is observed that 60% of m_b values and 77% of observed M_s are closer to the values of M_{wg} than to the corresponding estimates of M_w. Furthermore, validation has also been performed for the values of M_s (all depths) in the intermediate magnitude range $5.0 \le M_s \le 7.5$, and it is observed that 75% of M_s values more closely matched the M_{wg} values than those of M_w.

A random global dataset of 200 events with m_b, M_s, and M_{wg} (estimated by equation 5) and M_w (estimated by equation 3) is presented in Table 2 to demonstrate the closeness of the proposed M_{wg} scale with the instrumentally measured m_b or M_s. In the 200-event random dataset, 85% of M_s and 65% of m_b results are observed to be closer to M_{wg} than to M_w.

Furthermore, to check the similarity of M_{wg} and M_w scales with other observed instrumentally measured magnitude scales (i.e., M_e), a globally distributed dataset of 1361 energy magnitude (M_e) events from the period 1995–2007 has been considered. On comparison among M_e, M_w, and M_{wg}, it is revealed that M_{wg} is closer to M_e than to M_w (53% of M_{wg} are closer to M_e).

Moreover, to check the similarity of M_{wg} with observed global radiated energy, we collected all the global data for radiated energy from Choy and Boatwright (1995) for the period 1981–1991 for magnitudes ≥ 5.8. Choy and Boatwright (1995) compiled 397 global radiated energy events data, of which we used only 394 events that have radiated energy along with seismic moment values. Kanamori (1977) and Hanks and Kanamori (1979) used the Gutenberg energy equation (equation 1) to derive M_w. M_s has been used as M_w in the energy equation. Therefore, we estimate radiated energy using equation (1) considering M_s equal to M_w or M_{wg}. It has been observed that 76% of instrumentally recorded radiated energy values are found to be closer to the radiated energy values obtained using M_{wg} than to those values obtained using M_w (Fig. 4, Table 3). An analysis of the 394 observed radiated energy events shows that the use of M_w will overestimate the radiated energy (Fig. 4) and produce an average error of 0.368 magnitude unit (m.u.). Thus, this analysis attests that M_{wg} is an accurate measure of radiated energy in the global context.

The superiority of the M_{wg} scale over M_w, particularly for small and intermediate events, is primarily owing to three reasons: (1) direct consideration of seismic moment values in the development of M_{wg} rather than making the assumption of a constant value for stress drop in the term E_s/M_0 while deriving the M_w scale. (2) Because M_w is based on long-period surface-wave magnitudes, it is therefore not a good estimator for the high-frequency or strong-motion amplitude measurements that are useful for estimating the potential shake damage of actual earthquakes. On the other hand, M_{wg} is computed from low- and high-frequency spectra of a seismic signal. (3) Proper representation of global seismicity in terms of small-, intermediate-, and high-magnitude events

Table 2
Comparison of Various Observed Magnitudes

S. No.	Date (yyyy/mm/dd)	Time (hh:mm:ss.s)	Latitude (°)	Longitude (°)	Depth (km)	M_s	m_b	M_0	M_w	M_{wg}
1	1978/10/01	13:23:50.5	6.65	123.94	44.6	5.4	5.6	6.46×10^{24}	5.8	5.6
2	1979/01/12	07:29:30.3	−28.71	−177.45	26.8	6.3	6	7.92×10^{25}	6.6	6.4
3	1979/08/22	11:09:35.1	44.62	150.34	9.4	5.1	5.1	1.14×10^{24}	5.3	5
4	1979/11/20	22:01:44.4	13.35	−90.28	39.6	6	5.5	3.38×10^{25}	6.3	6.1
5	1980/03/07	22:50:26.7	40.4	63.63	10	4.1	4.7	1.62×10^{23}	4.8	4.4
6	1981/06/10	02:13:23.2	75.53	122.75	10	5.4	5.5	3.56×10^{24}	5.7	5.4
7	1981/06/20	04:10:02.2	−20.09	169.02	58	5.5	5.5	6.17×10^{24}	5.8	5.5
8	1981/09/06	01:21:27.3	38.36	13.69	9.6	5.5	5.8	9.69×10^{24}	6	5.7
9	1982/04/25	06:11:33.5	−58.69	−25.2	33	4.3	5.3	7.73×10^{23}	5.2	4.9
10	1982/10/05	20:39:48	43.84	147.34	38.3	5.7	6.1	1.59×10^{25}	6.1	5.9
11	1983/01/10	01:09:34.9	37.14	−14.12	10	5.2	5.3	2.45×10^{24}	5.6	5.3
12	1983/03/03	00:20:19.6	51.48	159.75	34.9	4.4	4.9	1.78×10^{23}	4.8	4.4
13	1983/03/06	09:17:36.4	−54.53	157.28	10	5.8	5.8	1.60×10^{25}	6.1	5.9
14	1983/04/02	05:58:35.9	−28.54	−66.59	49.1	4.9	5.5	1.02×10^{24}	5.3	5
15	1983/06/04	14:50:45.3	−6.31	146.83	26	5.9	5.8	1.78×10^{25}	6.1	5.9
16	1983/11/25	21:54:14.6	−5.5	152.06	49.6	5.8	5.6	1.36×10^{25}	6.1	5.8
17	1984/01/06	03:42:41.7	14.82	−3.82	8.7	4.5	4.8	1.33×10^{24}	5.4	5.1
18	1984/08/08	22:08:31	1.35	122.69	37.5	4.4	4.8	4.45×10^{23}	5.1	4.7
19	1985/01/04	19:50:20.5	44.28	149.46	26	4.9	5.1	7.29×10^{23}	5.2	4.9
20	1985/05/17	02:44:10.9	−34.18	−72.19	54.5	4.7	5.1	1.50×10^{24}	5.4	5.1
21	1985/06/29	23:20:37.4	0.47	126.13	37.3	4.2	4.9	3.32×10^{23}	5	4.6
22	1985/07/22	09:06:13.2	−6.23	148.82	56	5.3	5.1	6.07×10^{24}	5.8	5.5
23	1985/08/31	22:52:33	−9.76	34.27	10	4.4	4.7	6.65×10^{23}	5.2	4.8
24	1985/12/03	12:22:18.1	−15.59	−171.94	10	4.5	4.9	1.04×10^{24}	5.3	5
25	1986/01/27	08:34:51.2	56.16	164.35	28	6.3	5.6	2.71×10^{25}	6.3	6
26	1986/06/07	23:40:24.8	−1.33	−24.35	10	5.1	4.9	2.37×10^{24}	5.5	5.2
27	1986/09/15	19:38:53.2	44.17	149.66	18.6	4.5	4.9	3.00×10^{23}	5	4.6
28	1986/11/10	11:30:29.2	12.19	93.76	33.4	5.1	5.3	1.59×10^{24}	5.4	5.1
29	1987/01/03	01:41:26	−29.54	−111.83	10	5.8	5.3	7.73×10^{24}	5.9	5.6
30	1987/02/14	23:17:52.8	−54.47	5.84	10	5.3	5.4	4.65×10^{24}	5.7	5.5
31	1987/03/06	10:24:45.1	−23.92	−175.66	33	5.7	5.4	4.54×10^{24}	5.7	5.5
32	1987/03/13	09:51:34	49.97	−129.73	14.3	5.2	5.1	1.63×10^{24}	5.4	5.1
33	1987/04/05	23:51:24.3	−29.24	−176.99	21.9	4.5	4.9	4.57×10^{23}	5.1	4.7
34	1987/07/18	14:54:57.7	−9.08	107.71	19	4.5	5.3	3.81×10^{23}	5	4.7
35	1987/08/09	08:17:51	0.53	126.08	51.8	4.7	5.3	1.00×10^{24}	5.3	5
36	1987/11/19	22:23:58	−6.69	147.58	51.1	4.7	5.3	1.60×10^{24}	5.4	5.1
37	1988/07/16	20:46:55.6	52.01	−170.7	52.6	4.6	5.4	8.50×10^{23}	5.3	4.9
38	1988/08/09	16:51:36.6	24.21	122.33	52.8	4.6	5.3	6.09×10^{23}	5.2	4.8
39	1988/08/29	21:21:0	−5.46	102.28	26.3	4.5	4.9	1.02×10^{24}	5.3	5
40	1988/09/04	23:56:34.9	−21.17	169.28	13.7	5.5	5.1	6.40×10^{24}	5.8	5.6
41	1988/11/26	20:20:14.4	1.56	126.5	40.1	4.4	5.2	8.68×10^{23}	5.3	4.9
42	1988/12/30	21:16:30.2	−6.48	148.95	28.8	5.7	5.3	6.44×10^{24}	5.8	5.6
43	1989/02/10	21:52:22.3	−23.15	169.23	33	4.5	5	1.04×10^{24}	5.3	5
44	1989/08/17	22:22:20	33.71	22.94	0.9	6.6	6.1	3.98×10^{25}	6.4	6.1
45	1989/08/30	16:37:18.2	12.06	140.49	23	5	5.1	1.39×10^{24}	5.4	5.1
46	1989/10/31	19:35:02.1	−9.26	112.07	49.3	5.2	5.3	2.99×10^{24}	5.6	5.3
47	1989/11/02	03:38:41.9	−10.38	−13.17	10	4.9	5.2	8.20×10^{23}	5.2	4.9
48	1990/04/23	15:32:49.3	22.43	98.88	9.6	6.3	5.7	1.93×10^{25}	6.2	5.9
49	1990/05/26	22:35:07.3	−21.31	−174.32	35.8	5.8	5.2	1.48×10^{24}	5.4	5.1
50	1990/07/02	12:34:50.3	40.68	143.79	5.6	5.4	5	1.03×10^{24}	5.3	5
51	1990/07/07	10:25:44.1	2.7	−79.83	0.9	4.3	5.2	1.08×10^{24}	5.3	5
52	1990/07/25	08:01:28.2	36.41	141.79	38.8	5.7	5.5	3.87×10^{24}	5.7	5.4
53	1990/10/09	15:39:25.7	53.62	−165.87	39	4.9	5.2	1.13×10^{24}	5.3	5
54	1990/10/12	11:08:35.7	42.9	12.9	3.9	5	5.1	8.84×10^{23}	5.3	4.9
55	1990/11/25	02:36:52.8	−13.25	174.73	33	4.9	4.7	9.12×10^{23}	5.3	4.9
56	1991/01/29	22:46:40.9	12.88	−90.86	54.4	4.7	5.2	1.33×10^{24}	5.4	5.1
57	1991/03/20	13:08:58.9	−5.77	−80.88	42.9	5.6	5.3	1.10×10^{25}	6	5.7
58	1991/04/13	05:48:47.9	−9.2	−108.76	10	4.1	3.9	2.90×10^{23}	4.9	4.6
59	1991/07/04	18:17:33.5	−3.4	146.83	10	4.6	5.1	8.87×10^{23}	5.3	4.9
60	1991/08/21	09:49:48.7	−3.95	−104	10	5.4	4.9	5.44×10^{24}	5.8	5.5
61	1991/10/05	09:48:44.2	20.07	−116.05	10	4.6	5.5	1.30×10^{24}	5.4	5.1

(*continued*)

Table 2 (*Continued*)

S. No.	Date (yyyy/mm/dd)	Time (hh:mm:ss.s)	Latitude (°)	Longitude (°)	Depth (km)	M_s	m_b	M_0	M_w	M_{wg}
62	1991/11/09	00:25:36.8	−65.48	170.89	12.7	4.2	4.4	5.65×10^{23}	5.1	4.8
63	1991/12/15	06:36:38.3	−30.46	−177.89	58	5.4	5.6	3.50×10^{24}	5.7	5.4
64	1992/03/27	02:55:34.6	31.87	−40.98	10	4.6	5.1	1.00×10^{24}	5.3	5
65	1992/03/27	11:58:19.8	−14.48	−178.01	36.6	5.8	5.7	9.69×10^{24}	6	5.7
66	1992/04/18	00:32:39.9	−13.16	−74.41	39.6	4.8	5.5	2.26×10^{24}	5.5	5.2
67	1992/07/23	19:44:52.2	−15.67	−71.63	15.4	5	5	9.07×10^{23}	5.3	4.9
68	1992/11/10	21:08:55.4	53.85	160.67	43.7	5.4	5.5	5.20×10^{24}	5.8	5.5
69	1993/02/26	09:16:52.4	−26.6	−114.59	33	5.7	5.8	1.26×10^{25}	6	5.8
70	1993/05/01	04:05:42.6	−4.48	146.11	16.3	5.1	5.4	1.97×10^{24}	5.5	5.2
71	1993/05/10	09:13:29.9	51.9	−175.11	37.9	5	5	4.60×10^{23}	5.1	4.7
72	1993/09/01	07:14:48.8	−30.83	−177.92	19.7	5.2	5.6	2.05×10^{24}	5.5	5.2
73	1993/09/08	04:52:32.7	21.35	−45.85	10	4.6	4.7	5.28×10^{23}	5.1	4.8
74	1993/09/08	05:55:39.8	21.32	−45.83	10	4.6	5	7.03×10^{23}	5.2	4.9
75	1993/09/13	09:56:59.6	48.91	−128.28	13.3	4.6	5.2	5.92×10^{23}	5.1	4.8
76	1993/10/29	07:29:57.2	6.81	123.87	29.7	5.8	5.6	2.60×10^{25}	6.2	6
77	1993/12/29	08:00:44.1	38.75	24.8	1.8	5.4	5	1.37×10^{24}	5.4	5.1
78	1994/01/10	15:18:55.1	0.17	97.95	28.3	5.5	5.5	3.91×10^{24}	5.7	5.4
79	1994/06/18	22:38:17.8	−10.23	113.6	44	5.1	5.5	2.25×10^{24}	5.5	5.2
80	1994/06/30	13:41:43.2	24.42	−110.27	10	5.4	5.6	4.44×10^{24}	5.7	5.4
81	1994/11/07	10:59:25.1	10.29	93.81	55.1	4.5	4.9	4.29×10^{23}	5.1	4.7
82	1995/01/15	02:40:19.4	27.48	128.54	52.3	5.3	5.7	3.27×10^{24}	5.6	5.3
83	1995/04/18	08:57:09.4	28.92	142.21	33.5	5.7	5.7	4.41×10^{24}	5.7	5.4
84	1995/05/02	00:17:18.7	−35.08	78.63	10	4	4.4	4.80×10^{23}	5.1	4.7
85	1995/05/12	16:12:37.3	12.29	47.47	10	5.1	5.3	1.97×10^{24}	5.5	5.2
86	1995/06/03	22:15:14.1	−5.34	−175.2	33	3.9	5.3	4.73×10^{23}	5.1	4.7
87	1995/06/07	16:01:18.1	62.04	−26.59	10	4.1	4.7	1.94×10^{23}	4.8	4.4
88	1995/06/11	16:33:24.8	45.18	150.83	25.6	4.6	5.2	5.98×10^{23}	5.2	4.8
89	1995/08/21	00:28:25.1	−31.28	−67.86	25.1	4.6	5.5	1.16×10^{24}	5.3	5
90	1995/11/16	05:00:46.5	−43.91	−16.13	10	5.3	5.4	1.46×10^{24}	5.4	5.1
91	1996/01/01	08:05:09.6	0.68	119.98	15.4	7.5	6.3	7.78×10^{27}	7.9	7.8
92	1996/01/31	05:07:14.1	43.25	46.9	35.5	5.5	5.3	4.50×10^{24}	5.7	5.4
93	1996/03/09	13:49:28.1	54.25	−168	34.6	5.5	5.2	4.51×10^{24}	5.7	5.4
94	1996/03/27	08:03:44.6	−9.66	112.76	33	5	5.6	2.60×10^{24}	5.6	5.3
95	1996/04/23	05:45:09.8	−16.66	120.16	34.1	5.7	5.7	2.04×10^{25}	6.2	5.9
96	1996/05/11	13:43:48	−6.68	155.05	59.6	6.1	5.6	3.41×10^{25}	6.3	6.1
97	1996/06/06	18:40:29	10.68	126.09	25.9	6.3	5.7	5.66×10^{25}	6.5	6.3
98	1996/07/31	23:56:57.4	40.4	−124.17	16	5.8	5.6	1.19×10^{25}	6	5.8
99	1996/11/12	21:37:43.5	−54.13	−1.84	33	5.7	5.5	6.28×10^{24}	5.8	5.6
100	1996/12/31	03:05:13.5	−35.07	−179.26	58.6	4.7	4.8	1.02×10^{24}	5.3	5
101	1997/03/11	19:27:08.2	37.7	142.17	35.1	4.6	5.1	4.51×10^{23}	5.1	4.7
102	1997/07/07	22:39:23.8	44.04	148.51	37.7	4.9	5.4	1.28×10^{24}	5.4	5
103	1997/10/16	16:30:26.2	45.15	93.75	37.3	4.6	5.1	4.37×10^{23}	5.1	4.7
104	1997/12/06	10:05:05.1	53.92	161.88	38.5	5.5	5.3	3.67×10^{24}	5.7	5.4
105	1998/01/16	17:05:38.3	−6.12	142.66	34.5	5	5.5	1.33×10^{24}	5.4	5.1
106	1998/02/14	01:11:29.1	−64.86	177.01	10	4.7	5	1.05×10^{24}	5.3	5
107	1998/05/14	22:53:37.1	52.74	−35.2	10	5.4	4.9	3.46×10^{24}	5.7	5.4
108	1998/06/26	20:40:56.3	30.27	−41.87	9.7	4.7	4.9	1.03×10^{24}	5.3	5
109	1998/07/08	17:33:37.9	−24.9	−116.11	10	5.2	5	4.70×10^{24}	5.7	5.5
110	1998/10/04	06:26:24.9	−54.65	−130.81	10	4.4	4.7	7.90×10^{23}	5.2	4.9
111	1998/11/08	07:25:49.7	−9.13	121.45	46.9	5.9	6	3.85×10^{25}	6.4	6.1
112	1999/01/21	01:16:36.4	−20.38	168.77	37.1	4.3	4.8	3.68×10^{23}	5	4.6
113	1999/04/17	21:23:49.1	−1.6	99.68	21.5	5.1	5.6	1.59×10^{24}	5.4	5.1
114	1999/05/07	00:38:18.6	23.54	99.54	33	5.7	5.4	3.32×10^{24}	5.6	5.4
115	1999/09/18	06:50:58.3	−6.44	147.78	51.4	5.1	5.1	2.60×10^{24}	5.6	5.3
116	1999/09/25	04:00:40	−46.74	37.82	10	5.6	5.5	7.40×10^{24}	5.9	5.6
117	1999/11/04	21:56:39.1	39.29	143.53	1.5	5.2	5.3	1.09×10^{24}	5.3	5
118	1999/12/08	06:28:46.9	10.13	−103.85	10	5.1	4.9	4.12×10^{24}	5.7	5.4
119	1999/12/28	00:37:49.5	7.58	94.14	23.8	5.1	5.2	2.09×10^{24}	5.5	5.2
120	2000/02/15	01:16:44.9	−38.01	179.84	12	4.7	4.9	1.12×10^{24}	5.3	5
121	2000/05/15	00:23:58.1	−18.96	−175.6	19.5	6.5	5.6	1.12×10^{26}	6.7	6.5
122	2000/05/25	11:02:21	−34.1	−14.72	10	4.7	4.5	7.25×10^{23}	5.2	4.9
123	2000/10/08	08:27:52.4	−10.94	162.12	38	6.8	6.2	1.50×10^{26}	6.8	6.6

(*continued*)

Table 2 (*Continued*)

S. No.	Date (yyyy/mm/dd)	Time (hh:mm:ss.s)	Latitude (°)	Longitude (°)	Depth (km)	M_s	m_b	M_0	M_w	M_{wg}
124	2000/11/17	06:09:22.9	−6.45	105.25	42.2	4.5	5	8.80×10^{23}	5.3	4.9
125	2000/12/16	20:28:48.3	−19.36	−173.27	15	5.6	5.2	3.86×10^{24}	5.7	5.4
126	2000/12/30	14:37:48.3	46.92	154.09	15.6	4.3	4.8	3.16×10^{23}	5	4.6
127	2001/03/24	03:59:50.3	52.94	−167.7	24.8	6.8	6.1	3.20×10^{26}	7	6.8
128	2001/03/24	22:19:03.9	−55.33	146.05	10	5.8	5.3	1.44×10^{25}	6.1	5.8
129	2001/04/08	06:09:48.1	15.45	119.19	31.9	5.6	5.1	1.29×10^{24}	5.4	5
130	2001/06/16	01:08:30	1.13	118.39	22.5	4.7	4.9	1.60×10^{24}	5.4	5.1
131	2001/07/18	00:31:21.5	−19.77	−70.58	10	5.2	4.5	4.21×10^{23}	5	4.7
132	2001/09/15	15:04:39	−22.45	−174.92	43.7	6	5.4	9.31×10^{24}	5.9	5.7
133	2001/12/05	21:26:09.8	55.59	165.76	9.9	6.6	6	1.20×10^{26}	6.7	6.5
134	2002/01/26	23:00:19.8	40.04	52.91	29.4	4.7	5.3	9.90×10^{23}	5.3	5
135	2002/02/13	08:41:16.2	−1.3	127.53	33.5	5.6	5.7	9.40×10^{24}	5.9	5.7
136	2002/05/06	03:04:22.4	30.88	70.29	33.6	5.6	5.6	7.54×10^{24}	5.9	5.6
137	2002/09/17	23:09:24.4	0.94	−26.4	10	5.2	5.2	2.48×10^{24}	5.6	5.3
138	2002/09/22	12:17:20.3	23.63	121.01	38.6	4.8	5	9.30×10^{23}	5.3	4.9
139	2002/12/05	10:38:53	16.29	120.57	33.1	4.7	5.2	7.80×10^{23}	5.2	4.9
140	2003/03/20	18:09:42.6	0.77	−29.68	24.4	5.8	5.7	2.40×10^{25}	6.2	6
141	2003/04/15	00:51:49.7	−15.13	−173.75	38.4	4.7	4.7	7.20×10^{23}	5.2	4.9
142	2003/07/09	10:57:22	31.45	119.24	9.9	5.7	5.4	1.76×10^{24}	5.5	5.1
143	2003/08/13	22:54:51.8	34.4	−119.66	8.9	5.7	5.4	5.80×10^{24}	5.8	5.5
144	2003/08/23	15:46:12.2	21.39	−108.82	10	5	5.2	2.00×10^{24}	5.5	5.2
145	2003/09/17	23:56:24.6	−5.64	103.54	46	4.4	5.2	5.38×10^{23}	5.1	4.8
146	2003/11/14	04:28:32.6	−16.64	172.31	2.6	5.7	5.5	1.00×10^{25}	6	5.7
147	2003/11/19	12:42:50.1	−6.5	154.2	9.7	5.7	5.4	1.71×10^{25}	6.1	5.9
148	2003/12/07	19:27:34.3	−44.1	168.73	5	5.7	6	5.50×10^{24}	5.8	5.5
149	2004/01/06	16:41:29.8	39.14	143.59	10.5	5.2	5.2	1.23×10^{24}	5.4	5
150	2004/02/17	04:37:28.8	−56.03	157.93	10	5.7	5.3	1.95×10^{25}	6.2	5.9
151	2004/06/16	09:35:13.1	−52.89	159.97	10	5.7	4.8	2.35×10^{25}	6.2	6
152	2004/06/21	06:45:34.8	−6	104.85	38.6	4.9	5.5	1.47×10^{24}	5.4	5.1
153	2004/07/04	06:16:05.6	7.7	−72.12	26.8	4	5.5	1.21×10^{24}	5.4	5
154	2004/08/05	07:02:40.3	−17.28	167.83	21.2	5.3	5.2	3.76×10^{24}	5.7	5.4
155	2004/08/09	01:56:30.4	−44.62	35.41	15	5.1	5.2	2.54×10^{24}	5.6	5.3
156	2004/08/27	10:50:49.1	−36.79	78.57	10	5.7	5.2	8.08×10^{24}	5.9	5.6
157	2004/08/29	15:14:05.5	−56.51	−25.51	15	4.9	5.4	1.57×10^{24}	5.4	5.1
158	2004/10/25	21:25:43.5	0.75	98.21	19.6	4.2	4.8	2.30×10^{23}	4.9	4.5
159	2004/10/28	23:03:45.1	14.11	146.6	33.9	4.9	5	6.93×10^{23}	5.2	4.8
160	2004/12/29	15:50:03.7	5.46	94.71	47.6	4.5	5.3	5.29×10^{23}	5.1	4.8
161	2004/12/31	11:27:49.9	51.3	−174.14	30.8	4.1	4.8	3.10×10^{23}	5	4.6
162	2005/01/04	03:45:51.3	−3	145.82	23	5.4	5.5	4.13×10^{24}	5.7	5.4
163	2005/01/16	12:57:21.9	43.57	−127.26	10	4.9	4.7	2.75×10^{24}	5.6	5.3
164	2005/01/29	13:34:10.1	6.86	−76.73	10	5.3	5.5	4.16×10^{24}	5.7	5.4
165	2005/02/05	17:51:36	−40.71	175.8	34.2	5.1	5.3	1.24×10^{24}	5.4	5
166	2005/02/18	19:33:44.8	5.42	94.44	47.8	5.2	5.7	2.70×10^{24}	5.6	5.3
167	2005/03/01	13:08:13.9	43.82	149.22	2.2	5	5.3	7.04×10^{23}	5.2	4.9
168	2005/03/03	23:14:26	−13.31	175.01	13.9	5.8	5.8	1.06×10^{25}	6	5.7
169	2005/03/20	18:55:22.7	−45.72	96.27	10	4.9	5	7.94×10^{23}	5.2	4.9
170	2005/04/07	00:07:24	44.03	149.25	33.3	5.3	5.3	1.43×10^{24}	5.4	5.1
171	2005/04/15	07:52:15.2	−3.84	151.39	25.6	5.2	5.3	3.14×10^{24}	5.6	5.3
172	2005/04/16	21:57:02.6	−5.22	102.69	34.1	5.8	5.7	1.10×10^{25}	6	5.7
173	2005/04/26	08:43:32	−5.27	153.58	56.9	4.2	4.9	2.96×10^{23}	4.9	4.6
174	2005/05/04	00:34:09.7	40.59	23.56	13.7	5.1	5	1.10×10^{24}	5.3	5
175	2005/06/04	09:50:27.6	19.3	121.2	13.2	5.2	5.2	2.89×10^{24}	5.6	5.3
176	2005/06/24	13:28:00.3	−59.69	−26.16	33	5.4	5.3	5.12×10^{24}	5.8	5.5
177	2005/06/30	15:25:13.4	50.27	91.16	15	4.8	5	1.01×10^{24}	5.3	5
178	2005/07/05	00:09:57.7	−4.62	101.94	14.1	5	5.4	8.10×10^{23}	5.2	4.9
179	2005/07/23	22:17:05.7	−33.11	−178.54	10	4.8	5	7.76×10^{23}	5.2	4.9
180	2005/07/29	12:51:05.7	33.38	142.38	34.7	4.8	5.2	5.00×10^{23}	5.1	4.7
181	2005/08/16	05:40:50.2	−3.78	140.05	10	4.8	4.9	1.04×10^{24}	5.3	5
182	2005/08/22	21:31:17.3	30.96	141.8	37.1	5.2	5.1	1.61×10^{24}	5.4	5.1
183	2005/08/28	21:12:53.9	10.32	138.53	31	4.1	4.7	2.83×10^{23}	4.9	4.6
184	2005/09/15	20:53:04	51.28	179.23	10.7	4.8	5.2	8.15×10^{23}	5.2	4.9
185	2005/09/21	03:18:58.2	−12.93	165.96	15	5.2	5.2	2.93×10^{24}	5.6	5.3

(*continued*)

Table 2 (*Continued*)

S. No.	Date (yyyy/mm/dd)	Time (hh:mm:ss.s)	Latitude (°)	Longitude (°)	Depth (km)	M_s	m_b	M_0	M_w	M_{wg}
186	2005/10/02	03:42:50.1	50.23	−130.09	18.3	4.8	5.2	2.23×10^{24}	5.5	5.2
187	2005/10/21	14:24:10.1	1.81	−90.77	10	5.2	4.7	2.40×10^{24}	5.6	5.2
188	2005/10/30	10:43:55.8	31.25	−4.38	8	5.2	5.1	2.93×10^{24}	5.6	5.3
189	2005/11/03	02:06:17.8	−27.49	−176.17	18.7	5.7	5.3	3.93×10^{24}	5.7	5.4
190	2005/12/04	10:46:27.6	52.37	159.9	32.6	5.4	5.6	1.57×10^{24}	5.4	5.1
191	2005/12/29	06:19:03.8	9.46	93.74	33	5.9	5	1.20×10^{24}	5.4	5
192	2006/01/20	00:55:23	−11.02	162.17	33.2	5.4	5.4	6.12×10^{24}	5.8	5.5
193	2006/03/25	07:00:51.8	−5.05	102.03	20.8	4.1	5	1.90×10^{23}	4.8	4.4
194	2006/06/04	21:36:54.4	63.95	−21.28	10	5.2	5.1	1.56×10^{24}	5.4	5.1
195	2006/06/06	08:02:53.6	−4	140.05	51.9	4.1	4.7	3.62×10^{23}	5	4.6
196	2006/09/26	21:07:20	−26.45	−177.5	33	5.4	5.3	3.11×10^{24}	5.6	5.3
197	2006/10/01	19:17:16.4	14.38	53.74	10	5	4.9	3.49×10^{24}	5.7	5.4
198	2006/11/23	17:37:47.1	−25.35	70.13	10	4.2	4.7	3.22×10^{23}	5	4.6
199	2006/12/06	16:55:01.2	−55.21	−126.67	10	5	5.4	2.86×10^{24}	5.6	5.3
200	2006/12/12	17:23:16.5	−6.55	71.44	31.8	5.2	5.2	2.36×10^{24}	5.5	5.2

Comparison among M_w, M_{wg}, m_b, and M_s for 200 random observed global datasets.

has been considered. The conventional moment magnitude scale M_w is primarily based on southern Californian seismicity, particularly for small and intermediate events, whereas M_{wg} is based on the global seismicity.

Discussion and Conclusions

A reliable and standardized measure of the size or strength of an earthquake is an essential need, not only for categorization purposes but also for all kinds of tectonophysical and seismological applications. The M_w scale is based on seismic moment (dyn · cm) and is applicable for southern California in all magnitude ranges and is valid for globally distributed data for magnitudes ≥ 7.5. In this study, we investigate the use of the M_w scale on the global level for small-, intermediate-, and large-magnitude ranges. Investigations reveal that the M_w scale shows reasonable agreement with the other instrumentally measured earthquake sizes (e.g., M_s) in the higher magnitude range for which it was developed, but in the range of small and intermediate events, its deviation from the sizes observed in other ways (e.g., m_b, M_s) is significant.

A generalized seismic moment magnitude scale $M_{wg} = \log M_0/1.36\text{–}12.68$ has been proposed considering 25,708 globally distributed data pairs of body-wave magnitudes (m_b) from the ISC and seismic moments (M_0) from Global CMT during the period 1976–2006. To compare the proposed M_{wg} to the observed surface-wave magnitude M_s, a total of 18,521 M_s events from the ISC database during the period 1976–2006 have been considered. These event data also have m_b from the ISC and M_0 from Global CMT. The M_{wg} estimates are clearly closer to the global m_b and M_s values (Fig. 3 and Table 2). For instance, in the first row of Table 2, the m_b value is the same as that of M_{wg}, but less than M_w by 0.2 m.u. Moreover, M_s is 0.2 and 0.4 m.u. less than M_{wg} and M_w, respectively. Because the M_{wg} magnitude scale agrees better with body-wave magnitudes over the entire magnitude range, and with the surface-wave magnitudes when $M_s \leq 8.0$ (Fig. 3) than with the M_w values estimated using equation (3), the developed scale (M_{wg}) is a better representation of m_b and M_s. However, the sizes estimated by both scales (M_w and M_{wg}) provide nearly the same values for the higher magnitude range (i.e., $8.0 \leq M_{wg} \leq 8.9$). Furthermore, on analysis of 394 global radiated energy events with magnitude ≥ 5.8, it has been observed that M_{wg} provides better agreement with energy release in the global context over a wider range of magnitude. Thus, the proposed scale (M_{wg}) will better represent the earthquake sizes over the entire (lower, intermediate, and higher) magnitude range in the global context. M_{wg} would also be helpful for rapid determination of seismic moment for emergency warning purposes using equation (4) with $m_b \leq 5.5$ and $M_s > 5.5$.

Almost all the recent strong ground-motion attenuation relations have been developed in terms of the moment magnitude M_w. However, it is inappropriate to develop the ground-motion attenuation relations in terms of the moment magnitude for the entire range (e.g., magnitudes < 7.5 and magnitudes ≥ 7.5), mainly because the M_w scale is only consistent for magnitudes ≥ 7.5 at the global level. Moreover, because M_w is defined from very long-period spectral amplitudes, it is not expected to correlate well with the high-frequency ground motion important for engineering. A similar point of view has also been presented in other studies (e.g., Trifunac and Lee, 1990; Bormann and Giacomo, 2010). Both M_w and M_{wg} are given in terms of seismic moment, but their empirical formulas (e.g., $2/3 \times \log M_0 - 10.7$ and $\log M_0/1.36\text{–}12.68$) are different. Equation (3) is developed using equation (2), which is based on long-period surface waves. Equation (5) is developed using equation (4), which is based on the first few cycles of P waves at 1 s using 25,708 global events. Therefore, M_{wg} is expected to be closely related to high-frequency ground motion. Because M_{wg} is derived from M_0, and the formulation of M_{wg} (i.e., $\log M_0/1.36\text{–}12.68$) is derived from the relationship between body-wave magnitude and seismic moment (equation 4),

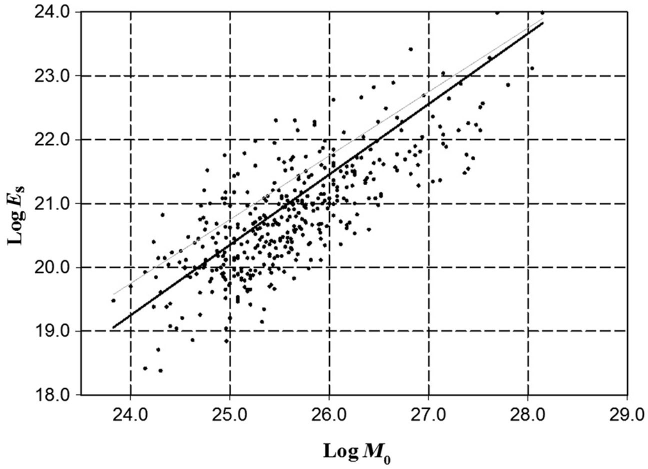

Figure 4. Radiated energy (E_s) of the global data set plotted as a function of seismic moment. The radiated energy values are predicted using M_w (gray solid line) and M_{wg} (black solid line) through the Gutenberg-energy equation $\log E_s = 1.5\ M_s + 11.8$. Most of the earthquakes using M_w overestimate the actual radiated energy.

Table 3

Comparison of M_{wg} and M_w Scales with Observed Radiated Energy Values

S. No.	S. No. in table 5 of Choy and Boatwright (1995)	LogE_S	LogM_0	M_{wg}	M_w	LogE_S (M_{wg})	LogE_S (M_w)
1	1	21.04	26.18	6.57	6.75	21.65	21.93
2	2	21.48	26.41	6.74	6.91	21.91	22.16
3	3	20.43	25.30	5.92	6.17	20.69	21.05
4	4	21.00	25.93	6.39	6.59	21.38	21.68
5	5	20.66	25.83	6.31	6.52	21.26	21.58
6	6	20.94	25.56	6.11	6.34	20.97	21.31
7	7	23.41	26.82	7.04	7.18	22.36	22.57
8	8	24.43	27.86	7.81	7.88	23.51	23.61
9	9	21.08	25.52	6.08	6.31	20.93	21.27
10	10	20.11	25.04	5.73	5.99	20.40	20.79
11	11	21.85	26.41	6.74	6.91	21.91	22.16
12	12	23.99	27.69	7.68	7.76	23.32	23.44
13	13	19.91	24.93	5.65	5.92	20.28	20.68
14	14	21.64	25.54	6.10	6.33	20.95	21.29
15	15	20.48	24.58	5.39	5.69	19.89	20.33
16	16	21.57	26.66	6.92	7.08	22.19	22.41
17	17	21.00	26.26	6.63	6.80	21.74	22.01
18	18	19.90	24.66	5.45	5.74	19.98	20.41
19	19	20.46	25.58	6.13	6.35	20.99	21.33
20	20	19.41	25.20	5.85	6.10	20.58	20.95
21	21	21.69	26.76	7.00	7.14	22.30	22.51
22	22	21.59	26.04	6.47	6.66	21.50	21.79
23	23	20.97	26.49	6.80	6.96	22.00	22.24
24	24	19.51	25.08	5.76	6.02	20.44	20.83
25	25	22.15	27.30	7.39	7.50	22.89	23.05
26	26	21.20	25.43	6.02	6.25	20.83	21.18
27	27	19.85	24.93	5.65	5.92	20.28	20.68
28	28	22.04	26.34	6.69	6.86	21.83	22.09
29	29	20.00	24.54	5.37	5.66	19.85	20.29

(*continued*)

Table 3 (*Continued*)

S. No.	S. No. in table 5 of Choy and Boatwright (1995)	LogE_S	LogM_0	M_{wg}	M_w	LogE_S (M_{wg})	LogE_S (M_w)
30	30	22.66	26.32	6.67	6.85	21.81	22.07
31	31	21.70	25.49	6.06	6.29	20.90	21.24
32	32	20.60	25.28	5.91	6.15	20.66	21.03
33	33	22.89	26.64	6.91	7.06	22.17	22.39
34	34	21.85	26.04	6.47	6.66	21.50	21.79
35	35	21.90	26.86	7.07	7.21	22.41	22.61
36	36	23.11	28.04	7.94	7.99	23.71	23.79
37	37	19.72	25.41	6.01	6.24	20.81	21.16
38	38	21.40	26.38	6.72	6.89	21.88	22.13
39	39	20.89	25.84	6.32	6.53	21.28	21.59
40	40	21.32	25.45	6.03	6.26	20.85	21.20
41	41	21.89	27.18	7.30	7.42	22.75	22.93
42	42	18.86	24.62	5.43	5.72	19.94	20.37
43	44	21.34	27.04	7.20	7.33	22.61	22.79
44	45	20.53	26.26	6.63	6.80	21.74	22.01
45	46	20.40	25.62	6.16	6.38	21.04	21.37
46	47	21.73	25.76	6.26	6.48	21.20	21.51
47	48	20.74	25.45	6.03	6.26	20.85	21.20
48	49	20.26	24.51	5.34	5.64	19.81	20.26
49	50	20.77	25.30	5.92	6.17	20.69	21.05
50	51	22.51	27.52	7.55	7.65	23.13	23.27
51	52	21.59	25.26	5.89	6.14	20.64	21.01
52	53	19.99	24.54	5.37	5.66	19.85	20.29
53	54	21.36	26.04	6.47	6.66	21.50	21.79
54	55	20.23	24.88	5.61	5.88	20.22	20.63
55	56	19.92	24.15	5.07	5.40	19.41	19.90
56	57	20.63	24.95	5.67	5.94	20.30	20.70
57	58	19.85	24.26	5.15	5.47	19.53	20.01
58	59	22.57	27.54	7.57	7.66	23.16	23.29
59	60	20.28	25.62	6.16	6.38	21.04	21.37
60	61	20.67	25.89	6.36	6.56	21.34	21.64
61	62	20.72	26.11	6.52	6.71	21.58	21.86
62	63	20.54	25.58	6.13	6.35	20.99	21.33
63	64	20.15	25.23	5.87	6.12	20.61	20.98
64	65	21.81	26.91	7.11	7.24	22.46	22.66
65	66	22.26	27.40	7.47	7.57	23.00	23.15
66	67	21.43	25.69	6.21	6.43	21.11	21.44
67	68	21.81	26.81	7.03	7.17	22.35	22.56
68	69	21.28	26.90	7.10	7.23	22.45	22.65
69	70	20.91	25.64	6.18	6.40	21.06	21.39
70	71	20.18	24.93	5.65	5.92	20.28	20.68
71	72	21.61	26.54	6.84	7.00	22.06	22.29
72	73	21.46	26.82	7.04	7.18	22.36	22.57
73	74	20.30	25.61	6.15	6.38	21.03	21.36
74	75	20.11	24.96	5.67	5.94	20.31	20.71
75	76	20.99	26.04	6.47	6.66	21.50	21.79
76	77	20.08	24.49	5.33	5.63	19.79	20.24
77	78	20.48	25.53	6.09	6.32	20.94	21.28
78	79	20.15	24.28	5.17	5.49	19.56	20.03
79	80	19.95	24.82	5.57	5.85	20.15	20.57
80	81	21.08	25.89	6.35	6.56	21.33	21.64
81	82	20.41	25.41	6.01	6.24	20.81	21.16
82	83	20.56	25.65	6.18	6.40	21.07	21.40
83	84	21.97	26.48	6.79	6.95	21.98	22.23
84	85	20.18	25.48	6.05	6.28	20.88	21.23
85	86	21.76	26.86	7.07	7.21	22.41	22.61
86	87	21.98	25.95	6.40	6.60	21.41	21.70
87	88	21.93	27.15	7.28	7.40	22.72	22.90
88	89	23.99	28.15	8.02	8.06	23.82	23.90
89	90	21.04	25.72	6.23	6.45	21.15	21.47

(*continued*)

Table 3 (*Continued*)

S. No.	S. No. in table 5 of Choy and Boatwright (1995)	LogE_S	LogM_0	M_{wg}	M_w	LogE_S (M_{wg})	LogE_S (M_w)
90	91	20.11	25.66	6.19	6.41	21.08	21.41
91	92	22.30	25.65	6.18	6.40	21.07	21.40
92	93	22.69	26.95	7.14	7.27	22.50	22.70
93	94	20.78	25.36	5.97	6.21	20.75	21.11
94	95	20.59	25.90	6.36	6.57	21.34	21.65
95	96	20.84	25.20	5.85	6.10	20.58	20.95
96	97	21.77	26.68	6.94	7.09	22.21	22.43
97	98	19.98	25.49	6.06	6.29	20.90	21.24
98	99	21.20	25.49	6.06	6.29	20.90	21.24
99	100	20.85	25.69	6.21	6.43	21.11	21.44
100	101	21.08	26.15	6.55	6.73	21.62	21.90
101	102	20.59	26.40	6.73	6.90	21.90	22.15
102	103	19.66	25.45	6.03	6.26	20.85	21.20
103	104	22.30	25.46	6.04	6.27	20.86	21.21
104	105	21.00	25.83	6.31	6.52	21.26	21.58
105	106	19.46	25.08	5.76	6.02	20.44	20.83
106	107	22.23	27.48	7.52	7.62	23.09	23.23
107	108	19.38	24.23	5.14	5.45	19.50	19.98
108	109	19.52	24.95	5.67	5.94	20.30	20.70
109	110	19.53	25.08	5.76	6.02	20.44	20.83
110	111	20.96	24.71	5.49	5.77	20.03	20.46
111	112	19.97	25.40	5.99	6.23	20.79	21.15
112	113	21.98	25.26	5.89	6.14	20.64	21.01
113	114	20.23	25.30	5.92	6.17	20.69	21.05
114	115	19.91	25.30	5.92	6.17	20.69	21.05
115	116	22.62	26.04	6.47	6.66	21.50	21.79
116	117	19.62	25.18	5.83	6.08	20.55	20.93
117	118	19.83	25.11	5.79	6.04	20.48	20.86
118	119	20.64	25.97	6.42	6.62	21.43	21.72
119	120	21.11	26.08	6.50	6.69	21.54	21.83
120	121	21.04	25.68	6.20	6.42	21.10	21.43
121	122	20.57	25.23	5.87	6.12	20.61	20.98
122	123	20.92	25.98	6.42	6.62	21.44	21.73
123	124	20.62	25.00	5.70	5.97	20.35	20.75
124	125	20.83	26.28	6.64	6.82	21.76	22.03
125	126	20.92	25.88	6.35	6.55	21.33	21.63
126	127	21.79	25.15	5.81	6.06	20.51	20.90
127	128	20.18	25.08	5.76	6.02	20.44	20.83
128	129	21.00	25.84	6.32	6.53	21.28	21.59
129	130	19.81	25.11	5.79	6.04	20.48	20.86
130	131	20.64	25.64	6.18	6.40	21.06	21.39
131	132	20.68	25.91	6.37	6.58	21.36	21.66
132	133	20.70	25.76	6.26	6.48	21.20	21.51
133	134	21.28	26.23	6.61	6.79	21.71	21.98
134	135	21.11	26.52	6.82	6.98	22.03	22.27
135	136	20.11	24.76	5.52	5.80	20.08	20.51
136	137	20.00	24.64	5.44	5.73	19.96	20.39
137	138	21.45	25.82	6.30	6.51	21.26	21.57
138	139	20.40	25.36	5.97	6.21	20.75	21.11
139	140	22.88	27.32	7.41	7.51	22.91	23.07
140	141	19.04	24.96	5.67	5.94	20.31	20.71
141	142	21.36	27.11	7.26	7.38	22.69	22.86
142	143	20.04	24.93	5.65	5.92	20.28	20.68
143	144	20.45	24.68	5.47	5.75	20.00	20.43
144	145	21.11	25.38	5.98	6.22	20.77	21.13
145	146	20.61	26.18	6.57	6.75	21.65	21.93
146	147	21.68	26.51	6.81	6.97	22.01	22.26
147	148	20.67	25.08	5.76	6.02	20.44	20.83
148	149	21.54	27.40	7.47	7.57	23.00	23.15
149	150	20.45	25.91	6.37	6.58	21.36	21.66

(*continued*)

Table 3 (*Continued*)

S. No.	S. No. in table 5 of Choy and Boatwright (1995)	LogE_S	LogM_0	M_{wg}	M_w	LogE_S (M_{wg})	LogE_S (M_w)
150	151	20.63	25.70	6.22	6.43	21.12	21.45
151	152	20.52	25.38	5.98	6.22	20.77	21.13
152	153	20.98	25.76	6.26	6.48	21.20	21.51
153	154	21.08	24.92	5.65	5.92	20.27	20.67
154	155	20.23	25.15	5.81	6.06	20.51	20.90
155	156	20.45	25.04	5.73	5.99	20.40	20.79
156	157	21.08	26.46	6.78	6.94	21.97	22.21
157	158	19.83	25.64	6.18	6.40	21.06	21.39
158	159	20.36	26.11	6.52	6.71	21.58	21.86
159	160	20.15	25.45	6.03	6.26	20.85	21.20
160	161	19.15	25.32	5.94	6.18	20.71	21.07
161	162	21.38	26.45	6.77	6.93	21.95	22.20
162	163	18.85	24.96	5.68	5.94	20.31	20.71
163	164	20.11	25.91	6.37	6.58	21.36	21.66
164	165	21.60	26.89	7.09	7.23	22.44	22.64
165	166	19.34	25.34	5.95	6.19	20.73	21.09
166	167	22.36	27.04	7.20	7.33	22.61	22.79
167	168	21.15	25.91	6.37	6.58	21.36	21.66
168	169	21.72	26.28	6.64	6.82	21.76	22.03
169	170	21.38	25.69	6.21	6.43	21.11	21.44
170	171	22.82	26.45	6.77	6.93	21.95	22.20
171	172	20.68	25.23	5.87	6.12	20.61	20.98
172	173	20.40	25.58	6.13	6.35	20.99	21.33
173	174	20.96	25.00	5.70	5.97	20.35	20.75
174	175	20.36	25.11	5.79	6.04	20.48	20.86
175	176	21.51	25.76	6.26	6.48	21.20	21.51
176	177	20.04	25.34	5.95	6.19	20.73	21.09
177	178	20.96	25.18	5.83	6.08	20.55	20.93
178	179	20.34	25.28	5.91	6.15	20.66	21.03
179	181	20.74	25.58	6.13	6.35	20.99	21.33
180	182	21.54	25.62	6.16	6.38	21.04	21.37
181	183	21.11	25.78	6.27	6.49	21.21	21.53
182	184	19.72	24.99	5.70	5.96	20.34	20.74
183	185	22.64	27.20	7.32	7.44	22.78	22.95
184	186	21.04	25.36	5.97	6.21	20.75	21.11
185	187	22.23	25.85	6.33	6.53	21.29	21.60
186	188	21.95	25.45	6.03	6.26	20.85	21.20
187	189	20.32	24.72	5.50	5.78	20.05	20.47
188	190	21.68	25.61	6.15	6.38	21.03	21.36
189	191	22.86	27.80	7.76	7.83	23.44	23.55
190	192	21.72	26.32	6.67	6.85	21.81	22.07
191	193	21.08	24.95	5.67	5.94	20.30	20.70
192	194	19.86	25.04	5.73	5.99	20.40	20.79
193	195	21.15	25.94	6.40	6.60	21.40	21.69
194	196	20.58	25.64	6.18	6.40	21.06	21.39
195	197	21.51	26.11	6.52	6.71	21.58	21.86
196	198	21.30	26.04	6.47	6.66	21.50	21.79
197	199	20.81	26.04	6.47	6.66	21.50	21.79
198	200	20.23	24.41	5.27	5.58	19.71	20.16
199	201	20.40	25.45	6.03	6.26	20.85	21.20
200	202	20.11	24.56	5.38	5.67	19.86	20.31
201	203	20.46	24.96	5.67	5.94	20.31	20.71
202	204	20.36	25.79	6.28	6.49	21.23	21.54
203	205	22.28	25.85	6.33	6.53	21.29	21.60
204	206	20.36	25.40	5.99	6.23	20.79	21.15
205	207	20.75	24.70	5.48	5.77	20.02	20.45
206	208	20.38	24.64	5.44	5.73	19.96	20.39
207	209	20.97	25.75	6.25	6.47	21.18	21.50
208	210	20.61	25.30	5.92	6.17	20.69	21.05
209	211	20.40	25.18	5.83	6.08	20.55	20.93

(*continued*)

Table 3 (*Continued*)

S. No.	S. No. in table 5 of Choy and Boatwright (1995)	LogE_S	LogM_0	M_{wg}	M_w	LogE_S (M_{wg})	LogE_S (M_w)
210	212	21.48	26.18	6.57	6.75	21.65	21.93
211	213	20.15	25.04	5.73	5.99	20.40	20.79
212	214	20.32	25.34	5.95	6.19	20.73	21.09
213	215	20.93	25.76	6.26	6.48	21.20	21.51
214	216	22.08	27.15	7.28	7.40	22.72	22.90
215	217	19.98	25.11	5.79	6.04	20.48	20.86
216	218	21.72	25.63	6.17	6.39	21.05	21.38
217	219	19.94	25.11	5.79	6.04	20.48	20.86
218	220	20.04	25.43	6.02	6.25	20.83	21.18
219	221	19.65	25.18	5.83	6.08	20.55	20.93
220	222	19.81	24.95	5.67	5.94	20.30	20.70
221	223	20.15	25.18	5.83	6.08	20.55	20.93
222	224	21.43	25.04	5.73	5.99	20.40	20.79
223	225	20.18	24.88	5.61	5.89	20.22	20.63
224	226	19.85	24.60	5.41	5.70	19.91	20.35
225	227	20.59	25.66	6.19	6.41	21.08	21.41
226	228	19.60	24.70	5.48	5.77	20.02	20.45
227	229	20.54	25.91	6.37	6.57	21.36	21.66
228	230	19.20	25.00	5.70	5.97	20.35	20.75
229	231	20.51	25.73	6.24	6.45	21.16	21.48
230	232	20.23	25.59	6.14	6.36	21.01	21.34
231	233	18.71	24.28	5.17	5.49	19.56	20.03
232	234	20.66	26.18	6.57	6.75	21.65	21.93
233	235	21.71	27.45	7.50	7.60	23.05	23.20
234	236	20.40	24.23	5.14	5.45	19.50	19.98
235	237	21.04	26.08	6.50	6.69	21.54	21.83
236	238	20.04	24.75	5.52	5.80	20.08	20.50
237	239	20.30	25.26	5.89	6.14	20.64	21.01
238	240	19.78	24.80	5.55	5.83	20.13	20.55
239	241	22.20	27.11	7.26	7.38	22.69	22.86
240	242	20.00	24.91	5.64	5.91	20.25	20.66
241	243	22.15	25.68	6.20	6.42	21.10	21.43
242	244	20.00	24.73	5.51	5.79	20.06	20.48
243	245	19.95	25.26	5.89	6.14	20.64	21.01
244	246	20.41	25.51	6.07	6.30	20.91	21.26
245	247	21.52	25.56	6.11	6.34	20.97	21.31
246	248	19.82	24.81	5.56	5.84	20.15	20.56
247	249	20.95	25.75	6.25	6.47	21.18	21.50
248	250	20.72	25.76	6.26	6.47	21.19	21.51
249	251	20.66	25.43	6.02	6.25	20.83	21.18
250	252	19.70	25.40	5.99	6.23	20.79	21.15
251	253	20.45	25.61	6.15	6.38	21.03	21.36
252	254	22.04	26.93	7.12	7.26	22.49	22.68
253	255	21.04	25.95	6.40	6.60	21.41	21.70
254	256	20.26	24.87	5.61	5.88	20.21	20.62
255	257	21.76	27.38	7.45	7.55	22.98	23.13
256	258	20.98	25.83	6.31	6.52	21.27	21.58
257	259	21.26	26.18	6.57	6.75	21.65	21.93
258	260	23.28	27.61	7.62	7.71	23.24	23.36
259	261	21.41	25.79	6.28	6.49	21.23	21.54
260	262	19.08	24.40	5.26	5.57	19.69	20.15
261	263	20.32	25.56	6.11	6.34	20.97	21.31
262	264	20.70	26.20	6.59	6.77	21.68	21.95
263	265	21.08	26.00	6.44	6.63	21.46	21.75
264	266	20.80	25.66	6.19	6.41	21.08	21.41
265	267	19.90	25.18	5.83	6.08	20.55	20.93
266	268	21.18	24.95	5.67	5.94	20.30	20.70
267	269	21.20	26.08	6.50	6.69	21.54	21.83
268	270	22.28	26.73	6.98	7.12	22.26	22.48
269	271	20.90	25.59	6.14	6.36	21.01	21.34

(*continued*)

Table 3 (*Continued*)

S. No.	S. No. in table 5 of Choy and Boatwright (1995)	LogE_S	LogM_0	M_{wg}	M_w	LogE_S (M_{wg})	LogE_S (M_w)
270	272	19.96	24.86	5.60	5.88	20.20	20.61
271	273	20.59	25.15	5.81	6.06	20.51	20.90
272	274	19.96	25.04	5.73	5.99	20.40	20.79
273	275	22.15	27.52	7.55	7.65	23.13	23.27
274	276	20.11	25.81	6.30	6.51	21.25	21.56
275	277	20.94	25.53	6.09	6.32	20.94	21.28
276	278	20.11	24.95	5.67	5.94	20.30	20.70
277	279	20.38	24.86	5.60	5.87	20.20	20.61
278	280	20.20	25.40	5.99	6.23	20.79	21.15
279	281	20.79	25.60	6.15	6.37	21.02	21.35
280	282	21.18	25.18	5.83	6.08	20.55	20.93
281	283	21.08	26.40	6.73	6.90	21.90	22.15
282	284	21.48	27.36	7.44	7.54	22.96	23.11
283	285	20.34	25.95	6.40	6.60	21.41	21.70
284	286	21.00	25.63	6.17	6.39	21.05	21.38
285	287	22.34	26.68	6.94	7.09	22.21	22.43
286	288	21.81	25.90	6.37	6.57	21.35	21.65
287	289	19.90	25.08	5.76	6.02	20.44	20.83
288	290	20.15	25.08	5.76	6.02	20.44	20.83
289	291	21.76	26.04	6.47	6.66	21.50	21.79
290	292	21.63	26.04	6.47	6.66	21.50	21.79
291	293	19.38	24.36	5.23	5.54	19.65	20.11
292	294	22.11	26.15	6.55	6.73	21.62	21.90
293	295	20.38	24.64	5.44	5.73	19.96	20.39
294	296	21.28	25.94	6.39	6.59	21.39	21.69
295	297	19.93	25.54	6.10	6.33	20.95	21.29
296	298	21.58	26.18	6.57	6.75	21.65	21.93
297	299	19.65	25.20	5.85	6.10	20.58	20.95
298	300	18.41	24.15	5.07	5.40	19.41	19.90
299	301	22.49	26.57	6.86	7.01	22.08	22.32
300	302	22.28	26.49	6.80	6.96	22.00	22.24
301	303	21.36	26.36	6.70	6.87	21.86	22.11
302	304	21.00	25.72	6.23	6.45	21.15	21.47
303	305	20.71	25.26	5.89	6.14	20.64	21.01
304	306	20.68	25.34	5.95	6.19	20.73	21.09
305	307	20.59	24.75	5.52	5.80	20.08	20.50
306	308	20.70	24.76	5.53	5.81	20.09	20.51
307	309	20.92	25.26	5.89	6.14	20.64	21.01
308	310	21.51	26.26	6.63	6.80	21.74	22.01
309	311	20.82	24.32	5.20	5.51	19.61	20.07
310	312	19.91	25.41	6.01	6.24	20.81	21.16
311	313	20.38	25.04	5.73	5.99	20.40	20.79
312	314	20.62	25.08	5.76	6.02	20.44	20.83
313	315	21.32	25.75	6.25	6.47	21.18	21.50
314	316	21.56	25.95	6.40	6.60	21.41	21.70
315	317	20.76	25.30	5.92	6.17	20.69	21.05
316	318	20.79	25.52	6.08	6.31	20.93	21.27
317	319	21.04	25.58	6.13	6.35	20.99	21.33
318	320	21.63	26.45	6.77	6.93	21.95	22.20
319	321	20.46	24.83	5.57	5.85	20.16	20.58
320	322	21.20	25.65	6.18	6.40	21.07	21.40
321	323	20.81	25.34	5.95	6.19	20.73	21.09
322	324	23.04	27.15	7.28	7.40	22.72	22.90
323	325	19.99	24.69	5.47	5.76	20.01	20.44
324	326	20.68	25.92	6.38	6.58	21.37	21.67
325	327	21.59	26.23	6.61	6.79	21.71	21.98
326	328	21.15	26.52	6.82	6.98	22.03	22.27
327	329	19.87	25.20	5.85	6.10	20.58	20.95
328	330	20.30	25.46	6.04	6.27	20.86	21.21
329	331	19.04	24.46	5.31	5.61	19.76	20.21

(*continued*)

Table 3 (*Continued*)

S. No.	S. No. in table 5 of Choy and Boatwright (1995)	$\mathrm{Log}E_S$	$\mathrm{Log}M_0$	M_{wg}	M_w	$\mathrm{Log}E_S$ (M_{wg})	$\mathrm{Log}E_S$ (M_w)
330	332	21.32	26.36	6.70	6.87	21.86	22.11
331	333	19.65	24.95	5.67	5.94	20.30	20.70
332	334	19.88	25.23	5.87	6.12	20.61	20.98
333	335	19.61	24.30	5.19	5.50	19.58	20.05
334	336	21.46	25.08	5.76	6.02	20.44	20.83
335	337	21.00	24.80	5.55	5.83	20.13	20.55
336	338	20.78	24.73	5.51	5.79	20.06	20.48
337	339	21.87	25.93	6.39	6.59	21.38	21.68
338	340	21.00	24.94	5.66	5.93	20.29	20.69
339	341	21.11	25.52	6.08	6.31	20.93	21.27
340	342	21.08	25.34	5.95	6.19	20.73	21.09
341	343	21.46	26.26	6.63	6.80	21.74	22.01
342	344	19.89	25.08	5.76	6.02	20.44	20.83
343	345	21.20	24.74	5.51	5.79	20.07	20.49
344	346	21.76	24.94	5.66	5.93	20.29	20.69
345	347	21.52	24.77	5.53	5.81	20.10	20.52
346	348	19.75	25.00	5.70	5.97	20.35	20.75
347	349	19.43	24.40	5.26	5.57	19.69	20.15
348	350	19.48	23.83	4.84	5.18	19.06	19.58
349	351	21.51	26.23	6.61	6.79	21.71	21.98
350	352	20.23	24.94	5.66	5.93	20.29	20.69
351	353	19.61	24.82	5.57	5.85	20.15	20.57
352	354	20.68	25.48	6.05	6.28	20.88	21.23
353	355	20.20	25.40	5.99	6.23	20.79	21.15
354	356	20.99	25.49	6.06	6.29	20.90	21.24
355	357	19.98	25.79	6.28	6.49	21.23	21.54
356	358	19.95	25.20	5.85	6.10	20.58	20.95
357	359	20.76	25.72	6.23	6.45	21.15	21.47
358	360	19.83	25.20	5.85	6.10	20.58	20.95
359	361	22.15	26.72	6.97	7.12	22.26	22.47
360	362	20.38	25.81	6.30	6.50	21.24	21.56
361	363	21.52	26.68	6.94	7.09	22.21	22.43
362	364	20.18	25.52	6.08	6.31	20.93	21.27
363	365	20.04	24.38	5.25	5.55	19.67	20.13
364	366	19.69	25.15	5.81	6.06	20.51	20.90
365	367	19.26	24.70	5.48	5.77	20.02	20.45
366	368	20.70	25.46	6.04	6.27	20.86	21.21
367	369	21.18	25.72	6.23	6.44	21.14	21.47
368	370	21.60	25.92	6.38	6.58	21.37	21.67
369	371	19.70	24.00	4.97	5.30	19.25	19.75
370	372	20.15	24.34	5.22	5.53	19.63	20.09
371	373	20.60	25.72	6.23	6.44	21.14	21.47
372	374	21.18	25.04	5.73	5.99	20.40	20.79
373	375	20.98	25.63	6.17	6.39	21.05	21.38
374	376	20.67	25.49	6.06	6.29	20.90	21.24
375	377	19.90	24.92	5.64	5.91	20.26	20.67
376	378	21.26	26.08	6.50	6.69	21.54	21.83
377	379	21.45	26.26	6.63	6.80	21.74	22.01
378	380	20.66	25.38	5.98	6.22	20.77	21.13
379	381	21.00	26.00	6.44	6.63	21.46	21.75
380	382	21.41	26.15	6.55	6.73	21.62	21.90
381	383	20.15	25.04	5.73	5.99	20.40	20.79
382	384	21.11	25.57	6.12	6.35	20.98	21.32
383	385	20.45	25.51	6.07	6.30	20.91	21.26
384	386	20.20	25.68	6.20	6.42	21.10	21.43
385	387	20.68	24.86	5.60	5.88	20.20	20.61
386	388	20.18	25.40	5.99	6.23	20.79	21.15
387	389	21.04	26.08	6.50	6.69	21.54	21.83
388	391	18.38	24.30	5.19	5.50	19.58	20.05
389	392	19.20	24.52	5.35	5.65	19.82	20.27

(*continued*)

Table 3 (*Continued*)

S. No.	S. No. in table 5 of Choy and Boatwright (1995)	$\mathrm{Log}E_S$	$\mathrm{Log}M_0$	M_{wg}	M_w	$\mathrm{Log}E_S$ (M_{wg})	$\mathrm{Log}E_S$ (M_w)
390	393	19.87	24.57	5.38	5.68	19.88	20.32
391	394	19.79	25.15	5.81	6.06	20.51	20.90
392	395	20.52	25.26	5.89	6.14	20.64	21.01
393	396	20.53	24.88	5.61	5.89	20.22	20.63
394	397	20.48	25.32	5.94	6.18	20.71	21.07

Comparison among M_{wg}, M_w, and 394 observed global radiated energy values compiled by Choy and Boatwright (1995); $\log E_S$, observed radiated energy; $\log M_0$, observed seismic moment; M_{wg}, proposed scale; M_w, M_w scale (Hanks and Kanamori, 1979); $\log E_s$ (M_{wg}), energy estimated using M_{wg}; $\log E_s$ (M_w), energy estimated using M_w.

M_{wg} is expected to relate more closely with both low- and high-frequency spectra of a seismic signal. For instance, for the Nepal earthquake (25 April 2015) with a seismic moment of 8.39×10^{27} and M_w 7.92, which caused relatively less damage than expected given the assigned magnitude, the proposed scale M_{wg} yields a magnitude of 7.85. The Tohoku-Oki earthquake (11 March 2011) with a seismic moment of 5.31×10^{29} has an M_w value of 9.1 and caused serious damage. In this case, the M_{wg} value is 9.2. The Sumatra earthquake (26 December 2004) with a seismic moment of 3.95×10^{29} and M_w 9.0 is assigned M_{wg} 9.1. For the offshore Maule earthquake (27 February 2010), both scales provide the same magnitude 8.8.

The derived generalized moment magnitude scale M_{wg} is also an unsaturated magnitude scale based on the seismic moment like M_w and is uniform throughout the magnitude range (i.e., $M_{wg} \geq 4.5$) irrespective of focal depths and seismic regions. It connects better to the observed global body wave, surface wave, energy magnitudes, and observed global seismic radiated energies. Thus, the M_{wg} scale will also be more appropriate for developing the strong ground-motion attenuation relationships (due to wider consistency in the magnitude range). The proposed magnitude scale M_{wg} covers both high- and low-frequency spectra of seismic signals and correlates better with earthquake damage potential. The proposed scale can also be read as the Das magnitude scale.

Data and Resources

Body- and surface-wave magnitudes of earthquakes for the entire globe from the International Seismological Centre (ISC, United Kingdom) database (http://www.isc.ac.uk/iscbulletin/search/bulletin, last accessed August 2010), and the moment magnitudes from the Global Centroid Moment Tensor (CMT) database (http://www.globalcmt.org/CMTsearch.html, last accessed October 2010) during the period 1976–2006 have been compiled in this study. A total of 25,708 events with body-wave magnitudes and their corresponding seismic moment values are considered in this study. Energy magnitudes (1361) and their corresponding moment magnitude values collected from the ISC during the period 1995–2007 have also been compiled. The ISC reports energy magnitude values from the National Earthquake Information Center (NEIC), U.S. Geological Survey (USGS) (https://earthquake.usgs.gov/earthquakes/search/, last accessed August 2010).

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