

Comparison between different earthquake magnitudes determined by China Seismograph Network*

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Abstract

By linear regression and orthogonal regression methods, comparisons are made between different magnitudes (local magnitude M_L , surface wave magnitudes M_S and M_{S7} , long-period body wave magnitude m_B and short-period body wave magnitude m_b) determined by Institute of Geophysics, China Earthquake Administration, on the basis of observation data collected by China Seismograph Network between 1983 and 2004. Empirical relations between different magnitudes have been obtained. The result shows that: ① As different magnitude scales reflect radiated energy by seismic waves within different periods, earthquake magnitudes can be described more objectively by using different scales for earthquakes of different magnitudes. When the epicentral distance is less than 1 000 km, local magnitude M_L can be a preferable scale; In case $M < 4.5$, there is little difference between the magnitude scales; In case $4.5 < M < 6.0$, $m_B > M_S$, i.e., M_S underestimates magnitudes of such events, therefore, m_B can be a better choice; In case $M > 6.0$, $M_S > m_B > m_b$, both m_B and m_b underestimate the magnitudes, so M_S is a preferable scale for determining magnitudes of such events ($6.0 < M < 8.5$); In case $M > 8.5$, a saturation phenomenon appears in M_S , which cannot give an accurate reflection of the magnitudes of such large events; ② In China, when the epicentral distance is less than 1 000 km, there is almost no difference between M_L and M_S , and thus there is no need to convert between the two magnitudes in practice; ③ Although M_S and M_{S7} are both surface wave magnitudes, M_S is in general greater than M_{S7} by 0.2~0.3 magnitude, because different instruments and calculation formulae are used; ④ m_B is almost equal to m_b for earthquakes around $m_B 4.0$, but m_B is larger than m_b for those of $m_B \geq 4.5$, because the periods of seismic waves used for measuring m_B and m_b are different though the calculation formulae are the same.

Key words: local earthquake magnitude; surface wave magnitude; body wave magnitude

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Introduction

Earthquake magnitude, the most common measure of an earthquake's size, is a basic parameter of an earthquake event and an import parameter for earthquake forecast and other earthquake-related studies (CHEN *et al*, 2000; CHEN and LIU, 2004).

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When studying earthquakes of Southern California, Richter (1935) first introduced local magnitude M_L , which is now known as Richter magnitude or Richter scale. Though empirical and without definite physical meaning, Richter scale is very convenient, and most importantly, it has laid a foundation for the development of earthquake magnitude. Local magnitude M_L is of great use, however, it cannot be used as a measure for distant earthquakes across the globe due to restrictions of the seismograph types used and applicable range of epicentral distances. Gutenberg (1945a) extended local wave magnitude M_L to the measurement of distant earthquakes. In the seismograms of shallow-focus distant earthquakes, the amplitude of surface wave is the largest. For earthquakes with epicentral distance $\Delta > 2\,000$ km, the maximum value of surface wave horizontal amplitude corresponds to the period around 20 s. Surface wave with a period around 20 s corresponds to Airy phase on the dispersion curve of a wave train and, hereby, Gutenberg put forward surface wave magnitude scale (Gutenberg, 1945a). Surface wave is absent for deep-focus earthquakes, but P wave is distinct for distant events, so Gutenberg and Richter used body waves (P, PP, S) in the determination of earthquake magnitude, and this scale for measuring earthquake magnitude is known as body wave magnitude (Gutenberg, 1945b, c; Gutenberg and Richter, 1942, 1944, 1956a, b).

When local magnitude, surface wave magnitude and body wave magnitude can be simultaneously determined for the same event, the results are supposed to be identical. However, the results of these magnitudes usually appear different. The relationship between measured values by different magnitude scales has long been an important research subject for seismologists. In 1945, Gutenberg (1945a, b, c) unified M_L , M_S and m_B as M , because he deemed the three magnitude scales equivalent. But he soon found that such was not the case. After analysis and comparison with a great deal of data, Gutenberg and Richter presented empirical relations between different magnitude scales (Gutenberg and Richter, 1956b). Kanamori (1983) summarized the relations between the magnitude scales and the variation range of magnitudes due to observation error and complexity of source characters such as stress drop, fault geometry and focal depth. Later, authors in different parts of the world successively presented empirical relations between different magnitude scales, some for the whole world, some for Europe (Ambrassey, 1990), Japan and former USSR, respectively, based on a variety of observed data (Utsu, 1982, 2002). GUO^① (1971) obtained an empirical relation between M_L and M_S for North China after studying the two magnitude scales in the area.

In China Seismograph Network, three kinds of magnitude scales are commonly used in daily data analysis and processing, *i.e.*, local magnitude M_L , surface wave magnitudes M_S and M_{S7} , and body wave magnitudes m_B and m_b (State Seismological Bureau, 1978). These magnitudes are derived from different methods and different instruments; therefore, no conversion is carried out between different magnitudes (LIU *et al.*, 2006). But in seismicity analysis, especially in the study of earthquake prediction, an empirical formula is usually used to convert the different magnitudes into a unified magnitude. However, researchers often use different empirical formulae in their analysis and research work, causing many problems. In the present study, we obtained reliable empirical relations between M_L , M_S , M_{S7} , m_B and m_b determined by China seismograph network with linear regression and orthogonal regression methods.

^①GUO Lü-can. 1971. Empirical relation between local magnitude M_L and surface wave magnitude M_S in North China. Material from China National Seismological Conference, Sanhe, Hebei Province, 1-10 (in Chinese).

1 Magnitude formulae used in China

LI Shan-bang, a Chinese pioneer seismologist, established a calibration function suitable for China, based on the definition and formula of Richter local magnitude and the characteristics of the short-period seismographs and middle- and long-period seismographs used in China seismograph network, but the result remained unpublished until it was described in the monograph *Earthquakes in China* (LI, 1981) published after his death. The formula goes as follows:

$$M_L = \lg A_\mu + R(\Delta) + S(\Delta) \quad (1)$$

where A_μ represents ground displacement (in μm), and it is the arithmetic mean value of maximum ground displacement in two horizontal components; Δ stands for epicentral distance (in km); $R(\Delta)$ is a calibration function, whose physical meaning lies in compensation for seismic wave attenuation with distance; $S(\Delta)$ represents station correction, which has different values for different stations and different instruments. It is stipulated that the records by Kirnos (SK) seismographs at Beijing National Earth Observatory (hereinafter referred to as Baijiatuan Observatory) should be taken as the standard records for computation of M_L , *i.e.* $S=0$, while extra calculations should be conducted to determine the values of S for other seismic stations and instruments.

Magnitudes were not measured and hence not included in China's earthquake reports before 1956. From 1957 to 1965, earthquake magnitudes were measured in China on the basis of a formula for calculating surface wave magnitudes proposed by Solov'yev and Shebalin of the former USSR (CHEN, 1989). After January 1966, a formula for surface wave magnitude based on Baijiatuan Observatory proposed by GUO and PANG (1981) was used in China's earthquake information release:

$$M_S = \lg \left(\frac{A}{T} \right)_{\max} + \sigma(\Delta) \quad 1^\circ < \Delta < 130^\circ \quad (2)$$

where $\sigma(\Delta)$ is a calibration function:

$$\sigma(\Delta) = 1.66 \lg \Delta + 3.5 \quad (3)$$

In equation (2), A represents vector sum of ground displacement of surface wave in two horizontal components; $A = (A_E^2 + A_N^2)^{1/2}$ (in μm); T is the corresponding period (in second, $1^\circ < \Delta < 130^\circ$, $3 \text{ s} \leq T \leq 25 \text{ s}$) (XU *et al.*, 1994); Δ stands for epicentral distance (in degree). Equation (2) is still in use today.

After 1985, a 763-long-period seismograph network was established and put into use in China, and the maximum amplitude and period of vertical Rayleigh wave were used to determine M_{S7} (CHEN *et al.*, 1988):

$$M_{S7} = \lg \left(\frac{A}{T} \right)_{\max} + \sigma(\Delta)_{763} \quad 3^\circ < \Delta < 177^\circ \quad (4)$$

In China, body wave magnitudes m_b and m_B are calculated with the maximum velocity of vertical particle movement of P or PP wave and the following formula by Gutenberg (1945b) is used in the calculation:

$$m_b \text{ or } m_B = \lg \left(\frac{A}{T} \right)_{\max} + Q(\Delta, h) + C \quad (5)$$

where A (in μm) is the displacement amplitude corresponding to the maximum velocity of particle movement of body wave; T is the period, and $Q(\Delta, h)$ is calibration function, which is a function of epicentral distance and focal depth. m_b is determined on the basis of records by DD-1 short-period seismographs, while m_B is determined on the basis of records by Kirnos (SK) or DK-1 intermediate- and long-period seismographs (LIU *et al*, 2006).

2 Regression methods

In this study, linear regression and orthogonal regression methods are used in the analysis of relationships between different magnitudes determined by China Seismograph Network.

2.1 Linear regression method

For two or more statistically correlated random variables, their statistical quantitative relationships can be determined by a vast amount of observation data, *i.e.*, a certain mathematic formula should be obtained to represent the relationships, and this formula is referred to as regression equation. Let us fit N pairs of data (x_i, y_i) ($i=1, 2, 3, \dots, N$) to the following linear equation:

$$Y = AX + B \quad (6)$$

The coefficients A and B can usually be determined by linear least squares regression (SR). Gutenberg and Richter (1956a, 1956b) presented a relational expression between m_B , M_S and M_L .

The SR regression is applicable in the case the deviation engendered by one variable is larger than the deviation engendered by another. Determining coefficients A and B and fitting linear equation (6) can result in two possible cases (Draper and Smith, 1998). The first is:

$$\text{SR1} \quad Y \leftarrow A_1 X + B_1 \quad (7)$$

This suits the conditions $\sigma_{xx}^2 \rightarrow 0$ and $\sigma_{yy}^2 > 0$, where σ_{xx}^2 and σ_{yy}^2 are variances of X and Y respectively. And the second is:

$$\text{SR2} \quad Y \rightarrow A_2 X + B_2 \quad (8)$$

This case is also known as reverse standard regression (Carroll and Ruppert, 1996), which suits the conditions $\sigma_{xx}^2 > 0$ and $\sigma_{yy}^2 \rightarrow 0$.

Linear regression deals only with the case when the deviation engendered by one variable is larger than the deviation engendered by another, therefore, an equal sign cannot be used for linear regression relationship, and this is the reason why we use arrows instead of equal signs in equations (7) and (8).

2.2 Orthogonal regression method

Orthogonal regression is often used to fit equation (6) in the case both variables are likely to change considerably. Let OR represent orthogonal regression:

$$\text{OR} \quad Y = A_3 X + B_3 \quad (9)$$

Hesse representation method is widely used for orthogonal regression (Carroll and Ruppert, 1996), *i.e.*, the two variables are both put on the right side of the equal sign, indicating both variables on the right side are changing, thus we have

$$p = n_x X + n_y Y \quad (10)$$

where $p=B_3/q$, $n_x=-A_3/q$, $n_y=1/q$, $q=(1+A_3^2)^{1/2}$, $-n_x/n_y=A_3$. If the above relation is applied to the magnitude scales M_x and M_y , SR1 is suited for the case when the relatively large deviation of M_x

makes a difference to M_y , while SR2 is suited for the case when the relatively large deviation of M_y makes a difference to M_x . However, as we know, no magnitude measurement is error free, both SR1 and SR2 may result in more or less deviation from the actual magnitude measurements. Hence, the study of relationships between magnitude scales with orthogonal regression is theoretically closer to actual magnitude determination (Madansky, 1959; Fuller, 1987; Carroll and Ruppert, 1996). For comparison, the relations between different magnitude scales obtained by SR1, SR2 and OR are presented respectively in this paper, but result analysis and conclusions are mainly based on the fitted formula derived from OR method.

3 Comparison between different magnitudes

We collected observation data of local magnitude M_L , surface wave magnitudes M_S and M_{S7} , body wave magnitudes m_B and m_b determined by China Seismograph Network during the period from 1983 to 2004. After analysis and comparison with general regression methods (SR1 and SR2) and orthogonal regression method (OR), we got the relations between different magnitudes, as shown in Table 1. The corresponding regression lines are shown in Figure 1, where line 1 and line 2 represent respectively the results from general linear regression SR1 and SR2 and line 3 represents the result from orthogonal regression OR. The distribution of differences between different magnitudes measured is shown in Figures 2~6 and comparison of the magnitudes with orthogonal regression is illustrated in Tables 2~6.

Table 1 Relations between different magnitudes

Magnitude	Number of events	Magnitude range	Regression method	Serial No. of lines	Relation	M
M_L-m_b	7 024	$3.0 \leq M_L \leq 7.0$	SR1	1	$m_b \leftarrow 0.45M_L + 2.47$	± 0.31
			SR2	2	$M_L \leftarrow 0.90m_b + 0.35$	± 0.43
			OR	3	$1.60 = 0.86m_b - 0.51M_L$	± 0.27
M_S-M_L	7 851	$2.5 \leq M_S \leq 7.5$	SR1	1	$M_L \leftarrow 0.79M_S + 0.95$	± 0.35
			SR2	2	$M_S \leftarrow 0.80M_L + 0.83$	± 0.36
			OR	3	$0.05 = 0.71M_L - 0.70M_S$	± 0.27
m_B-m_b	20 701	$3.2 \leq m_B \leq 7.7$	SR1	1	$m_b \leftarrow 0.72m_B + 1.23$	± 0.24
			SR2	2	$m_B \leftarrow 1.02m_b + 0.16$	± 0.28
			OR	3	$0.55 = 0.77m_b - 0.63m_B$	± 0.19
M_S-M_{S7}	25 002	$3.0 \leq M_S \leq 8.5$	SR1	1	$M_{S7} \leftarrow 0.94M_S + 0.06$	± 0.18
			SR2	2	$M_S = 0.98 M_{S7} + 0.28$	± 0.19
			OR	3	$-0.08 = -0.70M_S + 0.71 M_{S7}$	± 0.13
M_S-m_B	19 187	$3.3 \leq M_S \leq 8.9$	SR1	1	$m_B \leftarrow 0.67M_S + 1.98$	± 0.30
			SR2	2	$M_S \leftarrow 1.07m_B - 0.63$	± 0.38
			OR	3	$1.21 = 0.80m_B - 0.60M_S$	± 0.25

Note: M stands for root mean square.

3.1 Comparison between M_L and M_S

The seismic data used for regression analysis came from 7 851 events occurring between 1983 and 2004 ($\Delta \leq 1\ 000$ km, $2.5 \leq M_S \leq 7.5$). The distribution of differences between M_S and M_L is shown in Figure 2, from which we can see that the differences between M_S and M_L for most of the earthquakes range from -0.5 to 0.5 , with 0.0 occurring most frequently. From Figure 1, it is clear that the slope of line 3 denoting the relationship between M_L and M_S derived from OR is nearly equal to 1, and it stands between line 1 and line 2 derived from SR1 and SR2 respectively.

Following is the result derived from orthogonal regression (OR)

$$M_S = 1.01M_L - 0.07 \quad (11)$$

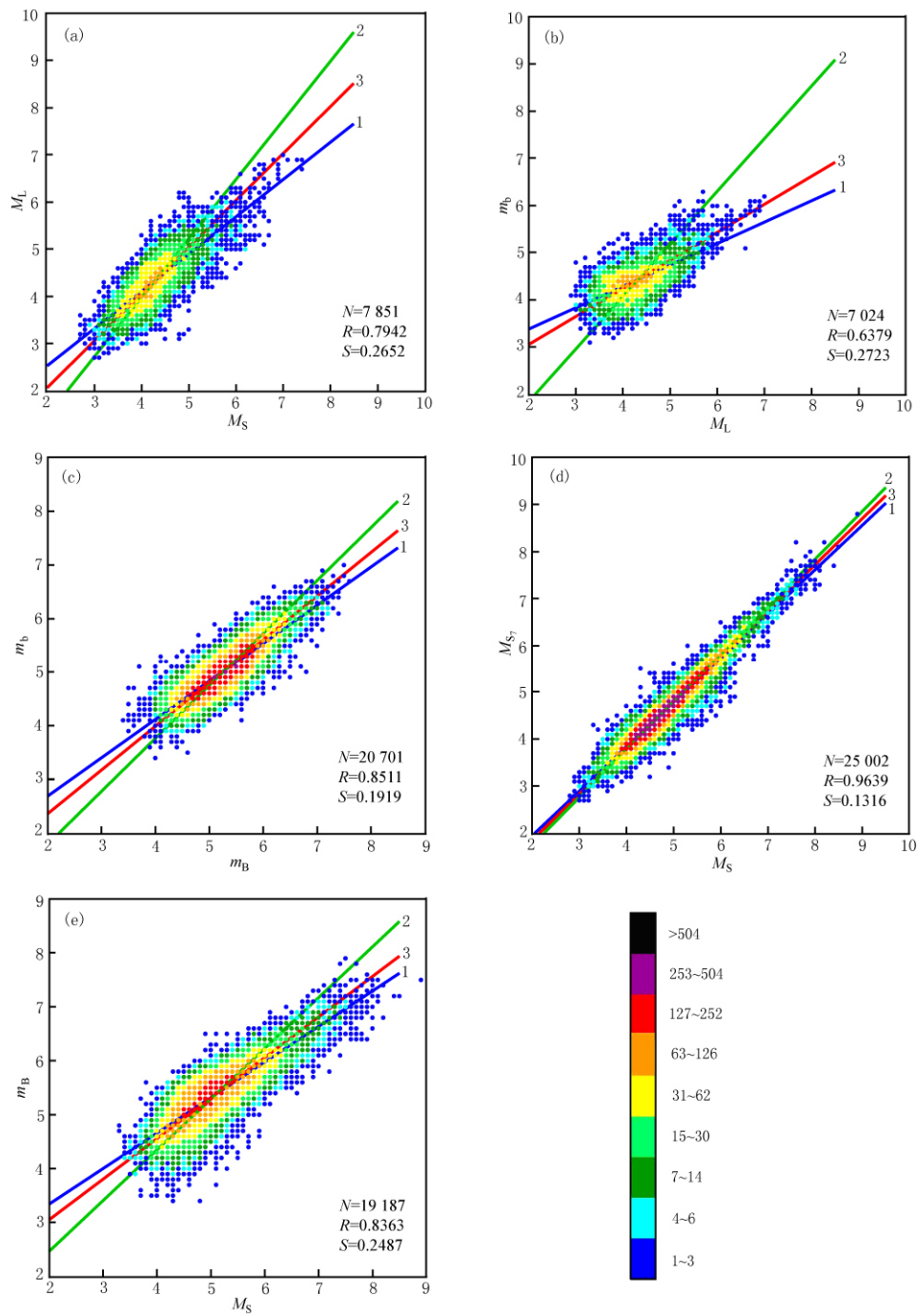


Figure 1 Relations between different magnitudes
 (a) M_S - M_L ; (b) M_L - m_b ; (c) m_b - m_B ; (d) M_S - M_{S7} ; (e) M_S - m_B . Line 1, line 2 and line 3 represent the results of SR1, SR2 and OR respectively; N is the number of events used; R is correlation coefficient of orthogonal regression; and S is root mean square of orthogonal regression, the diagram lower right is the data frequency per data point

Table 2 Comparison between M_L and M_S

M_L	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
M_S	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
$M_L - M_S$	0	0	0	0	0	0	0	0	0	0	0

The results from equation (11) can be found in Table 2, which shows that M_L and M_S for the events of $M_L \geq 2.5$ or greater are almost identical, and thus there is no need to convert between the two magnitudes in practice. This is because the period of Lg wave within 1 000 km is short (2 s), and so is the period of local surface wave (3~10 s) (XU *et al.*, 1994). Lg wave and local surface wave both propagate in the upper crust. After analytic comparison with a vast amount of seismic data, Kárník *et al.* (1962) found that the period of surface wave is approximately 3 s if the epicentral distance for measuring a surface wave diminishes to 2° .

By studying local magnitude M_L and surface wave magnitude M_S of North China, GUO (1971) obtained the following empirical relation^①:

$$M_L = 0.88M_S + 0.96 \quad (12)$$

The result was examined and approved at the China National Seismological Conference held in Sanhe, Hebei Province in 1971, at which a decision was made that the empirical formula is applicable in North China. But owing to specific historical conditions then, the result remained unpublished until 1990, when the *Handbook for Seismology Work* which included the result was published (SHI *et al.*, 1990). Following is the result of our study derived from general linear regression SR1

$$M_L \leftarrow 0.79M_S + 0.95 \quad (13)$$

which is almost identical with the result of GUO^① (1971).

3.2 Comparison between M_L and m_b

In China, the epicentral distances for measuring M_L are within the range of 1 000 km, and those for measuring m_b are $5^\circ \sim 105^\circ$. The seismic data used for regression analysis came from 7 024 events occurring from 1988 to 2004 ($5^\circ < \Delta < 10^\circ$, $3.0 \leq M_L \leq 7.0$). As can be seen from Figure 1, large discrepancy exists between M_L and m_b , because low velocity layers of the upper mantle and lateral heterogeneity of the crust leads to large uncertainty of the calibration function $Q(\Delta, h)$ of body wave magnitude when the epicentral distance is less than 20° . For that reason, the National Earthquake Information Center of US Geological Survey (USGS/NEIC) used $16^\circ \sim 100^\circ$ as the epicentral distance range for measuring body wave magnitude, instead of using local seismic data.

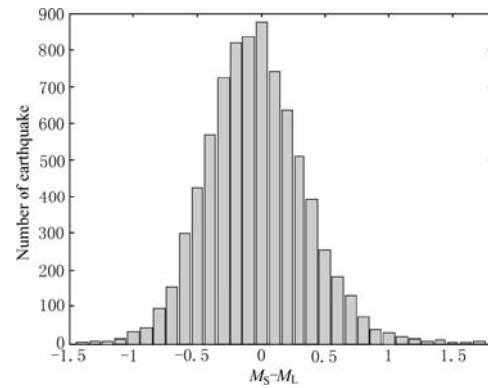


Figure 2 Distribution of differences between M_S and M_L

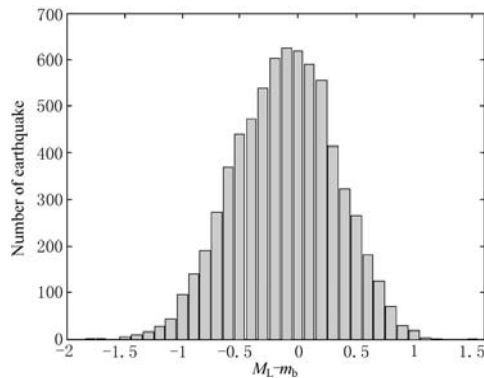
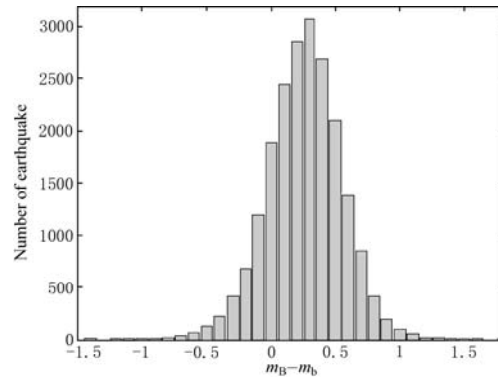
^①GUO Lü-can. 1971. Empirical relation between local magnitude M_L and surface wave magnitude M_S in North China [M]. Material from China National Seismological Conference, Sanhe, Hebei Province, 1-10 (in Chinese).

Table 3 Comparison between M_L and m_b

M_L	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
m_b	3.7	4	4.3	4.5	4.8	5.1	5.5	5.7	6
$M_L - m_b$	-0.7	-0.5	-0.3	0	0.2	0.4	0.5	0.8	1.0

3.3 Comparison between m_B and m_b

The seismic data used for regression analysis came from 20 701 events occurring between 1988 and 2004. The distribution of differences between m_B and m_b is illustrated in Figure 4, which shows that the differences between m_B and m_b for most of the earthquakes range from 0.0 to 0.6, with 0.3 occurring most frequently. We can see from this figure that, as different periods of seismic waves and different methods of measurements are used, m_B and m_b vary accordingly with the magnitudes of earthquakes: m_B is almost equal to m_b for the earthquakes around $m_B 4.0$, while m_B is larger than m_b for those of $m_B \geq 4.5$. This is because source rupture time for earthquakes of magnitude 4.0 or smaller is less than 5 s, while the corner frequencies of instrument response of both DD-1 and SK seismographs to maximum ground displacement are 1 Hz or so.

Figure 3 Distribution of differences between M_L and m_b Figure 4 Distribution of differences between m_B and m_b Table 4 Comparison between m_B and m_b

m_b	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
m_B	2.8	3.4	4	4.6	5.3	5.9	6.5	7.1	7.7
$m_B - m_b$	-0.2	-0.1	0	0.1	0.3	0.4	0.5	0.6	0.7

3.4 Comparison between M_S and M_{S7}

The seismic data for regression analysis were from 25 002 events occurring between 1989 and 2004 ($3^\circ < \Delta < 130^\circ$, $3.0 \leq M_S \leq 8.5$). The distribution of differences between M_S and M_{S7} is displayed in Figure 5. From this figure, we can see that the correlation coefficient derived with OR method is as high as 0.963 9 and the root mean square between the two magnitudes is 0.131 6, showing very little discrepancy, besides, the difference between the results obtained with SR1, SR2 and OR methods is no greater than 0.1. The result from OR shows that the differences between M_S and M_{S7} for most of the earthquakes range from 0.1 to 0.3, with 0.2 appearing most frequently. This suggests that a systematic bias exists between M_S and M_{S7} , and the difference value is generally around 0.2. For earthquakes of $M_S \leq 6.5$, M_S is larger than M_{S7} by 0.2, while for those of $M_S \geq 6.5$, M_S is larger than M_{S7} by 0.3.

Table 5 Comparison between M_S and M_{S7}

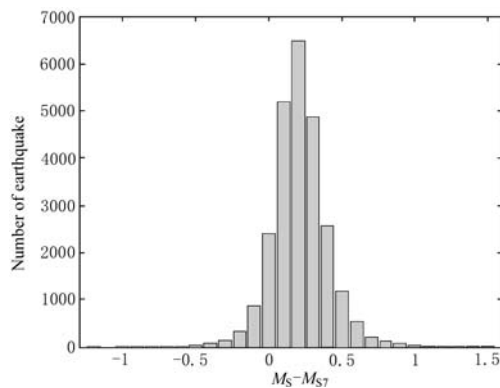
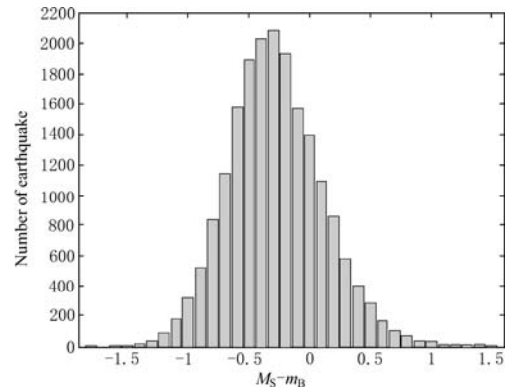
M_S	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
M_{S7}	2.8	3.3	3.8	4.3	4.8	5.3	5.8	6.3	6.7	7.2	7.7	8.2
$M_S - M_{S7}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3

3.5 Comparison between M_S and m_B

The seismic data for regression analysis were from 19 187 events occurring between 1979 and 2004 ($3.3 \leq M_S \leq 8.9$). The distribution of differences between M_S and m_B derived from OR is shown in Figure 6 and their relation is shown in Table 6. Although they are both determined on the basis of records with SK seismograph, M_S and m_B are not identical for the same earthquake because different periods of seismic waves are used. M_S and m_B are equal only when M is approximately 6.0; in the case $M < 6.0$, $m_B > M_S$, indicating that m_B can be a better choice; when $M > 6.0$, $M_S > m_B$, suggesting M_S is a preferable scale for measuring magnitudes of large events.

Table 6 Comparison between M_S and m_B

m_B	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
M_S	2.6	3.3	3.9	4.6	5.3	6.0	6.6	7.2	7.9	8.6
$M_S - m_B$	-0.9	-0.7	-0.6	-0.4	-0.2	0.0	0.1	0.2	0.4	0.6

Figure 5 Distribution of differences between M_S and M_{S7} Figure 6 Distribution of differences between M_S and m_B

4 Discussion and conclusions

We collected observation data of local magnitude M_L , surface wave magnitudes M_S and M_{S7} and body wave magnitudes m_B and m_b determined by China Seismograph Network during the period from 1983 to 2004. After analysis and comparison with general regression methods (SR1 and SR2) and orthogonal regression method (OR), we got the relations between different magnitudes. These equations are the results of linear regression with a vast amount of observed data, and considerable differences may exist between the magnitudes of a few events. The following conclusions are drawn from analysis of the orthogonal regression results:

1) When $M < 4.5$, there is little difference between the magnitude scales; when $4.5 < M < 6.0$, $m_B > M_S$, indicating M_S underestimates the magnitudes, therefore, m_B can be a better choice; when $M > 6.0$, $M_S > m_B > m_b$, m_B and m_b underestimates the magnitudes, suggesting M_S can be a preferable scale for measuring magnitudes of such events ($6.0 < M < 8.5$); when $M > 8.5$, a saturation phenome-

non appears in M_S , which cannot give an accurate reflection of the magnitudes of such large events.

2) In China, no systematic bias exists between local magnitude M_L and surface wave magnitude M_S in the case the epicentral distance is ≤ 1000 km, thus, there is no need to convert between M_L and M_S in practice.

3) m_B is almost equal to m_b for earthquakes around $m_B 4.0$, but m_B is larger than m_b for those of $m_B \geq 4.5$, because the periods of seismic waves used for measuring m_B and m_b are different though the calculation formulae are the same.

4) Although M_S and M_{S7} are both surface wave magnitudes, M_S is in general greater than M_{S7} by 0.2~0.3 magnitude, because the periods of seismic waves, calculation formulae and calibration functions are different.

5) Saturation phenomena appear in local magnitude M_L , surface wave magnitudes M_S and M_{S7} , and body wave magnitudes m_B and m_b : the saturation magnitude for m_b is about 6.5, for M_L about 7.0, for m_B about 8.0 and for M_S and M_{S7} about 8.5, which are quite consistent with the results of Kanamori (1983).

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References

- Ambrassey N N. 1990. Uniform magnitude re-evaluation of European earthquakes associated with strong-motion records [J]. *Earthquake Engineering & Structural Dynamics*, **19**: 1-20.
- Carroll R I and Ruppert D. 1996. The use and misuse of orthogonal regression in linear errors-in-variables models [J]. *The American Statistician*, **50**(1): 1-6.
- CHEN Pei-shan, ZUO Zhao-rong and XIAO Hong-cai. 1988. Determination of surface wave magnitudes by 763 long-period seismograph network [J]. *Acta Seismologica Sinica*, **10**(1): 11-24 (in Chinese).
- CHEN Pei-shan. 1989. An overview of the development of surface wave magnitude determination [J]. *Seismological and Geomagnetic Observation and Research*, **10**(6): 1-9 (in Chinese).
- CHEN Yun-tai and LIU Rui-feng. 2004. Earthquake magnitude [J]. *Seismological and Geomagnetic Observation and Research*, **25**(6): 1-12 (in Chinese).
- CHEN Yun-tai, WU Zhong-liang, WANG Pei-de, et al. 2000. *Digital Seismology* [M]. Beijing: Seismological Press: 1-30 (in Chinese).
- Draper N R and Smith H. 1998. *Applied Regression Analysis: Third Edition* [M]. New York: John Wiley & Sons: 100-125.
- Fuller W A. 1987. *Measurement Error Models* [M]. New York: John Wiley & Sons: 20-30.
- GUO Lü-can, and PANG Ming-hu. 1981. Surface wave magnitude of earthquakes and its station correction [J]. *Acta Seismologica Sinica*, **3**(3): 312-320 (in Chinese).
- Gutenberg B and Richter C F. 1942. Earthquake magnitude, intensity, energy and acceleration [J]. *Bull Seism Soc Amer*, **32**: 163-191.
- Gutenberg B and Richter C F. 1944. Frequency of earthquakes in California [J]. *Bull Seism Soc Amer*, **34**: 185-188.
- Gutenberg B and Richter C F. 1956a. Earthquake magnitude, intensity, energy and acceleration [J]. *Bull Seism Soc Amer*, **46**: 105-145.
- Gutenberg B and Richter C F. 1956b. Magnitude and energy of earthquakes [J]. *Annali di Geofisica*, **91**: 1-15.
- Gutenberg B. 1945a. Amplitude of surface waves and magnitude of shallow earthquakes [J]. *Bull Seism Soc Amer*, **35**: 3-12.
- Gutenberg B. 1945b. Amplitudes of P, PP and S and magnitude of shallow earthquakes [J]. *Bull Seism Soc Amer*, **35**: 57-69.
- Gutenberg B. 1945c. Magnitude determination for deep-focus earthquakes [J]. *Bull Seism Soc Amer*, **35**: 117-130.
- Kanamori H. 1983. Magnitude scale and quantification of earthquakes [J]. *Tectonophysics*, **93**: 185-200.
- Kármik V, Kondorskaya N V, Riznichenko Y V, et al. 1962. Standardization of the earthquake magnitude scale [J]. *Studia Geophysica et Geodaetica*, **6**(1): 41-48.
- LI Shan-bang. 1981. *Earthquakes in China* [M]. Beijing: Seismological Press: 1-30 (in Chinese).
- LIU Rui-feng, CHEN Yun-tai, Peter Bormann, et al. 2006. Comparison between earthquake magnitudes determined by China seismograph network and US seismograph network (II): Surface wave magnitude [J]. *Acta Seismologica Sinica*, **19**(1): 1-7.
- Madansky A. 1959. The fitting of straight lines when both variables are subject to error [J]. *J Amer Statist Assoc*, **54**: 173-205.
- Richter C F. 1935. An instrumental earthquake magnitude scale [J]. *Bull Seism Soc Amer*, **25**: 1-32.
- SHI Zhen-liang, ZHANG Shao-quan, ZHAO Rong-guo, et al. 1990. *Handbook for Seismology Work* [M]. Beijing: Seismological Press: 123-132 (in Chinese).
- State Seismological Bureau. 1978. *Technical Specification for Seismic Station Observation* [M]. Beijing: Seismological Press: 1-12 (in Chinese).
- Utsu T. 1982. Relationships between magnitude scales [J]. *Bull Earthq Res Inst, Univ of Tokyo*, **57**: 465-497.
- Utsu T. 2002. Relationships between magnitude scales [M]//Lee W H K, Kanamori H, Jennings P C, et al. *International Handbook of Earthquake and Engineering Seismology: Part A*. San Diego: Academic Press: 733-746.
- XU Shao-xie, LU Yuan-zhong, GUO Lü-can, et al. 1994. *General Ruler for Earthquake Magnitude* (GB17740-1999) [S]. Beijing: China Standard Press: 1-7 (in Chinese).