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Comparison between earthquake magnitudes determined by China seismograph network and US seismograph network (II): Surface wave magnitude*

LIU Rui-feng$^{1)}$ (刘瑞丰) CHEN Yun-tai$^{1)}$ (陈运泰) Peter Bormann$^{2)}$ REN Xiao$^{1)}$ (任 枭)
HOU Jian-min$^{1)}$ (侯建民) ZOU Li-ye$^{1)}$ (邹立晔) YANG Hui$^{1)}$ (杨 辉)

1) *Institute of Geophysics*, *China Earthquake Administration*, *Beijing* 100081, *China*
2) *GeoForschungsZentrum*, *D*-14478 *Potsdam*, *Germany*

Abstract

By using orthogonal regression method, a systematic comparison is made between surface wave magnitudes determined by Institute of Geophysics of China Earthquake Administration (IGCEA) and National Earthquake Information Center of US Geological Survey (USGS/NEIC) on the basis of observation data collected by the two institutions between 1983 and 2004. A formula is obtained which reveals the relationship between surface wave magnitudes determined by China seismograph network and US seismograph network. The result shows that, as different calculation formulae and observational instruments are used, surface wave magnitude determined by IGCEA is generally greater by 0.2 than that determined by NEIC: for M=3.5~4.5 earthquakes, it is greater by 0.3; for M=5.0~6.5 earthquakes, it is greater by 0.2; and for $M\geq7.0$ earthquakes, it is greater by no more than 0.1.

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

Earthquake magnitude is the most common measure of an earthquake′s size, and is one of the basic parameters of an earthquake. There are three most familiar scales of earthquake magnitude: M_L (local earthquake magnitude), M_S (surface wave magnitude) and m_B/m_b (body wave magnitude). Richter (1935) introduced M_L when studying earthquakes in Southern California. In 1945, Gutenberg (1945a) put forward surface wave magnitude scale to determine earthquake magnitude (M_S) using surface waves (20 s) of shallow-focus earthquakes within a 15°~30° epicentral distance, and revealed a relationship between amplitude and epicentral distance by combining theory with practical experience. Soon after, Gutenberg (1945b) introduced m_b, using P, PP and S waves of shallow-focus earthquakes to determine earthquake magnitude while taking the effects of geomet-

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E-mail of the first author: liurf@seis.ac.cn

rical spreading, medium absorption and dispersion into account. In the following decades, earthquake magnitude was widely used in the world. National and international seismic institutions have developed empirical formula for different regions according to their own research results and observation data. Over the years, calculation methods of earthquake magnitude have constantly been improved, yet great differences appear in the process of evolution, as a result, the same earthquake often has different magnitudes as determined by different countries. A magnitude ≥ 6 earthquake can be recorded and its magnitude be determined by almost all the seismic stations in the world, therefore, the unification of earthquake magnitude scale has attracted much attention of seismologists all over the world.

In this paper, a systematic comparison is made between surface wave magnitudes determined by Institute of Geophysics of China Earthquake Administration (IGCEA) and National Earthquake Information Center of US Geological Survey with orthogonal regression method and on the basis of observation data collected by the two institutions between 1983 and 2004. A formula is obtained which reveals the relationship between surface wave magnitudes determined by China seismograph network and US seismograph network.

1 Magnitude formula used in the US

Since Gutenberg (1945a) put forward the concept of M_S, magnitude has been widely used in almost all the countries in the world. Kárnĭk *et al* (1962) studied the calibration functions of 14 authors, performed a weighted average on them and developed a formula for measuring M_S:

$$M_S = \lg\left(\frac{A}{T}\right)_{\max} + 1.66\lg\Delta + 3.3 \qquad 20° < \Delta < 160°,\ h \leq 50\ \text{km} \tag{1}$$

where $(A/T)_{\max}$ is the maximum value of A/T, A is vector sum of two horizontal components of surface wave displacement, $A = (A_E^2 + A_N^2)^{1/2}$ (in μm), T is corresponding period (in s).

The above formula is called Moscow-Prague formula or Prague formula. In order to ensure the consistency of magnitude measurement, the organizing committee of International Association of Seismology and Physics of the Earth′s Interior (IASPEI) presented the formula to the whole world at the IASPEI conference held in Zürich in 1967, so it is also known as the IASPEI formula. Later on, NEIC, International Seismological Center (ISC) and many other seismological institutions adopted the IASPEI formula. The adoption of the IASPEI formula has brought about consistency of magnitudes determined by different countries (CHEN, 1982).

It should be pointed out that while recommending the formula for measuring surface wave magnitude, IASPEI suggested using Rayleigh wave with period (20±3) s and $20° \leq \Delta \leq 160°$; however, the original Prague formula has no restrictions in this regard. In measuring surface wave magnitude of shallow earthquakes ($h \leq 50$ km) with the same formula [equation (1)], ISC used vertical and horizontal components of surface waves ($5° \leq \Delta \leq 160°$, 10~60 s) (not restricted to Rayleigh wave) to calculate M_S, whereas NEIC used horizontal component (A/T) of surface waves with period (20±2) s (not restricted to Rayleigh wave) before 1975, and vertical component (A/T) of surface waves after 1975 to calculate M_S.

2 Magnitude formula used in China

Owing to historical reasons, the M_S formula recommended by IASPEI has never been used in China. After January of 1966, China began to use the following M_S formula (with Baijiatuan seismic station of Beijing as the benchmark) proposed by GUO and PANG (1981) in its earthquake report:

$$M_{\mathrm{S}} = \lg\left(\frac{A}{T}\right)_{\max} + \sigma(\mathit{\Delta}) \qquad 1° < \mathit{\Delta} < 130° \tag{2}$$

where

$$\sigma(\mathit{\Delta}) = 1.66\lg\mathit{\Delta} + 3.5 \qquad 1° < \mathit{\Delta} < 130°$$

A is vector sum of two horizontal components of surface wave displacement and $A = (A_{\mathrm{E}}^2 + A_{\mathrm{N}}^2)^{1/2}$ (in μm), T is corresponding period (in s), $3 \le T \le 25$ s is chosen for different station-epicenter distances ($1° < \mathit{\Delta} < 130°$) (XU, 1994); $\mathit{\Delta}$ represents station-epicenter distance (in degree). This formula is still being used today.

After 1985, a 763-long-period seismograph network was established and put into use in China. The parameters of the seismograph are identical with those of the long-period seismograph of the world wide standardized seismograph network (WWSSN), by which vertical components of Rayleigh wave (with maximum amplitude and period) were used to determine M_{S7}.

$$M_{\mathrm{S7}} = \lg\left(\frac{A}{T}\right)_{\max} + \sigma(\mathit{\Delta})_{763} \qquad 3° < \mathit{\Delta} < 177° \tag{3}$$

Comparing equation (3) with equation (1), we can see that the two equations yield identical results between 20° and 160°. They differ in that the station-epicenter distance for M_{S7} is $3° < \mathit{\Delta} < 177°$, as contrasted to $20° < \mathit{\Delta} < 160°$ for M_{S} presented by IASPEI. Table 1 shows calibration function of M_{S} measured by the 763-long-period seismograph. As shown in the table, $\sigma(\mathit{\Delta})_{763}$ between 20° and 160° is consistent with the calibration function $1.66\lg\mathit{\Delta}+3.3$ presented by IASPEI.

Table 1 Calibration function $\sigma(\mathit{\Delta})$ of M_{S} for the 763-long-period seismograph

$\mathit{\Delta}$/(°)	σ/($\mathit{\Delta}$)	$\mathit{\Delta}$/(°)	σ/($\mathit{\Delta}$)	$\mathit{\Delta}$/(°)	σ/($\mathit{\Delta}$)	$\mathit{\Delta}$/(°)	σ/($\mathit{\Delta}$)
3	4.48	50	6.11	100	6.63	150	6.96
5	4.81	55	6.18	105	6.65	155	6.98
10	5.13	60	6.24	110	6.69	160	6.99
15	5.34	65	6.30	115	6.72	165	6.98
20	5.51	70	6.35	120	6.76	170	6.94
25	5.65	75	6.40	125	8.79	175	6.83
30	5.75	80	6.45	130	6.82	177	6.62
35	5.87	85	6.50	135	6.82		
40	5.96	90	6.54	140	6.89		
45	6.04	95	6.59	145	6.93		

3 Comparison between earthquake magnitudes determined by China seismograph network and US seismograph network

After 1964, the United States began to set up progressively the world wide standardized seismograph network (WWSSN), which covers an extensive area and has the seismographs feature satisfying consistency. USGS/NEIC used data from WWSSN and determined M_{S} according to unified earthquake magnitude scale.

In 1978, IGCEA began to compile *China Annual Earthquake Report* using seismic data from class I and class II seismic stations within the country and calculated surface wave M_{S}, body wave m_{B} and m_{b} according to a unified scale. These seismic stations are equipped with similar instru-

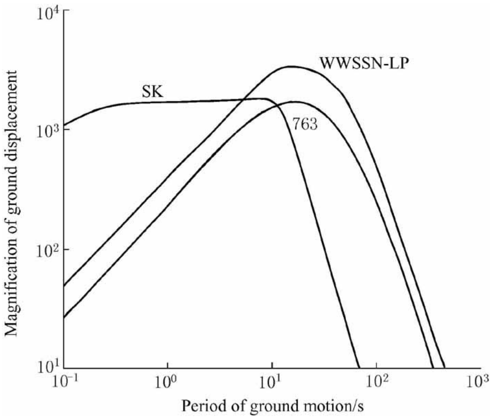

Figure 1 Amplitude-frequency characteristics of seismographs for analog recording used by IGCEA and USGS/NEIC
WWSSN-LP stands for long-period seismograph of WWSSN, SK represents Kirnos broadband seismograph used in China, and 763 represents 763-long-period seismograph

ments, which feature conformity. Class I stations are equipped with DD-1 or DD-2 short-period seismographs, Kirnos (SK) middle- and long-period seismographs and 763-long-period seismographs; class II stations are equipped with DD-1 or DD-2 short-period seismographs, DK-1 middle- and long-period seismographs, some of them also have Kirnos (SK) middle- and long-period seismographs and 763-long- period seismographs (see Figure 1 for amplitude-frequency characteristics). In order to ensure standardization and consistency of seismic observation, China Earthquake Administration (CEA) formulated *Observation Standardization for Seismic Stations* (trial implementation) in 1978, which made it possible for seismic stations in China to have standardized and unified earthquake magnitude measurement. Therefore, observation data of China seismograph networks from 1983 to 2004 are chosen in this study for analytical comparison between surface wave magnitudes determined by China seismograph network and US seismograph network. Besides, correlation coefficient of linear fitting is calculated (HE and LIU, 2001).

3.1 Comparison between M_S(IGCEA) and M_S(NEIC)

M_S(IGCEA) (hereinafter shortened as M_S) is the surface wave magnitude determined by IGCEA on the basis of two horizontal components of surface waves (18~22 s) recorded with SK seismographs, according to formula (2); M_S(NEIC) is the surface wave magnitude determined by NEIC on the basis of vertical components of surface waves (18~22 s) recorded with WWSSN-LP seismographs, and on the basis of vertical components of surface waves (18~22 s) recorded by broadband digital seismographs after 1990s, according to formula (1). The data we used came from 14 808 earthquakes (1983~2004), which are shown in Figure 2. Orthogonal regression leads to the following result:

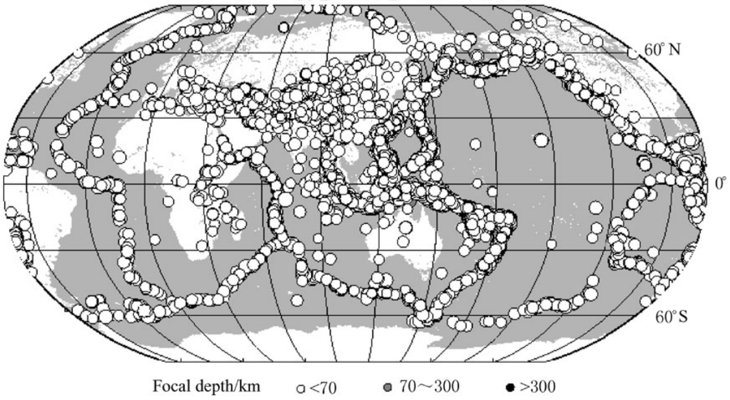

Figure 2 The 14 808 earthquakes (1983~2004) used in the determination of M_S and M_S(NEIC)

$$M_S(\mathrm{NEIC}) = 1.07M_S - 0.61 \tag{4}$$

The correlation coefficient is derived as γ=0.90, and root-mean-square deviation is 0.211 6.

The relationship between M_S and M_S(NEIC) is shown in Figure 3, from which we can see that the maximum magnitude used in this study is M_S=8.5, the minimum is M_S=3.5 and most of them range between 4.0 and 7.0.

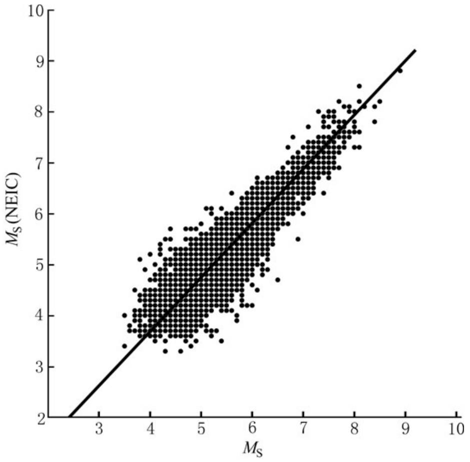

Figure 3 Relationship between M_S and M_S(NEIC)

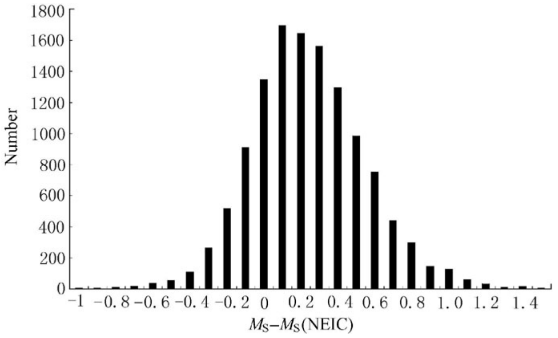

Figure 4 Difference value distribution of M_S and M_S(NEIC)

Difference value distribution of M_S and M_S(NEIC) is shown in Figure 4, from which we can see that the difference value between M_S and M_S(NEIC) for most earthquakes ranges between 0.0~0.4, with 0.1 being the most commonly seen. A statistical comparison between surface wave magnitudes determined by IGCEA and NEIC according to equation (6) is shown in Table 2. If earthquake magnitude determined by NEIC is taken as the benchmark, it is evident that the magnitude determined by IGCEA for M=3.5~4.5 earthquakes is generally greater by 0.3 than that determined by NEIC; for the M=5.0~6.5 earthquakes, it is greater by 0.2; and for those $M\geq$7.0 earthquakes, it is greater by no more than 0.1.

Table 2 Comparison between M_S determined by IGCEA and M_S(NEIC)

M_S(NEIC)	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
M_S	3.8	4.3	4.8	5.2	5.7	6.2	6.7	7.1	7.6	8.1	8.5
M_S−M_S(NEIC)	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.0

The difference between M_S (IGCEA) and M_S (NEIS) is explained by the followings:

1) Different calculation formulae are used. NEIC used equation (1) while IGCEA used equation (2) for calculating surface wave magnitude. Equation (2) differs from equation (1) not only in the range of station-epicenter distance, but also in the numerical factor on the right side: the numerical factor in equation (2) is 3.5 instead of 3.3 for the station-epicenter distances 1°<Δ<130°.

2) Different components are used. NEIC only used vertical components to calculate surface wave magnitudes of earthquakes (20°<Δ<160°, 18~22 s), while IGCEA used two horizontal components to calculate surface wave magnitudes of earthquakes (1°<Δ<130°, 3~25 s).

3) Different seismographs are used. NEIC used WWSSN-LP, while IGCEA used Kirnos (SK)

seismographs. Figure 1 shows that WWSSN-LP differs from SK in frequency band: WWSSN-LP is a long-period seismograph with frequency bandwidth between 1.0~500 s, peak value at about 15.0 s and high sensitivity at 1.0~100 s; whereas SK is a broadband seismograph, whose frequency bandwidth is 0.1~40 s and spectrum appears flat at 0.2~11.0 s.

3.2 Comparison between M_{S7} and M_S(NEIC)

After 1985, a 763-long-period seismograph network was established and put into use in China. As shown in Figure 1, the frequency characteristic of 763-long-period seismograph is identical with that of WWSSN. After 1989, IGCEA began to use M_{S7} as surface wave magnitude, which is determined on the basis of vertical components of Rayleigh wave (with maximum amplitude and period) recorded with 763-long-period seismograph, according to equation (3). The data we used came from 13 107 earthquakes (1989~2004), which are displayed in Figure 5. Here we have the following result:

$$M_S(\text{NEIC}) = 1.06\,M_{S7} - 0.34 \tag{5}$$

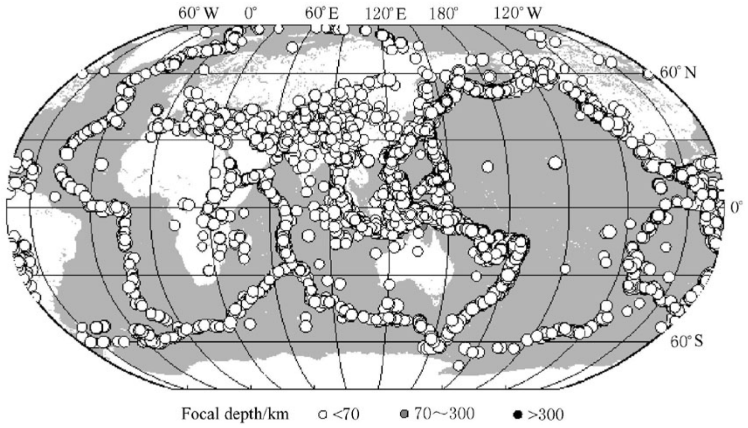

Figure 5 Epicenter distribution of the 13 107 earthquakes (1989~2004) used for measuring M_{S7} and M_S(NEIC)

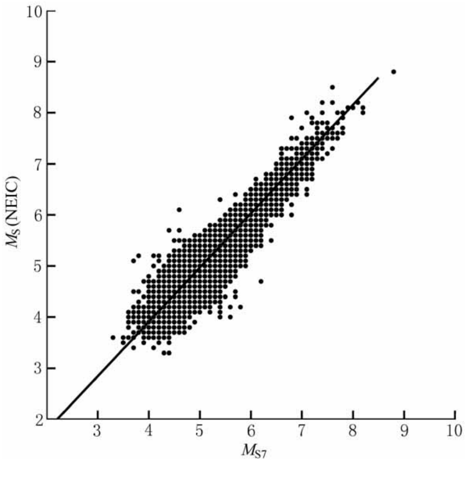

Figure 6 Relationship between M_{S7} and M_S(NEIC)

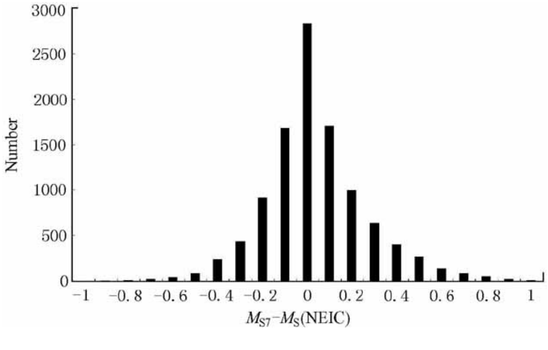

Figure 7 Difference value distribution of M_{S7} and M_S(NEIC)

The correlation coefficient is derived as γ=0.93, and root-mean-square deviation is 0.170 5. The relationship between M_{S7} and M_S(NEIC) is shown in Figure 6 and difference value distribution of M_{S7} and M_S(NEIC) is shown in Figure 7.

Referring to Figure 7, we see that the difference value between M_{S7} and M_S(NEIC) for most of the earthquakes ranges between −0.1~0.1, with 0.0 being the most commonly seen. A statistical comparison between M_{S7} (determined by IGCEA) and M_S(NEIC) according to equation (7) is shown in Table 3, which shows that for the M=5.5~6.5 earthquakes, the results determined by IGCEA and NEIC show no difference; for the M=3.5~4.5 and M=7.0~8.5 earthquakes, the difference value between them ranges from 0.1 to 0.2.

Table 3 Comparison between M_{S7} determined by IGCEA and M_S(NEIC)

M_S(NEIC)	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
M_{S7}	3.6	4.1	4.6	5.0	5.5	6.0	6.5	6.9	7.4	7.9	8.3
M_{S7}–M_S(NEIC)	0.1	0.1	0.1	0	0	0	0	−0.1	−0.1	−0.1	−0.2

4 Discussion and conclusions

In 1983, IGCEA began to use two horizontal components of surface waves (3~25 s) recorded with SK seismographs and the formula developed by GUO and PANG (1981) to determine surface wave magnitude M_S. After 1989, IGCEA began to use vertical components of Rayleigh wave (with maximum amplitude and period) recorded with the 763-long-period seismograph and a formula similar to that of IASPEI to determine surface wave magnitude M_{S7}. NEIC used vertical components of surface waves (18~22 s) recorded with WWSSN-LP seismograph and the IASPEI formula to determine surface wave magnitude. Regression analysis leads to the following conclusions:

1) M_S determined by IGCEA is generally greater by 0.2 than that determined by NEIC because different calculation formulae and components of records are used. If earthquake magnitude determined by NEIC is taken as the benchmark, we can see that the magnitude determined by IGCEA for M=3.5~4.5 earthquakes is on the whole greater by 0.3 than that determined by NEIC; for M=5.0~6.5 earthquakes, it is greater by 0.2; and for $M\geq$7.0 earthquakes, it is greater by no more than 0.1

2) M_{S7} determined by IGCEA is roughly consistent with M_S(NEIC).

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