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Re-calculation of the attenuation functions for Local Magnitude from the upgraded Central Weather Bureau Seismic Network in Taiwan

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ABSTRACT

The empirical attenuation functions for Local Magnitude (M_L) currently used in Taiwan have been known for overestimated magnitudes around 0.2 compared with moment magnitude (M_W) for shallow earthquakes (depths ≤ 35 km). Moreover, for deep earthquakes (depths > 35 km), M_L (> 6) can be larger than M_W around 0.5. Based on global observations and seismological theory, M_L is equal to M_W for magnitudes 4 - 6, whereas M_L is smaller than M_W for magnitudes > 6. This indicates that the attenuation functions for the Taiwan region need to be re-calculated. In this study, we used the new data set collected at the upgraded Central Weather Bureau Seismic Network (CWBSN24) from January 2012 to April 2019 and totally there are 692 events with $M_L \geq 3$ and 35228 amplitude data used for analysis. To accommodate the complicated tectonic environment in Taiwan, there are four attenuation functions, $\log A_0(\Delta)$, based on the focal depths and hypocentral distances, which are:

$$\log A_0(\Delta) = \begin{cases} -0.00401R - \log R - 0.58 & (0\text{ km} < \Delta \leq 80\text{ km}) \\ -0.00234R - 0.83\log R - 1.11 & (80\text{ km} < \Delta) \end{cases}$$

for shallow earthquakes (focal depth, $h \leq 35$ km), and

$$\log A_0(\Delta) = \begin{cases} -0.00077R - 0.83\log R - 1.26 & (\text{Latitude} \geq 23^\circ\text{N}) \\ -0.00176R - 0.83\log R - 1.16 & (\text{Latitude} < 23^\circ\text{N}) \end{cases}$$

for deep earthquakes ($h > 35$ km),
where Δ is epicentral distance, R ($= \sqrt{\Delta^2 + h^2}$) is hypocentral distance. M_L calculated by using the old attenuation functions for deep and large ($M_L > 5.5$) earthquakes is larger than that by using the new ones about 0.4. With the new empirical attenuation functions, the relationship between M_L and M_W follows the global observations and also the new M_L avoids the confusion for the public when releasing the official earthquake reports.

1. INTRODUCTION

The current official operation for calculation of Local Magnitude (M_L) in Taiwan is according to the empirical formulas proposed by Shin (1993), which used the simulated Wood-Anderson seismograms converted from the three-components short-period seismograms of the Central Weather Bureau Seismic Network (CWBSN) from September 1991 to February 1992. It has been reported that the values of M_L are larger than those of moment magnitude (M_W) around 0.2 for shallow earthquakes (≤ 35 km), in general (Wu et al. 2005). Moreover, not only for shallow earthquakes but for deeper ones, the values of M_L are much larger than those of M_W. For example, on 31[th] May 2016, there was an earthquake occurred in northeastern offshore of Taiwan. The focal depth and M_L reported by the Central Weather Bureau, Taiwan (CWB) are 256.9 km and 6.9, respectively, but meanwhile the depth and M_W reported by the U.S. Geological Survey (USGS) are 246.4 km and 6.4. The difference between these two magnitudes is 0.5. This is an unusual case because M_L greater than 6 is saturated and smaller than M_W owing to only high frequency (≥ 2 Hz) energy measured by M_L (Kanamori 1983). This indicates

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that the current empirical formulas have systematic biases and need to be re-calculated the attenuation functions for the calculation of M_L. With the new empirical formulas, the calculation of M_L can reduce the gap between M_L and M_W and avoid the confusion for the public when releasing the official earthquake reports. In this study, in order to obtain new attenuation functions, we used the data set of 692 earthquakes ($M_L \geq 3$) from the upgraded Central Weather Bureau Seismic Network (CWBSN24) from January 2012 to April 2019.

2. DATA AND ANALYSIS

The old seismic network, CWBSN, is with 12-bit A/D converter and the timestamps were given after the data were transmitted to the center, which both caused the averaged time delay and shifted earthquake origin times around 0.2 s (Chang et al. 2012). Because of this reason, since 2012, the three-components short-period seismic network of the CWB, which consists of 71 stations, has been fully upgraded with 24-bit A/D converter and on-site GPS timestamp, called CWBSN24 (Fig. 1a). In this study, we selected the earthquake list from the CWB earthquake catalogue based on four criteria: (1) $M_L \geq 3$; (2) region within longitude 120° - 124°E and latitude 20° - 26°N; (3) time period from January 2012 to April 2019; and (4) earthquakes also listed in the USGS earthquake catalogue for further M_L comparison with M_W or mb. Totally, there are 692 events with 35228 maximum amplitudes from 71 stations (Fig. 1b). The amplitudes calculated from the simulated Wood-Anderson seismograms from short-period seismograms as described in Shin (1993). The maximum amplitude from each station is determined by the root sum squared of peak amplitudes in the NS and EW components (Shin 1993), which is the official procedure for data processing in the CWB. Previous global studies have shown the relationship between M_W and M_L: M_W is larger than M_L for magnitudes larger than 6, M_W is equal to M_L for magnitudes from 4 to 6, and for smaller magnitudes (2 - 4) M_W is around 0.67 M_L (Kanamori 1983; Deichmann 2006; Havskov and Ottemöller 2010). However, M_W versus M_L plot (Fig. 2) for the Taiwan region shows that M_W greater than 4.5 is systematically lower than M_L, which is different with previous global studies (Kanamori 1983; Hanks and Boore 1984; Havskov and Ottemöller 2010). This highlights the need for re-calculation of the attenuation functions.

M_L is widely used for local seismic network and originally proposed by Richter (1935) as:

$$M_L = \log A - \log A_0(\Delta) \tag{1}$$

where A is the maximum amplitude in millimeters recorded on the standard Wood-Anderson seismograph, Δ is an epicentral distance, and A_0 is the attenuation function, which relates to geometrical spreading, anelastic attenuation, and wave scattering. $\log A_0$ is empirically determined and strongly depends on the tectonic regions. Based on the focal depth (h) and epicentral distance (Δ) of earthquakes, Shin (1993) has first proposed three $\log A_0(\Delta)$ functions for the Taiwan area:

$$\log A_0(\Delta) = \begin{cases} -0.00716R - \log R - 0.39 & (0\text{ km} < \Delta \leq 80\text{ km}) \\ -0.00261R - 0.83\log R - 1.07 & (80\text{ km} < \Delta) \end{cases} \tag{2}$$

for shallow earthquakes ($h \leq 35$ km) and

$$\log A_0(\Delta) = -0.00326R - 0.83\log R - 1.01 \tag{3}$$

for deep earthquakes ($h > 35$ km)
where R (= $\sqrt{\Delta^2 + h^2}$) is the hypocentral distance.

Wu et al. (2005) has found that at shallow depths ($h \leq 35$ km) M_L is larger than M_W by using the $\log A_0(\Delta)$ [Eqs. (2) and (3)] of Shin (1993) for calculation. Therefore, Wu et al. (2005) used a regression model between M_L and M_W from the data set of the Taiwan Strong Motion Instrumental Program (TSMIP) to obtain a new $\log A_0$:

$$\log A_0(R) = 0.332 - 1.568\log R \pm 0.280 \tag{4}$$

A maximum amplitude [$A(\Delta)$] of S wave recorded in a seismograph is affected by the factors of source, path, and site effects, and can be expressed as

$$A(\Delta) = CR^{-n}e^{-\gamma R}S \tag{5}$$

where γ and n are the attenuation and geometrical spreading coefficients, respectively, and C and S are source-related and site-dependent constants, respectively. We can take logarithm on both sides of Eq. (5) as

$$\log[A(\Delta)R^n] = -0.4343\gamma R + \log C + \log S \tag{6}$$

In the left hand side, the reduced amplitude, of Eq. (6) has a linear relationship with the hypocentral distance R. Therefore, γ can be simply determined from the slope of the linear regression of the data. The terms C and S are the intercept of the linear regression of the data, which are the combination effects. According to $\log A_0(\Delta = 100) = -3$, which is the definition of M_L by Richter (1935), we can obtain $\log C$ to have the attenuation functions, $\log A_0(\Delta)$. The term $\log S$ is the residual term, as ΔM_L, from the average for each station and will be mentioned in Discussion section.

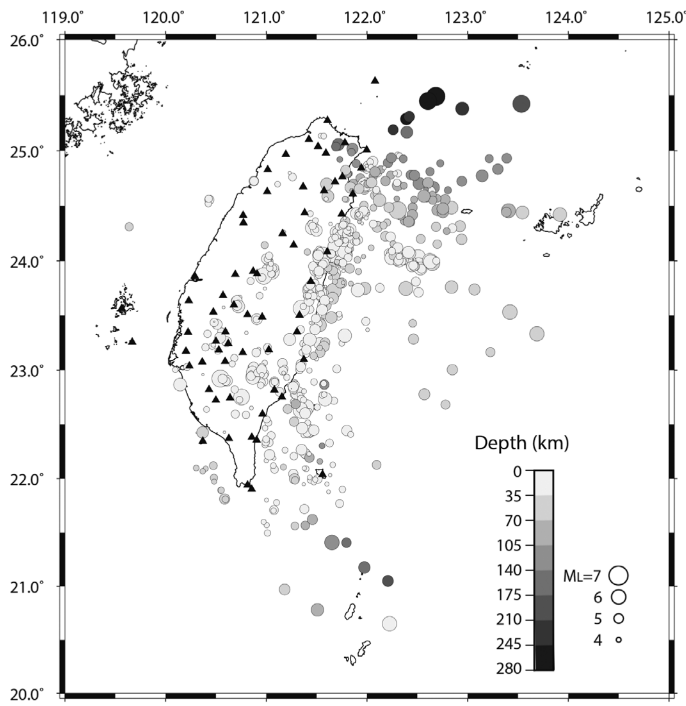

Fig. 1. The distributions of seismic stations (black triangles) and earthquakes (circles) used in this study.

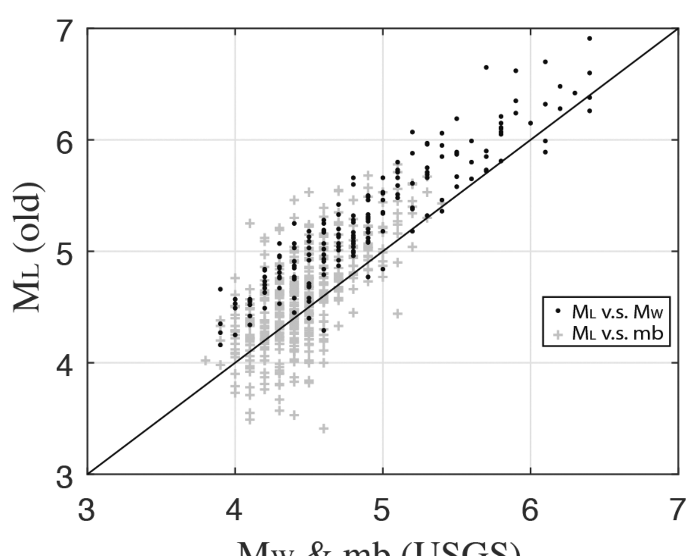

Fig. 2. The comparison of M_L (old) and M_W and mb. M_L (old): M_L determined from the attenuation functions from Shin (1993).

3. RESULTS

Based on the focal depths and epicentral distances, there are three attenuation functions applied in the Taiwan area [Eqs. (2) to (3)] (Shin 1993). In this study, we have further divided deep earthquakes into northern and southern parts to reflect the different tectonic environments of the Ryukyu and Manila subductions zones, respectively. Totally, there are four regimes and the n value is set to 1 for shallow ($h \le 35$ km) and near-distance (0 km < $\Delta \le 80$ km) earthquakes and for other regimes the n values are set to 0.83 for considering *Lg* wave propagation (Shin 1993). The results of the 4 cases based on the earthquake depths and epicentral distances are shown as follows:

Case 1: $h \le 35$ km and 0 km < $\Delta \le 80$ km

In total, 488 events with 5488 amplitudes are used for regression. The slope obtained from the relationship between the reduced amplitude and hypocentral distance based on Eq. (6) is 0.00923 and γ is 0.00401 km^{-1} (Fig. 3a). After applied the definition of $\log A_0(\Delta = 100) = -3$, the attenuation function (Fig. 4) is

$$\log A_0(\Delta) = -0.00401R - \log R - 0.58 \quad (7)$$

Case 2: $h \le 35$ km and 80 km < Δ

517 events with 20260 amplitudes are used for regression and the slope and γ are 0.00539 and 0.00234 km^{-1}, respectively (Fig. 3b). The attenuation function (Fig. 4) for this case is

$$\log A_0(\Delta) = -0.00234R - 0.83\log R - 1.11 \quad (8)$$

Case 3: $h > 35$ km and earthquakes located in latitude ≥ 23°N

150 events with 7824 amplitudes are used for regression and obtained the slope and γ are 0.00177 and 0.00077 km^{-1}, respectively (Fig. 3c). The attenuation function (Fig. 4) is

$$\log A_0(\Delta) = -0.00077R - 0.83\log R - 1.26 \quad (9)$$

Case 4: $h > 35$ km and earthquakes located in latitude < 23°N

33 events with 1656 amplitudes are used for regression and the slope and γ are 0.00405 and 0.00176 km^{-1}, respectively (Fig. 3d). The attenuation function (Fig. 4) is

$$\log A_0(\Delta) = -0.00176R - 0.83\log R - 1.16 \quad (10)$$

4. DISCUSSION

For the comparison between the new and old attenuation functions (Fig. 4), the Eqs. (7) and (8) of Cases 1 and 2 obtained in this study are similar to the Eqs. (2) and (3) of Shin (1993), respectively, for shallow earthquakes ($h \le 35$ km). If we take the form $Q = \pi f/\gamma U$, as the seismic quality factor, where f is the frequency of the wave, and U is its velocity. The seismic quality factors from Eqs. (7) and (8) are 129 and 221, respectively, by assuming $f = 1.25$ Hz and $U = 3.3$ km s^{-1} for averaged S wave speed in the crust. On the other hand, the seismic quality factors from Eq. (2) are 72 and 198, respectively. The new attenuation functions show slightly lower seismic energy decay (higher Q) than the old ones. If we consider deep earthquakes ($h > 35$ km), either Eqs. (9) or (10) obtained in this study has much lower attenuation than Eq. (3). The seismic quality factors from Eqs. (9) and (10) are 555 and 242, respectively, by assuming $f = 1.25$ Hz and $U = 4.0$ km s^{-1} for averaged S wave speed in the crust, whereas Q value from Eq. (3) is 130. In general, Q values are larger toward to deeper depths. For example, Qs values range from around 100 to 500 above 35 km depths and below 35 km depths Qs values are much higher than 500 for the Taiwan region based on 3D Q tomography (Wang et al. 2010). The Q values obtained in this study are consistent with those from previous studies (Wang et al. 2010). Also, Q values between the northern and southern deep earthquakes are very different, which shows the need for distinguishing deep earthquakes to two regimes.

Based on the new attenuation functions [Eqs. (7) to (10)], we can obtain the new M_L [Eq. (1)] for 692 events to compare with the old M_L and M_W (Fig. 5). Figure 5a shows that the new M_L is smaller than the old one, especially toward to larger magnitudes. For example, the M_L 6.9 earthquake originally reported by CWB as mentioned in Introduction is adjusted to M_L 6.1 after applied the new attenuation functions. On the other hand, the USGS moment magnitude of this earthquake is 6.4, which is closer to the new M_L. Furthermore, Fig. 5b shows that the relationship between the new M_L and M_W (USGS) is around 1:1 for magnitudes greater than 4, which is consistent with the observations (Kanamori 1983; Hanks and Boore 1984; Havskov and Ottemöller 2010). Also, both the distributions of mb (USGS) and M_W (USGS) versus the new M_L plots are more clustered than those versus the old M_L, especially toward to larger magnitudes (Figs. 2 and 5b). Figures 5c and d show the old M_L and new M_L subtract with M_W (USGS) and mb, respectively. The new M_L values are closer to the M_W (USGS) and mb (USGS) values than the old M_L ones.

For the comparison among other magnitudes [M_W (AutoBATS), new M_L, and old M_L], the M_W (AutoBATS) (Jian et al. 2018) have a good agreement with M_W (USGS), and the old and new M_L have higher values than M_W (USGS) for magnitude 4 to 6 (Fig. 6). Around magnitude 4 to 6, the old and new M_L are about 0.4 and 0.2 units higher than both M_W (AutoBATS) and M_W (USGS), respectively. Previous studies have shown that the old M_L is 0.2 unit higher than M_W

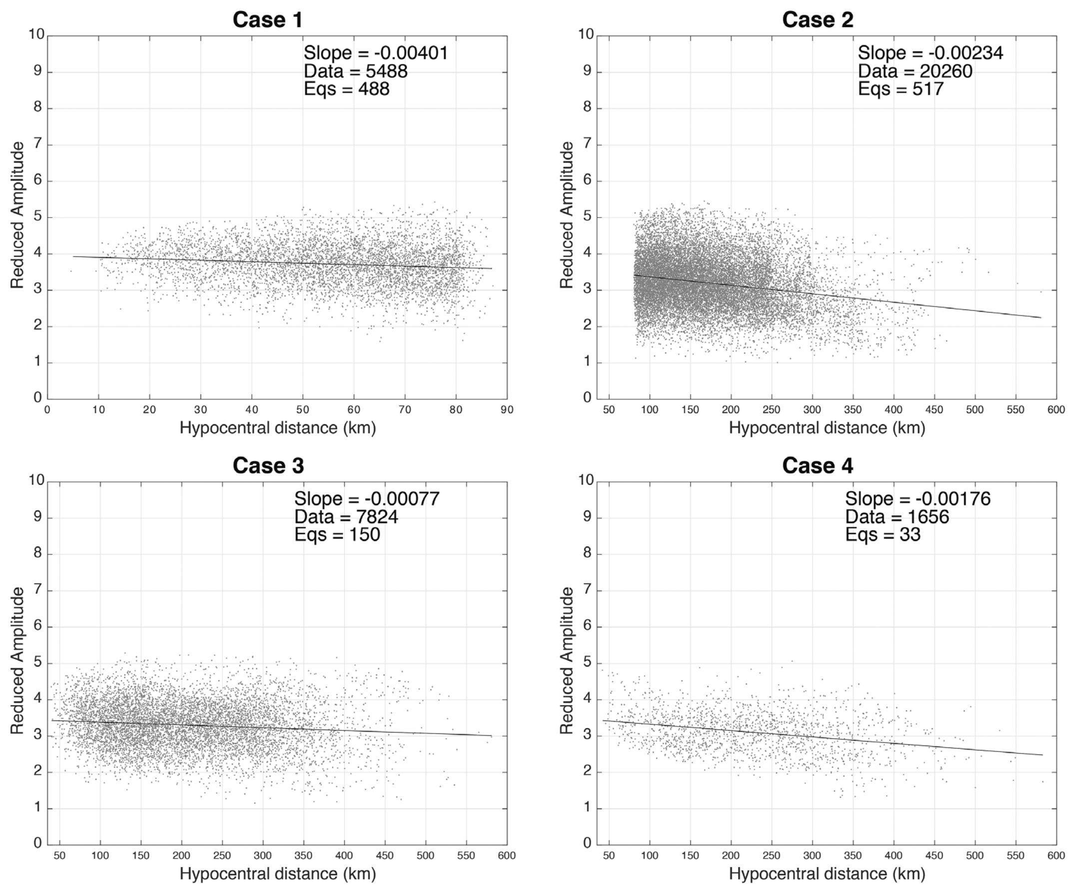

Fig. 3. Reduced amplitude versus hypocentral distance for four cases.

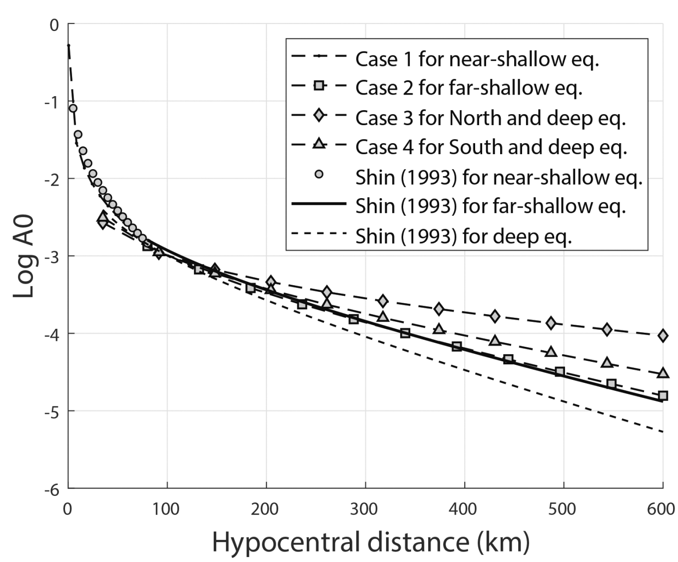

Fig. 4. The attenuation functions, $\log A_0(\Delta)$, obtained in this study and Shin (1993).

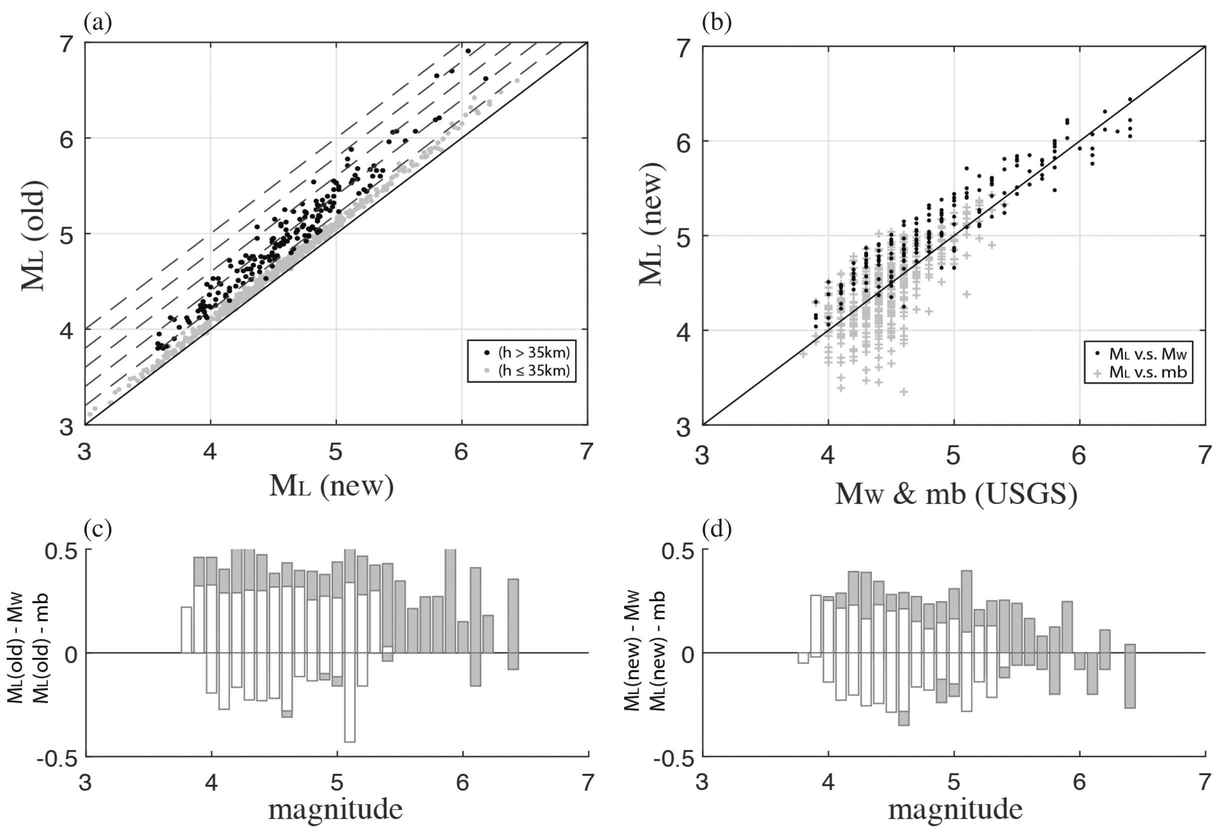

Fig. 5. The comparison of M_L (new) and other magnitudes [M_L (old), M_W (USGS), and mb (USGS)]. (a) M_L (old) versus M_L (new). Gray dot: focal depth ≤ 35 km (Cases 1 and 2). Black dot: focal depth > 35 km (Cases 3 and 4). M_L (new): M_L determined by the attenuation functions from this study. Dashed line: every 0.2 increment with the slope 1. (b) M_L (new) versus M_W (USGS) and mb (USGS). (c) The spread ranges of M_L (old) - M_W (USGS) (gray bar) and M_L (old) - mb (USGS) (white bar) for each magnitude bin. (d) The spread ranges of M_L (new) - M_W (USGS) (gray bar) and M_L (new) - mb (USGS) (white bar) for each magnitude bin.

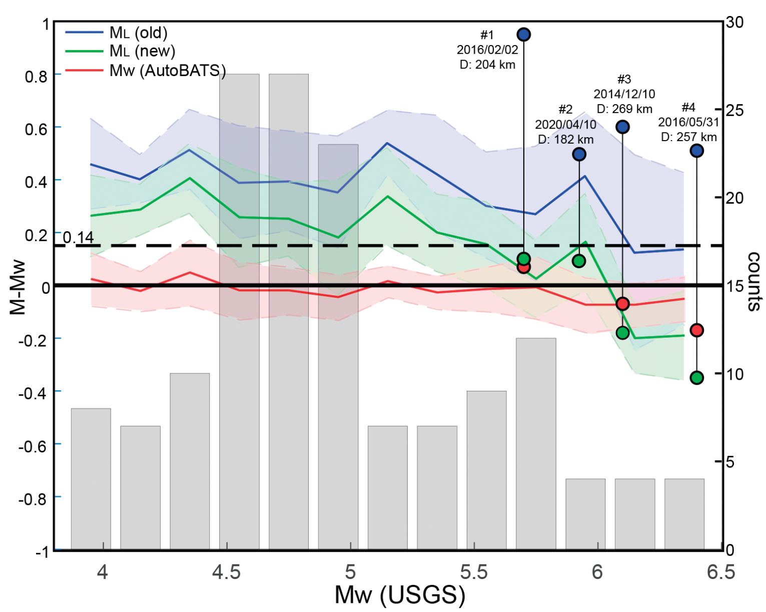

Fig. 6. The magnitudes [M_W (AutoBATS), M_L (new), and M_L (old)] comparison with respect to M_W (USGS). The red, green and blue lines and polygons indicate the averaged discrepancy values and standard deviations for M_W (AutoBATS), M_L (new), and M_L (old), respectively. The 0.14 dashed line indicates the possible overestimated unit for the calculation of the maximum amplitude by CWB with respect to that by the definition of Richter (1935). Circles with red, green, and blue colors are the magnitudes of the deep earthquakes determined by M_W (AutoBATS), M_L (new), and M_L (old), respectively.

for the crustal events ($h < 35$ km) (Wu et al. 2005; Lee et al. 2014; Jian et al. 2018). In this study, we included both shallow and deep earthquakes for analysis. As a result, the old M_L is 0.4 unit larger than M_W, which is even larger than the study by Wu et al. (2005). After applying the new attenuation functions in this study, the new M_L is down to 0.2 unit larger than M_W. The 0.2 unit discrepancy between the new M_L and M_W could result from two factors, the calculation of maximum amplitudes and earthquake locations. Considering the calculation of maximum amplitudes by CWB, the root sum squared of peak amplitudes in the north-south and east-west components, could lead to 1.4 times larger than the definition of the calculation of maximum amplitudes by Richter (1935), which the maximum amplitude is averaged from two horizontal components. As a result, the new M_L is 0.14 unit larger than M_W. The other factor, the discrepancy of earthquake locations determined by CWB and USGS, could lead to at least ~0.06 unit discrepancy between the new M_L and M_W (USGS). This can be also shown by the trends of the systematical variations of the old M_L, the new M_L, and M_W (AutoBATS) with respect to M_W (USGS). For magnitude greater than 6, the phenomenon of M_L saturation as the effect of Wood-Anderson simulator can be obviously observed in the new M_L (Fig. 6), which is reasonable for the relationship between M_L and M_W (Hanks and Boore 1984; Deichmann 2006). Four deep earthquakes (focal depths greater than 150 km) determined by the new attenuation functions as examples to show the main contribution of this study, especially for deep earthquakes. Events #1, #3, and #4 occurred in northeastern offshore of Taiwan, and #2 occurred in southeastern offshore. In these cases, the discrepancies between the old and new M_L can reach as large as 1 and the old M_L is also significantly larger than M_W (Fig. 6).

log$S$ for each station can be evaluated by using the form $\log S = \log A_{rec}/A_{avg} = \Delta M_L$, where A_{rec} is the amplitude from the simulated Wood-Anderson seismograph from the seismograph recorded in one seismic station and A_{avg} is the averaged amplitude from the simulated Wood-Anderson seismographs from the seismograph recorded in the seismic network (Fig. 7). ΔM_L values are related to site effects and radiation patterns. For the first order in all of the cases, the seismic stations in western Taiwan have large positive ΔM_L

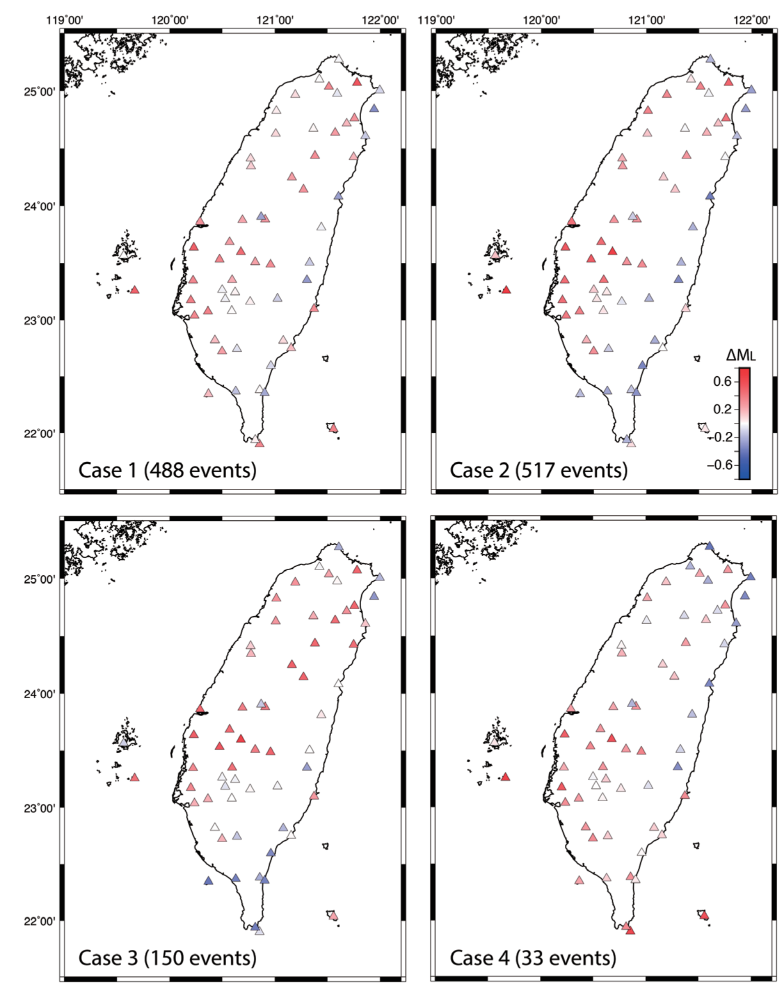

Fig. 7. log$S$ obtained from different cases.

values due to local site effects. ΔM_L values of Cases 3 and 4 not only represent local site effects but also ray paths from north and south for deep earthquakes, respectively.

5. CONCLUSIONS

We obtained new attenuation functions from the new data set of the CWBSN24 for the calculation of M_L in Taiwan. For shallow earthquakes ($h \leq 35$ km), the new attenuation functions are similar to those proposed by Shin (1993), whereas for deep earthquakes ($h > 35$ km) the new attenuation functions show significantly higher Q values. After applied the new attenuation functions, the new M_L values have better relationships with the mb and M_W values than the old ones. The new attenuation functions can be easily implemented to the official earthquake reports for the calculation of M_L.

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