Earthquake Research in China

Volume 32, Number 4, 2018

Moment Magnitude and Its Calculation[1]

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In this paper, we give a brief introduction to the proposal and development history of the earthquake magnitude concept. Moment magnitude M_W is the best physical quantity for measuring earthquakes. Compared with other magnitude scales used traditionally, moment magnitude is not saturated for all earthquakes, regardless of big and small earthquakes, deep and shallow earthquakes, far field and near field seismic data, geodetic and geological data, moment magnitude can be measured, and can be connected with well-known magnitude scales such as surface wave magnitude M_S. Moment magnitude is a uniform magnitude scale, which is suitable for statistics with wide magnitude range. Moment magnitude is the preferred magnitude selected by the International Seismological community, and it is preferred by the departments responsible for publishing seismic information to the public. Moment magnitude is a uniform magnitude scale, which is suitable for statistics with wide magnitude range. Moment magnitude is a preferred magnitude for international seismology, it is preferred by the agency responsible for providing information about earthquakes to the public. We provide all formulas used in the calculation of moment magnitude, and the calculation steps in detail. We also analyzed some problems and rules to solve these problems by using different formulas and numerical value calculation steps.

Key words: Earthquake magnitude; Local magnitude M_L; Surface wave magnitude M_S; Body wave magnitude m_b; Magnitude saturation; Moment magnitude M_W; Energy magnitude M_e

INTRODUCTION

Since the advancement of the conception of earthquake magnitude in the late 1920s and the early 1930s, the magnitude scale has experienced development from local magnitude to surface wave magnitude, body wave magnitude to moment magnitude and even energy magnitude. Moment magnitude is an absolute mechanical scale and it is not saturated. Whether it is for large or small earthquakes, micro-seismic earthquakes, or even extremely micro-seismic earthquakes, for shallow earthquakes or deep earthquakes, the use of far-field, near-field seismic data,

[1] Received on March 28, 2018. This paper supported by the Monitoring Task of Department of Earthquake Monitoring and Prediction, China Earthquake Administration (2018) and Technical Support and Effect Analysis of New Magnitude National Standard Implementation.

geodetic surveys, or any data in geological data, the moments can be measured. Moment magnitude can be coupled with well-known magnitude scales such as surface wave magnitude M_S. The moment magnitude is a uniform magnitude scale and is suitable for statistics with a wide range of magnitudes. Because of the above advantages, moment magnitude has become the preferred magnitude chosen by the international seismological community, and is the priority magnitude for the seismic information department responsible for magnitude release to the public. Moment magnitude measurement has become one of the routine tasks in seismic observation practice. This paper will briefly describe the concept of seismic magnitude and its historical development, briefly introduce moment magnitude, analyze the advantages of moment magnitude, explain the calculation method of moment magnitude, and introduce the problems encountered in the calculation of moment magnitude and the solutions.

1 FROM LOCAL TO MOMENT MAGNITUDE

Earthquake magnitude, referred as magnitude, is a measure of the magnitude of an earthquake itself that is, not related to the location of the observation (Richter C. F., 1935, 1958). After the seismologists understood how to locate the earthquake, the problem that followed the study was how to measure the size of the earthquake. Whether it is from a scientific point of view or from the perspective of social needs, measuring the size of an earthquake is a significant piece of work (Fu Chengyi et al., 1985; Chen Yuntai et al., 2004; Liu Ruifeng et al., 2015).

The best way to measure the size of an earthquake is to determine the overall characteristics of its seismic moment and source spectrum. In order to determine the seismic moment and source spectrum, it is necessary to simulate or invert the waveform of the seismic body wave or surface wave. From a practical point of view, there is a need for a simple and easy method of determining the size of an earthquake, such as measuring the magnitude of an earthquake by using the amplitude of a seismic wave such as a body wave (P-wave or S-wave). However, measuring the magnitude of the earthquake by using the amplitude of the body wave and the characteristics of the waveform is disadvantageous because the waveform of the far-field body wave is directly proportional to the rate of change of the seismic moment over time, namely the seismic moment rate (Aki K. et al., 1980), therefore, even for earthquakes with the same seismic moment, if the time history of the fault dislocation is different from the source time function, the waveform and amplitude of the generated far-field body waves are also different. In addition, different types of seismographs have different frequency bands, and the waveforms and amplitudes of the same seismic phases recorded by them are also different. In spite of this, it is still widely used to determine the size of the earthquake—the magnitude by measuring the amplitude. This is because: ① the method of determining the magnitude is simple and easy; ② the magnitude is used to measure the earthquake in a relatively narrow but high frequency band. For example, the local magnitudes mentioned below is measured in the frequency band around 1Hz (Hertz), and this frequency band happens to be (although not always) the band in which most buildings and structures are destroyed by earthquakes.

Magnitude is a measure of the relative magnitude of an earthquake by measuring the amplitude of a seismic phase in a seismic wave. It was proposed and developed by Charles Francis Richter (1900 – 1985) of the United States in the early 1930s (Richter C. F., 1935) under the suggestion by Beno Gutenberg (1889 – 1960). Before Richter, from the late 1920s to the early 1930s, only Kiyoo Wadati of Japan (1902 – 1995) used similar methods to determine the size of Japanese earthquakes (Wadati K., 1928, 1931; Richter C F., 1935). The term magnitude is used by Harry Oscar Wood (1879 – 1958) to suggest that Richter (Richter C. F., 1935) distinguishes it from the intensity which indicates the impact of destruction of an earthquake or the amount of destruction in different locations. In seismology, the scalar seismic moment is referred to as the seismic moment when it does not cause confusion. The scalar seismic moment is different from the seismic moment tensor. It is the physical size of an earthquake defined by the product of the area of the seismic fault, the average sliding distance of the fault (mean offset distance) and the shear modulus of the medium near the fault plane. The term earthquake moment was first proposed by Ketti Aki (1930 – 2005) based on his study of the 1964 Niigata earthquake in Japan (Aki K., 1966). Seismic moments can be measured either by the far-field displacement spectrum of the seismic wave, which is much larger than the source, or by near-field seismic waves, geology, and geodetic surveys. Aki K. (1966) used a variety of data to determine the seismic moments of the Niigata earthquake. The result was very consistent and is a very strong and quantitative support for the theory that the earthquake originates in the fault (fault theory). 30 years went by from the first time Rickett measured the magnitude in 1935 to 1966 when Aki proposed and measured seismic moments. Moment magnitude was proposed by Hiroo Kanamori of the United States (1936 –), George Purcaru of Germany (1939 – 2016) and Hans Berckehemer (1926 – 2014) and Thomas of the United States between 1977 and 1982 (Kanamori H., 1977; Purcaru G. et al., 1978, 1982; Hanks T. C. et al., 1979). It took more than 10 years from the presentation and measurement of the concept of earthquake moments in 1966 to the presentation of the moment magnitude scale from 1977 to 1979.

2 MAGNITUDE SATURATION

When the magnitude of the observed seismic wave is used to determine the magnitude (e.g., local magnitude M_L, body wave magnitude m_b, long period body wave magnitude m_b, surface wave magnitude M_S, etc.), the amplitude of the seismic wave in a specific frequency band is determined due to different magnitude scales. When the magnitude is greater than a certain level, and the maximum amplitude of the measurement no longer increases, and the measured magnitude of the earthquake does not increase with the increase of the earthquake, it is called magnitude saturation. The magnitude saturation is due to the fact that the displacement spectrum of a typical seismic signal is characterized by the corner frequency. When the frequency is higher than the corner frequency, the displacement amplitude spectrum decreases rapidly. When the earthquake is larger, the corner frequency moves toward the low frequency. Thus, when the magnitude of an earthquake is measured with a certain magnitude scale, if the magnitude scale is used to determine the magnitude of an earthquake, if the magnitude is higher than the corner frequency, the magnitude scale will appear saturated. In the magnitude determination based on the seismograms recorded by short-period seismographs, the smaller the period, the smaller the corresponding saturation magnitude. For example, when the moment magnitudes M_W are greater than 6.0, 6.5, 7.0, and 8.0, respectively, the body-wave magnitude m_b, the local magnitude M_L, the long-period body wave magnitude, m_B, and the surface-wave magnitude M_S begin to saturate, respectively; they reach complete saturation at 6.5, 7.0, 7.5, and 8.5, respectively. Actual observations show that $m_b > 6.5$, $M_L > 7.0$, $m_B > 7.5$ and $M_S > 8.5$ are very rare.

Magnitude saturation is a reflection of magnitude scale and frequency. In order to objectively measure the size of the earthquake, a magnitude scale is needed, which does not appear to be saturated as m_b, M_L, m_B and M_S described above.

Moment magnitude is a magnitude scale that will not be saturated.

3 RATIO OF SEISMIC WAVE ENERGY TO SEISMIC ENERGY MOMENT

For the sake of narrative convenience, before introducing the moment magnitude, this section first introduces related terms such as seismic wave energy and seismic energy moment ratio and their physical concepts.

During an earthquake, due to fault slip, the energy that propagates outward in the form of seismic waves is called seismic wave energy, seismic radiated energy, radiated seismic energy, and radiated energy or radiation energy. All these are referred to as seismic energy. Let E_P be the total strain energy (mainly including elastic strain energy and gravitational potential energy) released by the entire earth media system before and after the earthquake. It is equal to the work W done by the entire earth media system before and after the earthquake to the outside world.

$$E_P = W = \frac{1}{2}(\sigma^0 + \sigma^1)DA \tag{1}$$

In the formula, σ^0 and σ^1 are called the initial stress and the final stress respectively, and the latter is also called the residual stress. A is the area of the fault plane; D is the average slip of the fault. We call

$$\bar{\sigma} = \frac{1}{2}(\sigma^0 + \sigma^1) \tag{2}$$

the average stress, so the total strain energy E_P released by the entire earth media system before and after the earthquake is

$$E_P = \bar{\sigma}DA \tag{3}$$

From the sliding to the stop of the seismic fault, the earth media system must overcome the friction between the fault planes to do work. The work done by the earth media system to overcome friction E_F is known as friction energy. If the dynamic friction stress is expressed as σ_f, the friction energy E_F (Kanamori H., 1994) is

$$E_F = \sigma_f DA \tag{4}$$

The energy consumed by a new fault plane during an earthquake rupture is called rupture energy, also known as surface energy. So far, the estimation of the fracture energy is still very rough; so research is still being done on it.

Let's temporarily ignore rupture energy. However, in some cases, the fracture energy may become so important that it can't be ignored (Kanamori H. et al., 2006).

Seismic wave energy E_S can be obtained from the law of energy conservation.

$$E_S = E_P - E_F - E_G \tag{5}$$

If the breaking energy E_G is not considered for a moment, the seismic wave energy can be obtained from equations (1) to (5).

$$E_S = E_P - E_F = (\bar{\sigma} - \sigma_f)DA = \frac{(\sigma^0 + \sigma^1 - 2\sigma_f)}{2}DA \tag{6}$$

Seismic radiant energy E_S is only a part of the total potential energy E_P released during an earthquake and is usually related to E_S and E_P the following formula.

$$E_S = \eta E_P \tag{7}$$

In the formula, η is called seismic efficiency, also referred to as the seismic efficiency coefficient. By definition, $\eta \leqslant 1$, substituting equation (3) and equation (6) into equation (7), we can determine the seismic efficiency without considering fracture energy.

$$\eta = \frac{\sigma^0 + \sigma^1 - 2\sigma_f}{\sigma^0 + \sigma^1} = 1 - \frac{\sigma_f}{\bar{\sigma}} \tag{8}$$

It can be seen from equation (8) that seismic efficiency is related to dynamic frictional stress

σ_f and average stress $\bar{\sigma}$. Since both σ_f and $\bar{\sigma}$ are physical quantities not easy to measure, seismic efficiency is also a physical quantity that is not easy to measure.

Substituting equation (3) into equation (7) yields

$$\eta\bar{\sigma} = \frac{\mu E_S}{M_0} \tag{9}$$

In the formula, M_0 is a scalar seismic moment, or simply a seismic moment.

$$M_0 = \mu DA \tag{10}$$

μ is the rigidity of the medium. Definitions

$$\sigma_a = \eta\bar{\sigma} \tag{11}$$

σ_a is called apparent stress. Apparent stress can be obtained from equation (11) and equation (9) (Wyss M. and Brunce J. 1968, 1971)

$$\sigma_a = \frac{\mu E_S}{M_0} \tag{12}$$

It can be known from equation (11) that since $\eta \leqslant 1$, the apparent stress is the lower limit of the average stress

$$\sigma_a \leqslant \bar{\sigma} \tag{13}$$

By equation (8) the following can be obtained

$$\sigma_a = \bar{\sigma} - \sigma_f \tag{14}$$

If the dynamic frictional stress σ_f is equal to the final stress σ^1, that is, $\sigma_f = \sigma^1$, then

$$\sigma_a = \frac{\Delta\sigma}{2} \tag{15}$$

In the formula, $\Delta\sigma$ is the stress change that occurs along with the formation of a seismic fault, that is, the stress released on the fault plane during an earthquake — stress drop

$$\Delta\sigma = \sigma^0 - \sigma^1 \tag{16}$$

thus the formula corresponding to equation (12) is

$$\Delta\sigma = \frac{2\mu E_S}{M_0} \tag{17}$$

The above analysis shows that although the average stress $\bar{\sigma}$ is a physical quantity that is not easy to measure, the apparent stress σ_a that is the lower limit of the average stress can be obtained by measuring μ, E_S and M_0. μ, E_S and M_0 are the physical quantities obtained by appropriate measurement. Although it is not the average stress measured by equation (12), it is still very valuable to be able to measure the apparent stress as the lower limit of the average stress. In addition, if the dynamic frictional stress is equal to the final stress, then the apparent stress is equal to 1/2 of the stress drop.

The apparent stress has a dimension of "stress" and is often easily confused with other stresses. To avoid confusion, you can define dimensionless parameters $\tilde{e}$

$$\tilde{e} = \frac{\sigma_a}{\mu} = \frac{E_S}{M_0} \tag{18}$$

Equation (18) is the ratio of seismic wave energy E_S to seismic moment M_0. It is called seismic energy-moment ratio, also called scaled energy, or reduced energy. The seismic energy moment ratio has a dimension of strain and is a dimensionless quantity that represents the seismic wave energy radiated from a unit of seismic moment (Kanamori H. et al., 2000, 2006). Seismic energy moment ratio (scale energy, equivalent energy) multiplied by the rigidity coefficient μ of the medium in the source region is the apparent stress.

According to Kanamori H. et al. (1975) and Abe K. (1995), the stress drop in the crust and mantle is $\Delta\sigma \approx (2—6)$ MPa, $\mu \approx (3—6) \times 104$ MPa; if you take $\Delta\sigma = 5$ MPa, $\mu = 5 \times 104$

MPa, that is

$$\frac{\Delta\sigma}{2\mu} = 5 \times 10^{-5} \tag{19}$$

Substituting equation (19) into equation (17), i. e. (Stein S. et al., 2003)

$$\frac{E_S}{M_0} \approx 5 \times 10^{-5} \tag{20}$$

or

$$\lg E_S = \lg M_0 - 4.3 \tag{21}$$

Equation (20) or its equivalent equation (21) is called Kanamori's condition. Kanamori's condition indicates that the ratio of the seismic wave energy to the seismic moment released during the earthquake is approximately 5×10^{-5}. From equation (20), we can see that the dimension of the seismic moment is the same as the dimension of the seismic wave energy. If the international system is adopted (Système International d'Unitès, SI), $[E_S] \sim$ J, $[M_0] \sim$ N·m, Since 1J = 1N·m, so $[E_S/M_0] \sim 1$. If we use the centimeter-gram-second system (CGS system), then $[E_S] \sim$ erg, $[M_0] \sim$ 1 dyn·cm. Since 1 erg = 1 dyn·cm, so $[E_S/M_0] \sim 1$. Although the dimensions of E_S and M_0 are the same, their physical meanings are different, and numerically, the seismic wave energy is only $5 \times 10^{-5} = 0.00005$ of the seismic moment released during the earthquake. This is not surprising, because the seismic moment released during an earthquake is not the energy of the seismic wave radiated by the earthquake. It is essentially the integral of the stress change (unit: N/m^2) within the volume of the entire source region [(unit: m^3): (N·m^2) × m^3, that is N·m]. Although the two units are equal, in order to clearly express that the seismic moment and the seismic wave energy are two physical quantities with different properties, we always express the seismic moment with N·m (or dyn·cm), and use J (or erg) to indicate seismic wave energy. Therefore, M_0/μ is the integral of the strain in the volume of all the source regions. M_0/μ is multiplied by the average stress $\Delta\sigma/2$ acting on the fault plane during the earthquake to obtain the seismic wave energy radiated during the earthquake.

4 MOMENT MAGNITUDE

The seismic energy E_S and surface wave magnitude M_S have the following semi-empirical relationship, Gutenberg-Richter seismic wave energy-magnitude relationship (Kanamori H., 1977; Purcaru G. et al., 1978, 1982).

$$\lg E_S = 1.5M_S + 4.8 \tag{22}$$

In the formula, E_S is in units of N·m. Substituting equation (20) or equation (21) into equation (22) gives the relationship between the seismic moment M_0 and the surface wave magnitude M_S.

$$\lg M_0 = 1.5M_S + 9.1 \tag{23}$$

or the relationship between surface wave magnitude and seismic moment

$$M_S = (\lg M_0 - 9.1)/1.5 = (2/3)(\lg M_0 - 9.1) \tag{24}$$

Replacing the M_S in equation (24) with M_W gives the definition of a new magnitude scale M_W (Kanamori H., 1977; Purcaru G. et al., 1978, 1982; Hanks T. C. et al., 1979).

$$M_W = (\lg M_0 - 9.1)/1.5 = (2/3)(\lg M_0 - 9.1) \tag{25}$$

The new magnitude scale M_W is called the moment magnitude, which is the same as the surface wave magnitude M_S in the magnitude range of the surface wave magnitude M_S unsaturated, and it will not be saturated when the size of the earthquake exceeds this range. The moment magnitude cannot be saturated because it is calculated from the seismic moment M_0 by the above formula.

In theory, there is no upper or lower limit for the magnitude. However, as a brittle fracture that occurs within a limited, non-uniform rock layer plateau, the maximum scale of tectonic earthquakes should naturally be smaller than the scale of rock layer plates. In fact, no earthquakes exceeding M_W9.5 have been recorded so far, and the largest earthquake recorded by the instrument was the Chile $M_W = 9.5$ earthquake on May 22, 1960. The minimum earthquake was the $M_W = -4.4$ earthquake recorded at a depth of 3,500m underground in the Mponeng gold mine in South Africa (Kwiatek G. et al., 2010)

5 MOMENT MAGNITUDE NUMERICAL CALCULATION

The definition equation (25) of the moment magnitude is the standard form adopted by IASPEI (2005, 2013) formally adopted (Bormann P., 2015). If the centimeter-gram-second system (CGS system) is used, the corresponding definition of the moment magnitude definition (Hanks T. C. and Kanamori H., 1979) is

$$M_W = (\lg M_0 - 16.1)/1.5 = \frac{2}{3}(\lg M_0 - 16.1) \tag{26}$$

In the formula, M_0 has a unit of dyn·cm, 1 dyn·cm $= 10^{-7}$ N·m.

The first part and the second part of the right side of equation (25) are equivalent. The first part is to calculate the factor ($\lg M_0 - 9.1$) in parentheses before dividing by 1.5. The second equation is to multiply (2/3) by $\lg M_0$ and 9.1 in parentheses, and then subtract them. Finally, it is rounded down to the precision required (usually accurate to 0.1) (usually rounded to the second decimal place). Equation (26) is essentially equivalent to equation (25), except that the unit used is different. Whether it is using equation (25) or equation (26), it is the factor $\lg M_0$ and the constant factor 16.1 which is subtracted first and then divided by 1.5, or multiplied by (2/3) and then subtracted, the result is the same.

Equation (26) is the definition used by Kanamori H. (1977) to introduce the moment magnitude, and it is the formula he and some authors use in other articles. But in other places, some authors use another formula defined by Hanks T. C. et al. (1979).

$$M_W = (\lg M_0)/1.5 - 10.7 \tag{27}$$

At first glance, equations (26) and (27) are equivalent, and using these two formulas should yield the same results, which is not always the case. Since equation (26) is equivalent to the following equation

$$\begin{aligned} M_W &= \frac{2}{3}\lg M_0 - 10.73 \\ \text{or } M_W &= \frac{2}{3}\lg M_0 - 10.7333\cdots \end{aligned} \tag{28}$$

We can see that equation (27) is the second term (constant term) $16.1/1.5 = 10.73 = 10.7333\cdots$ on the right side of equation (26), which is obtained by rounding off the second decimal place to the nearest 0.1. So if it is also accurate to 0.1, the M_W (calculated as M_W^{HK}) from equation (28) is

$$M_W^{HK} = M_W + 0.0333\cdots \tag{29}$$

If the M_W calculation result is expressed as

$$M_W = x_1 x_2 . x_3 x_4 \cdots \tag{30}$$

Then

$$M_W^{HK} = x_1 x_2 . x_3 x_4 \cdots + 0.0333\cdots \tag{31}$$

For the second decimal place below the decimal point in equation (30), we can get:

$$\begin{cases} M_W = x_1x_2.x_3 & x_4 \leqslant 4 \\ M_W^{HK} = x_1x_2.(x_3+1) & x_4 \geqslant 5 \end{cases} \tag{32}$$

If we round off the second digit below the decimal point of equation (31), we can get:

$$\begin{cases} M_W^{HK} = x_1x_2.x_3 & x_4 \leqslant 1 \\ M_W^{HK} = x_1x_2.(x_3+1) & x_4 \geqslant 2 \end{cases} \tag{33}$$

That is

$$\begin{cases} M_W^{HK} = M_W = x_1x_2.x_3 & x_4 \leqslant 1 \\ M_W^{HK} = x_1x_2.(x_3+1), M_W = x_1x_2.x_3 & 2 \leqslant x_4 \leqslant 2 \\ M_W^{HK} = M_W = x_1x_2.(x_3+1) & x_4 \geqslant 5 \end{cases} \tag{34}$$

When the second digit x_4 below the decimal point is $2 \leqslant x_4 \leqslant 4$, the M_W calculated by equation (26) is 0.1 more than that calculated by using equation (27). As we saw earlier, this is due to equation (27) that first calculates the right constant term and rounds it off, and then subtracts it from $(\lg M_0)/1.5$.

6 CONCLUSION

On May 12, 2017, the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and the National Standardization Administration issued the National Standards Announcement No. 11 (2017) of the People's Republic of China, and officially issued the new national earthquake magnitude rule, General Rules for Earthquake Magnitude (GB17740 – 2017). The new rule fully embodies the diversity and complexity of magnitude, and stipulates six magnitudes of local magnitude M_L, short-period body wave magnitude m_b, broadband body wave magnitude $m_{B(BB)}$, surface wave magnitude M_S, broadband surface wave magnitude $M_{S(BB)}$ and moment magnitude M_W, establishing preliminarily the China magnitude measurement system to make the method of magnitude measurement more scientific.

The new rule stipulates that the moment magnitude M_W is the preferred magnitude for seismic network surveys and is the preferred magnitude for releasing seismic information to the public. In the new rule, the formula for the moment magnitude M_W is the definition of the moment magnitude equation (25), which is the same as that adopted by the IASPEI (2005, 2013). After General Rules for Earthquake Magnitude (GB17740 – 2017) is implemented, the determination and release of earthquake magnitude in China will be in line with international standards.

This paper has been published in Chinese in the journal of *Seismological and Geomagnetic Observation and Research*, Volume 39, Number 2, 2018.

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