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Quantification of Earthquakes

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Because earthquakes are the result of complex geophysical processes, it is not a simple matter to find a single measure of the size of an earthquake. Further, extremely large earthquakes saturate the conventional magnitude scale. Recent estimates of energy released by such earthquakes suggest values high enough to have possible implications for plate motion, the Chandler wobble and rotation of the Earth.

DURING 1976 a large number of destructive earthquakes occurred: on 4 February, Guatemala suffered an earthquake of magnitude 7.5, with the loss of 23,000 lives; on 6 May, an earthquake of magnitude 6.5 cost Italy 1,000 lives; on 27 July, an earthquake of magnitude 8.0 struck China with the loss of 650,000 lives. The Chinese (Tangshan) earthquake is one of the most disastrous events since the 1556 Chinese earthquake in which 830,000 people perished. Moreover, there have been several other destructive earthquakes in the same year: Fig. 1 clearly demonstrates that 1976 was one of the worst years for earthquake casualties in recent times. However, the damage caused by an earthquake depends not only on its physical size but also on various factors such as when and where it occurs, and Fig. 1 therefore does not necessarily represent the physical 'size' of earthquakes. The question of how we measure the 'size' of an earthquake has been historically a very important yet difficult seismological problem.

Earthquake magnitude scales and seismic energy

Since the physical process underlying an earthquake is very complex, we cannot express every detail of an earthquake by a single parameter. However, it would be convenient if we could find a single number that represents the overall physical size of an earthquake. This was the very concept of the earthquake magnitude scale, the so-called Richter scale, introduced by Charles F. Richter[1] in 1935. Richter used the maximum amplitude of seismic waves recorded by the Wood–Anderson seismograph. After correcting for the decay of the amplitude with distance from the epicenter, he established the local magnitude scale (M_L) for earthquakes in Southern California, using the logarithm of the observed amplitude of seismic waves. The seismic waves used for local magnitude have periods ranging approximately from 0.1 to 2 s, equivalent to a wavelength of 300 m to 6 km. Since Richter's scale was introduced more or less empirically, it was not quite clear in the beginning what physical parameter of an earthquake this scale represented. However, the Richter scale turned out to be extremely useful for various purposes. The method was so simple that magnitudes could be assigned to hundreds of earthquakes on a routine basis. Since M_L is defined in the period range where the effect of seismic waves on buildings is most pronounced, it is a very good measure of the strength of ground shaking at a given distance, and is very useful for various engineering purposes.

Because of this remarkable success of the M_L scale, Gutenberg[2] extended this kind of measure to earthquakes in distant sites. For earthquakes at very large distances, seismic surface waves with a period around 20 s are often dominant on seismograms. Gutenberg therefore defined another magnitude scale, M_S, called the surface-wave magnitude, using the amplitude of surface waves with a period of 20 s. The wavelength of these surface waves is about 60 km. Gutenberg[3] also used seismic body waves (P and S waves) to define another scale, m_b, called the body wave magnitude. The period of these body waves is usually from 1 to 10 s. Thus M_S and m_b represent different parts of the frequency spectrum of seismic waves, so that each of these scales represents a different physical parameter of an earthquake. However, extensive studies of Gutenberg and Richter suggested that m_b and M_S seem to be related to each other and could be used to represent a fundamental physical parameter, the energy of seismic waves, E. Through repeated revisions, Gutenberg and Richter[4] finally derived a relation $\log_{10} E = 1.5\ M_S + 11.8$ (E in ergs). This relation made it possible to estimate seismic energy from the magnitude M_S, which can easily be routinely measured. Of course, we cannot expect a very accurate estimate of seismic energy from such a crude parameter through such a simple relation. Nevertheless, this relation provided the only means for quantifying earthquakes in terms of the energy of elastic waves.

The monumental book of Gutenberg and Richter[5], *Seismicity of the Earth*, catalogues most large earthquakes that occurred from 1904 to 1949. In the later work of Gutenberg[6] and in the second edition of *Seismicity of the Earth* the catalogue was extended to the period from 1897 to 1952. Fortuitously, after these catalogues were completed, a number of very large earthquakes occurred starting with the Kamchatka earthquake,

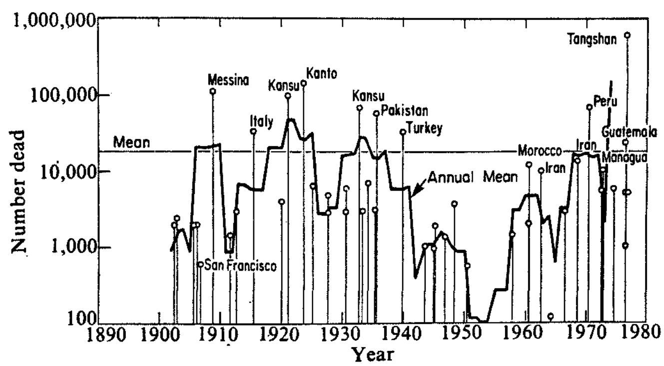

Fig. 1 Loss of life caused by major earthquakes. The vertical bars are for the individual event and the solid curve shows the annual average (unlagged 5-year running average).

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$M_S=8\frac{1}{4}$ on 4 November 1952. Here, 'large' refers to the length of the fault. The 1952 Kamchatka earthquake was followed by the Fox (Aleutian) Island earthquake in 1957, ($M_S=8\frac{1}{4}$), the Chilean earthquake in 1960 ($M_S=8.3$), the Kurile Island earthquake in 1963 ($M_S=8.1$), the Alaskan earthquake of 1964 ($M_S=8.4$) and the Rat Island earthquake of 1965 ($M_S=7\frac{3}{4}$). The faults which broke in these earthquakes are extremely long (as long as 800 to 1,000 km for the 1960 Chilean earthquake and the 1957 Fox Island earthquake). No faults that long are known to have ruptured for events before 1952, although the data before 1904 are incomplete. We will use the term 'great earthquakes' for these events with a very long fault.

Seismic waves generated by these great earthquakes are quite spectacular. Very long-period (200–300 s or even longer period) waves which last for several days after the earthquake are often recorded on long-period seismograms. However, the amplitude of relatively short-period (about 20 s) waves generated by these earthquakes is not particularly large, and is about the same as for 'ordinary' large earthquakes. Therefore M_S for these events is not particularly large, in spite of the extremely large fault length and the pronounced long-period waves. Since the energy was calculated only from M_S, the energy release of these 'great' earthquakes was thought to be comparable to that for other 'ordinary' large earthquakes. Why does the amplitude of short-period waves not grow as the length of the fault increases? The amplitude of seismic waves represents the energy released from a volume of crustal rock whose representative dimension is comparable to the wavelength. Several studies[7] suggest that the energy density per unit volume of crustal rock is almost constant regardless of the size of the earthquake. Since the wavelength of seismic waves used for the determination of M_S is only about 60 km, the amplitude of 20-s waves does not increase as the fault length increases beyond 60 km; therefore the M_S scale saturates. Since these giant earthquakes occurred after the publication of *Seismicity of the Earth*, Gutenberg and Richter did not have the opportunity to consider the saturation problem.

Not much further effort was devoted to the question of energy estimation until the early 1960s, when remarkable progress was made in long-period seismology. Owing to the worldwide deployment of the standardised long-period seismographs and the development of the theory of the generation and propagation of very long-period (up to 1 h) waves, it became feasible to use very long-period waves for quantitative analyses of an earthquake source. Such long-period waves have wavelengths of several hundreds to several thousands of kilometers, which are comparable to the fault length of great earthquakes, and are therefore suitable for measuring the overall 'size' of great earthquakes.

Seismic moment

One of the major breakthroughs in this field was made by the introduction of the concept of seismic moment. Aki[8] applied elastic dislocation theory to the study of earthquake mechanism. According to elastic dislocation theory, the amplitude of very long-period waves is proportional to the quantity $M_0=\mu DS$ where S is the surface area of the fault, D is the average displacement discontinuity on the fault plane and μ is the rigidity of the material surrounding the fault. M_0 is called the seismic moment. In order to obtain M_0 from the observed seismograms, the effect of propagation, attenuation and the geometry of the fault must be removed. Fortunately, unlike short-period (for example, 20-s) waves, these long-period waves are very coherent so that accurate measurements of M_0 are possible. Thus the seismic moment is one of the most reliable seismological parameters that represents the 'size' of an earthquake. Because M_0 does not saturate, it is a more suitable parameter to represent the size of great earthquakes than the conventional magnitude scales such as M_S.

Several attempts were made to use long-period (100–200 s) waves to quantity large earthquakes[9–11]. Bruce and Engen[10] introduced a new scale, 100 s magnitude M_{100}, which is based on the amplitude of surface waves with a period of 100 s instead of 20 s. This scale clearly demonstrated that long-period waves are very useful for distinguishing great earthquakes from ordinary large earthquakes.

In recent years, extensive efforts have been made to determine M_0 for great earthquakes as well as large and small earthquakes. The determination of M_0 for recent events can be made relatively easily and very accurately by using high-quality standardised seismograms. The determination of M_0 for old events is less accurate because of the poor quality of old seismograms. Nevertheless, by combining various techniques, the seismic moments of 44 earthquakes out of 52 events of $M_S \geq 8$ which occurred since 1921 have been estimated. For the period from 1904 to 1920, the data are not very complete. Fig. 2 shows the moments for the individual earthquakes as well as the annual average[12]. Since the seismic moment directly represents the overall deformation at the earthquake source, Fig. 2 indicates the temporal variation of the amount of crustal deformation associated with earthquakes. It is clear that the seismic activity measured by the seismic moment was very high during the period from 1950 to 1965. The annual average seismic energy release during this period is almost two orders of magnitude larger than that during the period prior to 1950. Is this temporal variation real, or is it an artefact of the poor quality of the record for the period before 1950? Although the quality of the moment determination is somewhat poor before 1950, it is almost certain

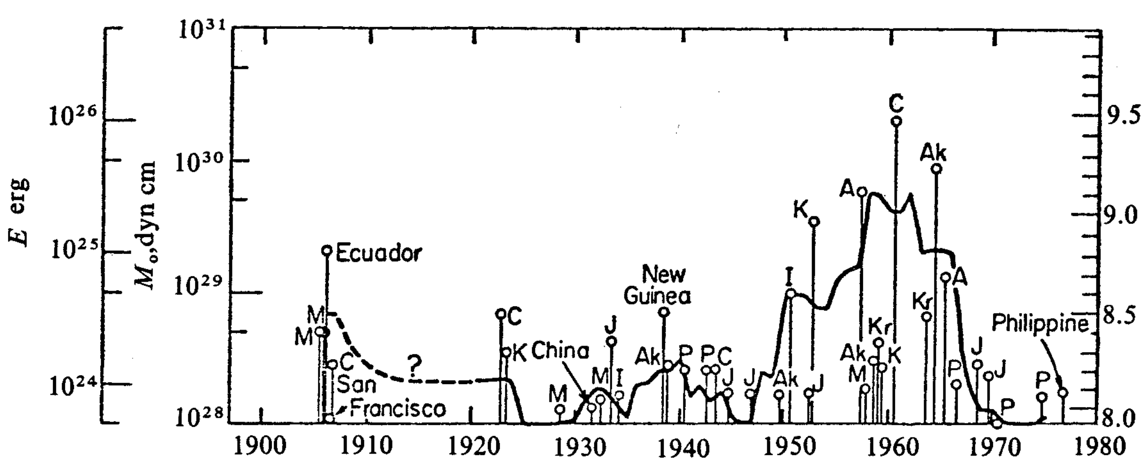

Fig. 2 The seismic moment M_0, seismic energy E, and the magnitude M_W of great and large earthquakes. The solid curve shows the annual average of seismic energy obtained by taking unlagged 5-year running average. A: Aleutian; Ak: Alaska; C: Chile; I: India; J: Japan; K: Kamchatka; Kr: Kurile; M: Mongolia; P: Peru.

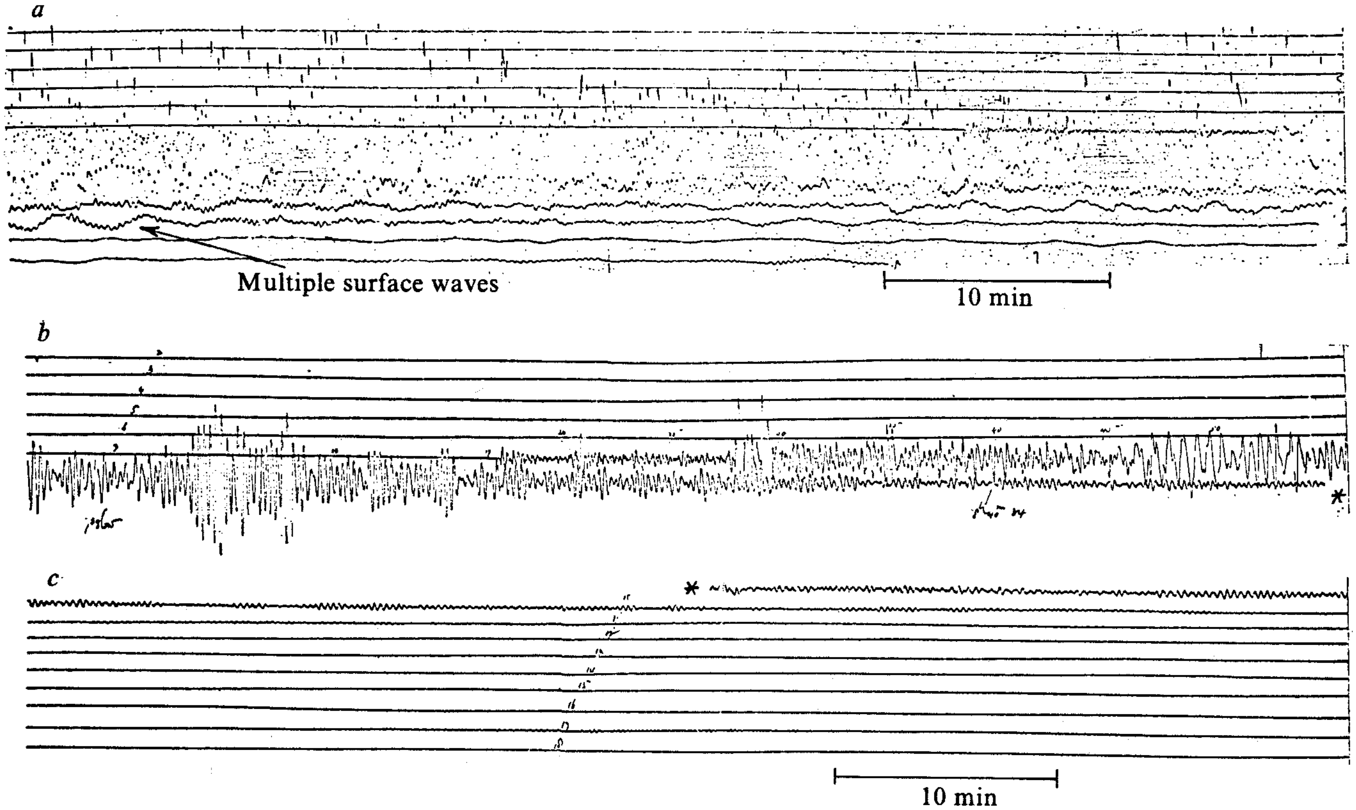

Fig. 3 Comparison of *a*, the 1960 Chilean earthquake ($M_S = 8.3$) and *b*, the 1929 Aleutian Island (Fox Island) earthquake ($M_S = 8.1$) recorded by the Milne–Shaw seismograph. The long-period surface waves—marked as multiple surface waves—which are clearly recorded for the 1960 Chilean earthquake distinguish a great earthquake (Chilean earthquake) from a large earthquake (Fox Island earthquake).

that no earthquake from 1920 to 1950 was as large as the 1960 Chilean earthquake. As shown by Fig. 3, the difference between 'great' and 'large' earthquakes is quite obvious even on old seismograms. Thus, the pattern shown in Fig. 2 is probably real despite the differing quality of the data.

It is also clear in Fig. 2 that the annual average has decreased very dramatically in recent years. This trend is opposite to the trend shown in Fig. 1. This negative correlation clearly suggests that the physical size and the social impact of an earthquake are not directly related.

Seismic moment and seismic energy

The seismic moment can be related to the energy released in earthquakes. Suppose the stress on the fault plane is reduced from σ_0 to σ_1 in an earthquake. Then the reduction in the strain energy is $\Delta W = \sigma DS$ where $\sigma = (\sigma_0+\sigma_1)/2$ is the average stress, D is the average offset on the fault plane, and S is the area of the fault plane. Combining this with the expression for the seismic moment M_0 we have $\Delta W = (\sigma/\mu)M_0$. If we assume that the fault motion stops when the stress on the fault becomes approximately equal to the frictional stress σ_f, that is $\sigma_1 = \sigma_f$, the above equation reduces to

$$\Delta W - \sigma_f DS = (\Delta\sigma/2\mu)M_0$$

where $\Delta\sigma$ is the stress drop $\sigma_0-\sigma_1$. Since $\sigma_f DS$ is heat loss during faulting, the left-hand side of this equation gives the total strain energy minus heat loss. Therefore $(\Delta\sigma/2\mu)M_0$ can be considered as the energy available for generation of seismic waves. The stress drop $\Delta\sigma$ is known to be nearly constant for most great and large earthquakes (see for example ref. 13) and $(\Delta\sigma/2\mu)$ is approximately 2×10^4. Therefore $M_0/(2\times10^4)$ gives an estimate of seismic energy E. Thus Fig. 2 can be considered as representing the temporal variation of seismic energy release. Note that the energy release in the 1960 Chilean earthquake is 10^{26} erg, which is about 60 times larger than the value estimated from M_S.

Since the magnitude scale has been used for nearly 40 yr not only among seismologists but also by the news media, it is convenient to express the 'size' of an earthquake in terms of a magnitude scale. To this end, the energy $M_0/(2\times10^4)$ can be converted into a magnitude scale by using the energy–magnitude relation, $\log E = 1.5\ M+11.8$. A new magnitude scale, M_W is defined by [12]:

$$M_w = (\log M_0/1.5)-10.7 \qquad (M_0 \text{ in dyn cm})$$

In this scheme, the magnitude is defined in terms of the energy whereas in the old scheme, the energy is calculated from the magnitude. On this scale, $M_W = 9.5$ for the 1960 Chilean earthquake, 9.2 for the 1964 Alaskan earthquake, 9.1 for the 1957 Aleutian Island earthquake, and 9.0 for the 1952 Kamchatka earthquake. In Fig. 2, the M_W scale is given on the right. Comparison of M_W with M_S or M_L shows that M_W agrees very well with M_S and M_L for earthquakes with a smaller fault dimension; thus the M_W scale is a convenient extension of the old magnitude scale to great earthquakes.

Fig. 4 shows the spatial distribution of large earthquakes for the period 1904 to 1976. The values of M_W are given in the bracket for the ten largest earthquakes. It is notable that most of these earthquakes occurred along the Circum-Pacific subduction zones. These ten earthquakes account for more than 90% of the total seismic energy released from 1904 to 1976.

Although this estimate of the energy release of great earthquakes is much larger than that estimated earlier from the magnitude scale, it is still relatively small compared with the average rate of heat flow from the Earth's interior, 7×10^{27} erg yr^{-1}. The average annual rate of the seismic energy release is 4.5×10^{24} erg yr^{-1}, which is about three orders of magnitude smaller than the heat flow. Even for the largest event, the 1960 Chilean earthquake, the seismic energy is 10^{26} erg, which is about 1.4% of annual heat flow. However, the total strain

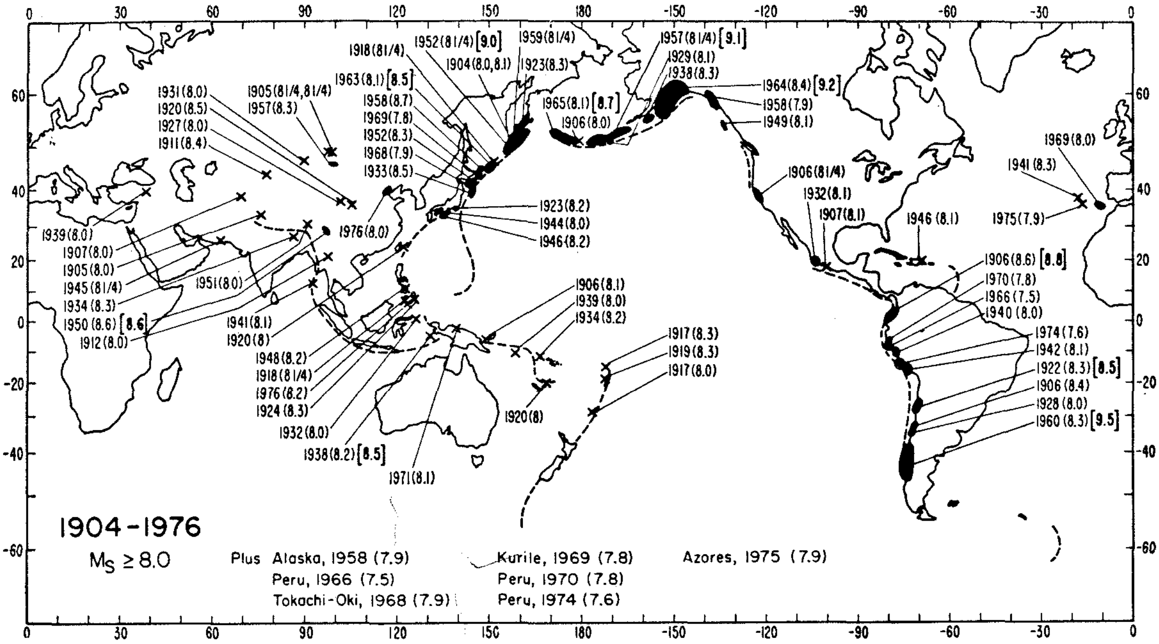

Fig. 4 Great and large earthquakes for the period from 1904 to 1976. The surface-wave magnitude M_S is given in the parentheses and M_W is given in the brackets for the ten largest earthquakes. Major rupture zones are indicated by dark zones.

energy change associated with an earthquake can be much larger (100 times more) than the seismic energy, if the stress drop in earthquakes is only a small fraction of the ambient tectonic stress. The discrepancy between the stress drop in earthquakes (10–100 bar) and the strength of rocks measured in the laboratory (several kilobar) suggests this possibility, but the problem remains unresolved up to now. If this is the case, the total energy involved in the earthquake process can be very significant in the energy budget of the Earth.

Since the total crustal deformation associated with great earthquakes is very large, the study of great earthquakes has a direct bearing on various global problems such as the Chandler wobble, plate motion and the rotation of the Earth[14–16]. For the moment, the data and analysis are not complete enough to study this problem in detail, but with recent improvements in instrumentation[17] many important problems in this field may be resolved in the near future.

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