

METHODS FOR ESTIMATING MAXIMUM  
EARTHQUAKE MAGNITUDES

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SUMMARY

This paper presents a summary of techniques used to evaluate fault-specific maximum earthquake magnitudes and discusses the limitations and uncertainties in applying each technique.

INTRODUCTION

At present, there is no uniquely accepted method for assigning a maximum earthquake magnitude to a given fault. The various approaches have generally been developed from empirical relationships between magnitude and fault parameters, including fault rupture length and amount of surface fault displacement measured in the field following surface faulting earthquakes, and fault length and downdip width assessed from studies of aftershock sequences.

Compilations of these data for worldwide historical earthquakes have been used to perform regressions of magnitude on length, magnitude on displacement, and magnitude on area. In addition, seismic moment can be related to static fault parameters and to magnitude, and a relationship between magnitude and slip rate has been proposed. Each method has some limitations, including non-uniformity in the quality of the empirical data, a somewhat limited data set, and a possible inconsistent grouping of data from different tectonic environments. Values for magnitudes derived from these relationships represent expected or average values. Assessment of a maximum magnitude is ultimately a judgment that incorporates an understanding of specific fault characteristics, the regional tectonic environment, the similarity to other faults in the region, and data on regional seismicity.

The techniques used to evaluate maximum earthquake magnitudes and the limitations and uncertainties in applying each technique are presented below.

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## DISCUSSION OF TECHNIQUES

### Rupture Length Versus Magnitude

The most common approach to estimating maximum magnitude is through a comparison of fault rupture length and earthquake magnitude. From data on historical earthquakes, empirical relationships have been established between rupture length and earthquake magnitude by several authors (Refs. 1, 2, 3, 4, 5, 6). The relationships allow an average magnitude to be selected for a given rupture length.

In applying this technique to reach maximum magnitude estimates, a maximum rupture length is estimated for a fault, and a corresponding magnitude is selected based on the regressions of worldwide data. Data errors in these regressions may be present in the measurement of the length of surface rupture, as well as in the instrumental magnitude determinations (Ref. 7). Considerable uncertainty often exists in the selection of the appropriate rupture length to be used in the analysis. Rupture lengths of past surface-rupture events on a fault may provide direct evidence; in the absence of these data, indirect evidence must be used to estimate rupture lengths. Geologic and geomorphic investigations may identify discontinuities in the surface expression of a fault along its length that can be used to segment the fault. Individual segments identified in this way may represent rupture segments whose length can be used in magnitude estimates.

A more indirect method of estimating rupture length is based on the assumption that a fraction of the total fault length will rupture during a given earthquake. Slemmons (Ref. 5) has developed a relationship between total fault length and percent rupture for major strike-slip faults. This relationship suggests that the percent rupture decreases with decreasing total fault length. The range of percent rupture for Slemmon's data set is from 17 percent to 38 percent, and the total fault lengths range from 300 to 1300 km. A similar relationship has not been developed for shorter faults or for other fault types. The most common practice has been to assume that up to one-half of a fault's total length can rupture during a given event. This assumption, proposed by Wentworth and others (Ref. 8), is based on review of historical surface ruptures in southern California. However, North American historical earthquakes have been associated with surface ruptures from 2 percent to more than 75 percent of the total fault length (Ref. 8). In addition, the total length of the fault is sometimes difficult to delineate. Thus, the fractional-length approach to selecting an appropriate rupture length should only be used in the absence of more direct evidence.

The rupture length versus magnitude relationships from Slemmons (Ref. 5) are:

Normal faults:	$M_s = 0.809 + 1.341 \log L$
Reverse faults:	$M_s = 2.021 + 1.142 \log L$
Strike-slip faults:	$M_s = 1.404 + 1.169 \log L$

where  $L$  is the rupture length, in meters.

#### Fault Rupture Area Versus Magnitude

Because the energy released during an earthquake is related to the size of the source's rupture surface, the fault rupture area (defined as the product of the rupture length and the downdip width of the fault) is more closely related to earthquake magnitude than fault rupture length. For a given rupture length, different widths of faults may rupture, depending largely upon fault type and tectonic environment. To accommodate this variation, empirical relationships have been established between fault rupture area and surface-wave magnitude ( $M_s$ ) for historical events (Refs. 9, 10). Fault area has a much higher correlation with magnitude than does rupture length (Ref. 9). Even with errors in rupture area up to a factor of two, estimates of magnitude vary only by 0.3 magnitude units (Ref. 9).

Estimates of the length and width of historical fault rupture are usually based on the spatial pattern of earthquake aftershocks. Uncertainty exists regarding the expectable dimensions of a maximum earthquake on any particular fault (Ref. 11); however, the maximum depth to which faulting can be expected to occur within a region often can be estimated with a fairly high level of confidence from seismicity data and geologic information on crustal structure. In addition, compilations of length-to-width ratios (aspect ratios) for historical earthquakes (for example, Ref. 12) may provide estimates of fault width for a given rupture length. The area versus magnitude relationship developed by Wyss (Ref. 9) for all fault types is:

$$M_s = 4.15 + \log A$$

where  $A$  is the area of the fault rupture surface, in  $\text{km}^2$ .

#### Displacement Versus Magnitude

Maximum observed surface displacement has been empirically related to magnitude for historical surface faulting earthquakes (Refs. 1, 2, 4, 5). This relationship has particular appeal because several recent geologic studies (Refs. 13, 14) have shown that prehistoric displacements on a fault can be measured; these displacement values can then be used to estimate earthquake magnitudes.

Most of the uncertainty in the displacement versus magnitude relationship is associated with variability in the quality and uniformity of the field measurements of displacement included in the data set. For dip-slip faults, the data base includes measurements of both vertical scarp height and slip. However, for example, measured scarp height for normal-slip faults may be greater than the net tectonic slip, due to modification of the scarp by graben formation and backtilting. In addition, it is uncertain whether maximum displacement, which is usually limited to one location or a segment of the fault, is a more meaningful

physical parameter than average displacement; average displacement data are not readily available for most historical surface ruptures.

The maximum displacement versus magnitude relationships from Slemmons (Ref. 5) are:

$$\begin{array}{ll} \text{Normal faults:} & M_s = 6.668 + 0.750 \log D \\ \text{Reverse faults:} & M_s = 6.793 + 1.306 \log D \\ \text{Strike-slip faults:} & M_s = 6.974 + 0.804 \log D \end{array}$$

where D is the maximum surface displacement, in meters.

#### Seismic Moment and Moment Magnitude

Because surface-wave magnitude saturates at about  $M_s 7 \frac{1}{2}$ , seismic moment ( $M_o$ ) is a more accurate measure of the total energy release during large earthquakes (Ref. 15).  $M_o$  is defined by  $AD\mu$ , where  $\mu$  is the rigidity (usually taken as  $3 \times 10^{11}$  dyn/cm<sup>2</sup> for crustal rocks), D is the average displacement on a fault in cm, and A is the area of the fault rupture surface in cm<sup>2</sup>. Relationships between seismic moment and magnitude have been derived based on worldwide earthquake data. Kanamori (Ref. 15) defines a magnitude scale,  $M_w$ , that does not saturate at the upper end and is equivalent to surface-wave magnitude in the range 6.0 to 8.0.  $M_w$  can therefore be considered a continuation of the  $M_s$  scale for large earthquakes. For  $M_w$  greater than  $7 \frac{1}{2}$  and  $M_s$  greater than 5 but less than  $7 \frac{1}{2}$ , Hanks and Kanamori (Ref. 16) define a moment magnitude scale,  $M_w$ , that is related to seismic moment by the relationship:

$$M_w = \frac{2}{3} \log M_o - 10.7$$

Direct determination of  $M_o$  is made by using long-period seismic waves. Indirect estimates of  $M_o$  can be made from measured average surface displacements, rupture lengths, and estimated fault width. Uncertainties involved in the estimation of all these parameters have been discussed. Seismic moment can then be calculated using the formula:

$$M_o = (3 \times 10^{11}) \times (\text{area}) \times (\text{average displacement})$$

and a moment magnitude can be derived from the above equation.

An assumption made in the derivation of the moment magnitude relationship is constant stress drop for large earthquakes (Ref. 15). Some error may be introduced into moment magnitude calculations because of regional variation in stress drop (Ref. 6). In addition, uncertainties in the estimation of amount of displacement, rupture length, and fault width may lead to errors in the estimation of seismic moment.

Hanks and Kanamori (Ref. 16) list the values of M and  $M_s$  (surface-wave magnitude) of 15 large California earthquakes. An analysis of the differences between the two magnitude values shows that, in California, M is an unbiased estimator of  $M_s$ , with a standard deviation of 0.24. This implies that an estimate of the surface-wave magnitude,  $M_s$ , of an

hypothesized earthquake, using the value of  $M$  determined from its static fault parameters ( $A$ ,  $D$ , and  $\mu$ ) via its moment  $M_0$ , will have a standard deviation of approximately one-quarter of a magnitude unit.

#### Slip Rate Versus Magnitude

The possibility that the rate of slip across a fault may be proportional to the maximum earthquake was suggested by Smith (Ref. 17). Smith relates total Holocene slip and fault area to total seismic moment on the fault, and then uses empirical relationships between seismic moment and magnitude to estimate the corresponding maximum earthquake. Slemmons (Ref. 4) relates slip rate and recurrence interval to magnitude, using his regression of displacement and magnitude.

In a comparison of slip rates and maximum historical earthquakes (Ref. 18), it was observed that an upper bound seems to exist on the maximum magnitude earthquake for a given slip rate for strike-slip faults in tectonic environments similar to that of southern California. Thus, slip rate may provide a guide to estimating maximum earthquake magnitude for these cases. Preliminary analyses indicate a wide scatter in the data and an apparently weak correlation between earthquake magnitude and slip rate for reverse and normal faults.

The relationship for strike-slip faults was developed by Woodward-Clyde Consultants (Ref. 18):

$$M_s = 7.223 + 1.263 \log S$$

where  $S$  is the slip rate, in millimeters per year.

#### Historical Seismicity

Particularly for faults having high levels of activity, the maximum historical earthquake generated by the fault may be considered the maximum earthquake. Uncertainties in this type of evaluation stem from the usual brevity of historical records, uncertainties in measurements of the size of past earthquakes, and uncertainties in the association of historical events with specific faults. Techniques for assessing maximum magnitudes for regions based on historical seismicity have been proposed (Refs. 19, 20, 21); however, it is not clear that the existence of a maximum magnitude has been demonstrated in any instrumental earthquake catalog (Ref. 22).

#### CONCLUSION

Combining several magnitude estimation techniques can result in more reliable estimates of maximum magnitude than the application of any single technique. In this way, a wide range of fault behavioral information can be included in the analysis, and the resulting magnitude estimates will be those that are best substantiated by the available data. To assess the range of magnitude estimates for a source, uncertainties in the fault

parameters and in the magnitude relationships must be identified and evaluated.

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