IMPORTANCE OF ASSESSING DEGREES OF FAULT ACTIVITY FOR ENGINEERING DECISIONS

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SUMMARY

Classifying faults as either "active" or "inactive" is a scientific oversimplification that usually results in overconservatism in the siting and design of structures. Because of the need to more accurately define the range in the degree of activity of faults, the behavioral characteristics of more than 150 active faults worldwide were compared. The faults were found to differ by several orders of magnitude in many of their characteristics, especially in rates of slip and in size and frequency of earthquakes. A classification scheme has been developed using six different activity classifications to provide a more realistic framework for seismic hazard and risk assessments.

INTRODUCTION

Decisions with regard to seismic safety for many critical facilities have become legal battles in which opponents to the facility grasp the earthquake issue as an excuse to invalidate the facility or the chosen site, and, in defense, site advocates often tend to understate the earthquake issues. In many cases, the seismic safety decision process has consumed years, has cost millions of dollars, and has become a disservice to society.

A major factor that has confused nontechnical decision makers is that earthquake hazards have been characterized by classifying faults as either "active" or "inactive" based soley on the recency of fault displacement. This has led to rigid legal definitions of fault activity based on a specified time criterion. For example, the U.S. Nuclear Regulatory Commission considers a fault active if it has evidence of multiple displacements in 500,000 years, or evidence of a single displacement in 35,000 years. For the purpose of classifying faults at sites of major dams, the U.S. Bureau of Reclamation has used 100,000 years, and the U.S. Army Corps of Engineers has used 35,000 years as their criteria for time intervals since the most recent fault displacement. Once a fault is classified as active by applying these criteria, it is considered equal to other active faults from a legal point of view. This is a scientific oversimplification and usually results in unrealistic overconservatism in the siting and design of structures.

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Realistic earthquake hazard assessments and risk analyses must recognize the differences that exist in the degree to which faults are active. Because of the need to more accurately define the range in degree of activity of faults to provide a more satisfactory framework for seismic hazard and risk assessments by decision-makers, a classification scheme that considers the different factors that cause variations in fault activity has been developed. Using this degree of fault activity classification scheme should result in a more realistic, technical basis for seismic safety decisions.

FAULT ACTIVITY CHARACTERISTICS

Significant differences exist in the degree to which various faults are active. The differences in relative degree of activity are manifested by several fault behavioral characteristics, including rate of strain release or fault slip, amount of fault displacement in each event, length of fault rupture, earthquake size, and earthquake recurrence interval. These behavioral characteristics are a function of the tectonic environment, the fault type and geometry, the rate of strain accumulation, the direction of crustal stress, the stratigraphic character and physical properties of the earth's crust, and the complexity and physical properties of the fault zone.

Slip Rate

The geologic slip rate provides a measure of the average rate of deformation across a fault. The slip rate is calculated by dividing the amount of cumulative displacement, measured from displaced geologic or geomorphic features, by the age of the geologic material or feature. The geologic slip rate is an average value through the geologic time period being considered, and reliable to the extent that strain accumulation and release over the time period has been uniform and responding to the same tectonic stress environment. In some tectonic environments, the current stress conditions have only been in effect for about 1.5 million years; in others, the stress conditions have been in force for 4 to 5 million years, or even for more than 10 million years. Many faults, particularly the highly active ones, displace multiple markers of different ages, allowing comparisons of slip rates through time.

Slip Per Event

The amount of fault displacement for each fault rupture event differs among faults and fault segments and provides another indication of relative differences in degrees of fault activity. The differences in amounts of displacement are governed by the tectonic environment, fault type and geometry and pattern of faulting, and the amount of accumulated strain being released.

The amount of slip per event can be directly measured in the field during studies of historical faulting, and is usually reported in maximum and average values. Displacements for prehistoric rupture events can be estimated for some faults from detailed surface and subsurface seismic geologic investigation (for example, Ref. 1, 2).

It is often difficult to decide what value is most accurate and representative of maximum or average displacements from data available in the literature. Often, reported displacement values represent apparent displacement or separation across a fault. For normal faulting events, scarp height has typically been reported as a measurement of the tectonic displacement. The scarp height, however, often exceeds the net tectonic displacement across a fault by as much as two times, due to graben formation and other effects near the fault (Ref. 2). In the case of thrust faults, the reported vertical displacement often is actually the measure of vertical separation, and the net slip on the fault has been underestimated by a significant amount.

Rupture Length

The length of the fault rupture significantly influences the size of the resulting earthquakes. It is mechanically not possible for a large earthquake to be released along a fault of short length, and, from worldwide data of historical earthquakes, a rough correlation exists between fault rupture length and earthquake magnitude (Ref. 3).

Earthquake Size

The earliest measures of earthquake size were based on the maximum intensity and areal extent of perceptible ground shaking. Instrumental recordings of ground shaking led to the development of the magnitude scale. Although the scale permitted quantitative comparisons of earthquake size, magnitude was defined empirically from the amplitudes of seismic waves, and the "size" that it measured was not definable in terms of any aspect of the physical process of faulting. In defining seismic moment, theoretical seismology has provided a physically meaningful measure of the size of a faulting event. Seismic moment is related directly to the static parameters of an earthquake, including shear modulus, average fault displacement, and the rupture area.

The magnitude value is a good estimate of earthquake size to the extent that the period of the wave used is longer than the rupture duration of the earthquake. The surface-wave magnitude scale, M_s, uses 20-second-period surface waves, and saturates at $M_s = 7.5$. That is, the amplitudes of 20-second-period surface waves stop increasing linearly with magnitude at $M_s = 7.5$, and become insensitive to further increases in earthquake size. Thus, earthquake size is not accurately reflected by the M_s measurement when earthquake size exceeds $M_s = 7.5$. Local magnitude, M_L, and body wave magnitude, m_b, use shorter period waves and thus saturate at even lower magnitudes.

Hanks and Kanamori (Ref. 4) have proposed a moment-magnitude scale, M, in which magnitude is calculated from seismic moment using an empirical formula. The moment-magnitude scale does not saturate, because it is based on seismic moment, a true measure of the size of an earthquake. Moment magnitude is well calibrated with the M_w scale of Kanamori (Ref. 5), which is a theoretically based moment-magnitude scale, and with M_S and M_L below their respective saturation levels.

The use of magnitude or seismic moment as a criterion for the comparison of fault activity requires the choice of the magnitude or moment value that is characteristic of the fault. Of course, in many instances it is not possible to ascertain whether historical seismic activity is characteristic of the fault through geologic time, unless a long historical seismic record is available or evidence of the sizes of past earthquakes is available from seismic geology studies of paleoseismicity. In a few cases, detailed seismic geology studies have yielded data on the sizes of past surface faulting earthquakes (Ref. 1, 2). In general, these data involve measurements of prehistoric rupture length and/or displacement, and a seismic moment or magnitude can be estimated probably within one-half magnitude.

Recurrence Interval

Faults having different degrees of activity differ by several orders of magnitude in the average recurrence intervals of significant earthquakes. Comparisons of recurrence provide a useful means of assessing the relative activity of faults, because the recurrence interval provides a direct link between slip rate and earthquake size. Recurrence intervals can be calculated directly from slip-rate and displacement-per-event data. In some cases, where the record of historical seismicity is sufficiently long compared to the average recurrence interval, seismicity data can be incorporated when estimating recurrence. In many regions of the world, however, the historical seismicity record is too brief; some active faults have little or no historical seismicity and the recurrence time between significant earthquakes is longer than the available historical record along the fault of interest. Plots of frequency of occurrence versus magnitude can be prepared for small to moderate earthquakes and extrapolations to larger magnitudes can provide estimates of the mean rate of occurrence (b-values) of larger magnitude earthquakes. This technique has limitations, however, because it is based on regional seismicity, and cannot result in reliable recurrence intervals for specific faults.

CLASSIFICATION SCHEME

The behavioral characteristics of more than 350 active faults worldwide were researched for analysis. Particular emphasis was placed on examining data from faults that have experienced historical surface displacement, because data were expected to be available for most fault activity characteristics. One hundred fifty faults were chosen to represent all styles of faulting within different tectonic environments around the world. Data were obtained on the various activity characteristics of these faults, and order-of-magnitude differences were recognized. Cluff and others (Ref. 6) show classes of active faults established based on patterns of combinations of characteristics (Table 1).

TABLE 1

FAULT CLASSIFICATION CRITERIA

CLASS 1

Slip Rate ≥ 10 mm/yr
Slip per Event ≥ 1 m
Rupture Length ≥ 100 km
Seismic Moment ≥ 10^{26} dyne-cm
Magnitude ≥ M_s 7.5
Recurrence Interval ≤ 500 yrs

CLASS 1A

Same as Class 1, except:
Slip Rate ≥ 5 mm/yr
Recurrence Interval ≤ 1000 yrs

CLASS 1B

Same as Class 1, except:
Slip per Event ≤ 1 m
Magnitude ≤ M_s 7.0
Recurrence Interval generally ≤ 100 yrs

CLASS 2

Slip Rate: 1-10 mm/yr
Slip per Event ≥ 1 m
Rupture Length 50-200 km
Seismic Moment ≥ 10^{25} dyne-cm
Magnitude ≥ M_s 7.0
Recurrence Interval: 100-1000 yrs

CLASS 2A

Same as Class 2, except:
Slip per Event ≤ 1 m
Magnitude ≤ M_s 7.0
Short (< 100 yrs) Recurrence Interval

CLASS 2B

Same as Class 2, except
Slip per Event ≥ 5 m
Rupture Length ≥ 100 km
Recurrence Interval ≥ 1000 yrs

CLASS 3

Slip Rate: 0.5-5 mm/yr
Slip per Event: 0.1-3 m
Rupture Length: 10-100 km
Seismic Moment ≥ 10^{25} dyne-cm
Magnitude ≥ M_s 6.5
Recurrence Interval: 500-5000 yrs

CLASS 4

Slip Rate: 0.1-1 mm/yr
Slip per Event: 0.01-1 m
Rupture Length: 1-50 km
Seismic Moment ≥ 10^{24} dyne-cm
Magnitude ≥ M_s 5.5
Recurrence Interval: 1000-10,000 yrs

CLASS 4A

Same as Class 4, except:
Slip per Event ≥ 0.5 m
Rupture Length ≥ 10 km
Seismic Moment ≥ 10^{25} dyne-cm
Magnitude ≥ M_s 6.5

CLASS 5

Slip Rate < 1mm/yr
Recurrence Interval ≥ 10,000 yrs

CLASS 6

Slip Rate < 0.1 mm/yr
Recurrence Interval ≥ 100,000 yrs

Six general classes of active faults and five sub-clases have been identified. The sub-classes have most of the same characteristics as the larger classes, but important differences in fault behavior necessitated sub-class designations. A brief discussion of several faults will illustrate the classification scheme.

The south-central segment of the San Andreas fault, from Cholame to San Bernardino in southern California, can be considered a Class 1 fault. A geologic slip rate of about 40 mm/yr has been calculated for Holocene displacement along the fault. Recurrence intervals ranging from about 100 to 330 years have been estimated for great earthquakes similar to the 1857 event (M 8) that produced up to 9.5 m of right slip. The Parkfield segment of the San Andreas fault is Class 1B because, although the slip rate is similar to that of the south-central segment, the magnitude (less than M_s 6.5), displacement (less than 0.5 to 1.0 m), and recurrence interval (less than 30 years) of historical earthquakes are much different. Available evidence indicates that such behavior --frequent small rupture events--is characteristic of this segment, whereas less frequent, large rupture events characterize the adjacent south-central segment.

The Motagua fault of Guatemala, source of the 1976 M_s 7.5 earthquake, is typical of the larger faults of Class 2. The late Quaternary slip rate is about 6 mm/yr, typical rupture events produce about 1 to 2 m of right slip, and recurrence intervals of around 200 years appear to be characteristic. Somewhat less active strike-slip faults, such as the Calaveras and Hayward faults in northern California, are also included in Class 2. The Wasatch fault of Utah is a good example of a Class 2 intraplate normal fault: slip rate is about 1.5 mm/yr, displacement per event is 1 to 3 m, recurrence intervals along individual segments range from 500 to 2500 years, and are probably less than 500 years for the entire fault.

The Elsinore fault in southern California is a typical Class 3 strike-slip fault: slip rate is about 3 mm/yr, slip events are relatively small, and recurrence intervals are moderately long, up to a few thousand years. The Sierra Madre fault, source of the 1971 San Fernando earthquake, illustrates Class 3 reverse faulting: slip rate is 1 to 2 mm/yr and recurrence intervals range from a few to several thousands of years. Many Basin and Range normal faults fall into Class 3, including the Dixie Valley and Pleasant Valley faults.

Many Class 4 faults have been recognized. The Greenville fault in northern California is typical: slip rate is probably less than 0.5 mm/yr; minor surface faulting was associated with an earthquake of magnitude less than 6. Most of the reverse faults of the Transverse Range of California are in Class 4; their slip rates generally are 0.2 to 0.8 mm/yr. Class 4A is an important sub-class. It represents a group of faults having relatively low slip rates, large-magnitude earthquakes, and relatively long recurrence intervals. For example, the Zenkoji fault in Japan has a slip rate of less than 0.2 mm/yr, yet produced an estimated M_s 7.4 earthquake in 1847.

Faults of Class 5, and especially Class 6, generally behave similarly to faults of Class 4A: low slip rates are accompanied by large earthquakes having very long recurrence intervals. The most dramatic example is the Pitaycachi fault, source of the 1887 Sonora, Mexico, earthquake. The slip rate appears to be only about 0.02 mm/yr, yet an estimated M_L 7.5 earthquake in 1887 was accompanied by as much as 4 m of normal fault displacement. Geomorphic studies of the fault zone suggest a hiatus of several hundred thousand years between periods of fault displacement.

The principal advantage of this degree of activity fault classification scheme is that all the characteristics that can be used to define fault behavioral activity are incorporated, thus, this scheme incorporates the range of fault behavior. In using this classification, if certain characteristics of a fault are known, then relatively restricted values for other characteristics of the fault can be calculated or deduced.

During the analysis of fault activity data, it was quickly recognized that faults do not behave in simple order-of-magnitude classifications. Significant overlap is recognized among various characteristics. A fault that has a slip rate of 0.7 mm/yr and a recurrence interval of 2000 years of a 0.5 m displacement might fit either Class 3 or Class 4. The Rose Canyon and the La Nacion faults near San Diego, California, would be Class 5 with regard to recurrence interval, and Class 6 with regard to slip rate. The choice of a particular classification will depend on the preponderance of evidence of fault activity; where two options are available, it is generally appropriate to choose the class having the higher degree of activity.

VALUE IN SEISMIC HAZARD ASSESSMENTS

Seismic geology and seismicity studies for more than ten hydroelectric projects in Colombia, South America provide examples of how seismic hazard evaluations using the degree of fault activity concept can assist decision-makers in making assessments of relative risk to critical structures. Because Colombia is a tectonically active region where earthquakes are relatively common, prudence dictated that detailed seismic hazard evaluations be performed for every major hydroelectric project planned. Many of these studies have been conducted by Interconexion Electrica S.A. (ISA), the central consortium of power companies for Colombia, and their consultants for the past 10 years, and several of these projects are now being designed and constructed.

It was found that the degree of fault activity on faults in Colombia could be reassessed based on the increased understanding of regional tectonics and Quaternary faulting rates gained during successive investigations. Faults considered active because they have the potential for slip in the current tectonic stress regime were first considered to have a moderate to high degree of activity (Class 1). Further detailed seismic geologic and seismicity studies showed that the slip rates and amounts of displacement on some faults were less than originally estimated, and several large historical earthquakes were incorrectly located. Not having a rigid, legal definition of fault activity to constrain decision-makers allowed this new data to be taken into consideration. The degree of fault activity on these faults was reassessed as low to moderate (Class 3). As a result, choices could be made between alternate sites, and significant savings are being realized in the design and construction of major projects where such assessments of the seismic hazard can be made with confidence.

The results of the seismic hazard studies also provided a mechanism to quantitatively compare the hazard from faulting with the other possible hazards. For example, at one dam site in Colombia, the likelihood of surface fault rupture through the dam foundation was found to be 1000 to 10,000 times less than the likelihood of a large landslide entering the reservoir. This information aided decision-makers in the evaluation and selection of the type of dam for this site.

In California, the siting of a liquefied natural gas (LNG) terminal became so entangled in debates over seismic safety that the project cost rose to $400 million prior to facility design, and the extensive delays eventually resulted in cancellation of the project. Although many scientific and environmental issues were the subjects of debate during the site-approval phases of this project, most of them could be easily evaluated. The seismic safety issues, however, were more complicated and were developed into major obstacles to the siting of this controversial facility.

Fault activity was defined in such a way that the seismic issues could be and were misused. One major stumbling block in the decision process was a legalistic definition of fault activity based on a specific time criterion: faults older than 100,000 to 140,000 years were "safe;" younger ones were not. The criteria also included the term "maximum credible earthquake." Use of this term invites controversy, because what it credible to one person may not be credible to another.

The LNG case was finally resolved by engaging a panel of experts, who shunned the previously adopted criteria and terminology (Ref. 7). The panel addressed the "active fault" problem by describing the earthquake sources important to the proposed LNG terminal site according to their degree of activity. This involved estimating earthquake magnitudes for various recurrence intervals for each earthquake source. Instead of "maximum credible earthquake," the panel recommended that likely maximum earthquakes for different recurrence intervals be considered when choosing design parameters. This approach allows choices to be made that are consistent with judgments about acceptable risk.

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