U.S. Earthquake Frequency Estimation–
Ratemaking for Unusual Events

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Abstract

In our work on ratemaking, financial modeling, catastrophe modeling and planning, actuaries often must estimate the expected frequencies of unusual events. However, actual historical data for unusual events is too sparse to be very useful, so we must look to other sources for help. One example of these rare events is earthquakes. In recent years, the scientific community has performed significant research to better estimate the likehoods of earthquakes throughout the United States. Papers published by that community have presented much information that should be helpful in our quest to use earthquake frequencies in ratemaking, modeling and other actuarial work. This paper will present a basic discussion of scientific measures to estimate earthquake probabilities, a list of useful sources, and a discussion of several issues important to the understanding of earthquake ratemaking.

Introduction

Actuaries traditionally have had difficulty pricing coverages that have potential for large severity, but that have low frequency. Often, the prices charged for these coverages are determined by underwriting judgment and market forces, with little or no actuarial involvement. The catastrophe portions of property coverages are an obvious example of this situation. Among the insured catastrophe perils, earthquake is probably the most difficult to price.

Historically, pricing for the catastrophe portion of property rates has involved averaging losses over decades and large regions. However, changes in exposures and insurance coverages during those decades make traditional actuarial methods based on insurers' loss data very uncertain. The introduction of computer simulation models for estimating potential catastrophe losses now gives actuaries tools to help estimate catastrophe rates. For instance, the California Earthquake Authority, which writes a majority of the personal lines earthquake business in California, uses rates that were based on loss costs from computer simulation modeling. This type of model simulates losses from a large number of specific possible events. In order to convert these losses to loss costs, models take these simulated losses and apply frequency estimates to each event. These frequency estimates are critical, since any inaccuracy in frequency translates directly into inaccuracy in the loss costs.

The severity portion of an earthquake model carries significant uncertainty, but the frequency portion is probably more difficult to estimate accurately. There have been few historical events that have caused appreciable damage, and even fewer catastrophic earthquakes. Historical evidence is of limited use. Those responsible for ratemaking utilizing computer model output may believe that they don't need to know specifics about earthquake frequency since the estimates are imbedded in the models that they use. However, it is important to understand how frequencies are estimated because they are so critical to the rate that is indicated by the model.

This paper will describe some basics of how scientists estimate earthquake frequencies, where to look for frequency information and current issues on which experts disagree. The uncertainty of these estimates and the effect on ultimate rates will also be discussed.

Experts

If insurance loss data is confined to too short a time span to be useable, we need to find information elsewhere. The experts in earthquake frequency are seismologists and geologists. Seismologists study the historical earthquake records and the geological records. Geologists study the earth's crust to estimate how often the earth will move in certain areas. It is important to realize that 150-200 years is very short in the framework of geologic time. Thus, the geologic record of many thousands of years becomes paramount in estimating earthquake recurrence times.

We can look to published papers in professional journals, government publications and professional meeting presentations for the latest scientific research. Some of the sources for U. S. seismic frequency estimates are the Seismological Society of America (SSA), United States Geological Service (USGS), California Division of Mines and Geology (CDMG), Southern California Earthquake Center (SCEC), American Geophysical Union (AGU), and Earthquake Engineering Research Institute (EERI). Sources for earthquake frequencies outside of California include state geological surveys. Of course, universities provide much of the research underlying all the estimates. These groups are constantly providing new information to better understand the chance of earthquake occurrence.

Methods

Since estimating recurrence is so uncertain, scientists use a number of methods to arrive at their estimates. They measure the seismic slip of the earth's crust and the amount that slip that will be accounted for by an earthquake. They use statistical measures to extend the historical record to estimate likelihoods of very rare events. And, they use paleoseismic research to discover evidence of old earthquakes.

Seismic Slip Analysis

The earth's crust is comprised of tectonic plates that continually move with respect to one another. Where the plates meet, this movement is evidenced as strain in the crust. When the strain builds to a certain level, the crustal rock cannot hold it any more and it moves – earthquake! The amount of displacement resulting from this release of strain is known as seismic slip. Overall slip along a plate boundary can be estimated fairly accurately by modern measurement methods, so this method is useful for seismic areas at plate boundaries. Seismologists observe displacement of the ground in actual events, and can then estimate return times that accommodate the slip rate. The amount of slip is correlated to the amount of energy released by the earthquake, which is measured by the *magnitude* of the event. There are several types of magnitude definition, but for the purposes of this paper, we are using *Richter Magnitude* when we use the term.

A simplified example shows how this works. The San Andreas Fault is the boundary between the North American and Pacific plates in California. Along that fault, there is approximately two inches of plate movement per year. In the 1906 earthquake, there was up to 20 feet of displacement at various places along the fault. At two inches a year, it would take 120 years to build up enough slip to move that 20 feet. Thus, if

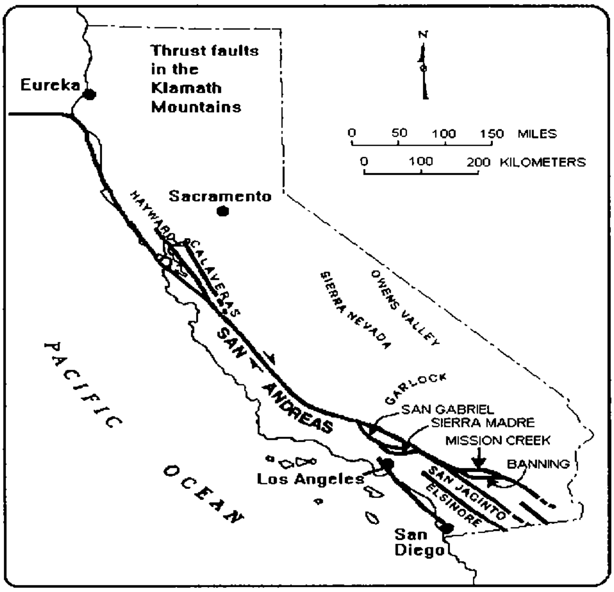


Figure 1

the San Andreas were a simple system that accommodated all the plate movement, the return time for this event could be estimated at about 120 years.

The real world, of course, is significantly more complex. Figure 1 shows the major faults in the San Andreas system in California. The faults are not simple lines, but a series of fractures, of which only a few are shown. There is significant work in apportioning the overall slip of two inches a year to individual faults, each capable of taking up some of the slip. For instance, in the above example, the San Andreas actually only accommodates about half the plate movement. In addition, there is the possibility of more than one fault segment breaking in the same event ("cascading event") and the fact that the release of strain in an event on one fault can change the strain in nearby parallel faults.

Gutenberg-Richter Relationship

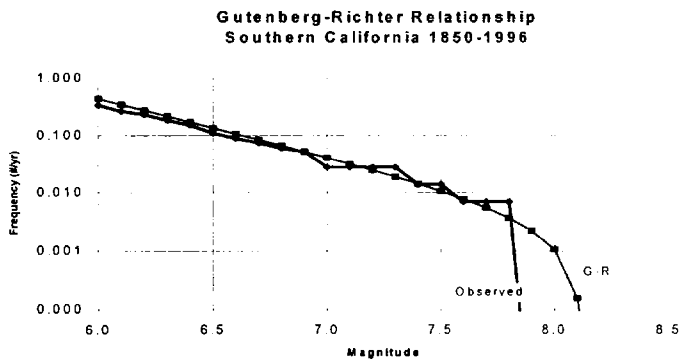
The rate of earthquake activity within a fairly large region can be estimated using a statistical approach, wherein the historical record of earthquake magnitudes and frequencies are fitted to a logarithmic equation. This equation is:

$$\text{Log } N = a - bM$$

In this equation, N is the number of earthquakes of magnitude equal or greater than magnitude M during a certain time period, while a and b are determined by fitting the equation to the historical record. Figure 2 shows an example of a curve for southern California.

This equation is used to estimate the likelihood of various earthquake magnitudes for an area, as well as to extend the historical record to magnitudes greater than historically observed. The use of the Gutenberg-Richter relationship is one of the areas of controversy among experts. The argument about the applicability of this relationship versus using a "characteristic earthquake" will be discussed later.

Figure 2



Paleoseismology

Since frequency of great earthquakes is often measured in terms of centuries and the U.S. historical record is less than 200 years, scientists have had to go beyond the record to discover how long the time is between the big shakes. Paleoseismology, the science of identifying and dating past earthquakes by examining the geological record, has proven to be very useful in extending our knowledge back from the historical record. There have been significant paleoseismic studies in most U.S. seismic areas, some of which are discussed below.

In one such study in Oregon, Nelson[7] and Bradley of the USGS studied soils buried beneath marshes. These soils show evidence of ground subsidence, much of which has probably been caused by major earthquakes. For instance, the 1700 earthquake discussed below probably caused significant subsidence. There have been 16 disturbances in the past 7,500 years, implying an average return time of about 500 years, assuming all the disturbances were caused by earthquakes. These, however, were not evenly spaced over the 7,500 years.

Up the coast in Washington, a similar study of buried soils showed one very large shallow earthquake about 1,000 years ago on a fault that runs directly beneath Seattle. Shallow earthquakes, less than 10 miles or so below the surface, can cause significant shaking, since there is less of the crust to absorb the energy released by the quake than from a deeper event.

The above work in Oregon and Washington is very important, since the Pacific Northwest has the chance for a great subduction earthquake. That is, an earthquake where one fault pushes under another and which can generate earthquakes of 9.0 magnitude or greater. The Juan de Fuca plate moving eastward beneath the North American plate along the coast of Oregon, Washington and a portion of British Columbia would cause this earthquake. Native American lore in that area told of a great earthquake about 300 years ago. An earthquake of that size and type would have almost certainly caused a major tsunami (seismic sea wave) that would have proceeded across the Pacific. Accordingly, Japanese records were searched and, as expected, there was a record of a tsunami in January 1700. From those records, scientists have calculated that a great subduction event happened off the Pacific Northwest coast on January 27, 1700.

Juan de Fuca Plate

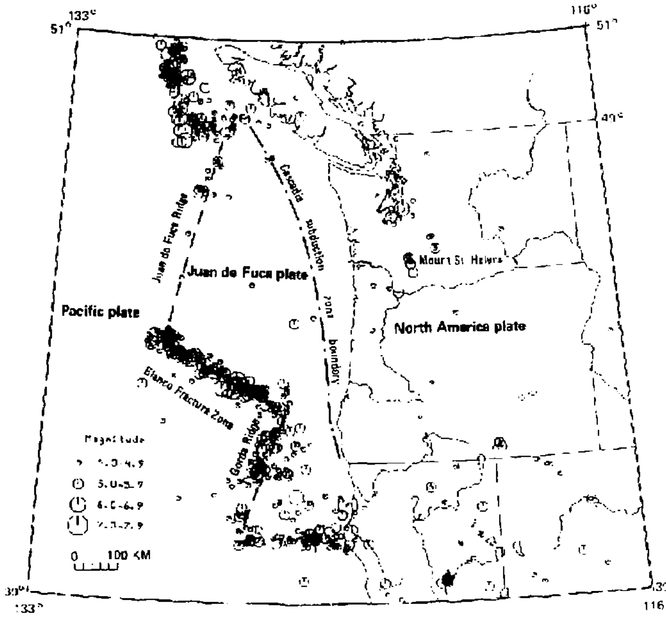


Figure 3

In the New Madrid seismic area of the Central U.S., there has been great concern about a large earthquake. This area suffered a series of great earthquakes (magnitudes over 8.0) in 1811-1812, but there is very little historically to help us estimate the return time of such an event. To investigate the area, paleoseismologists *such as* Buddy Schwieg[16] *of the USGS and* Steve Wesnousky[17] *of*

Nevada-Reno have dug trenches in the affected areas. The walls of the trenches were then studied to see evidence of past earthquakes.

In the 1811-12 earthquakes, there was significant liquefaction of the soil. This is a condition where the earthquake mixes sandy soil and water to create a fluid soil. This condition is often evidenced as sand blows, fluid sand shooting up to the surface, looking like large anthills. In the trenches, there was evidence of sand blows that have been carbon-dated at approximately 900 and 1300 A.D, with two others in the past 2,000 years. This would imply a return time of about 500 years for events large enough to cause sand blows. Some of these may not have been quite as large as the 1811-12 events, although one may have been larger. Thus, scientists have estimated that events of over 8.0 probably have return times of between 400 and 1,100 years. There are a couple of items that show the difficulty in this type of estimation. First, studies of different fault segments show different areas of liquefaction at different times. In addition, Schweig and others have shown evidence of another earthquake between 1400 and 1600 A.D.

There has also been significant trenching activity in Southern California. One very interesting finding arose after the magnitude 7.3 Landers earthquake of 1992, east of San Bernadino, which was an event that ruptured multiple faults. Kerry Sieh[13] of Cal Tech, discovered through trenching that some of these faults had not broken for over 10,000 years, so, of course, would have no historical record.

Sieh also has done work in the southern San Andreas Fault system (Pallet Creek) that shows an additional source of uncertainty in likelihood estimation. In that area he showed ten precisely dated earthquakes over the past 2,000 years. However, they were not evenly spaced over that time. There were four clusters of two or three events each preceded by periods of dormancy that lasted two to three hundred years. Each cluster happened within a one hundred-year period. Thus, the long-term recurrence for these events is about 200 years, but the time between specific events could be much lower. Similar studies have indicated that clustering has occurred in other locations, and is common. Thus, even when scientists can identify the average recurrence time of an earthquake on a fault segment, the actual time between events can vary significantly.

These are samples of paleoseismic research that have provided very helpful information. From this information, we have much better estimates of probabilities of very large events than available from history, but we are also aware of the difficulties involved in the process, and the uncertainties introduced in the frequency estimates.

Sources of Frequency Information

There are several publicly available sources of frequency estimates. Of course, given the seismicity of California, that area has received the majority of the attention.

U.S.G.S. Open-File Report 88-398[19]

In 1988, the USGS published a study of the frequencies of California earthquakes, covering the major strike-slip faults of the San Andreas fault system. The work was done by a group of academics and other scientists known as the Working Group on California Earthquake Probabilities. The study, USGS Open-File Report 88-398, produced probabilities for three major seismic areas, the San Francisco Bay area, the Southern San Andreas Fault and the San Jacinto fault. In order to help the public understand them, the likelihoods were expressed in terms of the probability of a certain magnitude event over the next thirty years. The 1988 probabilities are summarized in the table below. Both the 30-year and annual probabilities are shown.

Table 1

Geographic Region of Fault	Expected Magnitude	Probability of Occurrence in 30 Years	Annual Probability
San Francisco Bay Area	7.0	50%	2.3%
Southern San Andreas Fault	7.5-8.0	60%	3.0%
San Jacinto Fault	6.5-7.0	50%	2.3%

U.S.G.S. Circular 1053[18]

The 1989 Loma Prieta earthquake on the San Andreas Fault south of San Francisco precipitated a new look at the 1988 work. In 1990, the Working Group revised its estimates for the San Francisco Bay Region, covering the North San Andreas Fault and the Hayward Fault in the East Bay. This was published in USGS Circular 1053. In addition to reflecting the change in stress after the Loma Prieta event, the Working Group also considered faster fault-slip rate estimates and included the Rogers Creek Fault, the northern extension of the Hayward Fault. The changes in probabilities are shown in the following table.

Table 2

Fault Segment	Expected Magnitude	30 Year Prob 1988	Annual Prob 1988	30 Year Prob 1990	Annual Prob 1990
San Andreas - N	7.0	20%	0.7%	23%	0.9%
Hayward North	7.0	20%	0.7%	28%	1.1%
Hayward South	7.0	20%	0.7%	23%	0.9%
Rodgers Creek	7.0	NA	NA	22%	0.8%
Total S. F. Bay Area		50%	2.3%	67%	3.6%

This is a rather significant increase over the 1988 estimate; even excluding the Rodgers Creek Fault brings the 1990 estimate for the area to about 60%, a 20% increase.

SCEC Study[20]

The 1994 Northridge earthquake sparked another revision to the 1988 report, this time for Southern California. The Southern California Earthquake Center coordinated a new study by the Working Group that updated the Southern California probabilities from the 1988 study (for the San Andreas and San Jacinto faults) and also considered other potentially damaging earthquakes in that region. The study was published in the April, 1995 issue of the *Bulletin of the Seismological Society of America (BSSA).*

The modeling was considerably more complex and included the entire Southern California region. The models predicted a 30-year probability for a magnitude 7 or larger event of between 80% and 90%. Because of the differences in methodologies, this study is hard to compare to the 1988 estimates, but it definitely increased the perception of the earthquake problem in Southern California. The SCEC study added several fault segments, included provision for "blind thrust-fault" earthquakes (those that do not break the surface, for example, Northridge) and revised some slip rates upwards. They also produced a method to include the chance of more than one fault segment breaking in a single event (known as "cascading earthquakes"). The 1992 Landers and the 1857 Ft. Tejon earthquakes were examples of this type of event, so this method should help provide more realistic estimates of return periods for large events.

However, there has been some controversy about this study. When the predicted probabilities are compared to the historical record, they exceed the historical earthquake. The current discussions of that anomaly will be discussed later.

USGS Hazard Maps

In 1997, the USGS and the CDMG published new hazard maps for the U.S., showing levels of ground shaking at specified exceedance probabilities throughout the country. While these are not strictly frequency studies, these maps combine frequency and severity, and as such, are good for comparing overall hazard to other sources.

Non-California Sources

While this paper has concentrated on California probability sources, the potential loss from earthquakes in other areas of the country is certainly important, and so are their likelihoods. Other areas include the New Madrid seismic area, the Pacific Northwest, Charleston, S. C., and Salt Lake City. Some sources for these areas, in addition to the paleoseismic work above, are listed in the References section.

Ratemaking Effects

Loss costs underlying earthquake rates can be quite sensitive to the model frequency estimates of the largest, most rare events. For instance, assume experts believe that the return time for a magnitude 8 or greater event in the New Madrid seismic zone is between 500 and 1,000 years. This size event would be considerably more damaging than lesser events in a library of potential events in a model, so the choice of frequency could have a significant effect on the total loss costs for that seismic zone. As a simplistic example, see Table 3 on the next page. If the frequency of the worst event in that table were doubled, the overall loss cost would rise from $7 to 10 million.

Current Controversies

Although seismologists have developed many very useful methodologies to improve their earthquake probability estimates, there is still much uncertainty. There are disagreements among the scientists about the best estimation methods. A few of the current issues will be discussed to show the extent of the uncertainties.

Gutenberg-Richter vs. Characteristic Earthquakes

Earlier, the Gutenberg-Richter relationship was explained. While most will agree that this is a useful concept, there is disagreement over when it should be used. For a specific fault segment, many scientists believe that there will only be one certain size event, known as a "characteristic" earthquake. They believe that strain will build to a certain point, and then the fault will break. The amount of slip will be essentially the same each time, and will result in a similar fault rupture and, thus, a similar magnitude earthquake. For that fault, Gutenberg-Richter would not apply, since there wouldn't be a distribution of possible magnitudes. If this is true for all individual fault segments, then Gutenberg-Richter is only a valid concept for a region of such faults. The question is, "How big must a region be for the relationship to be valid?"

This is a very important question for earthquake modeling, since assuming a distribution of several possible magnitudes on a large number of faults may give different answers than a distribution that assumes only one potential magnitude per fault. It is typical for earthquake loss models to simulate several different magnitude events on each fault segment, giving decreasing probabilities to increasing magnitudes. If only one magnitude can happen, the distribution of probabilities by magnitude for a library of events will be different.

In a simplistic case, we have assumed that the characteristic earthquake for a certain fault is a 7.0, and a Guttenberg-Richter relationship shows the possibility of damaging quakes from 6.0 to 7.5. We have also assumed that the losses for various size events follow the pattern in the table below. The table shows potential losses with assumed frequencies and losses for the spectrum of events where the total annual frequency is 0.15 events per year.

Table 3

Magnitude	Annual Frequency	Loss ($Millions)
6.0	.08	10
6.5	.04	30
7.0	.02	100
7.5	.01	300
Annual Total	.15	7

If the characteristic event of 7.0 were the only event to occur, the frequency of that event would be 0.15. Thus, the annual average loss would be 0.15 x $100, or $15 million, more than twice that of the Gutenberg-Richter assumption. While this is a simplistic example, differences like this can occur for a number of seismic areas, so that this difference in opinion can potentially have a large overall effect.

The Paradox

In the August 1997 issue of the *BSSA*, Didier Sornette and Leon Knopoff[14] published a paper called, "The Paradox of the Expected Time until the Next Earthquake." The authors address the question; "Can it be that the longer it has been since the last earthquake, the *longer* the expected time till the next?" This is in opposition to the conventional wisdom says that, as the time since the last event increases, the probability of the next occurrence increases. The common assumption is that strain is released in an event, and then begins building up until it reaches a point that the earth gives way again. This seems intuitively correct, but the authors argue that this is not always the case. This is important for ratemaking, since the frequencies used in the models often use the best estimate of the near-term frequency, rather than the long-term frequency for an event. For example, if the long-term return time for a certain earthquake is 100 years (frequency of 0.01), but it has been 75 years since the last event of that type, the frequency used will be much higher than 0.01.

Their analysis suggests that the answer to this question depends on the inherent statistical distributions of the fluctuations in the interval times between earthquakes. Several distributions, including the periodic, uniform, semi-Gaussian and the Weibull (with exponent greater than 1), all have a *decreasing* return times with the passage of time since the last event, as we would expect. However, the lognormal, power law and Weibull with exponents less the 1 have *increasing* return times.

One explanation for this possibility is found in examining clusters of past earthquakes. If we believe that earthquakes in an area behave in a clustering fashion, we can expect a repeat of an event relatively shortly after an event that follows a long dormancy. But, as the time following that event gets longer, we might believe that we are in another long dormant time, rather than a time between clustered events.

In ratemaking, this means that the uncertainty of these events is increased. Not only do we have to estimate the long-term frequency, with its uncertainty, but we also have to factor in the effect of the time since the last event, and whether this increases or decreases the frequency used in the ratemaking process for the next year.

The Enigma in the SCEC Report

As mentioned earlier, since the release of the SCEC report, seismologists have hotly discussed the reasons why the estimates significantly exceed those implied by the historical record. The graph in figure 4 shows the difference. The top line is the predicted frequency, while the bottom is the historical record. Since this is a on logarithmic scale, the prediction is actually about twice that of history in the magnitude 6.0 to 7.0 range, where we find many damaging events.

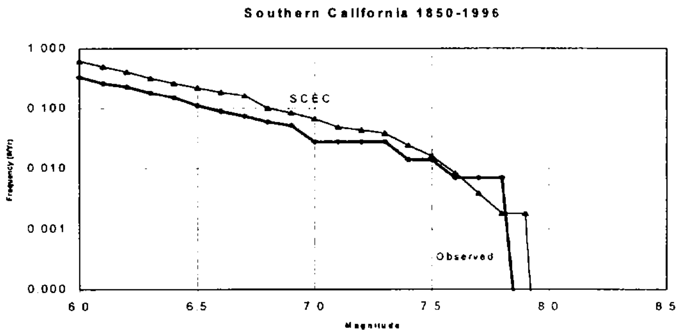


Figure 4

Three possible reasons have been put forth to explain this difference. First, slip has been taken up aseismically; that is, there has been slow movement of the earth without earthquakes ("creep") and folding of the crust. Secondly, we may have been "lucky" over the past 150 years, or so. That is, the actual frequency has been significantly lower than the long-term frequency for the area. Thirdly, there is the possibility of an event much larger than the historical maximum, which was a Richter magnitude of about 8.1. This may or may not be a significant problem, depending on the accuracy of the historical record. That is, small changes in the magnitude estimates of older historical events could account for much of the difference. The report itself addressed this, suggesting that earthquake activity in the region for magnitude 7 and greater earthquakes has be anomalously low since 1850, although there was one great earthquake. Just one additional great earthquake would erase the difference. This is one example of the sensitivity of earthquake frequency estimates.

David Jackson of SCEC has been addressing this enigma with the following theory. There seems to be no evidence that any significant creep has occurred in the area, and, we can theorize that the 150-year period is long enough to show a reasonably accurate estimate of long-term occurrence rates for medium earthquakes (magnitude 6-7), where the difference is greatest. Thus, Dr. Jackson has felt that the most likely answer was that a much larger event could occur than the largest historical quake, the 1857 Ft. Tejon event. This "mega-earthquake" needs only to have a return time of about 1,000 years to take up the excess slip that is unaccounted for.

However, during the March 1998 annual meeting of the SSA, two teams of researchers disputed the necessity for a "mega-earthquake." SCEC has further reviewed its study and found a number of small flaws that combined to overestimate the estimate of the amount of slip building up in Southern California. They have revised the model such that the difference between historical and theory has virtually disappeared. At the same meeting, USGS scientists questioned the historical list of magnitude 6 and greater events that was used by SCEC. They argue that the list may have ignored quakes that occurred early in the time period, when inland California was relatively unpopulated. They point out that the observed earthquake rate since 1903 is almost 50% greater than that recorded since 1850. If there were an appropriately higher early rate, the SCEC difference would be reduced. This may or not be the case, since 150 years of earthquake history is so short compared to geologic time. (Note that the earthquake rate in the San Francisco area was very high in the 70 years prior to 1906, and has been very low since.)

The answer to this enigma can certainly effect the loss costs that are modeled in Southern California. If the "true" relationship includes about half the moderate earthquakes that are currently reflected in a model, but has a very rare large one that is not now reflected, "true" loss costs will certainly be different, although it is difficult to estimate whether they would be higher or lower.

Conclusion

Now that scientifically based catastrophe modeling is being used to support earthquake insurance rating, we must be aware of the importance of the probabilities used and the uncertainty in those probabilities. The scientific community, led by the USGS, CDMG and SCEC in California, continues to research the area to give us better information. This research will continue to progress, and we can expect the estimates to evolve. However, the significant disagreements among the scientists, even in California, highlight the uncertainty involved.

We as ratemakers must be aware of the assumptions underlying the rates. When loss costs are based on computer models, the frequency assumptions are often buried in the models. We need to know the sensitivity of the estimates so we can understand the uncertainty of the rates, and make informed pricing decisions.

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