Earthquake Probabilities in the San Francisco Bay Region: 2002–2031

By Working Group On California Earthquake Probabilities

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U.S. DEPARTMENT OF THE INTERIOR
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EXECUTIVE SUMMARY

Drawing on new data and new methodologies, we have concluded that there is a 0.62 probability (i.e., a 62% probability) of a major, damaging earthquake striking the greater San Francisco Bay Region (SFBR) over the next 30 years (2002–2031). Such earthquakes are most likely to occur on seven main fault systems identified in this study, but may also occur on faults that were not characterized as part of the study (i.e., in the “background”) (Figure ES.1). Our results come from a comprehensive analysis led by the USGS and involving input from a broad group of geologists, seismologists, and other earth scientists representing government, academia and the private sector. The results of this study are appropriate for use in estimating seismic hazard in the SFBR, and estimating the intensity of ground shaking expected for specified “scenario” earthquakes. In addition, they provide a basis for calculating earthquake insurance premiums, planning and prioritizing expenditures for seismic upgrades of structures, and developing building codes.

Introduction

Earthquakes in the San Francisco Bay Region result from strain energy constantly accumulating across the region because of the northwestward motion of the Pacific Plate relative to the North American Plate (Figure ES.2). The region experienced large and destructive earthquakes in 1838, 1868, 1906, and 1989, and future large earthquakes to relieve this continually accumulating strain are a certainty. For our study we define the SFBR as extending from Healdsburg on the northwest to Salinas on the southeast. It encloses the entire metropolitan area, including its most rapidly expanding urban and suburban areas. We have used the term "major" earthquake as one with **M**≥6.7 (where **M** is moment magnitude). As experience from recent earthquakes in Northridge, California (**M**6.7, 1994, 20 killed, \$20B in direct losses) and Kobe, Japan (**M**6.9, 1995, 5500 killed, \$147B in direct losses), earthquakes of this size can have a profound impact on the social and economic fabric of densely urbanized areas.

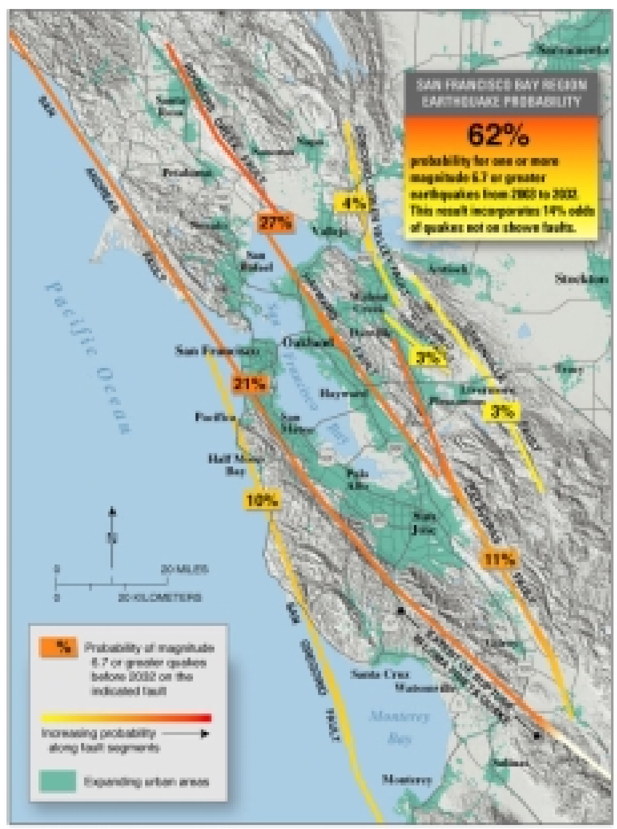

Figure ES.1. Probabilities of one or more major (M≥6.7) earthquakes on faults in the San Francisco Bay Region during the coming 30 years. Color indicates the probability that each fault segment will rupture in such a quake.

Working Group probability study

To evaluate the probability of future large earthquakes in the San Francisco Bay Region, the U.S. Geological Survey has established a series of Working Groups on California Earthquake Probabilities (hereafter referred to as WG88, WG90, WG99). Each of these Working Groups has expanded on the work of its predecessors, applying, in turn, the data and methodology available at the time and drawing on input from broad cross-sections of the earth science community.

WG88 and WG90 established a framework for estimating earthquake probabilities based on simple physical models for the San Andreas and Hayward faults in the Bay Area, and on the San Andreas, San Jacinto, and Imperial Faults in southern California. WG99 extended this framework into a more comprehensive, regional one for the SFBR based on a greatly expanded set of geological and geophysical observations. In its calculations, WG99 combined the results of multiple viable models when a single consensus model did not exist. Summaries of WG99 methods and results were published in 1999 on the tenth anniversary of the Loma Prieta earthquake, as U.S. Geological Survey Open-File Report 99-517, and USGS Fact Sheet 151-99.

The present study (hereafter referred to as WG02) is a continuation and extension of WG99 and updates the results of that study. WG02 adopts the basic framework used by WG99 and expands on it by:

- incorporating additional data;
- more fully analyzing the possible effects of the 1906 earthquake (the "stress-shadow" effect) on the current earthquake potential in the SFBR;
- more fully developing the uncertainties associated with the calculated probabilities;
- exploring some of the implications for earthquake hazard in SFBR;
- making available a full documentation of the methods and computer codes used[1].

Figure ES.2. Faults and plate motions in the San Francisco Bay Region. Faults in the region, principally the seven faults shown here and characterized in this report, accommodate about 40 mm/yr of mostly strike-slip motion between the Pacific and North American tectonic plates. Yellow lines show the locations of the 1868 M6.8 earthquake on the southern portion of the Hayward Fault and the 1989 M6.9 Loma Prieta earthquake near the San Andreas fault northeast of Monterey Bay.

Broadened modeling approach

This WG02 report builds on previous analyses of earthquake likelihood, modifying some of the methodologies used in those studies and introducing new ones. The earthquake probabilities presented here are the product of model calculations consisting of three basic elements. The first element is the *SFBR earthquake model*, which determines the average magnitudes and long-term rates of occurrence

[1] Computer codes will be released in a separate USGS publication.

of earthquakes on the principal faults and for the region as a whole. These average long-term rates of earthquakes lead to average, time-independent probabilities of earthquakes at or above a particular magnitude level of interest (e.g., **M**≥6.7).

The second element consists of a suite of *time-dependent earthquake probability models*, which incorporate physical aspects of the causes and effects of earthquakes that vary with time. The two most important of these are the progression of faults through the "earthquake cycle" and the interactions of faults, through which the stress released by an earthquake on one fault is transferred in part to other faults or adjacent fault segments. The most significant interaction effect—that produced by the 1906 earthquake—figures prominently in the modeling. There is no consensus within the earth science community, or within this Working Group, as to whether the SFBR remains within the 1906 stress shadow (as suggested by seismicity data for the past 96 years), is now emerging from it (as suggested by the occurrence of the Loma Prieta earthquake and by calculations based on models of viscous flow in the lower crust and mantle), or has emerged from it (as suggested by simple elastic fault interaction models). The addition of a suite of probability models to represent this range of thinking represents the most substantial difference between the analysis reported by WG99 and that reported here.

The third new element introduced in our calculations is the characterization of the rate of occurrence of *"background" earthquakes*—earthquakes in the Bay region that do not occur on the principal faults. The probability for these events is based on seismicity rates known since 1836, extrapolated to **M**≥6.7 events. Background earthquakes include events such as the September 2001 M5.1 Napa earthquake, and the 1989 M6.9 Loma Prieta earthquake.

WG02 has devoted considerable effort to defining and quantifying uncertainties in all data, models, and parameters used in the analysis. In the calculations, estimates of uncertainty from all parts of the model are carried through to the end, providing an objective basis for assessing the reliability of the model calculation results and pointing to critical research needed to increase the precision and reliability of future assessments.

Summary of main results

1. *Regional earthquake probability.* There is a 0.62[2] probability (i.e., a 62% probability) of at least one magnitude 6.7 or greater earthquake in the 3-decade interval 2002-2031 within the SFBR. Such earthquakes are most likely to occur on the seven fault systems characterized in the analysis, but may also occur on faults that were not characterized in this study (i.e., in the "background"). This result is consistent with regional 30-year probability estimates made by WG88 (0.5), WG90 (0.67), and WG99 (0.70), given the differences among these studies and their uncertainty ranges.

Table ES.1. Probabilities of one or more **M**≥6.7 earthquakes in the SFBR, 2002–2031.

Source fault	Probability	95% Confidence Bounds
SFBR region	0.62	[0.37 to 0.87]
San Andreas	0.21	[0.02 to 0.45]
Hayward/Rodgers Crk	0.27	[0.10 to 0.58]
Calaveras	0.11	[0.03 to 0.27]
Concord/Green Valley	0.04	[0.00 to 0.12]
San Gregorio	0.10	[0.02 to 0.29]
Greenville	0.03	[0.00 to 0.08]
Mt. Diablo thrust	0.03	[0.00 to 0.08]
Background	0.14	[0.07 to 0.37]

[2] This result, like virtually every other result in this report, is associated with a confidence range that reflects uncertainties in the analysis. The 95% confidence bounds for the regional probability is [0.37 to 0.87] (Table ES.1).

2. *Geographic distribution of probability.* The earthquake likelihood is distributed broadly across the SFBR, from the San Gregorio fault on the west to the Green Valley and Greenville faults on the east (**Figure ES.1**). The easternmost faults along the rapidly developing Interstate 680 corridor in central and eastern Contra Costa and Alameda Counties have a mean combined probability for **M**≥6.7 earthquakes of 0.19[3]. Combining this with the contributions from the Hayward-Rodgers Creek fault, the central and southern parts of the Calaveras fault, and half the background earthquake likelihood, the probability for **M**≥6.7 earthquakes east of San Francisco Bay is 0.46 [0.17 to 0.64]. West of San Francisco Bay, the San Andreas and San Gregorio faults have a mean combined probability for a **M**≥6.7 earthquake of 0.32. With half of the background probability included, this part of the SFBR has a probability of 0.34 [0.05 to 0.57] for one or more **M**≥6.7 earthquakes in 2002-2031.

3. *Highest-probability faults.* Consistent with previous probability estimates, the Hayward-Rodgers Creek and San Andreas fault systems have the highest probabilities of generating a **M**≥6.7 earthquake before 2032. The Hayward fault is of particular concern because of the dense urban development along and directly adjacent to it and the major infrastructure lines (water, electricity, gas, transportation) that cross it.

4. *Background earthquakes*. The probability of a sizeable earthquake on a fault *not* characterized by WG02 (i.e., an earthquake in the "background") is substantial. For events **M**≥ 6.7, the likelihood is 0.14 [0.07 to 0.37], greater than that on any individual fault system other than the Hayward-Rodgers Creek and San Andreas faults. Many of the significant recent earthquakes in California, including the 1989 Loma Prieta event, have occurred on faults that were not recognized at the time of their occurrence.

5. *Larger earthquakes (**M**>7.0, **M**>7.5).* The magnitude of an earthquake is directly related to the size of the fault rupture. Our analysis suggests a 30 year probability of an earthquake **M**7.5 or larger striking the region is only 0.l0 (0.02 to 0.20). Only the San Andreas and San Gregorio faults, both lying west of San Francisco Bay, have sufficient length to generate such a large event. When the magnitude threshold is dropped to M7, the probability is considerably larger, 0.36 (0.17 to 0.60) and is concentrated on faults adjacent to the most developed parts of the region, the San Andreas, Hayward-Rodgers Creek, and San Gregorio fault systems.

6. *Smaller earthquakes (**M**>6.0).* We estimated the probability of a moderate earthquake (**M**6.0 to **M**6.7) over the next 30 years to be at least 0.80 (at least four times as likely to happen as not). As the recent past has demonstrated, earthquakes of this magnitude and smaller can produce significant damage over localized areas. For example, the 1984 **M**6.2 Morgan Hill earthquake on the southern Calaveras fault caused $10 million damage, while a **M**5.1 earthquake that occurred in September 2000 in a rural area 10 miles northwest of Napa caused $70 million damage to that community.

7. *Stress shadow.* Probability estimates for the next 30-year interval depend critically on the degree to which the SFBR has emerged from the seismic quiescence that followed the great 1906 San Francisco earthquake. The quiescence is thought to be caused by a region-wide drop in stress produced by that earthquake. Regional seismicity rates from the last few decades of the 20th century (**Figure ES.3**) suggest that the SFBR has been emerging from this quiescence, but has not returned to the high rate of earthquakes experienced in the 1800's. Until a better understanding of the evolution of the 1906 "stress shadow" is developed, this fundamental uncertainty will continue to ham-

[3] Probabilities are combined according to Equation (5.9) of this report.

per the accuracy of time-dependent probability estimations in the SFBR.

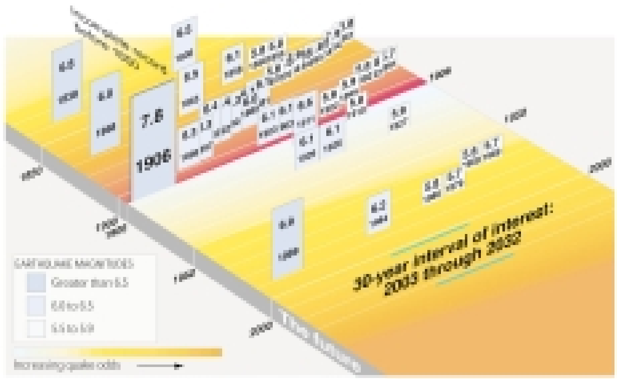

Figure ES.3. Earthquakes **M**≥5.5 in the SFBR since 1850. The decrease in rate of large earthquakes in the 20th century has been attributed to a region-wide drop in stress due to the 1906 M7.8 earthquake, the "stress shadow" hypothesis.

8. *Reliability of results.* Generally speaking, the larger the spatial and temporal scales, the more reliable the results. The earthquake probabilities for the SFBR as a whole, for example, are more reliable than those for any individual fault. Similarly, earthquake probabilities for several decades are more reliable than those for the next year.

Implications for earthquake hazard

Earthquake probabilities are one key component in estimating the seismic hazard in a region, but not the only one. Most earthquake damage is caused by strong, sustained ground shaking. The strength and duration of shaking at a particular location depends on the earthquake's size, its distance from the location, soil conditions at the location, and details about the rupture itself and the propagation of the seismic waves from it.

WG02 has identified 35 potential earthquake rupture sources on the seven faults characterized in this study. For each potential source, a "scenario" map of the expected shaking intensity was constructed, using existing knowledge about the expected propagation and site effects in the SFBR. **Figure ES.4** shows the expected shaking intensity distribution related to a M6.9 event on the southern Hayward fault, a likely repeat of the 1868 earthquake. This particular event has a likelihood of occurrence of 0.11 over the next 30 years.

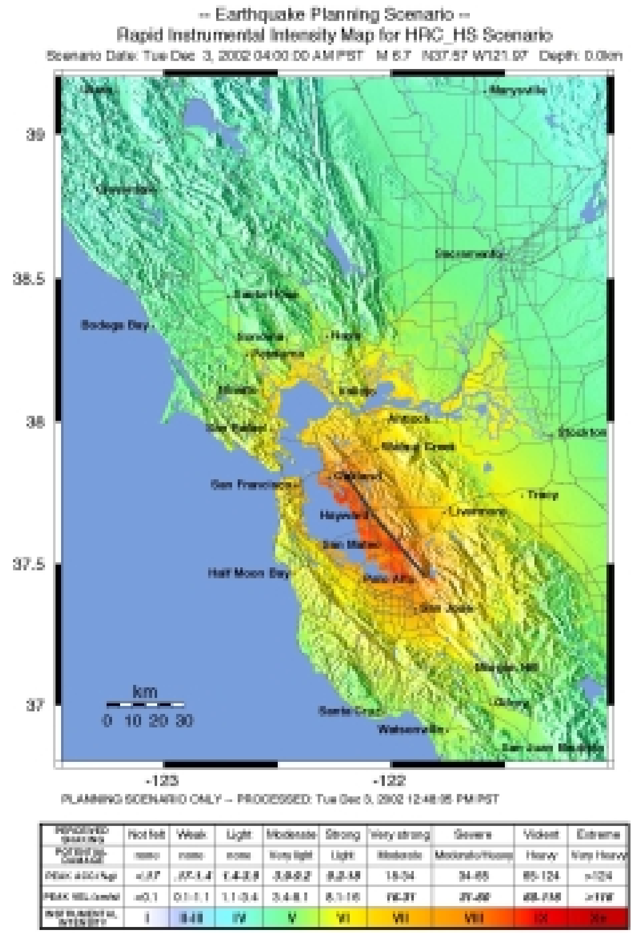

Figure ES.4. Scenario ShakeMap illustrating the strength and regional extent of shaking that can be expected from a future **M**6.7 earthquake on the southern Hayward fault.

The full suite of 35 potential earthquake sources (and their probabilities) have been combined with the likelihood of background earthquakes to produce regional shaking hazard maps (**Figure ES.5**). These shaking hazard maps quantify the expected shaking in terms of modified Mercalli intensity (MMI), a scale that is related to damage. These maps represent average expectations and do not attempt to characterize details of the distribution of ground shaking and damage expected in any individual earthquake. The hazard map shown in **Figure**

ES.5 depicts the MMI shaking level[4] at a given site with a 50% chance of being exceeded in 30 years. This type of information is used as the input into the seismic design criteria in building codes.

Both the scenario shaking intensity maps and regional shaking hazard maps show that future earthquakes, regardless of where they occur in the San Francisco Bay region, are expected to produce damaging ground motions over broad areas and at substantial distances from their locations. Furthermore, the hazard maps show that sites located on rock have even odds in 30 years of experiencing up to MMI VII shaking, which is likely to damage only weak structures. In contrast, most sites on soft soils surrounding San Francisco Bay and the Sacramento River Delta generally have even odds in 30 years of experiencing MMI VIII or stronger shaking, which is expected to cause significant damage in engineered structures.

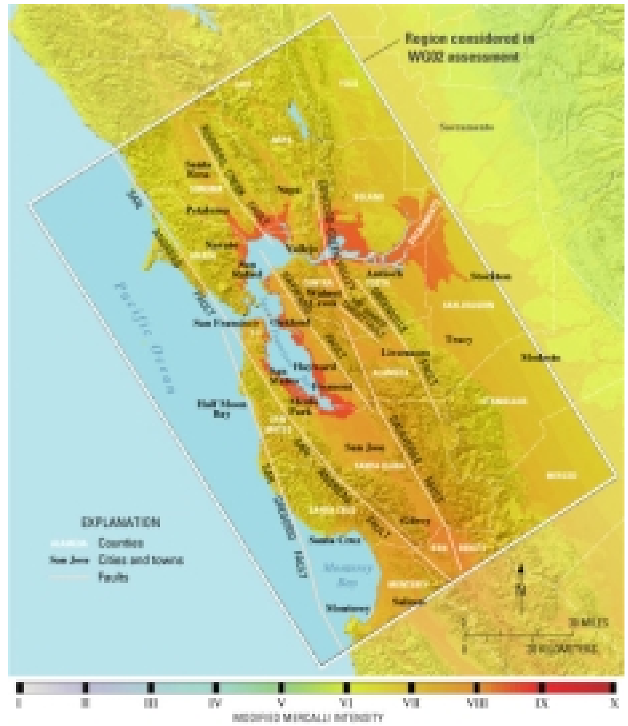

Figure ES.5. Shaking hazard of the SFBR, expressed as the modified Mercalli Intensity (MMI) having even odds of being exceeded in 30 years. Shaking hazard is high throughout the region, and especially pronounced on the soft-soil areas surrounding the bay.

[4] The MMI scale is described and tabulated at http://neic.usgs.gov/neis/general/handouts/mercalli.html.

Working Group Participants and Reviewers

The 1999 and 2002 incarnations of the Working Group on California Earthquake Probabilities solicited the participation and open discussion of the earthquake research community. Participants included scientists from Federal and State governments, private industry, consulting firms, and academia.

Thirteen people were voting members of the **WG02 Overview Group**, which had responsibility for guiding the study and completing this report:

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Norm Abrahamson............................Pacific Gas & Electric
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The following persons also participated in the WG99 and/or WG02 studies:

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