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"A General Evaluation Approach to
Risk-Benefit for Large Technological Systems
and its Application to Nuclear Power"

David Okrent, Project Director

A SURVEY OF EXPERT OPINION ON LOW PROBABILITY EARTHQUAKES

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Any opinions, findings, conclusions
or recommendations expressed in this
publication are those of the author(s)
and do not necessarily reflect the views
of the National Science Foundation.

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PREFACE

This report represents one aspect of a National Science Foundation funded study at UCLA entitled, "A General Evaluation Approach to Risk-Benefit for Large Technological Systems and Its Application to Nuclear Power," (NSF Grant GI-39416). The objectives of this project can be defined to include the following:

1) To make significant strides in the provision of improved bases or criteria for decision-making involving risk to the public health and safety (where a risk involves a combination of a hazard and the probability of that hazard).

2) To make significant strides in the structuring and development of improved, and possibly alternative, general methodologies for assessing risk and risk-benefit for technological systems.

3) To develop improvements in the techniques for the quantitative assessment of risk and benefit.

4) To apply methods of risk and risk-benefit assessment to specific applications in nuclear power (and possibly other technological systems) in order to test methodologies, to uncover needed improvements and gaps in technique, and to provide a partial, selective, independent assessment of the levels of risk arising from nuclear power.

Reports prepared previously under this grant include the following:

1. Mathematical Methods of Probabilistic Safety Analysis, G. E. Apostolakis, UCLA-ENG-7464 (Sept. 1974)
2. Biostatistical Aspects of Risk-Benefit: The Use of Competing Risks Analysis, H. N. Sather, UCLA-ENG-7477 (Sept. 1974)
3. Applying Cost-Benefit Concepts to Projects which Alter Human Mortality, J. Hirshleifer, T. Bergstrom, E. Rappaport, UCLA-ENG-7478 (Nov. 1974)

4. Historical Perspectives on Risk for Large Scale Technological Systems, by W. Baldewicz, G. Haddock, Y. Lee, Prajoto, R. Whitley and V. Denny, UCLA-ENG-7485 (Dec. 1974)

5. A Prediction of the Reliability of the Core Auxiliary Cooling System for a HTGR, K. A. Solomon, D. Okrent and W. E. Kastenberg, UCLA-ENG-7495 (Jan. 1975)

6. Pressure Vessel Integrity and Weld Inspection Procedure, K. A. Solomon, D. Okrent and W. E. Kastenberg, UCLA-ENG-7495 (Jan. 1975)

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INTRODUCTION

Earthquakes pose a potential hazard to the public health and safety and the question of "What is an adequate seismic design basis?" enters into many aspects of society including schools, hospitals, dams, and nuclear power plants. Seismic history is generally much too short to provide an accurate statistical basis for determining low probability earthquakes at each and every potential site (e.g., earthquakes having a probability of occurrence of one in 10^4 per year or one in 10^6 per year). And detailed knowledge of the cause or source of earthquakes, while improving rapidly, is far from complete, particularly for the eastern United States.

As one way of examining the uncertainties in the prediction of low probability earthquakes, a number of experts in the field were invited to review eleven sites within the United States and provide their independent estimates on seismicity. Because a description of local geology and seismicity is provided in the Safety Analysis Report submitted in connection with the application for construction of a nuclear power plant, these reports provided a convenient source of information and eleven such sites were selected around the country.

The seven individuals who participated in the seismic survey are listed in alphabetical order in Table 1. They were each sent the same descriptive material about the eleven sites listed in Table 2, together with a questionnaire (see Table 3). They were free to use any other sources of information they wished but were asked to spend only a week or so of actual work in preparation of their responses. They were free to answer only some of the questions or to skip sites if they wished.

Table 1

PARTICIPANTS IN SURVEY

(in alphabetical, not numerical, order)

Professor Bruce A. Bolt

Department of Geology and Geophysics
University of California, Berkeley

Professor David M. Boore

Department of Geophysics
Stanford University

Professor Nathan M. Newmark

Department of Civil Engineering
University of Illinois at Urbana

Professor Benjamin M. Page

Department of Geology
Stanford University

Professor Stewart W. Smith

Graduate Program in Geophysics
University of Washington, Seattle

Professor George Thompson

Department of Geology
Stanford University

Professor James T. Wilson

Institute of Science and Technology
University of Michigan, Ann Arbor

Table 2

LIST OF SITES

No.	Site Name	(State)
1	Brunswick	(North Carolina)
2	Cooper	(Nebraska)
3	Davis Besse	(Ohio)
4	Diablo Canyon	(California)
5	Grand Gulf	(Mississippi)
6	Pilgrim	(Massachusetts)
7	Rancho Seco	(California)
8	River Bend	(Louisiana)
9	Summer	(South Carolina)
10	Summit	(Delaware)
11	Trojan	(Oregon)

Table 3

SITE QUESTIONNAIRE[†]

1. Name of Site.

2. What are the probabilities of occurrence per year (or recurrence interval) of a free field earthquake at foundation level?

   a)

MM Intensity	Probability/Year	Uncertainty
V		
VI		
VII		
VIII		
IX		
X		
XI		
XII		

   b)

Peak Horizontal Ground Acceleration	Probability/Year	Uncertainty
0.05 g*		
0.10 g		
0.15 g		
0.20 g		
0.25 g		
0.30 g		
0.40 g		
0.50 g		
0.60 g		
0.80 g		
1.0 g		
> 1.1 g		

3. a) What is the dominant frequency band of the earthquake having a probability of one in 10^6/year that produces the largest vibratory effects at the site?

   b) What is the probable duration of that frequency band?

4. What relation between MM intensity and ground acceleration would you suggest or have you used for this site?

5. Was the presence of a nearby fault dominant in your evaluation of the site? Comment.

6. Was a particular tectonic structure or province significant in your evaluation of the site? Comment.

7. Was seismic history significant or dominant in your evaluation of the site? Comment.

8. Are your lower probability earthquakes (e.g., one in 10^6/year) determined by the geology and seismic activity of the region or by other considerations? Comment.

9. What ratio of peak vertical to peak horizontal acceleration would you estimate to be applicable (with what uncertainty)?

10. What information not included in the site geologic and seismic description was important to your evaluation?

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*For example, 0.05 g could be taken as representing the interval 0.025 g < a < 0.075 g.

†Some participants will choose to omit some categories (or even some sites) in their responses.

The original groundrules were that the results would be made public but not directly attributed to the individual participants (or respondents).

The results for each site have been grouped into a few tables, followed by a summary of the bases presented by each respondent and a brief summary by the editor (called the reviewer).

Following the results for all eleven sites are some brief sections which summarize the correlations employed between intensity and peak acceleration, and the estimates of uncertainty.

In the presentation of results each respondent has been assigned a number which is used throughout. The numbers do not coincide with the alphabetical order.

BRUNSWICK is near the town of Southport, North Carolina, approximately 25 miles south of Wilmington in Brunswick County.

COOPER is located in Washington County, Nebraska, adjacent to and south and west of a meander of the Missouri River. The site is approximately 2 1/2 river miles below the Chicago and Northwestern Railroad Bridge at Blair, Nebraska and about 15 miles northwest of Omaha, Nebraska.

DAVIS BESSE is situated on low flat land bordering Lake Erie, roughly equidistant from Toledo and Sandusky, Ohio.

DIABLO CANYON is located in San Luis Obispo County approximately 190 miles south of San Francisco. It is adjacent to the Pacific Ocean, 12 miles west-southwest of the city of San Luis Obispo.

GRAND GULF is located in Claiborne County in southwestern Mississippi. It is on the east side of the Mississippi River about 25 miles south of Vicksburg.

PILGRIM is on the western shore of Cape Cod Bay in the town of Plymouth, Plymouth County, Massachusetts.

RANCHO SECO is on the eastern side of the Sacramento Valley, about 25 miles southeast of Sacramento, two miles east of Clay, California.

RIVER BEND is located in West Feliciana Parish on the east bank of the Mississippi River, approximately 24 miles north-northwest of Baton Rouge, Louisiana.

SUMMER is in Fairfield County, South Carolina about 25 miles northwest of Columbia, South Carolina and about 3 miles northeast of Parr.

SUMMIT is located just south of the Chesapeake and Delaware Canal about fifteen miles south southwest of Wilmington, Delaware.

TROJAN is in northwest Oregon on the Columbia River 31 air miles (north) from Portland, Oregon and about six miles from Kelso-Longview.

BRUNSWICK

Respondent No.	1	2*	3	4	5	6	7
MM Intensity			Probability per Year				
V	10^{-2}		10^{-2}	7×10^{-2}			10^{-2}
VI	10^{-2}		10^{-4}	10^{-2}	5×10^{-3}		10^{-3}
VII	10^{-3}		10^{-6}	10^{-3}	3×10^{-3}		10^{-5}
VIII	10^{-5}			5×10^{-7}	10^{-3}	10^{-6}	10^{-6}
IX	10^{-7}				10^{-4}		10^{-7}
X	10^{-8}				10^{-5}		10^{-8}
XI	10^{-8}				10^{-6}		$<10^{-8}$
XII	10^{-8}						$<10^{-8}$
Peak Horizontal Acceleration			Probability per Year				
.05G	10^{-2}		10^{-4}	8×10^{-3}			10^{-2}
.1g	10^{-3}		10^{-5}	2×10^{-3}			10^{-3}
.15g	10^{-4}		10^{-6}	3×10^{-4}			10^{-5}
.2g	10^{-5}	$<3\times10^{-5}$		6×10^{-5}	2×10^{-3}	10^{-6}	10^{-5}
.25g	3×10^{-6}			6×10^{-6}	10^{-3}		10^{-6}
.3g	10^{-6}			8×10^{-7}	5×10^{-4}		10^{-6}
.4g	4×10^{-7}	$<2\times10^{-5}$					10^{-7}
.5g	10^{-7}				10^{-4}		10^{-7}
.6g	3×10^{-8}	$<10^{-5}$					10^{-7}
.8g	10^{-8}	$<7\times10^{-6}$					10^{-7}
1.0g	10^{-8}	$<3\times10^{-6}$			10^{-5}		10^{-8}
>1.1g	10^{-8}				10^{-6}		10^{-8}
Dominant Frequency and Duration for 10^{-6}/year Earthquake							
Cycles/sec	2		1–2	2–5		1/3–10	
Seconds	10		5	15		20	

*Probabilities per year are for accelerations greater than the size indicated.

BRUNSWICK

COMMENTARY

Respondent #1

The 10^{-6}/year earthquake is based on seismic history. The Newark-Wilmington area was active with a maximum MMVII event in 1871. An intensity VII event is possible close to this site.

The relationship between intensity and acceleration is controlled by the fact this is a relatively soft site.

Respondent #2

It is apparent from the seismicity map that the site in question is removed from the clusters of larger earthquakes. In a 300-mile circle around both Summer and Brunswick the recurrence relations are quite similar but the spatial location of events with respect to the sites is different. The probabilities should be less at Brunswick than for Summer; how much less will not be quantified.

Respondent #3

Low tectonic straining now of the Atlantic Coastal Plain is significant and the 1886 Charleston earthquake must be compared with other known seismicity back 200 years. The 10^{-6}/year earthquake is determined mainly by correlations between this type of geology and seismic activity around the world, although the Charleston earthquake was a dominant consideration. Some extra caution was used in deciding peak acceleration level due to lack of observational base of seismic wave behavior on East Coast.

Respondent #4

Brunswick and Pilgrim end up having similar evaluation. For each an MMVI-MMVII has an estimated return period of 200 years, while an MMVIII has an estimated return period of 2×10^6 years.

Respondent #5

The Charleston earthquakes have an overriding influence. Pending resolution of their origin, it is proposed that they were generated at an ancient continental margin rift zone which, at rare intervals, undergoes sudden adjustment as the border of the continent continues to rise.

Respondent #6

Seismic history was important, as influenced by the Charleston shock. Considerations of world-wide seismicity also influenced judgment. In areas of low seismicity probabilities as low as 10^{-6}/year are very speculative.

Respondent #7

The coastal plain province is plainly quiet except for the Charleston anomaly. The Triassic faults without later movements (> 200 million years) serve as a useful limiting reference. Considerations of geology and seismic history are used in estimating lower probability earthquakes.

Reviewer

The MM intensity having a probability of 10^{-4}/year varies from VI to IX among the respondents with a median of about VII. The 10^{-6}/year intensity varies from VII to XI with a median between VIII and IX. The acceleration having a probability of 10^{-4}/year varies from 0.05g to 0.5g with a median of about 0.15g. The acceleration having a probability of 10^{-6}/year varies from 0.15g to about 1g with a median of about 0.3g.

The respondent with the larger probabilities of large accelerations has postulated the possibility that the Charleston earthquake may arise at an ancient continental margin rift zone and may, with low probability, appear elsewhere along the coast.

Respondent #2 has generally low probabilities for accelerations, but the probabilities (derived at the Summer site) fall off very slowly with increasing "g" value. Respondents #4 and #7 have a generally similar character in their estimates of "g" values, but the intensities are less similar. Respondent #3 included some additional conservatism in his g value estimates, but nevertheless predicted the lowest "g" values.

Of the three respondents (#1, 4, and 5) giving the largest "g" values, only one specifically attributed the estimate to the possibility of a "Charleston-type" earthquake near the site.

Respondent No.	1	2*	3	4	5	6	7
MM Intensity				Probability per Year			
V	10^{-2}			10^{-1}	10^{-2}		10^{-3}
VI	10^{-3}		10^{-2}	3×10^{-2}	5×10^{-3}		10^{-5}
VII	10^{-4}		10^{-6}	5×10^{-3}	2×10^{-3}	10^{-6}	10^{-7}
VIII	10^{-6}			5×10^{-5}	10^{-4}		10^{-8}
IX	10^{-8}			5×10^{-9}	10^{-6}		$<10^{-8}$
X	10^{-8}						$<10^{-8}$
XI	10^{-8}						$<10^{-8}$
XII	10^{-8}						$<10^{-8}$
Peak Horizontal Acceleration				Probability per Year			
.05g	10^{-2}		10^{-3}	2×10^{-2}	5×10^{-3}		10^{-3}
.1g	10^{-3}	10^{-4}	10^{-6}	4×10^{-3}			10^{-5}
.15g	10^{-4}			10^{-3}	2×10^{-3}	10^{-6}	10^{-5}
.2g	10^{-5}	6×10^{-5}		4×10^{-4}	5×10^{-4}		10^{-6}
.25g	3×10^{-6}			10^{-4}	1×10^{-4}		10^{-7}
.3g	10^{-6}			4×10^{-5}			10^{-7}
.4g	4×10^{-7}	4×10^{-5}		8×10^{-7}			10^{-7}
.5g	10^{-7}				10^{-6}		10^{-8}
.6g	3×10^{-8}	2×10^{-5}					10^{-8}
.8g	10^{-8}	10^{-5}					$<10^{-8}$
1.0g	10^{-8}	$<3\times10^{-6}$					$<10^{-8}$
>1.1g	10^{-8}						$<10^{-8}$
				Dominant Frequency and Duration for 10^{-6}/year Earthquake			
Cycles/sec	3	3–5	2–5	2–5		1/3–10	
Seconds	5		3–5	15		20	

*Probabilities per year are for accelerations greater than the size indicated.

COOPER

COMMENTARY

Respondent #1

The presence of the Humbolt fault and La Platte fault and the apparently unassociated earthquake at 40 miles, together with the general lack of subsurface control, leads to the postulation of a maximum VII event close to the site.

Respondent #2

A recurrence relation based on historic seismicity was used in combination with attenuation relations (particularly Nuttli's) for peak motions. The site appears to be within a band of historic earthquakes, and thus the recurrence relation could be applied. The recurrence relation was extrapolated to large magnitudes, which introduces an associated uncertainty which may become enormous.

Respondent #3

The site is on a flood plain with no fault within 160 km with displacement in recent times. The region is generally inactive with some recovery glaciation. A trend of epicenters to the west provides parameters for attenuation and duration of shaking. Analogy with similar tectonic regions of low seismic activity is used to determine the 10^{-6}/year earthquake. It is very unlikely, on geologic evidence, that intensity VII would be exceeded at site.

Respondent #4

This site is estimated to be similar to Summit and Summer in that an MMVII has an estimated return period of about 200 years, while an MMVIII has an estimated return period of 2×10^4 years.

Tectonic structure or province is significant as it influences the possibility of moving previous earthquakes closer to the site. Seismic history was taken into account as much as possible in defining the return period for an index earthquake, usually taken as 200 years. The lower probability earthquakes were determined not only by the geology and seismology of the region, but by the maximum earthquake that had occurred near the site, taking into account that an earthquake of intensity about two levels higher than previously felt might be achieved.

Respondent #5

The Nemaha arch, extending north from Kansas (in the subsurface) is locally bounded by faults which seem to produce small (to moderate?) earthquakes. Until more is known about the potential of this structure, it should be regarded with suspicion.

History is significant for this site. Earthquakes of MMIV-VII have occurred through the years, sparsely sprinkled all over the province. Many are without relationship to known faults. The few faults which have been mapped are buried and are presumed to be "dead," but minor activations may occur.

Respondent #6

Tectonic structure in relation to relevant earthquakes is not clear. One consideration may be that it is near the Charleston-New Madrid small circle. The seismic history and the general geologic stability were of particular importance in estimating the 10^{-6}/year earthquake.

Respondent #7

The La Platte fault was a serious consideration, but its cumulative seismic moment over a very long time span indicates a small rate of seismic energy release. The interior, cratonic structure and the midcontinent gravity structure, quiescent since Pre-Cambrian, are significant considerations, as are the large distance to New Madrid and the history of only small earthquakes nearby.

Reviewer

The MM intensity having a probability of 10^{-4}/year varies from a V-VI to an VIII with a median of VII. The 10^{-6}/year intensity ranges from a VI-VII to a IX, with a median of about high VII. The acceleration having a probability of 10^{-4}/year varies from about 0.07g to about 0.26g with an average of 0.15g. The acceleration having a probability of 10^{-6}/year ranges from 0.1g to about 1g with a median of 0.3g.

The rate at which probability decreased with increasing acceleration varied widely among the respondents. Respondent #2 estimated a fairly low probability for 0.1g but only an order of magnitude lower probability for 0.5 or 0.8g. Other respondents estimated a change in probability which ranged from two to five orders of magnitude.

There does not appear to be a similar, identifiable correlation of dominant factors in judgment, either among those estimating a lesser seismicity or a greater seismicity.

DAVIS BESSE

Respondent No.	1	2*	3	4	5	6	7
MM Intensity			Probability per Year				
V	10^{-1}		10^{-2}	7×10^{-2}	10^{-2}		10^{-2}
VI	10^{-2}		10^{-3}	10^{-2}	5×10^{-3}		10^{-4}
VII	10^{-2}		10^{-6}	10^{-3}	10^{-3}	10^{-6} (VII–VIII)	10^{-6}
VIII	10^{-3}			5×10^{-7}	10^{-5}		10^{-7}
IX	10^{-5}				10^{-6}		10^{-8}
X	10^{-6}						$<10^{-8}$
XI	10^{-8}						$<10^{-8}$
XII	10^{-8}						$<10^{-8}$

Peak Horizontal Acceleration	1	2*	3	4	5	6	7
			Probability per Year				
.05g	10^{-1}		10^{-5}	8×10^{-3}	5×10^{-3}		10^{-2}
.1g	10^{-1}	10^{-4}	10^{-6}	2×10^{-3}			10^{-4}
.15g	10^{-1}			3×10^{-4}	10^{-3}	10^{-6}	10^{-5}
.2g	10^{-1}	8×10^{-5}		6×10^{-5}			10^{-6}
.25g	10^{-2}			6×10^{-6}	10^{-5}		10^{-6}
.3g	10^{-2}			8×10^{-7}			10^{-7}
.4g	10^{-3}	5×10^{-5}					10^{-7}
.5g	10^{-5}				10^{-6}		10^{-8}
.6g	10^{-6}	3×10^{-5}					$<10^{-8}$
.8g	10^{-7}	2×10^{-5}					$<10^{-8}$
1.0g	10^{-8}	1×10^{-5}					$<10^{-8}$
>1.1g	10^{-8}						$<10^{-8}$

Dominant Frequency and Duration for 10^{-6}/year Earthquake

	1	2*	3	4	5	6	7
Cycles/sec	2	1-3	1-3	2-15		1/3-10	
Seconds	10	5	5	15		<20	

*Probabilities per year are for accelerations greater than the size indicated.

DAVIS BESSE

COMMENTARY

Respondent #1

The presence of the St. Lawrence seismic trend and the Bowling Green fault at a distance of 35 miles were dominant considerations. It is a "soft" site. The maximum credible earthquake within 200 miles is an MMIX with a recurrence time of 200 years.

Respondent #2

The earthquakes near Anna, Ohio were the dominant factors in assigning probabilities. Nutti's relation between MM intensity and magnitude was used. The earthquakes in the New Madrid area were not a controlling factor.

Respondent #3

Minor earthquake sources would be over 100 km away on average. The Bowling Green fault (50 km away) has not moved since Paleozoic. Properties of Lake Plains intra-plate region are particularly significant in assessment. The scattered nature of minor shallow seismicity without surface faulting denotes low risk.

Deposits, fill and sediments over Pre-Cambrian suggest some local amplification of small wave amplitudes propagating freely in the Pre-Cambrian basement.

Respondent #4

Davis Besse appears to be similar to Grand Gulf and River Bend in that an MMVI has an estimated return period of 200 years, while an MMVII has an estimated return period of 2×10^4 years.

Respondent #5

The province contains one or two seismic areas which are unexplained. Pending further knowledge, similar areas might be expected to become evident anywhere in the province. However, the earthquakes of the seismic areas are not large. Seismic history of interest includes the Anna earthquakes and several others of MMV-VI a few tens of miles from the site. Also, no surface faulting is indicated in the Quaternary deposits of the province.

Respondent #6

The possibility of the St. Lawrence-New Madrid trend being real was considered. The structures producing the relatively weak shocks in the area are not certain. Seismic history was significant in estimating the 10^{-6}/year earthquake.

Respondent #7

The tectonic province is one of general stability, assuming no tectonic continuity between New Madrid and the St. Lawrence Valley. Seismic history was significant both in evaluating the probability of small shocks and as a check on the tectonics for larger shocks.

Reviewer

The MM intensity having a probability of 10^{-4}/year varies from MMVI to MMVIII-IX with a median of about VII plus. The 10^{-6}/year intensity varies from MMVII to X with a median of about VIII. The acceleration having a probability of 10^{-4}/year varies from <.05g to 0.45g, with a median of about 0.1g. The 10^{-6}/year acceleration varies from 0.10g to 1g with a median of about 0.3g.

Several respondents mention the St. Lawrence or St. Lawrence-New Madrid seismic trend. Together with the Bowling Green fault, this seems to have influenced respondent #1 toward larger earthquakes of larger probability, but not the others. Respondent #3 finds it a very quiescent region, respondents #6 and #7 only slightly less so. Respondents #2 and #5 suggest a much more gradual fall-off of probability per year with increasing acceleration than the others.

DIABLO CANYON

Respondent No.	1	2*	3	4	5	6	7
MM Intensity		Probability per Year					
V				10^{-1}			10^{-1}
VI			10^{-1}	4×10^{-2}	10^{-6}		10^{-1}
VII			10^{-2}	2×10^{-2}	5×10^{-3}		10^{-2}
VIII			10^{-3}	5×10^{-3}	3×10^{-3}		10^{-3}
IX			10^{-5}	10^{-4}	10^{-4}		10^{-6}
X			10^{-6}	10^{-5}	2×10^{-6}		10^{-7}
XI				2×10^{-6}	10^{-6}		$<10^{-7}$
XII							$<10^{-7}$
Peak Horizontal Acceleration		Probability per Year					
.05g		5×10^{-3}	10^{-2}	4×10^{-2}			10^{-1}
.1g		2×10^{-3}	10^{-3}	2×10^{-2}	10^{-2}		10^{-1}
.15g			10^{-3}	7×10^{-3}	5×10^{-3}		10^{-2}
.20g		1×10^{-3}	10^{-3}	3×10^{-3}	3×10^{-3}		10^{-2}
.25g			10^{-3}	2×10^{-3}	3×10^{-3}		10^{-3}
.3g			10^{-4}	10^{-3}	10^{-3}		10^{-3}
.4g		6×10^{-4}	10^{-4}	3×10^{-4}	2×10^{-4}		10^{-5}
.5g			10^{-6}	7×10^{-5}	10^{-4}		10^{-6}
.6g		3×10^{-4}		10^{-6}	2×10^{-5}		10^{-7}
.8g		2×10^{-4}		10^{-8}	10^{-5}		$<10^{-7}$
1.0g		10^{-5}			2×10^{-6}		$<10^{-7}$
>1.1g					10^{-6}		$<10^{-7}$
Dominant Frequency and Duration for 10^{-6}/year Earthquake							
Cycles/sec		5	5-8	2-5			
Seconds			17	15			

*Probabilities per year are for accelerations greater than the size indicated.

DIABLO CANYON

COMMENTARY

Respondent #2

The Nacimiento fault and the offshore fault were more important than the San Andreas fault in determining the larger ground motions. The "offshore structural zone" was crucial. From the little geologic information available, along with earthquake epicenters and analogy to onshore fault systems, it appeared that the offshore structural zone is comparable to the Nacimiento fault. Lacking detailed evidence to the contrary, the zone was treated as being active over a length of 120 km, with the closest approach of the zone to the site being 5-8 km. This close distance makes the offshore zone very important, in spite of the apparent low seismicity (assumed to be over 10 times less active than the Nacimiento zone).

A standard $\log N = a - bM$ equation was determined for seismicity along the Nacimiento and offshore faults. Such an equation does not seem to work locally on the San Andreas. Instead, a magnitude 8-1/2 event (similar to the 1857 earthquake) was assumed to occur every 200 years, and magnitude 6-7 events were assumed, on the basis of past experience, to occur every 30 years in the Parkfield region.

Respondent #3

Both the San Andreas and Nacimiento systems have recent and/or Quaternary movements. The largest vibratory effects are generally derived from an 8.5 magnitude earthquake on the San Andreas; however, the MMX is arrived at from considerations of an unlikely magnitude 7+ earthquake on the nearby Nacimiento fault system.

Respondent #4

Diablo Canyon received its greatest acceleration from a major earthquake on the San Andreas fault.

Respondent #5

The offshore fault zone which passes within approximately four miles of the site dominated the evaluation. The landward continuation of the zone, near San Simeon, appears to displace Late Pleistocene marine terraces.

It is also significant that fairly strong earthquakes have occurred west of the San Andreas fault zone, and a few of these (albeit the locations are inaccurate) may well have originated in the offshore fault zone.

Respondent #7

The Nacimiento and San Andreas faults are dominant. The active San Andreas system and the evidence of late Cenozoic quiescence in or near the site are critical in the evaluation.

Reviewer

The MM intensity having a probability of 10^{-4}/year falls between VIII plus and IX for the four respondents. The 10^{-6}/year intensity varies between IX and XI plus. The acceleration having a probability of 10^{-4}/year varies from 0.35g to more than 0.8g with a median of about 0.5g. The 10^{-6}/year acceleration varies from 0.5g to >1.1g with a rough average of 3/4 g.

The respondents clearly differ in their assessment of the significance of the "offshore structural zone," and to some extent with regard to the relative importance of the Nacimiento and San Andreas faults.

GRAND GULF

Respondent No.	1	2*	3	4	5	6	7
MM Intensity			Probability per Year				
V	10^{-2}			2×10^{-2}	5×10^{-3}		10^{-2}
VI	3×10^{-3}		10^{-3}	5×10^{-3}	3×10^{-3}		10^{-4}
VII	10^{-3}		10^{-5}	5×10^{-5}	10^{-3}		10^{-6}
VIII	3×10^{-5}		10^{-6}	5×10^{-8}	10^{-5}		10^{-7}
IX	10^{-6}				10^{-6}		10^{-8}
X	10^{-7}						$<10^{-8}$
XI	10^{-8}						$<10^{-8}$
XII	10^{-8}						$<10^{-8}$
Peak Horizontal Acceleration			Probability per Year				
.05g	10^{-2}	2×10^{-4}	10^{-3}	4×10^{-3}	3×10^{-3}		10^{-2}
.1g	10^{-3}	2×10^{-5}	10^{-4}	4×10^{-4}			10^{-4}
.15g	10^{-4}		10^{-6}	4×10^{-5}	10^{-3}		10^{-5}
.2g	10^{-5}		10^{-6}	10^{-6}	10^{-4}		10^{-6}
.25g	10^{-6}		10^{-6}	6×10^{-8}	10^{-5}		10^{-6}
.3g	5×10^{-7}						10^{-7}
.4g	10^{-7}						10^{-7}
.5g	5×10^{-8}				10^{-6}		10^{-7}
.6g	3×10^{-8}						10^{-8}
.8g	10^{-8}						$<10^{-8}$
1.0g	10^{-8}						$<10^{-8}$
>1.1g	10^{-8}						$<10^{-8}$
Dominant Frequency and Duration for 10^{-6}/year Earthquake							
Cycles/sec	1		1-2	1-3			
Seconds	15			20			

*Probabilities per year are for accelerations greater than the size indicated.

GRAND GULF

COMMENTARY

Respondent #1

The province approach was used, with geology the determining factor in estimating lower probability earthquakes. The low frequency event on the Baton Rouge zone provides controlling ground acceleration.

Respondent #2

The earthquakes at the southern end of the Mississippi Valley earthquake region control the probabilities assigned. The almost complete lack of historical seismicity within 100 miles of the site makes it very difficult to assign probabilities for the large ground motions. To be conservative one should probably apply the recurrence relations for the Mississippi Valley region to the area near the site.

Respondent #3

The region is essentially aseismic. The southern limit to the "New Madrid zone" is somewhat hazy. This leads to more caution than may be needed if tectonics were better mapped. Again, the cause of intra-plate earthquake is not well understood.

Respondent #4

Grand Gulf is similar to River Bend and Davis Besse in that an MMVI has an estimated return period of 200 years, while an MMVII has a return period of 2×10^4 years.

Respondent #5

The New Madrid zone, with possible extension as far south as Memphis, was dominant in the evaluation. Seismic history was significant for small earthquakes and also as a means of estimating site response to "New Madrid" earthquakes.

Respondent #7

The New Madrid fault zone dominated the evaluation. The tectonics of the New Madrid region and the subdued structural activity of the Mississippi embayment and Gulf Coast are the most important factors. Cumulative seismic moment and geological time span of faulting in the New Madrid region can be estimated and gives a maximum probability for the largest earthquakes, assuming post activity continues unchanged in the future.

Seismic history is dominant in evaluating the numerous, random, small earthquakes, and reinforces the tectonics for larger earthquakes.

Reviewer

The MM intensity having a probability of 10^{-4}/year varies from VI to VII-VIII among the respondents with a median of about VII. The 10^{-6}/year intensity ranges from an MMVII to an MMIX with a median of MMVIII. The acceleration having a probability of 10^{-4}/year varies from about 0.07g to about 0.2g with a median of less than 0.15g, while the 10^{-6}/year acceleration varies from 0.15g to 0.5g.

Several respondees identified the New Madrid zone as the controlling tectonic feature. None "moved" it near the site, though respondent #2 mentioned the possibility.

Respondent No.	1	2*	3	4	5	6	7
MM Intensity			Probability per Year				
V	10^{-3}		10^{-2}	7×10^{-2}			10^{-2}
VI	10^{-4}		10^{-4}	10^{-2}	5×10^{-3}		10^{-3}
VII	3×10^{-5}		10^{-6}	10^{-3}	3×10^{-3}		10^{-6}
VIII	10^{-5}		10^{-6}	5×10^{-7}	2×10^{-3}	10^{-6}	10^{-7}
IX	10^{-7}				10^{-3}		10^{-8}
X	2×10^{-8}				10^{-5}		$<10^{-8}$
XI	10^{-8}				10^{-6}		$<10^{-8}$
XII	10^{-8}						$<10^{-8}$
Peak Horizontal Acceleration			Probability per Year				
.05g	10^{-1}		10^{-4}	8×10^{-3}	5×10^{-3}		10^{-2}
.1g	10^{-2}		10^{-6}	2×10^{-3}			10^{-3}
.15g	10^{-3}			3×10^{-4}	3×10^{-3}		10^{-4}
.2g	10^{-4}	2×10^{-4}		6×10^{-5}			10^{-6}
.25g	10^{-5}			6×10^{-6}	2×10^{-3}	10^{-6}	10^{-6}
.3g	4×10^{-6}			8×10^{-7}			10^{-7}
.4g	3×10^{-7}	1×10^{-4}					10^{-7}
.5g	10^{-7}				10^{-3}		10^{-8}
.6g	2×10^{-8}	8×10^{-5}			3×10^{-4}		$<10^{-8}$
.8g	10^{-8}	4×10^{-5}			10^{-4}		$<10^{-8}$
1.0g	10^{-8}	2×10^{-5}			10^{-5}		$<10^{-8}$
>1.1g	10^{-8}				10^{-6}		$<10^{-8}$
Dominant Frequency and Duration for 10^{-6}/year Earthquake							
Cycles/sec	3	5	2-5	2-15		1/3-10	
Seconds	25		5-10	15		20-30	

*Probabilities per year are for accelerations greater than the size indicated.

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PILGRIM

COMMENTARY

Respondent #1

The basis for judgement is the occurrence of an intensity VIII at 50 miles and the relatively low rate of current seismicity. The Boston-Ottawa zone is an interesting hypothesis but cannot be used for firm engineering estimates. As a result, the conclusion is drawn that an intensity VIII at the site is possible, although not very probable.

Site conditions are such that high frequency ground motion would not be significantly attenuated and intermediate frequencies would be amplified.

Respondent #2

The spatial grouping of past earthquakes seems to indicate that the Pilgrim site is in the midst of a zone in which the occurrence of an earthquake is equally likely at any point. Thus, the recurrence relation giving number of earthquakes in a given magnitude class per year per km^2 can be applied directly at the site. The seismic history in the area was used to derive the recurrence relation. The assumption of equal likelihood for spatial location may seem at odds with the dense clustering north of Boston near Cape Ann. Without a well-defined tectonic reason for this clustering, however, the possibility must be admitted that the dense seismicity near Cape Ann could just as well be in the Plymouth region. Furthermore, in spite of the concentration near Cape Ann, the seismicity is diffuse enough to the south to justify the assumption of equal spatial probability.

Respondent #3

There are three likely sites of a source for the larger, low probability earthquake. A magnitude 6+ (like the 1755 shock) about 80 km NE of site would represent one possibility.

There remains considerable uncertainty concerning the form and reason for tectonic deformation in this region, e.g., the St. Lawrence Valley.

Respondent #4

Pilgrim and Brunswick appear to be similar in that an MMVI-VII has an estimated return period of 200 years, while an MMVIII has an estimated return period of 2×10^6 years.

Respondent #5

Faults which bound Triassic grabens occur in this province, and recent geophysical work suggests their presence underwater NE of Boston. Also, the Kelvin seamount chain "comes ashore" near Boston.

The seismic history is very significant. It suggests that old faults have been reactivated.

Respondent #6

The possible Cape Ann-Ottawa alignment is particularly significant to the evaluation. The long seismic history, and particularly the history along the Cape Ann trend, heavily influence the choice of an MMVIII rather than a VII.

Respondent #7

The tectonic province is one of stability modified by interior-plate and post-glacial stresses that seem to generate small earthquakes on old faults.

Seismic history and the alignment of historical earthquakes is a major consideration in the evaluation.

Reviewer

The MM intensity having a probability of 10^{-4}/year varies from VI to IX-X, with a median of about VII. The 10^{-6}/year intensity varies from MMVII to XI with a median of VIII. The acceleration having a probability of 10^{-4}/year varies from 0.05 to 0.8g with a median of almost 0.2g. The 10^{-6}/year acceleration varies from 0.1g to 1g with a median of 0.25g.

The respondents differ markedly in their bases. Respondents 6 and 7 are influenced by historical alignment; respondent 1 discounts the Boston-Ottawa zone; and respondent 2 chooses an equal probability per unit area despite the cluster north of Boston. Respondents 1 and 7 have a large fall-off in probability with increasing acceleration, while respondents 2 and 5 propose a much flatter behavior.

RANCHO SECO

Respondent No.	1	2*	3	4	5	6	7
MM Intensity			Probability per Year				
V	10^{-1}		10^{-2}	3×10^{-1}	2×10^{-1}		10^{-1}
VI	3×10^{-2}		10^{-3}	7×10^{-2}	4×10^{-2}		10^{-1}
VII	10^{-2}		10^{-5}	10^{-2}	3×10^{-3}	10^{-6} (VII–VIII)	10^{-4}
VIII	2×10^{-4}		10^{-6}	10^{-4}	10^{-4}		10^{-6}
IX	2×10^{-7}		10^{-6}	10^{-8}	10^{-5}		10^{-7}
X	5×10^{-8}				10^{-6}		10^{-8}
XI	10^{-8}						10^{-8}
XII	10^{-8}						10^{-8}
Peak Horizontal Acceleration			Probability per Year				
.05g	10^{-1}	6×10^{-3}	10^{-2}	3×10^{-2}	2×10^{-1}		10^{-1}
.1g	5×10^{-2}	2×10^{-3}	10^{-3}	7×10^{-3}	4×10^{-1}		10^{-1}
.15g	10^{-2}		10^{-3}	3×10^{-3}	3×10^{-3}	10^{-6}	10^{-3}
.2g	2×10^{-3}	10^{-4}	10^{-4}	8×10^{-4}	10^{-3}		10^{-4}
.25g	2×10^{-4}		10^{-6}	3×10^{-4}	10^{-4}		10^{-5}
.3g	2×10^{-5}			8×10^{-5}	5×10^{-5}		10^{-6}
.4g	10^{-6}	3×10^{-5}		2×10^{-8}	2×10^{-5}		10^{-6}
.5g	2×10^{-7}				10^{-5}		10^{-7}
.6g	5×10^{-8}	10^{-5}			5×10^{-6}		10^{-7}
.8g	10^{-8}				2×10^{-6}		$<10^{-7}$
1.0g	10^{-8}				10^{-6}		$<10^{-7}$
>1.1g	10^{-8}						$<10^{-7}$
Dominant Frequency and Duration for 10^{-6}/year Earthquake							
Cycles/sec	1		2-5	2-15		1/6-10	
Seconds	25		16-20	15		50	

*Probabilities per year are for accelerations greater than the size indicated.

RANCHO SECO

COMMENTARY

Respondent #1

The basis for judgment is the occurrence of the 1892 earthquake in the Sacramento Valley (IX, Winters) which would probably have caused an intensity VIII at the site had it occurred nearby. The current state of knowledge leads to the belief that a repeat of this earthquake at a place nearer to Sacramento is not out of the question.

Site conditions are such that high frequency motion would be significantly attenuated whereas long period motion might be significantly amplified.

Respondent #2

The seismic history indicates that no felt earthquakes have occurred near the site. In this sense the site appears to be truly aseismic, and the seismic shaking is due to earthquakes near the Bay area, the west side of the Sacramento Valley, Truckee and Nevada. Since these areas are all at some distance from the site, the ground motions at the site from even a large earthquake at these places should be small.

The lower probability events are based on an arbitrary extrapolation of the ground motion probability curves. It is assumed that the earthquakes giving the larger ground motions must be closer to the site than the known earthquake generating areas. This is a big assumption, and for this reason very little faith should be given to probabilities for accelerations greater than 0.1g.

Respondent #3

Seismicity was probably dominant in the evaluation. The role of a fault is subject to some concern over the lack of known substantial faulting on the west side of Great Valley in the 1892 Winters earthquake. The general tectonic trends in central California are rather well known.

Respondent #4

Rancho Seco and Trojan are similar in that an MMVII has an estimated return period of 100 years for each, while an MMVIII has an estimated return period of 10^4 years.

Respondent #5

The tectonic province is significant in the evaluation. It does have faults and earthquakes but lacks definitive surface faulting in the vicinity of the site. History is important, especially for judging incidence and intensities of earthquakes from distant sources.

Respondent #6

The probability of the site being shaken by shocks at distances like 100 miles is high, at least 10^{-2}/year. The MM intensity of these will be V to VI but the motion will be at low frequency and may have appreciable amplitude, even though the acceleration is low (San Andreas, Owen's Valley, Haywards, or Nevada area faults).

The probability of high acceleration shocks of local origin is less predictable. Statistics are inadequate, but one can argue that the well known active faults 50 miles and more away are taking up the strain release.

Respondent #7

The tectonic setting is very important, as the east side of the Sacramento Valley is comparatively stable (and geologically so for a long time) and it is distant from both the Coast Range and Great Basin seismic zones.

Reviewer

The MM intensity having a probability of 10^{-4}/year varies from VI-VII to VIII plus. The 10^{-6}/year intensity varies from VII-VIII to X with a median of VIII plus. The acceleration having a probability of 10^{-4}/year varies from less than 0.15 to less than 0.3g, while the 10^{-6}/year acceleration ranges from 0.15 to 1g with a median of about o.4g.

The spread in prediction of 10^{-6}/year acceleration is particularly large, but no specific tectonic features have been identified which could provide a ready base for these differences in judgment.

RIVER BEND

Respondent No.	1	2*	3	4	5	6	7
MM Intensity			**Probability per Year**				
V	10^{-3}		10^{-3}	2×10^{-2}	10^{-2}		10^{-2}
VI	10^{-4}		10^{-5}	5×10^{-3}	3×10^{-3}	10^{-6} (VI–VII)	10^{-4}
VII	3×10^{-5}		10^{-6}	5×10^{-5}	10^{-3}		10^{-6}
VIII	10^{-5}		10^{-6}	5×10^{-8}	10^{-5}		10^{-7}
IX	10^{-7}				10^{-6}		10^{-8}
X	5×10^{-8}						$<10^{-8}$
XI	10^{-8}						$<10^{-8}$
XII	10^{-8}						$<10^{-8}$
Peak Horizontal Acceleration			**Probability per Year**				
.05g	10^{-1}	2×10^{-4}	10^{-5}	4×10^{-3}	3×10^{-3}		10^{-2}
.1g	10^{-2}	2×10^{-5}	10^{-6}	4×10^{-4}		10^{-6}	10^{-4}
.15g	10^{-3}		10^{-6}	4×10^{-5}	10^{-3}		10^{-5}
.20g	10^{-4}			10^{-6}	10^{-4}		10^{-6}
.25g	10^{-5}			6×10^{-8}	10^{-5}		10^{-6}
.3g	3×10^{-6}						10^{-7}
.4g	4×10^{-7}						10^{-7}
.5g	10^{-7}				10^{-6}		10^{-7}
.6g	5×10^{-8}						10^{-8}
.8g	10^{-8}						10^{-8}
1.0g	10^{-8}						$<10^{-8}$
>1.1g	10^{-8}						$<10^{-8}$
Dominant Frequency and Duration for 10^{-6}/year Earthquake							
Cycles/sec	2	3-5	8-15	1-3		1/6-10	
Seconds	10		5-8	20		50	

*Probabilities per year are for accelerations greater than the size indicated.

RIVER BEND

COMMENTARY

Respondent #1

The dominant frequency for 10^{-6}/year earthquake is 1-2 Hz. Low frequency end is controlled by a New Madrid type event at distance and the high frequency part by a Donaldsville type event close in.

Respondent #2

Similar to Grand Gulf.

Respondent #3

Donaldsville earthquake at site leads to dominant frequency band for 10^{-6}/year events. The Baton Rouge slump faults are not dominant in the evaluation. The little internal shear deformation in the Gulf coastal plain is significant. Seismic history is inadequate in area with almost no seismic risk.

Respondent #4

The River Bend site is similar to Grand Gulf and Davis Besse in that an MMVI is estimated to have a recurrence interval of 200 years while an MMVII has an estimated recurrence interval of 2×10^4 years.

Respondent #5

The tectonic province is significant. The "growth faults" and salt dome structures do not seem to constitute hazards. Seismic history shows small earthquakes without concentrations.

Respondent #6

Slump faults are somewhat of a factor, as is the distant New Madrid. Main consideration is seismic history. Probability of MMV to MMVI from New Madrid may be as high as 10^{-3}/year.

Respondent #7

The tectonic province is favorable, showing little Cenozoic activity. The unfaulted Sangamon terrace is also favorable. Seismic history establishes the frequency of small shocks in the whole region.

Reviewer

The MM intensity having a probability of 10^{-4}/year varies from VI to VII-VIII, while the 10^{-6}/year intensity ranges from VI-VII to IX with a median of almost VIII. The acceleration having a probability of 10^{-4}/year varies from less than 0.05 to 0.2, while the 10^{-6}/year acceleration ranges from 0.1g to 0.5g with a median of about 0.25g.

Although there was a minor difference on the significance of the Baton Rouge faults, there appeared to be agreement among the respondees on the general seismic character. None proposed moving the New Madrid earthquake so far south that River Bend was relatively near the epicenter.

SUMMER

Respondent No.	1	2*	3	4	5	6	7
MM Intensity			Probability per Year				
V	10^{-2}		10^{-2}	10^{-1}			10^{-2}
VI	10^{-4}		10^{-3}	3×10^{-2}	5×10^{-3}		10^{-2}
VII	3×10^{-6}		10^{-4}	5×10^{-3}	10^{-3}		10^{-3}
VIII	5×10^{-7}		10^{-6}	5×10^{-5}	10^{-4}	10^{-6}	10^{-4}
IX	10^{-7}			5×10^{-9}	10^{-6}		10^{-7}
X	10^{-8}						10^{-8}
XI	10^{-8}						$<10^{-8}$
XII	10^{-8}						$<10^{-8}$
Peak Horizontal Acceleration			Probability per Year				
.05g	10^{-1}		10^{-3}	2×10^{-2}	5×10^{-3}		10^{-2}
.1g	10^{-2}		10^{-6}	4×10^{-3}			10^{-3}
.15g	10^{-3}			10^{-3}	10^{-3}		10^{-3}
.2g	10^{-4}	3×10^{-5}		4×10^{-4}			10^{-4}
.25g	10^{-5}			10^{-4}	10^{-4}	10^{-6}	10^{-4}
.3g	3×10^{-6}			4×10^{-5}			10^{-4}
.4g	4×10^{-7}	2×10^{-5}		8×10^{-7}	10^{-5}		10^{-5}
.5g	10^{-7}				10^{-6}		10^{-6}
.6g	5×10^{-8}	1×10^{-5}					10^{-8}
.8g	10^{-8}	7×10^{-6}					$<10^{-8}$
1.0g	10^{-8}	3×10^{-6}					$<10^{-8}$
>1.1g	10^{-8}						$<10^{-8}$
Dominant Frequency and Duration for 10^{-6}/year Earthquakes							
Cycles/sec	3	5	5-8	2-5		1/3-15	
Seconds	10		10-15	15		15-20	

*Probabilities per year are for accelerations greater than the size indicated.

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SUMMER

COMMENTARY

Respondent #1

The tectonic province was significant in evaluation of the site, and geology determined the low probability (10^{-6}/year) earthquakes. Low frequency accelerations are controlled by a Charleston type event at distance; higher frequency by a local maximum V on one of the nearby older faults. Seismic history and geologic record cannot exclude these faults from producing earthquakes of this size very close to the site.

Respondent #2

The historical seismicity seems to be on NE trends. The site is on the edge of the area of greatest seismicity, but the assumption was made that a given magnitude event would be equally likely at any point in the region under consideration. The epicenter map indicates that this simplification is not totally without merit.

Seismic history was the most important aspect in determining low probability events, which were obtained by extrapolation of a recurrence relation.

Respondent #3

Consideration was given to the thrust nature of regional deformation and no geological evidence of fault offsets in recent times. The Piedmont Province has general characteristics which were included in the evaluation. Unfortunately, the 1886 earthquake does not seem to fit unless it was smaller than often assumed (the Charleston damage may have been enhanced by filled land).

Two earthquakes were considered, namely a 5.5 magnitude nearby shock and another 1886 Charleston earthquake.

An intensity of VII+ is probably the maximum which is mechanically feasible.

Respondent #4

The Summer site appears to be similar to the Summit and Cooper sites in that an MMVII is estimated to have a return period of 200 years, while an MMVIII is estimated to have a return period of 2×10^4 years.

Respondent #5

The province's characteristics are significant: presence of ancient faults; quite a few small to moderate earthquakes; lack of surface faulting which would betoken strong earthquakes. Seismic history is significant for intensities to and including VII. Here, as at most sites, the lower probability (e.g. one in 10^6/year) were determined primarily by geologic circumstances which tend to indicate a virtual "cut-off" of plausibility.

Respondent #6

The relationship to postulated trends, including the 1886 Charleston shock, is the dominant consideration. If the trend is to the NW from Charleston, an MM intensity of VIII can be expected within 50 miles with a probability of at least 10^{-6}/year. If the trend is NE or non-existent, the probability may be much less.

Respondent #7

The province is a generally quiet one but the poorly understood Charleston shocks add a large note of uncertainty. The low probability (10^{-6}/year) earthquakes were determined mainly by the seismic activity of the region.

Reviewer

The MM intensity having a probability of 10^{-4}/year varies from VI to VIII with an average of VII plus. The 10^{-6}/year intensity varies from VII plus to IX with an average of VIII plus. The acceleration having a probability of 10^{-4}/year varies from <0.1g to 0.3g with a median of 0.2g, while the 10^{-6}/year acceleration ranges from 0.1g to 1g with a median of 0.35g.

The respondents have, to a considerable extent, changed order in a ranking made in terms of intensity or acceleration estimated at the 10^{-4}/year or 10^{-6}/year recurrence level.

Respondents #1 and #3 placed a repeat of the Charleston earthquake at its original position. Respondent #6, on the other hand, mentions the possibility of a northwest trend from Charleston. Respondent #2 employs recurrence interval methods and obtains a lesser probability of an acceleration of 0.2g but a larger probability for accelerations greater than 0.5g than do the other respondents.

Respondent No.	1	2*	3	4	5	6	7
MM Intensity			Probability per Year				
V	10^{-2}		10^{-3}	10^{-1}	10^{-2}		10^{-2}
VI	10^{-2}		10^{-3}	3×10^{-2}	5×10^{-3}		10^{-3}
VII	10^{-3}		10^{-6}	5×10^{-3}	3×10^{-3}	} 10^{-6} (VII–VIII)	10^{-6}
VIII	10^{-5}		10^{-6}	5×10^{-5}	10^{-3}		10^{-7}
IX	10^{-7}			5×10^{-9}	10^{-5}		10^{-8}
X	10^{-8}				10^{-6}		$<10^{-8}$
XI	10^{-8}						$<10^{-8}$
XII	10^{-8}						$<10^{-8}$
Peak Horizontal Acceleration			Probability per Year				
.05g	10^{-2}		10^{-3}	2×10^{-2}	10^{-2}		10^{-2}
.1g	10^{-3}		10^{-5}	4×10^{-3}			10^{-3}
.15g	10^{-4}		10^{-6}	10^{-3}	3×10^{-3}		10^{-4}
.2g	10^{-5}	2×10^{-5}	10^{-6}	4×10^{-4}		10^{-6}	10^{-6}
.25g	3×10^{-6}			10^{-4}	10^{-3}		10^{-6}
.3g	10^{-6}			4×10^{-5}	5×10^{-4}		10^{-7}
.4g	4×10^{-7}	1×10^{-5}		8×10^{-7}	2×10^{-4}		10^{-7}
.5g	10^{-7}				10^{-5}		10^{-7}
.6g	3×10^{-8}	7×10^{-6}					10^{-8}
.8g	10^{-8}	4×10^{-6}					10^{-8}
1.0g	10^{-8}	2×10^{-6}			10^{-6}		$<10^{-8}$
>1.1g	10^{-8}						$<10^{-8}$

Dominant Frequency and Duration for 10^{-6}/year Earthquake							
Cycles/sec	2	3	5-8	2-5		1/3-15	
Seconds	10		10-15	15		30	

*Probabilities per year are for accelerations greater than the size indicated.

SUMMIT

COMMENTARY

Respondent #1

Seismic history was used in determining the lower probability earthquakes. The province approach was taken, assuming an event similar to 1871 Newark-Wilmington is possible near the site, which is soft.

Respondent #2

Seismic history was used to construct a recurrence relation with the assumption that all regions surrounding the site are equally likely candidates for an earthquake. Since this represents a tremendous extrapolation of the existing data set, it really cannot be said that seismic history determined the lower probability earthquakes.

Respondent #3

The Piedmont Province was considered. The Huntington Valley fault was assumed active. There is much uncertainty about the presence and activity of regional faults.

Respondent #4

Summit appears to be similar to Summer and Cooper in that an MM VII has an estimated return period of 200 years while the estimate for an VIII is 2×10^4 years.

Respondent #5

There are many ancient faults in the nearby Piedmont province and several Triassic faults in the Coastal Plain as well as in the Piedmont. The history tends to suggest that certain old faults are reactivated, as (for example) near the N.Y. - N.J. boundary. Lack of surface faulting argues against the occurrence of truly great earthquakes.

The foundation material does not appear to be ideal with respect to earthquakes.

Respondent #6

Seismic history is important but the tectonic setting is also significant and the Charleston 1886 shock is a factor in setting the intensity at Summit.

Respondent #7

The coastal plain province with few exceptions is stable. The Paleozoic and Triassic faults seem to have been only slightly activated in the last 10^8 years. Seismic history was very important in evaluating possible reactivation of old faults and establishing the frequency of small shocks.

Lower probability earthquakes are determined largely by the geology.

Reviewer

The MM intensity having a probability of 10^{-4}/year varies from VI-VII to VIII plus with a median of VII while the 10^{-6}/year intensity ranges from VII to X with a median of VIII. The acceleration having a probability of 10^{-4}/year varies from 0.08g to .45g with a median of 0.15g, while the 10^{-6}/year acceleration ranges from 0.18 to 1g (two such estimates) with a median of 0.3g.

Those specific factors mentioned as influencing the evaluation vary rather widely from reactivation of old faults, to translation of the Newark-Wilmington shock, to implications of the Charleston earthquake.

Respondent No.	1	2*	3	4	5	6	7
MM Intensity			Probability per Year				
V	10^{-1}		10^{-2}	3×10^{-1}	5×10^{-2}		10^{-1}
VI	10^{-2}		10^{-3}	7×10^{-2}	3×10^{-2}		10^{-2}
VII	10^{-3}		10^{-3}	10^{-2}	5×10^{-3}		10^{-3}
VIII	10^{-5}		10^{-6}	10^{-4}	2×10^{-3}	10^{-6}	10^{-4}
IX	10^{-6}		10^{-6}	10^{-9}	10^{-4}		10^{-6}
X	10^{-7}				10^{-6}		10^{-8}
XI	10^{-8}						$<10^{-8}$
XII	10^{-8}						$<10^{-8}$
Peak Horizontal Acceleration			Probability per Year				
.05g	10^{-1}		10^{-2}	3×10^{-1}	5×10^{-2}		10^{-2}
.1g	10^{-1}	10^{-3}	10^{-3}	7×10^{-3}	3×10^{-2}		10^{-3}
.15g	10^{-2}	10^{-4}	10^{-4}	3×10^{-3}	5×10^{-3}		10^{-3}
.2g	10^{-2}		10^{-6}	8×10^{-4}	3×10^{-3}		10^{-3}
.25g	3×10^{-3}		10^{-6}	3×10^{-4}	2×10^{-3}	10^{-6}	10^{-4}
.3g	10^{-3}			8×10^{-5}	1×10^{-3}		10^{-4}
.4g	10^{-5}	4×10^{-5}		1.6×10^{-8}	2×10^{-4}		10^{-5}
.5g	10^{-6}				10^{-4}		10^{-6}
.6g	10^{-7}	2×10^{-5}					10^{-7}
.8g	10^{-8}	7×10^{-6}					10^{-8}
1.0g	10^{-8}	3×10^{-6}					$<10^{-8}$
>1.1g	10^{-8}						$<10^{-8}$
Dominant Frequency and Duration for 10^{-6}/year Earthquake							
Cycles/sec	1	5	1-5	2-5		1/4-10	
Seconds	15		few	15		30	

*Probabilities per year are for accelerations greater than the size indicated.

TROJAN

COMMENTARY

Respondent #1

The province is certain to have a VIII about once per century. This is a hard site; a nearby max VIII shock would produce accelerations of 0.5g but the probability of having one this close is only 10^{-6}.

Respondent #2

The seismic history was used to derive a recurrence relation giving number of earthquakes in a magnitude range per year per km^2. Given the recurrence relation and an attenuation relation, the probabilities of certain accelerations at the site depend on whether: (1) the concentrations of seismicity near Portland and Swift Dam are due to tectonic features unique to these areas, in which case the earthquakes would occur some distance from the Trojan site, or (2) the clustering reflects population density and the recurrence relation determined for the Portland, Swift Dam region holds everywhere with equal probability. The answers given correspond to (1) above. If (2) were correct, the probabilities should be increased by a factor of 10, since the limiting earthquakes can occur closer to the site.

Respondent #3

The deeper earthquakes from the Puget Sound area (greater than 40 km depth) were a key datum in the evaluation. There is insufficient linking of local shallow seismic sources (say, south of site) with regional geology.

Respondent #4

The Trojan site is similar to Rancho Seco in that a return period of 100 years is estimated for an MM VII while an MM VIII has an estimated return period of 10^4 years.

Respondent #5

A subduction zone with a slow rate of plate convergence dips beneath the region, from a filled "trench" offshore. This presumably generates occasional strong earthquakes like those of Olympia (April 13, 1949) and Seattle (April 29, 1965). Both of these were MM VIII.

Seismic history is important in the evaluation, as it shows marked earthquake activity in the province despite lack of evidence of surface faulting.

Respondent #6

The evaluation is influenced not so much by specific nearby faults, but by the seismic trends in the area indicating faulting. Areas of minor seismicity are to the east and south. The pattern of activity suggests an upper limit to shocks but one can only worry as to the time scale for this pattern. Nothing in the geology indicates a San Andreas or Western Nevada type activity. If an MM VIII shock occurred near the site, there is a possibility of short duration, high frequency accelerations greater than 0.25g.

Respondent #7

The site is within the tectonically active Pacific belt. Seismic history correlates with the tectonic province, although both suggest only moderate activity and little or no potential for great earthquakes.

Reviewer

The MM intensity having a probability of 10^{-4}/year ranges from VII to IX with an average of almost VIII, while the 10^{-6}/year intensity varies from VIII to X with an average of about IX. The acceleration having a probability of 10^{-4}/year ranges from 0.15g to 0.5g with a median of 0.28g while the 10^{-6}/year acceleration varies from 0.2g to 1g with a median of 0.5g.

The comparison for this site illustrates rather well a trend which is evident at many sites, namely, the agreement on MM intensity is generally far better than on acceleration, and the relationships used between intensity and acceleration vary considerably among the respondents.

Those specific factors identified by respondents as entering strongly into the evaluation process varied considerably.

CORRELATION BETWEEN INTENSITY AND PEAK ACCELERATION

Those respondents who reported using specific correlations between intensity and peak horizontal acceleration exhibited a considerable difference in approach in this regard. Respondent #3 used a variety of correlations as deemed appropriate, including those of Neumann [1954], Coulter, et.al. [1973] and Nuttli [1973]. Respondent #5 used Trifunac and Brady [1975] (their mean values as in their Table 1 and dashed line in Figure 3). Respondent #6 used the relationship $\log_{10} a = 0.4 \text{ MM} - 3/4$. And respondent #7 generally used Coulter, et.al. [1973].

It is not apparent how the differences in chosen correlation have affected prediction of acceleration. There appears to be some pattern of consistency between Respondent #6 and #7, in that if each reported a probability/year for an MMVII or VIII, they would report matching probabilities at the same acceleration (even if the probability of one respondent differed from the other). Trojan and Summer provide examples of this. A somewhat similar equivalence tends to exist between Respondents #5 and #7, but perhaps not with the same regularity.

Such an equivalency does not appear to exist between Respondents #4 and #7. And it does not exist between Respondents #3 and #7.

RATIO OF VERTICAL TO HORIZONTAL ACCELERATION

Only five respondents answered this question quantitatively. Of these, four gave a similar ratio for all sites as follows:

Respondent #1 $\frac{V}{H} = 0.7$

#2 $\frac{V}{H} = 0.55$ (0.35 - 0.85 for 1σ bands)

#4 $\frac{V}{H} = \frac{2}{3}$ (ranging from 0.5 to 1)

Respondent #5 $\frac{V}{H} = \frac{2}{3}$ (ranging from 0.4 to 0.8)

Respondent #3 gave individual estimates for each site ranging from $\frac{V}{H} = 0.5$ for Diablo Canyon and Rancho Seco to 0.8 for Pilgrim and Grand Gulf.

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ESTIMATES OF UNCERTAINTY

Respondent #2 estimated an uncertainty in probability/year of at least three and perhaps greater than ten for Cooper, Davis Besse, Diablo Canyon, Pilgrim, Summer, Summit and Trojan, while the uncertainties were generally much larger for the other sites.

Respondent #3 generally estimated an uncertainty of 10-20%.

Respondent #4 generally estimated an uncertainty of a factor of two in the probabilities per year.

Respondent #5 generally estimated an uncertainty of ±75% of the recurrence interval for the smaller g values or intensities and an order of magnitude in probability for the larger events.

Respondent #7 typically estimated ± an order of magnitude uncertainty in probabilities per year, and much more for the very large events. Also, in the mid-range, the uncertainty was sometimes estimated as one order of magnitude toward a larger probability but two in the direction of smaller probabilities.

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