

**REVIEW OF PROBABILISTIC SEISMIC HAZARD  
AND FAULT DISPLACEMENT ANALYSES  
AT NON-REACTOR SITES**

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## QUALITY OF DATA

**DATA:** Data referenced in this report is from literature and has not been quality assured by the CNWRA. Sources for the data should be consulted to determine the level of their quality.

**ANALYSES AND CODES:** Computer codes referenced in this report are not under CNWRA configuration control.

## 1 EXECUTIVE SUMMARY

This letter report summarizes a search for techniques and computer codes currently used to provide probabilistic seismic hazard analyses (PSHA) or probabilistic fault displacement analysis (PFDA) for non-reactor sites. The search included literature and telephone contacts with individuals and organizations performing such analyses. Several references were provided by these contacts. A particularly extensive analysis was provided by the State of Oregon: *Seismic Design Mapping, State of Oregon* by Geomatrix Consultants (Coppersmith et al., 1995). This document, about 300 pages in length and including several risk maps, and other reprints provided are available at the Center for Nuclear Waste Regulatory Analyses (CNWRA). Some refer to nuclear as well as non-reactor facilities.

Information was not found concerning PFDA for non-reactor sites or computer codes for such analyses. PFDA is related to PSHA and may be accomplished through the use of paleo-fault age dating and relationships between magnitude, fault offset, and rupture area (Hofmann, 1994). Analyses for probabilistic seismic hazards are carried out by a substantial number of consultants, government agencies, or working groups and councils established by them. Their techniques range from single-expert analyses with or without the aid of computer programs, to analyses using multiple-experts or expert-teams. In the latter techniques, opinions and data provide input to computer programs that generate seismic hazard curves of peak acceleration versus annual occurrence. The more complex analyses are seldom used, however, for non-reactor sites. Most analyses are by a single expert using relatively simple computer programs (e.g., EQRISK, FRISK, STASHA, and SEISRISK III). Geologic or tectonic models used to prepare input for these analyses are usually considered proprietary.

Making contacts with consultants, organizations and firms performing PSHA proved time consuming and was budget limited. Although many contacts were very helpful, others were reluctant to discuss their procedures. This survey, is therefore, not necessarily comprehensive although we believe it is a representative cross-section of the types of analyses currently being undertaken.

## 2 GENERAL REVIEW

This report summarizes a literature search for procedures used in analyses at non-reactor sites and a survey of methods of analysis used in private consulting firms for PSHA and PFDA. A number of professionals involved in seismic hazard analysis for nuclear and/or non-reactor facilities in California, Oregon, Washington, Eastern North America, and worldwide were contacted. No information was found regarding PFDA for non-reactor sites.

Communicating with professionals at private companies by telephone proved time consuming. Most of the telephone conversations were casual and not particularly informative. None of the analysis methods appeared to be unique [e.g., they use a code developed by Robin McGuire, modified versions of McGuire's codes, EQRISK or FRISK, the U.S. Geological Survey (USGS), SEISRISK II or III, and rarely their own version following the algorithms by Cornell (1968)]. A code called STASHA (Chiang et al., 1984) is sometimes used. In regions where seismic risk is high such as on the west coast of the U.S., consultants tend to use their own geological or fault models and also assess seismic hazards using deterministic approaches. Deterministic analyses usually do not include any probabilities. They are conservative if not near worst case evaluation of ground motions based upon the size and distance from the site, of faults or earthquake source zones and the largest historic magnitude within them. The models they use for the analysis at a given site are regarded as important to securing business and are often

proprietary. Therefore they are not willing to discuss their methods openly. Few reports or publications offered during the telephone inquiry's were received. Only one consultant, on the east coast, who used multiple expert opinions, responded.

The most useful material obtained during the present effort is a copy of the report prepared by Geomatrix Consultants of San Francisco, for the Oregon Department of Transportation (ODT), *Seismic Design Mapping, State of Oregon*. When the short summary was presented at the 1994 Fall AGU meeting with a title *Regional Source Characterization and Probabilistic Seismic Hazard Mapping with Uncertainty—an Example from the State of Oregon, USA*, by R.R. Youngs et al. (1994), a representative of the company was asked for a copy. Mr. Steven Starkey at ODT forwarded a copy.

Recent concerns with evidence that large subduction earthquakes may have taken place along the northern California - Oregon - Washington - and southern British Columbia coasts (see the article by Kerr, 1995) have resulted in an increased use of PSHA in this region. The Oregon State report (Coppersmith et al., 1995) is comprehensive for such an analysis in this region and for non-reactor sites. It should be noted that only a few non-reactor facility PSHA are published, e.g., (Coppersmith and Youngs, 1990; and Coppersmith et al., 1995).

The article entitled *Seismic Hazards in Southern California: Probable Earthquakes, 1994 to 2024* recently published by the Working Group on California Earthquake Probabilities (WGCEP, 1995) may be the most up-to-date summary of seismic hazard analysis specifically for southern California. This article was organized: (1) to update the data and review the methods for estimating probabilities of large earthquakes on the southern San Andreas and San Jacinto faults prepared by the WGCEP in 1988, and (2) to consider other potentially damaging earthquakes throughout southern California. It is the second in a continuing series of reports on earthquake hazards in southern California prompted by the 1992 M=7.3 Landers earthquake. A previous report [available from the Southern California Earthquake Center, (SCEC)] entitled *Future Seismic Hazards in Southern California: Phase I, Implications of the 1992 Landers Earthquake Sequence* (WGCEP, 1992) dealt primarily with short-term hazards through 1993 posed by the Landers earthquake and its aftershocks. The WGCEP (1995) article was published because hazards caused by "blind" faults, that do not necessarily break the surface, are now better understood. Examples of such faulting include the 1994 Northridge earthquake, as well as numerous lesser faults that individually appear to be not as hazardous as the Northridge situation, but pose a significant aggregate danger. Following the 1989 Loma Prieta earthquake, a similar reassessment of the chances for large earthquakes in northern California was made in a report *Probabilities of Large Earthquakes in the San Francisco Bay Region, California* prepared by the WGCEP (1990).

USGS Circular 1053 (WGCEP, 1990) further summarizes the efforts coordinated by SCEC to produce the post-Landers series of reports at the request of the National Earthquake Prediction Evaluation Council (NEPEC) and the California Earthquake Prediction Evaluation Council (CEPEC). NEPEC and CEPEC particularly asked the ad hoc working group to (1) include a regional perspective on the current tectonic environment, (2) review the methodology of the 1988 and 1990 reports and emphasize differences from the 1995 report, (3) consider new models for earthquake recurrence, (4) review recently available data for inclusion in updated probabilistic analyses, and (5) include examples of strong ground-motion predictions using existing models and attenuation relationships. A serious obstacle facing seismic hazard assessment using a deterministic approach is the characterization of earthquake potential for areas far from known major faults because historical seismicity and paleoseismic data are sparse (Ward, 1994).

Many "new models" of seismicity or earthquake occurrence/recurrence using recently available seismic and geodetic data were presented at the National Academy of Sciences colloquium on *Earthquake Prediction: The Scientific Challenge* at Beckman Center in Irvine, CA, February 1995. It was surprising that, compared to twenty five years ago, little has been improved in terms of the general characterization of earthquake occurrence which has a large degree of uncertainty. Therefore WGCEP's work on task (3), to consider new models for earthquake recurrence, may not be of much significance. Based upon WGCEP's efforts in developing earthquake probabilities in California (WGCEP, 1988, 1990, and 1995), the use of a specific geological or fault model based on rigorous considerations of geological, geophysical, and seismic data at a given site appears to produce more credible results than methods based primarily on multiple expert opinions.

In general seismic hazard analysis for nuclear facilities is performed with the assumption that the site is a long distance from earthquake faults, because the sites are often selected in areas where seismic risk appears to be relatively low. Seismic hazard analyses generally have not considered a situation where a modest or large earthquake could occur immediately beneath a site in a crowded metropolitan area, apparently because the analysts considered the event to be too improbable to consider. The assumption that seismic hazard, need be considered only from known faults many miles distant, or that very large earthquakes will not occur on large known faults, failed in recent events (e.g., the 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe, Japan earthquakes). These assumptions have been a fundamental difference between seismic hazard analyses for nuclear facilities and for non-reactor facilities.

The article in New York Times *Alarming Quake Study on California*, January 13, 1995 by Sandra Blakeslee pointed out serious problems concerning seismic hazard analyses. This article which summarizes lessons from the damages caused by the 1994 Northridge earthquake was based on an interview with Thomas H. Heaton and James Dolan of the USGS. Southern Californians have been anticipating a major earthquake, a larger one than the Northridge earthquake, for many years. The article states "New computer simulations show that many office buildings, hospitals, malls, and other structures that meet the latest engineering codes will probably collapse in a large earthquake." "Earthquake building codes have been based on the effects of smaller earthquakes or on large earthquakes many miles away from major metropolitan areas Dr. Heaton said". These statements imply current building codes urgently need to be revised. Another major earthquake (M=7.2) hit crowded urban areas in Kobe, Japan. Considerable damage or destruction of "earthquake resistant" structures occurred during this earthquake.

In summary when seismic risk or hazard analyses are carried out for non-reactor facilities in seismically active regions, the use of a specific fault or geological model based on adequate physical evidence for a given site is essential to assess the credibility of the analysis.

### 3 SURVEY RESULTS

Professionals who do business in seismic hazard analysis for non-reactor sites were contacted and the methods of analysis and models they use were surveyed. The first contact was with Robin McGuire during the 1994 Fall AGU meeting in San Francisco. According to him, his series of codes, EQRISK, FRISK, FRISK 88 (Risk Engineering Inc., 1988), and recently EZ-FRISK, (Risk Engineering Inc., 1995) are the most commonly used, with a single expert (or team of experts) opinion, rather than with multiple-experts' opinions as inputs to be statistically analyzed. SEISRISK II or III, developed by the USGS, (Bender and Perkins, 1987) is also popular but second in frequency of use to McGuire's codes.

Most of the telephone conversations with seismic hazard analysis professionals were casual and only partially informative. These professionals were reluctant to release information unless the interactions were likely to result in business opportunities. However as McGuire indicated, most of the people contacted are using his codes, modified versions, or SEISRISK II or III with specific fault or geologic models.

Consulting firms in southern California, where people have experienced substantial earthquakes in their lifetime, use very specific local geologic and paleoseismic models in the analysis, and augment PSHA or PFDA with deterministic approaches.

Jeff Johnson who once worked at Dames and Moore and now has his own consulting business in Seattle and southern California, uses his own geologic models in risk analysis. The computer codes he uses are McGuire's or Blake's version of McGuire's code (no reference available) or other codes based on Cornell's 1968 probabilistic model. After the 1994 Northridge earthquake he revised his southern California geologic models, which are not available to the public at present. Johnson was appointed to the California Safety Commission on January 5th, 1994, a few days before the Northridge earthquake. According to him the business expectations of his clients have not changed much even after the Northridge earthquake.

Walter J. Silva of Pacific Engineering and Analysis in El Centro, California, uses deterministic methods to calculate both strong ground motion time-histories and pseudo-velocity response spectra, (Silva, 1992; Silva and Wong, 1992, and related literature cited by them). They developed their own codes, which include theoretical methods for estimating near-field ground motion, for application worldwide including the U.S. Silva said that they validated their codes using the records from the 1994 Northridge earthquake. They are involved in the Yucca Mountain project in support of the U.S. Department of Energy (DOE) site characterization program.

John Wakabayashi in Hayward, CA, has done some work using a code developed by McGuire. He combines the seismic hazard analysis with effects of probabilistic liquefaction for the eastern San Francisco Bay area and the northern Sierra Nevada. An example is in Wakabayashi and Smith (1994).

Kenneth Campbell at Dames and Moore in Evergreen, CO, uses SEISRISK III (Bender and Perkins, 1987) and STASHA. He explained that the codes use the same equations and models but STASHA can handle dipping fault planes while SEISRISK III cannot.

Blair Gohl at HBT-AGRA in Vancouver, BC, uses EQRISK and a proprietary Monte Carlo code developed by Dr. Scott Dunbar of his organization. Dr. Gohl stated that consulting firms in British Columbia usually use the single-expert EQRISK or FRISK programs developed by Robin McGuire. Many such analyses have been made because the Canadian building code is more directly tied to probabilistic measures than U.S. building codes. Regulation of structures which may pose a secondary hazard to the populace requires a probabilistic analysis of hazard.

Consulting firms in the eastern U.S. usually use PSHA with relatively simple earthquake recurrence formulae, and often with multiple-expert opinions. Gail Atkinson, of Canada, consults in the assessment of seismic hazards both for nuclear- and non-reactor facilities in eastern North America. She uses a newer version of McGuire's code, FRISK 88 (Risk Engineering, 1988). This code has the capability to include uncertainties. Although the computer code may use multiple expert opinions, it traces only a limited number of logic-tree branches. The algorithm used by this process is not very clear, but may be similar

to genetic algorithms, and accordingly would not require heavy computation. See Zhou et al. (1995a,b) for discussions of the efficiency of genetic algorithms. Atkinson said that a typical computation time on her PC is in the order of minutes. An example of some aspects of Atkinson's procedure is in Atkinson and Somerville (1994).

Shintaro Abe at Central Research Institute of the Electric Power Industry (CRIEPI) in Japan, indicated that they usually use deterministic approaches to assess seismic risks for nuclear power plant sites in Japan where seismic risk is high just about everywhere. They usually determine geologic models by direct measurements with shallow high-resolution seismic reflections or paleo-seismological mapping to provide fault source descriptions for the risk analysis input file. It appears that Japanese electric power companies generously provide funds for these kinds of studies.

#### **4 UNCERTAINTIES AND OTHER PROBLEMS IN SEISMIC HAZARD ANALYSES**

In general the objective of PSHA is to capture all contributions to the hazard, which is estimated by a combination of potential earthquake sources, seismic wave paths and local conditions at a specified site (WGCEP, 1995). Results are described in terms of the probability of the site experiencing a ground motion of a specified level or larger in a specified future time window. The deterministic approach, which was used to define seismic design criteria for most U.S. nuclear and non-reactor sites a decade ago, does not carry units of time. The general methodology to calculate probabilistic seismic hazard at a site was well established in the literature published by Cornell (1968). Canadian building code practices and additional studies for facilities posing a secondary hazard to the public should they fail, have been probabilistic for at least two decades, Canadian National Research Council (1975) and Milne and Ragers (1972). An example of an additional study is Hofmann and McCammon (1982). They performed a single-expert analysis with the aid of the EQRISK computer program. Because of the nature of PSHA, the estimate of earthquake source potential requires major effort in acquiring geologic, geodetic, and historical seismicity data. It is desirable to include as many contributing factors as possible. However, there are limitations because of the expense in obtaining a very complete data set. Intense study of a particular area often leads to the discovery of reports of a near pre-history large earthquake, e.g. Gouin (1994).

To estimate future earthquake occurrence, a recurrence law is assumed, such as  $\log N = a - bM$ , where  $M$  is a magnitude,  $N$  is a cumulative number of earthquakes with a magnitude of  $M$  or smaller, and  $a$  and  $b$  are constants. The total slip rate implied by the estimated earthquake frequency is roughly equal to the long-term plate tectonic slip rate although departures of earthquake occurrence from the magnitude-frequency relationship predicted from past seismicity are often observed, e.g. Petersen and Wesnousky, 1994. The current rate of plate tectonic slip can be estimated from geodetic measurements, and we assume that strain accumulating in the brittle part of the crust is released seismically, except for known creeping fault segments. The "slip budget" resulting from the accumulated strain could be met by very large rare earthquakes or by more frequent moderate earthquakes. Thus, during a specified time span of forecast, the probability of an earthquake of a given magnitude depends on the assumed maximum earthquake in a given location. (WGCEP, 1995). However, there is controversy concerning how to specify the maximum magnitude on a fault, e.g. dePolo (1994), Abe (1994) and Wesnousky (1994)

These assumptions result in a great deal of uncertainty in the analysis because a substantial variation in  $a$ - and  $b$ -values, not only from region to region but also from time to time, is reported in the literature.

After years of study, the recurrence law for regions or for particular faults is still a matter of debate as evidenced by continued publication [e.g., Romanowicz (1992), Abercrombie and Brune (1994), Savage, (1994), Krinitzsky (1993), Wesnousky (1994) Scholz (1994)], including comments on Scholz (1994) by Chills (1994) and Romanowicz (1994). Therefore, even after inclusion of "multiple expert opinions," the analyses will have a great deal of uncertainty because of the nature of earthquake occurrence, unknown geological features, etc. (Hanks and Cornell, 1994). It is reasonable to use PSHA to assess seismic hazard for nuclear facilities with the assumptions discussed above, because the sites are selected in areas where seismic risk is low. However, because seismic activity is low and no obvious active faults may be detected nearby, the assumption of a particular earthquake recurrence is highly speculative and the analysis may rely on a large number of "expert opinions."

## 5 CONCLUSIONS

Nuclear facilities have been sited in areas of relatively low seismicity. Non-reactor facility sites are often near faults, some having a high earthquake potential. Until recently, California earthquake analysts often did not consider that maximum magnitudes for a given fault length would occur beneath a metropolitan area because the probability was thought to be infinitesimally small.

Since California earthquakes of the past decade, however, PSHA is often augmented with a deterministic analysis of nearby faults. Western North America analyses are usually made by a single expert. Fault sources, maximum magnitudes and recurrence are relatively well known. In eastern North America, inputs to PSHA are much less certain because of low seismicity and extensive soil which may cover faults. Consequently multiple-expert analyses are more frequently used and results are probably even less certain than for western North American sites. Complex codes are seldom used for non-reactor sites. If a computer code is used, it is likely to be one of McGuire's (EQRISK etc.), the USGS' SEISRISK III or Stanford University's STASHA.

Efforts to more fully define seismic hazard, as a function of time since the most recent large earthquake, are being pursued by governmental or quasi-governmental groups, e.g. WGCEP, SCEC, CEPEC, and NEPEC. Past predictions, however, are not regarded as successful. Perhaps only one of the past decade's California earthquakes, the 1989 Loma Prieta event, could be regarded as having been anticipated. An earthquake near its location was predicted (WGCP, 1988) with a 20 percent chance of occurring during a 20 year time span. A corollary to this prediction is an 80 percent chance that no earthquake would occur for a 20 year time span at the location of the Loma Prieta earthquake. Non-reactor facilities are generally considered to have a nominal life span of 50 years. Unlike predictions for more frequent flood and wind hazards, not enough time has passed to assess the effectiveness of PSHA for such facilities.

A summary of computer programs and methods being used in non-reactor PSHA found in the course of this investigation are in Table 1. Very brief descriptions of salient features, if known, are included in the table.

**Table 1. Summary of PSHA computer programs and methods used in non-reactor PSHA**

<b>PSHA Method</b>	<b>Year Developed</b>	<b>Reference</b>	<b>Description</b>
EQRISK	1976	McGuire, 1976	Similar to Monte Carlo, Single expert. Areal seismic source zones. Source code provided.
FRSIK	1978	McGuire, 1978	Similar to above, Single expert. 2-D surface fault (line) sources. Source code provided.
FRISK88	1988	Risk Engineering, 1988	As above with limited logic tree capability for uncertainty evaluation. For DOS.
EZFRISK	1995	Risk Engineering, 1995	As above, improved user interface. line or area sources, computes acceleration or spectra, accommodates up to 2 dip angles, e.g. for listric faults. For Windows.
Blake's FRISK	Unknown	*	Unknown modification of FRISK.
Dunbar's Code	1994 +	*	Monte Carlo, Single expert - details unknown.
SEISRISK II	1982	Bender and Perkins, 1982	Monte Carlo, Single Expert. Area or line sources. Source code provided.
SEISRISK III	1987	Bender and Perkins, 1987	As above but recurrence is gradational across source zone boundaries. Source code provided.
STASHA	1984	Chiang et al., 1984	Similar to SEISRISK II but accommodates dipping fault planes. Source code provided.
Johnson-Proprietary	1992 +	*	Unknown.
Geomatrix-Code	1988?	Coppersmith et al., 1995	Presumed similar to EPRI's EQHAZARD. Extensive use of logic trees. No code name presented.
WGCEP	1988-95	WGCEP, 1988, 1990, 1992, 1995	Fault and event interaction based procedure. Predicts probability of larger earthquakes on specific faults as a function of fault strain.
Silva	Ongoing, 1995	*	Deterministic, incorporates ground motion specification as described in Silva and Lee, 1987.
CRIEPE (Japan)	Ongoing, 1995	*	Deterministic. Details unknown.
<p>* The existence of these codes or methods are based on personal communications with the authors during the course of this investigation            NOTE: Other methods are known to be under development, e.g., Frankle, 1995, but were not found to be used for non-reactor siting.</p>			

## 6 REFERENCES

- Abe, K. 1994. Instrumental magnitudes of historical earthquakes, 1892 to 1898. *Bulletin of the Seismological Society of America* 84: 415-425.
- Abercrombie, R.E., and J.N. Brune. 1994. Evidence for a constant  $b$ -value above magnitude 0 in the southern San Andreas and San Miguel fault zones, and at Long Valley Caldera. *Geophysical Research Letters* 21: 1,647-1,650.
- Atkinson, G. M., and P. G. Somerville. 1994. Calibration of time history simulation methods, *Bulletin of the Seismological Society of America* 84: 400-414.
- Bender, B., and D.M. Perkins. 1982. *SEISRISK II, A Computer Program for Seismic Hazard Estimation*. U.S. Geological Survey Open File Report 82-293. Washington, DC: Department of the Interior.
- Bender, B., and D.M. Perkins. 1987. *SEISRISK III, A Computer Program for Seismic Hazard Estimation*. U.S. Geological Survey Bulletin 1772. Washington DC: U.S. Department of Interior.
- Blakeslee, S. 1995. *Alarming Quake Study on California*. New York, NY: New York Times.
- Canadian National Research Council. 1975. *National Building Code of Canada*. Ottawa: National Research Council.
- Chiang, W.-L., G.A. Guidi, C.P. Mortgat, C.C. Schoof, and H.C. Shah. 1984. *Computer Programs for Seismic Hazard Analysis - A User Manual - (Stanford Seismic Hazard Analysis - STASHA)*. Stanford, CA: The John A. Blume Earthquake Engineering Center, Stanford University.
- Chills, C.H. 1994. Reply to comments on "A reappraisal of large earthquake scaling. *Bulletin of the Seismological Society of America* 84: 1,677-1,678.
- Coppersmith, K.J., and R.R. Youngs. 1990. Probabilistic seismic hazard analysis using expert opinion: an example from the Pacific Northwest. *Reviews in Engineering Geology: Neotectonics in Earthquake Evaluation*, E.L. Krinitzky and D.B. Slemmons eds. Boulder, CO: Geological Society of America: Vol. III: 29-46.
- Coppersmith, K., L. DiSilvestro, K. Hansen, D. Wells, and R.R. Youngs. 1995. *Seismic Design Mapping, State of Oregon*. Geomatrix report-Project No. 2442, prepared for the Oregon Department of Transportation. San Francisco, CA: Geomatrix Corp.
- Cornell, C.A. 1968. Engineering seismic risk analysis. *Bulletin of the Seismological Society of America* 58: 1,583-1,606.
- dePolo, M.C. 1994. The maximum background earthquake for the basin and range province, western North America. *Bulletin of the Seismological Society of America* 84: 466-472.

- Frankle, A. 1995. Mapping seismic hazard in the central and eastern United States. Submitted to *Seismological Research Letters*.
- Gouin, P. 1994. About the first earthquake reported in Canadian history. *Bulletin of the Seismological Society of America* 84: 78-483.
- Hanks, T.C., and C.A. Cornell. 1994. Probabilistic seismic hazard analysis: a beginner's guide, *Proceedings of the American Nuclear Society 5th Symposium on Current Issues Related to Nuclear Power Plant Structures, Equipment and Piping, December 14-15, Orlando, Florida*. LaGrange Park, IL: American Nuclear Society.
- Hofmann, R.B. 1994. *SEISM 1.1 Test Analysis*. CNWRA 94-014. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.
- Hofmann, R.B., and N.R. McCammon. 1982. *Report to the Province of British Columbia Ministry of Transportation and Highways on Seismic Evaluations of the Annacis Island Bridge Site*. Vancouver, BC: Golder Associates Ltd.
- Kerr, R.A. 1995. Faraway tsunami hints at a really big northwest quake. *Science* 267: 962.
- Krinitzky, E.L. 1993. Earthquake probability in engineering - Part 2: Earthquake recurrence and limitations of Gutenberg-Richter *b*-values for the engineering of critical structures. *Engineering Geology* 36: 1-52.
- McGuire, R.K. 1976. *Fortran Computer Program for Earthquake Risk Analysis*. U.S. Geological Survey Open File Report 76-67. Washington, DC: Department of the Interior.
- McGuire, R.K. 1978. *FRISK-Computer Program for Seismic Risk Analysis Using Faults as Earthquake Sources*. U.S. Geological Survey Open File Report 78-1007. Washington, DC: Department of the Interior.
- Milne, W.G., and G.C. Rogers. 1972. Evaluation of earthquake risk in Canada. *Proceedings of the International Conference on Microzonation*. Seattle, WA, 1: 21-30.
- Petersen, M.D., and S.G. Wesnousky. 1994. Fault slip rates and earthquake histories for active faults in southern California. *Bulletin of the Seismological Society of America* 84: 1,608-1,649.
- Risk Engineering, Inc. 1988. *Program FRISK88: Description of Capabilities*. Boulder, CO: Risk Engineering Inc.
- Risk Engineering, Inc. 1995. *EZ-FRISK Version 2.0, A Windows Based Program for Seismic Hazard Evaluation*. Boulder, CO: Risk Engineering Inc.
- Romanowicz, B. 1992. Strike-slip earthquakes on quasi-vertical transcurrent faults: inferences for general scaling relations. *Geophysical Research Letters* 19: 481-484.

- Romanowicz, B. 1994. Comment on "A reappraisal of large earthquake scaling" by C. Scholz, *Bulletin of the Seismological Society of America*. 84: 1,675-1,676.
- Savage, J.C. 1994. Empirical earthquake probabilities from observed recurrence intervals. *Bulletin of the Seismological Society of America* 84: 219-221.
- Scholz, C.H. 1994. A reappraisal of large earthquake scaling. *Bulletin of the Seismological Society of America* 84: 215-218.
- Silva, W.J., and K. Lee. 1987. *W.E.S. Rascal Code for Synthesizing Earthquake Ground Motions*. U.S. Army Corps of Engineers Miscellaneous Paper S-73-1 Series, State-of-the-Art for Assessing Earthquake Hazards in the United States, Report 24. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
- Silva, W. 1992. Factors controlling strong ground motion and their associated uncertainties. *Dynamic Analysis and Design Considerations for High-Level Nuclear Waste Repositories*. Proceedings sponsored by the Structural Division/ASCE 132-161
- Silva, W., and I.G. Wong 1992. Assessment of strong near-field earthquake ground shaking adjacent to the Hayward Fault, California. *Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area*. California Division of Mines and Geology Special Publication 113-120.
- Wakabayashi, J., and D.L. Smith. 1994. Evaluation of recurrence intervals, characteristic earthquakes, and slip rates associated with thrusting along the coast range-central valley geomorphic boundary. *Bulletin of the Seismological Society of America* 84: 1,960-1,970.
- Ward, S.N. 1994. A multi-disciplinary approach to seismic hazard in southern California. *Bulletin of the Seismological Society of America* 84: 1,293-1,309.
- Wesnousky, S.G. 1994. The Gutenberg-Richter or characteristic earthquake distribution, which is it? *Bulletin of the Seismological Society of America* 84: 1,940-1,959.
- Working Group on California Earthquake Probabilities (WGCEP). 1988. Probabilities of large earthquakes occurring in California on the San Andreas fault. *U.S. Geological Survey Open File Report* 88-398.
- Working Group on California Earthquake Probabilities (WGCEP). 1990. *Probabilities of Large Earthquakes in the San Francisco Bay Region, California*. U.S. Geological Survey Circular: 1,053. Washington, DC: U.S. Department of Interior.
- Working Group on California Earthquake Probabilities (WGCEP). 1992. *Future Seismic Hazards in Southern California, Phase I: Implications of the 1992 Landers Earthquake Sequence*, California Division of Mines and Geology Special Publication. Sacramento, CA: Resource Agency.

- Working Group on California Earthquake Probabilities (WGCEP). 1995. Seismic hazards in Southern California: probable earthquakes, 1994 to 2024. *Bulletin of the Seismological Society of America* 85: 379-439.
- Youngs, R.R., K.J. Coppersmith, K.L. Hanson, L.A. DiSilvestro, and D.W. Wells. 1994. Regional source characterization and probabilistic seismic hazard mapping with uncertainty - an example from the State of Oregon, USA (abstract). *EOS, Transactions of the American Geophysical Union* 75: 451.
- Zhou, R., F. Tajima, and P.L. Stoffa. 1995a. Earthquake source parameter determination using genetic algorithms. *Geophysical Research Letters* 22: 517-520.
- Zhou, R., F. Tajima, and P.L. Stoffa. 1995b. Application of genetic algorithms to constrain near-source velocity structure for the 1989 Sichuan earthquakes. *Bulletin of the Seismological Society of America* 85: 590-605.

**APPENDIX A**  
**PROFESSIONALS CONTACTED**

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**APPENDIX B**

**REPORTS AND REPRINTS PROVIDED BY CONTACTS**

The following reports and reprints were forwarded by individuals contacted or were found to be particularly relevant from a search of literature during this survey of non-reactor PSHA activities. They are available at the CNWRA.

“Seismic Design Mapping, State of Oregon”  
prepared by Geomatrix Consultants (1995)

“Faraway Tsunami Hints at a Really Big Northwest Quake”  
by Kerr (1995)

“Alarming Quake Study on California,”  
an article in The New York Times on 01/13/95

“Assessment of Strong Near-Field Earthquake Ground Shaking  
Adjacent to the Hayward Fault, California,”  
by Silva and Wong (1992).

“Factors Controlling Strong Ground Motion and their  
Associated Uncertainties”  
by Silva (1992)