

Deterministic vs. probabilistic earthquake hazards and risks

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Abstract

Both probabilistic and deterministic methods have a role in seismic hazard and risk analyses performed for decision-making purposes. These two methods can complement one another to provide additional insights to the seismic hazard or risk problem. One method will have priority over the other, depending on how quantitative are the decisions to be made, depending on the seismic environment, and depending on the scope of the project (single site or a region). In many applications a recursive analysis, where deterministic interpretations are triggered by probabilistic results and vice versa, will give the greatest insight and allow the most informed decisions to be made. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Deterministic vs. probabilistic approaches to assessing earthquake hazards and risks have differences, advantages, and disadvantages that often make the use of one advantageous over the other. Probabilistic methods can be viewed as inclusive of all deterministic events with a finite probability of occurrence. In this context, proper deterministic methods that focus on a single earthquake ensure that that event is realistic, i.e. that it has a finite probability of occurrence. This points to the complementary nature of deterministic and probabilistic analyses: deterministic events can be checked with a probabilistic analysis to ensure that the event is realistic (and reasonably probable), and probabilistic analyses can be checked with deterministic events to see that rational, realistic hypotheses of concern have been included in the analyses.

Determinism vs. probabilism is not a bivariate choice but a continuum in which both analyses are conducted, but more emphasis is given to one over the other. Emphasis here means weight in the decision-making process, regarding whatever choices are available for risk reduction or loss mitigation. This includes system layout, design or retrofit levels, insurance, disaster planning, and recovery efforts. The most perspective will be gained if both deterministic and probabilistic analyses are conducted.

Factors that influence the choice include the decision to be made (i.e. the purpose of the hazard or risk assessment),

the seismic environment (whether the location is in a high, moderate, or low seismic risk region), and the scope of the assessment (whether one is assessing a site risk, a multi-site risk, or risk to a region). Details of these factors and how they are considered by deterministic and probabilistic methods are presented in the following sections.

2. Earthquake decisions

In any relevant seismic hazard or risk analysis the result will be used to make a decision. This might be the selection of design or retrofit criteria and levels, financial planning for earthquake losses (levels of insurance or reinsurance, or self-insurance), investments for redundant industrial systems, planning for emergency response and post-earthquake recovery, and planning for long-term recovery. Such decisions are best served with both deterministic and probabilistic perspectives, and the best analyses are conducted knowing the decisions to be made.

A general rule is that the more quantitative the decision to be made, the more appropriate is probabilistic hazard and risk assessment. Examples are as follows in Table 1.

In the first three examples above, consideration of all events and their probabilities is usually necessary for an informed decision. For seismic design and retrofits, deterministic scenarios are useful if they have been derived from magnitude and distance deaggregation—see, for example, [2,4]. Deterministic scenarios may also be useful to check worst-case events, e.g. the largest magnitude at the closest distance. Insurance/reinsurance decisions are likewise highly quantitative and deserve analyses that consider all

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Table 1
Examples of earthquake decisions

Decision	Quantitative aspects of decision	Predominant approach
Seismic design levels	Highly quantitative	Probabilistic
Retrofit design	Highly quantitative	Probabilistic
Insurance/reinsurance	Highly quantitative	Probabilistic
Design of redundant industrial systems	Quantitative or qualitative	Both
Training and plans for emergency response	Mostly qualitative	Deterministic
Plans for post-earthquake recovery	Mostly qualitative	Deterministic
Plans for long-term recovery, local	Mostly qualitative	Deterministic
Plans for long-term recovery, regional	Mostly quantitative	Probabilistic

possible events, and decisions are often made on the 250- or 500-year loss. These decisions also benefit from identification of a ‘maximum foreseeable loss’, which is a deterministic event defined by some criterion as the worst possible.

Informed design or retrofit decisions for an industrial complex, possibly involving redundant systems, might be made either on basis of probabilistic analysis or deterministic scenarios. For example, if the major hazard is from ground shaking and many faults contribute to that hazard, a probabilistic approach would be used, perhaps looking at the multi-variate shaking hazard at several locations simultaneously. If the system is a lifeline that crosses an active fault, a deterministic approach would be appropriate that examines the effect on the system of fault movement.

Plans for recovery from earthquake losses, whether immediate or long-term, usually involve deterministic exercises, just because the level of planning effort is so great that multiple events cannot be considered. Emergency planners must focus on a given scenario to check communications, mobility, response times, medical and personnel needs. While a deterministic scenario might play a large role, a probabilistic model might be used to select a particular event with characteristics sufficient to test response organizations and reveal deficiencies.

Fig. 1 shows where these example applications fall in the deterministic-probabilistic spectrum. This illustration is non-quantitative and is meant to show that, while all decisions will benefit from both probabilistic and deterministic considerations, emphasis will be placed on one analysis or the other for different decisions.

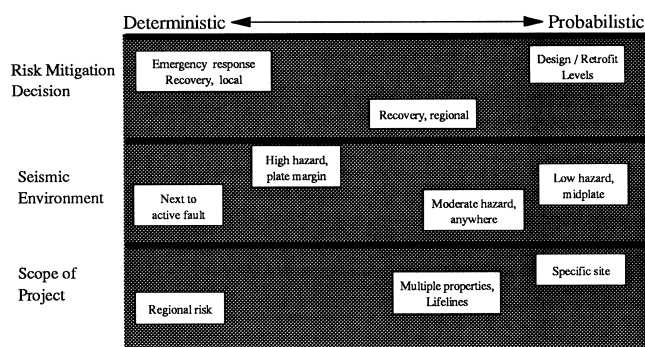


Fig. 1. Seismic risk applications in the deterministic-probabilistic spectrum.

3. Seismic environment

The seismic environment plays a strong role in the appropriateness of deterministic assessments. For high seismic regions at active plate margins (e.g. California or Japan) where the largest earthquakes may occur every 100–300 years, the design ground motion may be the 475-year shaking. This may correspond to the largest magnitude on the closest fault to the site, which is particularly relevant to a site located next to an active fault. A deterministic scenario for this event will allow details to be examined such as ground motion effects caused by rupture propagation. This may lead to insights on risk for a particular lifeline or city that might not be available from more encompassing probabilistic analyses. The high ground motions in Kobe from rupture propagation toward the city during the 1995 earthquake is an example of this detailed effect that might be identified by a deterministic analysis.

In moderate and low seismic regions, extreme deterministic scenarios will have probabilities of occurrence that are too low to be useful for most decision purposes. For example, if there are 1000 cities located in a mid-plate region, it would not be cost effective to design all structures in those cities for the 10,000-year event (the maximum, deterministic earthquake), even though five cities are likely to experience that ground shaking in the next 50 years (a typical design lifetime for structures). The reason is that designers make design decisions on a building-by-building basis—it would not be appropriate to design for an event that has only a 0.005 probability of occurrence during the structures lifetime. The 475-year return period ground motion (probability ~ 0.1 of exceedence in the structure’s lifetime) is a more typical choice.

Deterministic interpretations are still important in all seismic environments. Deaggregation of seismic hazard [2,4] allows us to focus on the events (magnitudes and distances) that dominate the seismic hazard, and to generate realistic spectra and time histories of motion. In fact the best seismic hazard applications are recursive analyses, as discussed below.

4. Scope of project

Finally, the scope of the project is important, that is, whether we are analysing a specific building, a group of

facilities or communities, or a region at risk. Fig. 1 illustrates the degree of deterministic and probabilistic analysis that is appropriate for projects of different scopes.

The analysis of a specific site generally usually requires a probabilistic approach, but a deterministic check on the resulting decision is appropriate. Generally many tectonic faults and unidentified seismic sources contribute to the seismic hazard and risk at a site, and the integration of these through a probabilistic analysis provides the most insight.

Multiple-site analyses (e.g. for a portfolio of exposed or insured properties, or for a lifeline) often require a probabilistic analysis because of multiple variables and complexities of the system. Often several technical fields are required for the analysis (seismology, earthquake engineering, structural engineering, mechanical engineering, and industrial design), and a set of deterministic assumptions with varying degrees of conservatism can be misleading. A probabilistic model provides a way for all technical fields to quantify their interactions and effects in a common format.

Regional assessments often benefit most from deterministic models, where the probability of occurrence of the scenario in, for example, any one city is small, but is large for the region. This concept of multiple deterministic scenarios will allow rational preparation, even though the details of the forecast earthquake may be wrong. The detailed scenario is also a strong motivational tool to those not familiar or comfortable with detailed mathematical models.

5. Recursive analysis

The most insightful assessment of seismic hazard and risk will be made through recursive analysis, wherein a seismic hazard or risk analysis is conducted, the dominant sources of hazard or risk are identified, and more sophisticated models of these sources are created at a higher level of detail than is possible for all sources. The hazard or risk analysis is then repeated with the higher level of detail, and the process is repeated. Conclusions are reached when the dominant sources are stable and when sufficiently detailed models of the sources have been created to reflect important trends.

A recursive analysis uses probabilistic assessments to identify deterministic events that dominate, we model the deterministic events in whatever level of detail is appropriate to bring out critical trends for that site, and we fold those critical trends back into a revised probabilistic assessment. The advantage is that we need not model every fault, every earthquake, and every ground motion record in precise detail; we let the initial analysis guide the level of effort, and put more resources where they are needed for an accurate hazard or risk assessment.

Probabilistic and deterministic analyses play mutually supportive roles in earthquake risk mitigation. A proper probabilistic analysis must include all credible deterministic scenarios, to itself be credible. A deterministic scenario must be rational enough to be included in a probabilistic

analysis, to give rationality to determinism. A good earthquake risk mitigation study will use both analyses to the maximum benefit.

As a simple example application of a recursive analysis, we examine the seismic hazard in Oakland, California, which comes from faults in the San Francisco Bay area (see Fig. 2). We calculate the seismic hazard in two phases, as follows.

5.1. Phase 1

This is the exploratory phase, where all faults are modeled in a preliminary fashion and ground motion is modeled with a generic equation. For this example we model faults using a segmented fault representation, with each segment having a characteristic magnitude distribution, following CDMG [3]. Segments for the Hayward fault are as follows:

Segment 1 Total Hayward fault, slip rate = 9 mm/year,
 $M_{\max} = 7.1$

Segment 2 Hayward north fault, slip rate = 9 mm/year,
 $M_{\max} = 6.9$

Segment 3 Hayward south fault, slip rate = 9 mm/year,
 $M_{\max} = 6.9$

The Oakland site lies approximately at the location where segments 2 and 3 intersect. We also used one ground motion attenuation equation (chosen for this example to be the Abrahamson and Silva model [1]). Fig. 3 shows the 100-year uniform hazard spectra for Phase 1. Sensitivity studies show that the Hayward fault dominates the hazard, indicating annual frequencies that are factors of three higher than other faults at ground motions of interest (spectral accelerations above 0.2 g). This is as shown in Figs. 4 and 5 for 10 Hz and 2 s, respectively. Thus in Phase 2 we concentrate on modelling ground motions from the Hayward fault.

5.2. Phase 2

In Phase 2 we model ground motions from events on the Hayward fault, taking into account rupture propagation and directivity. In place of a detailed time-domain model, we use the general relationships of Somerville et al. [5] to modify the Abrahamson and Silva equations [1]. These relationships model the effect of rupture directivity on ground motion for an average horizontal component of motion (i.e. average of fault normal and fault parallel components). The effect depends on site proximity to the fault, azimuth between rupture and site, and direction of rupture. In a real application we might use detailed time-domain modeling that accounts for rupture directivity and the radiation pattern of energy release to evaluate spectral amplitudes for specific components (fault normal and fault parallel). Fig. 3 shows the 100-year uniform hazard spectra for Phase 2.

Depending on the period, the effect of rupture propagation and directivity may be important. At long periods (5 s), these effects raise the UHS by about a factor of 1.3. At short

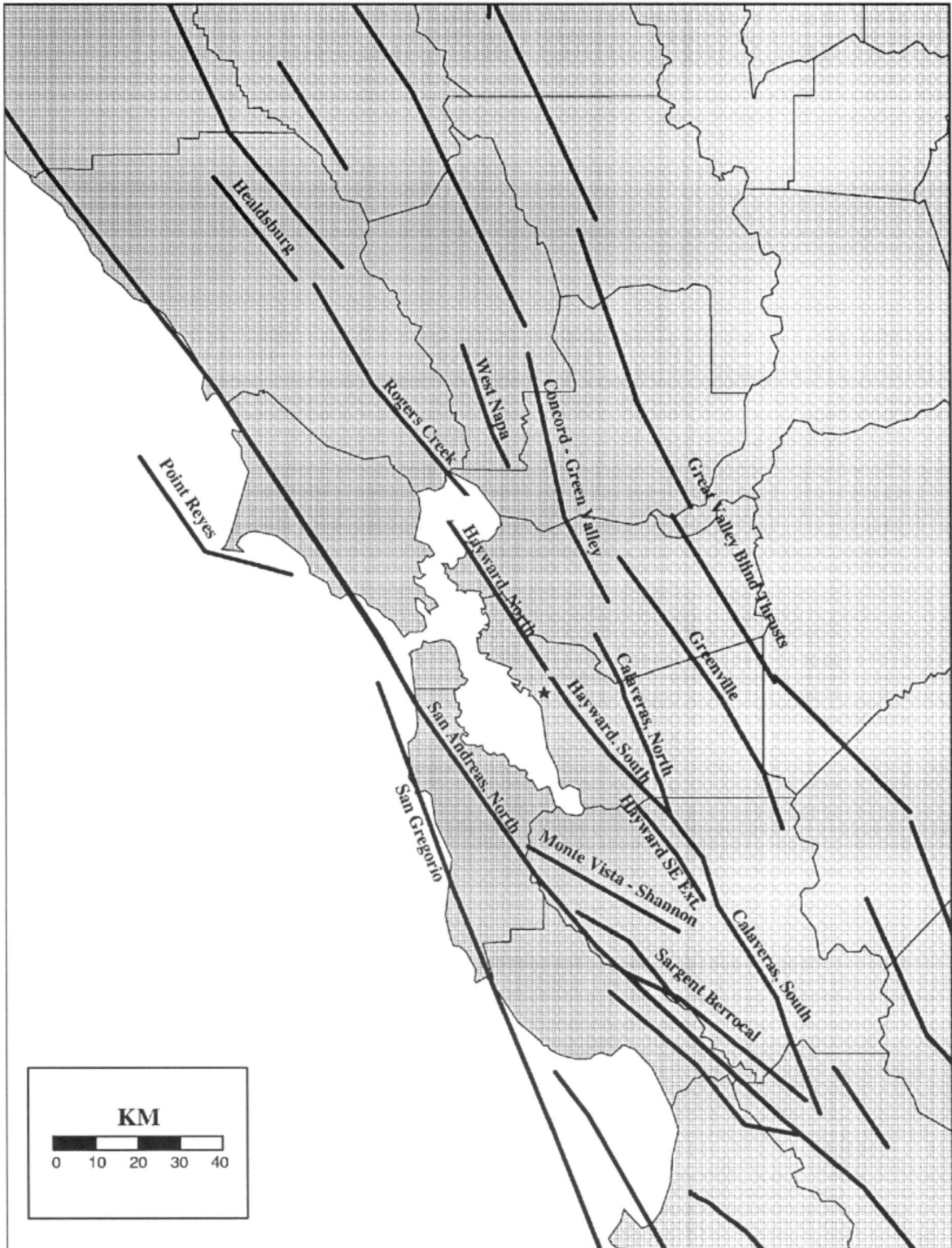


Fig. 2. Oakland site used in seismic hazard example.

periods there is no effect. For the fault normal component of motion the effect will be larger than 1.3 at 5 s; for the fault parallel component it will be smaller.

We can examine a deterministic event from the Phase 2

seismic hazard analysis by looking at the largest magnitude, at the closest distance, with the largest amplification resulting from directivity effects. Fig. 6 shows a deaggregation of seismic hazard by magnitude and distance for 2 s spectral

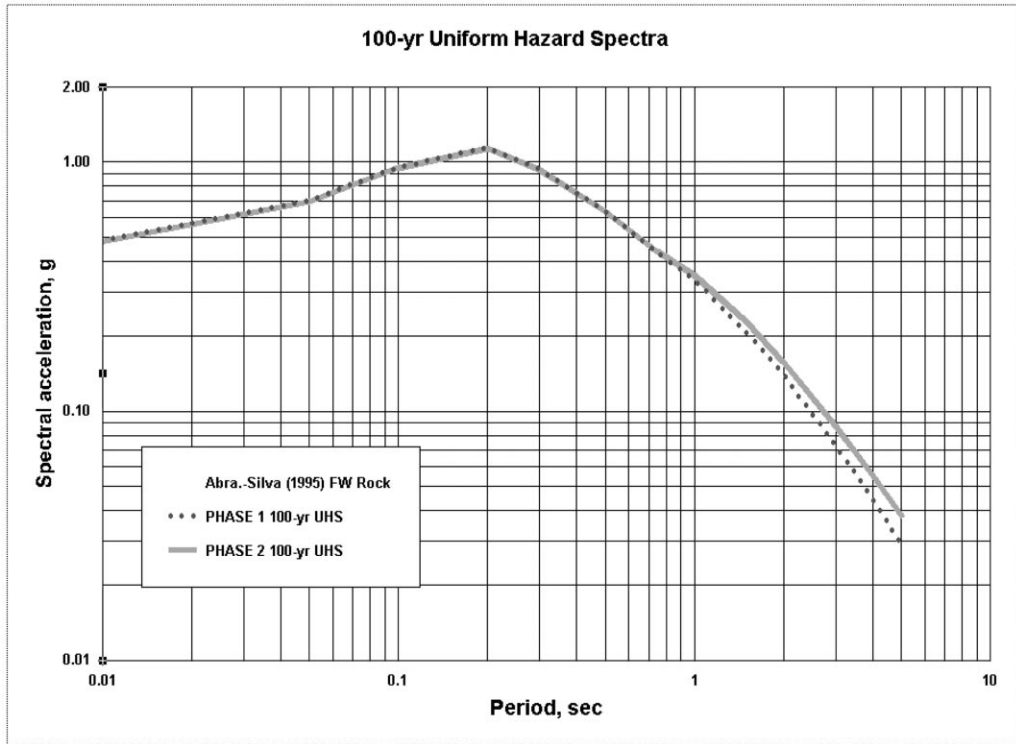


Fig. 3. 100-year UHS for Phases 1 and 2.

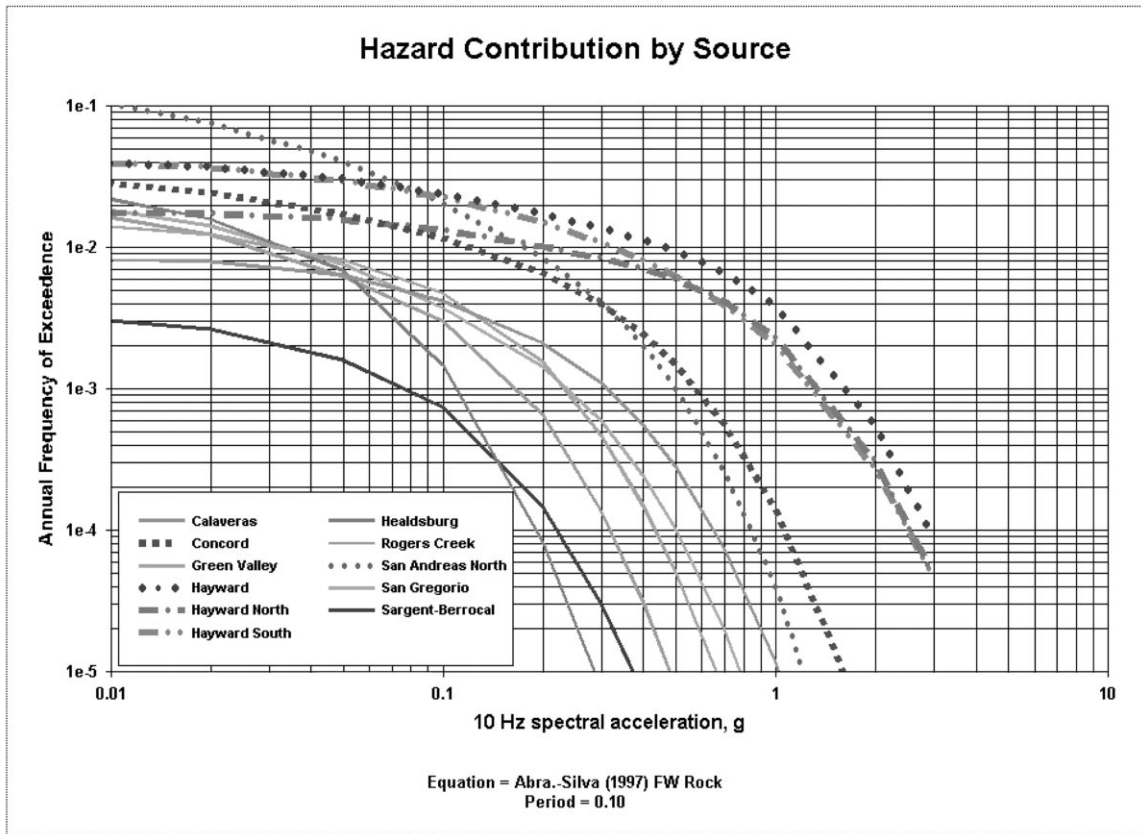


Fig. 4. Hazard contribution by source for 10 Hz spectral acceleration.

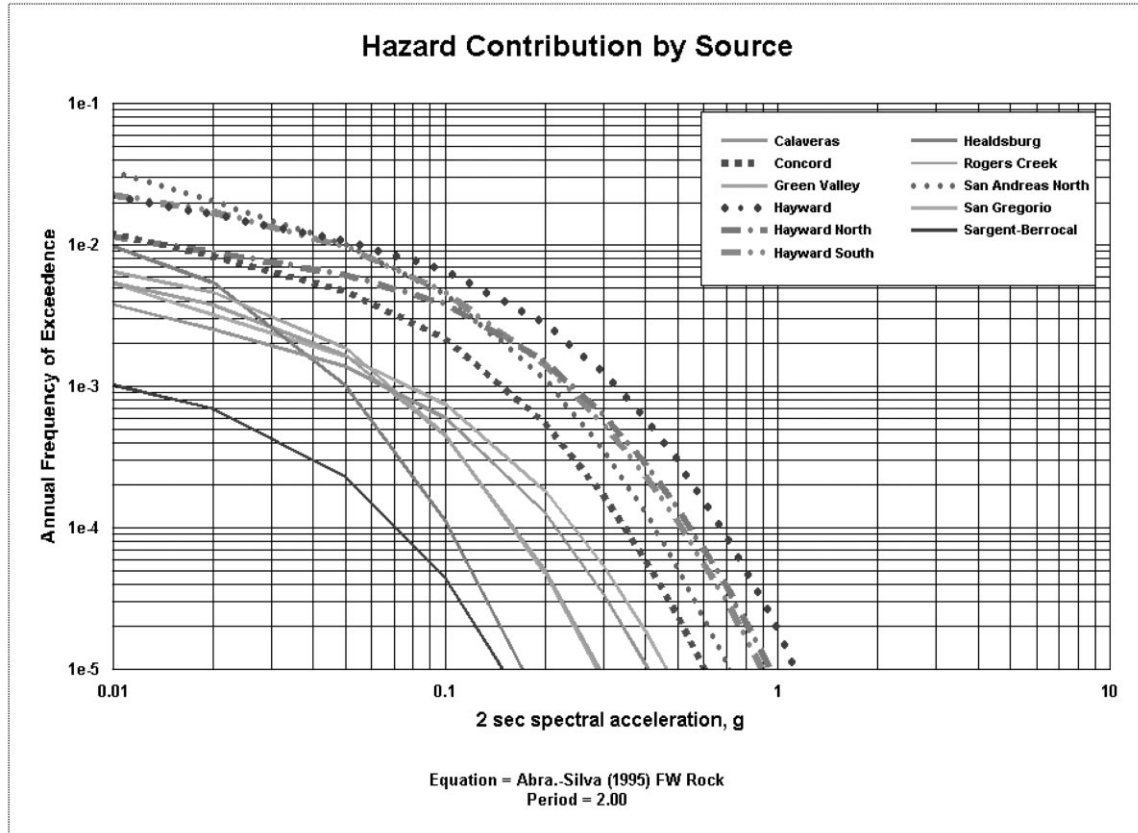


Fig. 5. Hazard contribution by source for 2 s spectral acceleration.

acceleration of 0.5 g. The deaggregation shows the dominant contribution of nearby, $M \sim 7$ events. The deterministic ground motion was calculated for $M = 7.1$ at 0.3 km from the fault trace. The ground motion could come from a detailed time-domain model; in this example it is calculated from the generic factors described above. Fig. 7 shows a comparison of the deterministic event with the seismic hazard from Phase 2. The 100-year uniform hazard spectrum lies slightly below the median deterministic spectrum, and the 475-year UHS lies close to the 84% deterministic ground motion.

It is not surprising that the deterministic earthquake causes median ground motions slightly above the 100-year UHS. With a length of about 115 km, a slip rate of 9 mm/year on all segments implies a recurrence interval of 42 years for $M > 6.5$. Many of these events will occur away from the site; in fact a $M7$ earthquake is only expected to rupture 50–60 km of the fault. Thus $M \sim 6.5$ events will occur near the site with an annual rate of about 0.01, and $M \sim 7$ events will occur with a lower rate. If we are worried about surviving the ‘worst-case’ event, the 100-year UHS will correspond to a motion slightly below the median motion for that event, but a longer return period (i.e. 475 years) will be required to replicate the 84% ground motion.

If our seismic decision involves designing a structure (e.g. a bridge) that will be in place for 50 years, the proper

approach would be to design it for the 475-year motion, with the philosophy that it should survive a maximum earthquake ($M = 7.1$) that causes high ground motions because of rupture propagation and directivity, with high confidence (84%). On the other hand, if we are retrofitting a structure to a higher seismic level, and the remaining lifetime of the structure is 20 years, we might accept the 100-year UHS as a reasonable level, knowing that the worst-case event (with a 20% chance of occurrence in 20 years) would exceed this level.

6. Conclusions

Deterministic and probabilistic seismic hazard analyses should be complementary. The strength of one over the other depends on the earthquake mitigation decisions to be made, on the seismic environment, and on the scope of the project. In general, more complex decisions and subtler, detailed seismic environments strongly suggest the probabilistic analysis, whereas simpler decisions and well-understood seismicity and tectonics point toward deterministic representations. This is not to say that one analysis should be used to the exclusion of the other. In fact the most insight will come from using both, allowing the probabilistic analysis to guide the choice of deterministic events, and

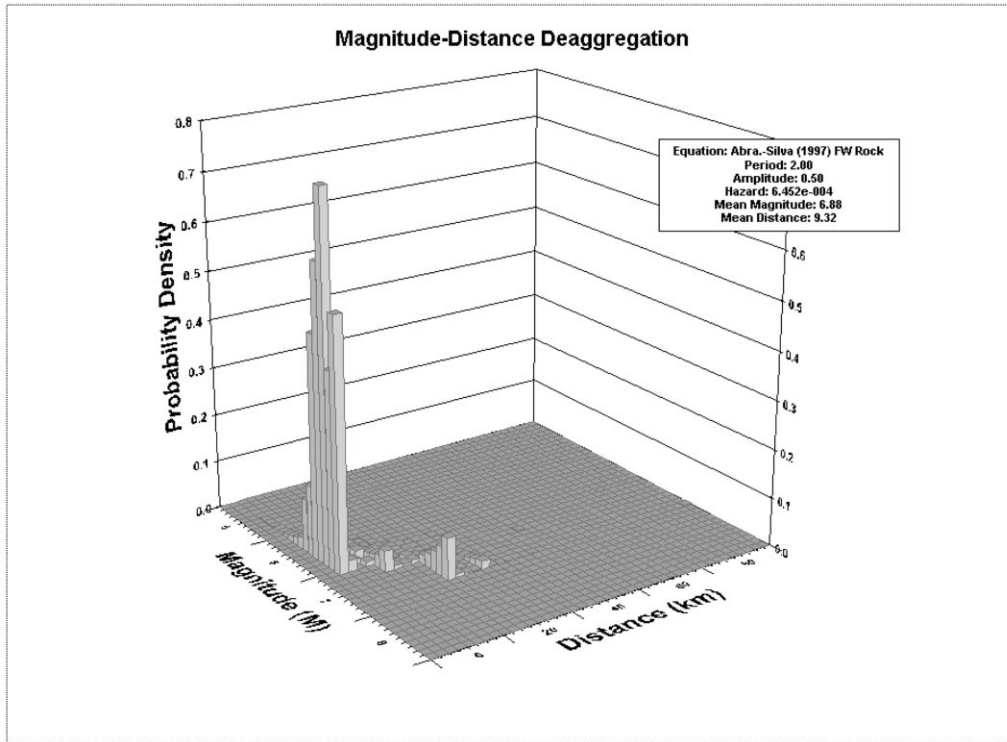


Fig. 6. Magnitude-distance contribution to 2-s hazard at 0.5 g.

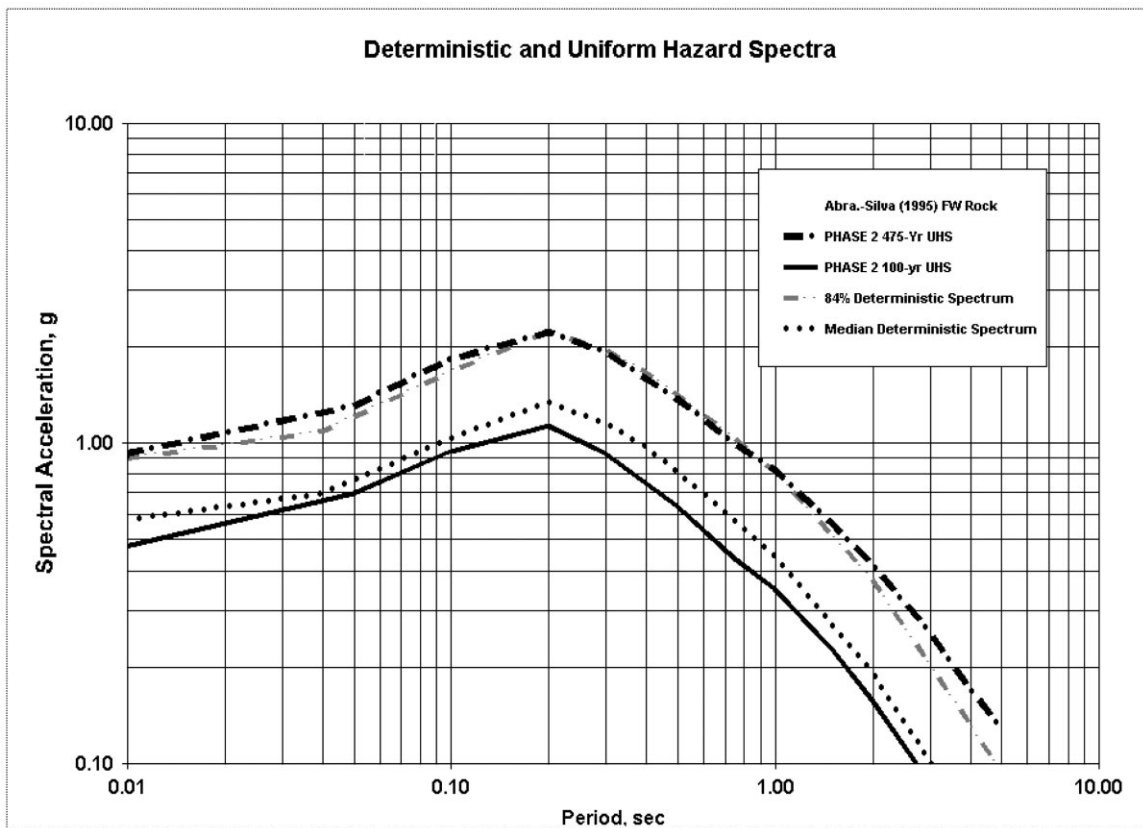


Fig. 7. 100- and 475-year UHS compared to median and 84% deterministic spectrum.

letting the deterministic events guide the refinement of the probabilistic analysis. In this way we will make more informed decisions to reduce seismic risk.

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