2 Approaches To Developing Design Ground Motions

There are two basic approaches to developing design ground motions that are commonly used in practice: deterministic and probabilistic. While both approaches have been used for over 30 years, there is widespread misunderstanding of the two approaches by engineering and earth science professionals practicing in field of earthquake engineering. This chapter gives descriptions of basic concepts of deterministic and probabilistic seismic hazard analyses. A numerical example of a simplified hazard analysis is given in Chapter 3.

2.1 Deterministic and Probabilistic Approaches

In the deterministic approach, individual earthquake scenarios (earthquake magnitude and location) are developed for each relevant seismic source and a specified ground motion probability level is selected (by tradition, it is either 0 or 1 standard deviation above the median). Based on the earthquake location, the distance to the site is computed. Given the magnitude, distance, and number of standard deviations for the ground motion, the ground motion is then computed for each earthquake scenario, using a ground motion prediction equation (often called an attenuation relation) that is based on either empirical ground motions or numerical simulations of ground motions. The largest ground motion from any of the considered scenarios is used for the design ground motion. The approach is “deterministic” in that single values of the parameters (magnitude, distance, and number of standard deviations for the ground motion) are selected for each scenario.

In the probabilistic approach, all possible and relevant deterministic earthquake scenarios (all possible magnitude and location combinations) are considered as well as all possible ground motion probability levels (a range of the number of standard deviations above or below the median). For each earthquake scenario, the distance to the site is computed and then the ground motions are computed for each number of standard deviations above or below the median using a ground motion attenuation relation. Up to this point, the probabilistic analysis is just a large number of deterministic analyses. Given this large suite of deterministic ground motions, which one do you select for design? One approach would be to select the largest ground motion from any of the scenarios. That is, select the scenario with the worst-case ground motion. The problem with that approach is that the largest ground motion will usually be very large and very expensive to design for. The largest ground motions are controlled by the number of standard deviations used in computing the ground motions from an attenuation relation (See Section 2.5). As noted above, the deterministic approach traditionally uses at most 1 standard deviation above the median for the ground motion, but in the probabilistic approach, larger number of standard deviations above the median ground motion are considered.

There are two reasons for not using the worst-case ground motion: it has a large impact on the cost of the design and it is so rare that its use is not justified. Both of these conditions must occur to rule out using worst-case ground motions. If there is not a large impact on cost or they are not too rare to worry about, then the worst-case ground motion may be appropriate for design.

How do we determine if the worst-case ground motions are too rare? This leads us to the key difference between the deterministic approach and the probabilistic approach. In the probabilistic approach, the rate at which each scenario ground motion occurs is also computed. This additional calculation allows us to determine if the worst-case ground motions are too rare to justify their use in design.

If the worst-case ground motions are too costly and too rare, then we need to back off from the worst-case ground motion until we reach a severity of shaking level that is either not too costly or not too rare. To do this, the scenarios are ranked in decreasing order of severity of shaking (e.g. decreasing amplitude of the ground motion). The rates of scenarios are then summed up from the most severe shaking to the least severe shaking. We step down the ranked list of scenarios, starting with the most severe shaking, and stop when we get to a ground motion that either is not "too rare" (e.g. the summed rates is large enough to justify using the ground motions) or it does not have a large impact on the cost of the design. The summed rate is called the "hazard". The hazard is the rate at which the ground motion equal or larger to a specified level occurs at the site. Plotting the sum of the rates against the ground motion is a hazard curve. An example is shown in Figure 2-1 for severity of shaking defined as the T=1 seconds spectral acceleration at 5% damping. What constitutes a hazard level that is not "too rare" depends on the consequences of failure and acceptable societal risks. The acceptable hazard level is typically defined by regulation. For example, in California, the 2001 California Building Code specifies a hazard level of 0.0021/yr (corresponding to 10% chance of being exceeded in 50 years) to define the ground motion for most structures. For the example hazard curve shown in Figure 2-1, a hazard level of 0.0021/yr corresponds to a spectral acceleration of 0.6 g.

In the above discussion, the scenarios were ranked in terms of their "severity of shaking". This vague term is used intentionally because what is severe shaking for one project may not be severe shaking for another project. In practice, the severity of shaking is usually parameterized by a simple scalar measure of the ground motion such as the peak acceleration, peak velocity, peak displacement, or response spectral values. Severity of shaking may also depend on more than one ground motion parameter. For example, in liquefaction evaluations, the severity of shaking depends on both the amplitude of the shaking and the duration of the shaking.

It is important to note that any scenario that may be selected in a deterministic approach is included in the list of scenarios considered in the probabilistic approach. The probabilistic approach just has many more scenarios. The main idea of the probabilistic approach is to provide a basis for selecting a "reasonable" design ground motion that is lower than the worst-case ground motion. Note that in practice, the deterministic approach also selects a ground motion that is lower than the worst-case, using generic rules (e.g. using 0 or 1 standard deviation above the median ground motion for a given scenario earthquake) to define the design ground motion.

2.2 Misinterpretations of Probabilistic and Deterministic Approaches

Over the last decade, I have been given numerous short courses and classes in California on the topic of development of design ground motions. Based on my experience, the majority of practicing engineers and earth scientists working in earthquake engineering do not understand the basics concepts of probabilistic hazard analysis and for many basic concepts of deterministic analyses are also misunderstood.

To get an understanding of the depth of the misunderstandings, over the last several years, I've asked senior seismologists, geotechnical engineers, and structural engineers to describe probabilistic and deterministic seismic hazard analyses as they understand it. The responses have varied greatly. Four examples of some of the basic misunderstandings of the deterministic and probabilistic approaches used in seismic hazard analysis are given below.

In the first example, "deterministic" and "probabilistic" are misinterpreted to refer only to the method used for estimating the ground motion from a specific earthquake scenario. In this misinterpretation, a deterministic analysis is thought to use a seismological numerical modelling method in the computation of the ground motions for a specified earthquake fault rupture geometry, slip distribution, seismic velocity structure, and other seismological properties (e.g. rupture velocity, rise-time, sub-event stress-drop), whereas, a probabilistic analysis is thought to use an empirical attenuation relation to in the computation of the ground motion based simply on the earthquake magnitude and distance. This misinterpretation comes from some engineers and seismologists involved in numerical methods for ground motion simulations. For them, the problem is deterministic if all of the source properties are specified, not just the earthquake magnitude.

In the second example, "deterministic" and "probabilistic" are misinterpreted to refer only to the method used for the site response. In this misinterpretation, a deterministic analysis is thought to involve a detailed site-specific site response study (e.g. running SHAKE with known soil properties), whereas, a probabilistic analysis is thought to use an empirical attenuation relation for a broad soil category to represent the site response.

This misinterpretation comes from some geotechnical engineers involved in site response studies. For them the problem is deterministic if all of the site properties are specified, not just a broad site classification.

In these first two examples, the misinterpretations result from seismologists and engineers thinking about what the words "deterministic" and "probabilistic" would mean to them in the context of their own specialty rather than what they mean in a seismic hazard analysis.

In the third example, "deterministic" is thought to refer to a use of a single set of parameter values for the scenario earthquake, whereas, "probabilistic" is thought to refer to the use of a weighted average of ground motions computed using different parameters for the scenario earthquakes. This misinterpretation is getting closer to the correct concepts in that a probabilistic analysis does consider multiple scenarios with different parameter values, but there is no averaging of the ground motions from the different scenaros in basic probabilistic analysis. The ground motions from the different scenarios are ranked, not averaged. Combining of ground motions from multiple scenarios does occur when uniform hazard spectra are developed (see chapter 12), but combining ground motions from different scenarios is not required in probabilistic analysis; it is a choice made to reduce engineering analysis costs.

In the fourth example, "deterministic" and "probabilistic" are misinterpreted to refer only to the occurrence of earthquakes. In this misinterpretation, a deterministic analysis is thought to use a specified earthquake scenario (magnitude and distance), whereas, a probabilistic analysis is thought to consider the probability of earthquakes occurring at a given location during given time interval. This misinterpretation is partly correct. A probabilistic analysis does consider the probability of earthquakes occurring at a given location and during a given time interval, but it also considers the probabilities of different levels of ground motion occurring at a specific site for each earthquake scenario.

All of the above examples come from senior professionals actively working in earthquake engineering. These misunderstandings are widespread. Without a common understanding of what the terms "deterministic" and "probabilistic" mean in seismic hazard analyses, it is no surprise that there are continuing arguments and controversies about the use of these two approaches. I believe that most of the controversies are a result of these basic misunderstandings of the definitions of deterministic and probabilistic seismic hazard analyses.

2.3 Controversies about the Probabilistic Approach

Although the probabilistic approach is widely used in practice, its use has been questioned (e.g. Krinitzsky, 1994a). Much of the current controversy was sparked by a letter to the editor of Civil Engineering Magazine by Krinitzsky (1994b). This letter and the series of responses it provided is a good indication of the poor understanding of both deterministic and probabilistic analysis by the earthquake engineering community.

The Kinistzsky (1994a) paper describes what he sees as fatal flaws in probabilistic seismic hazard analysis (PSHA). He argues that the simple models of earthquake recurrence often used in PSHA studies are not accurate for individual faults. He concludes that for critical structures, a maximum earthquake should be used and the ground motion attenuated from the source to the site (e.g. a deterministic approach). Krinistzsky has focused on the selection of the earthquake scenario (magnitude and distance) and not the resulting ground motion. In practice, the ground motion resulting from a deterministic approach is not the worst case; however, most people reading his paper believe that the approach he is advocating corresponds to the worst-case ground motion.

Many of the letters to the editor (Civil Engineering, 1995) supporting Krinitzsky (1994) fall into a school of thought that can be summarized as follows. A probabilistic approach guarantees some failures. The failures may be rare, but to the person that was killed, it does not matter that it was a rare event that killed them. To be safe, you need to design for the worst-case. The problem with this concept is that we design structures for ground motions not earthquakes, so the worst-case is the worst-case ground motion not just the largest magnitude earthquake. The worst-case ground motion is not just 1 standard deviation above the median. At least 2 and more likely 4 standard deviations should be considered to estimate the worst case. As shown in section 2.5 below, these worst-case ground motions are large even for sites with no known faults nearby. When faced with such large worst-case ground motions, the response of those opposed to the use of probability is "but you have to be reasonable". This gets us back to the issue of what is "reasonable".

The controversies over the use of the probabilistic approach continue on today, still driven by basic misunderstandings of PSHA. A current example is an article by Bruneau (2001), in the Newsletter of the Multi-disiplinary Center for Earthquake Engineering Research (MCEER). In this article, Bruneau uses the example of wearing or not wearing seat belts in a car to demonstrate the "pernicious effects" of using the probabilistic approach for seismic hazard mitigation. One character in his story used probabilistic analysis to justify not wearing a seat belt, because the chance of being in an accident is small, while the other character choose to wear his seat belt anyway. Despite the chances being low, the characters are involved in a head-on car crash and the one not wearing a seat belt is killed. Bruneau concludes that this is what happens if you use probabilistic approaches for mitigation of effects of rare events: someone will get killed.

What is wrong with Bruneau's example? He did not check that both the event is too rare and the cost impact is significant in deciding whether or not to wear a seat belt. Since the cost impacts are small, we wear seat belts even though the chance of ever needing one is very small.

Let's take this example of a car crash further. What if the characters were driving a small light-weight car and were in a head-on crash with a large heavy truck going 80 miles/hr? In this case, seat belts would not be adequate protection and both characters would be killed. The chance of dying in such a car crash is small, but it is not zero. Should we require all cars to be designed for this case? That would require all cars to much stronger and heavier to withstand such a collision (e.g. much more expensive). Using the probabilistic approach, we would not design for this case because it is both too rare and very costly to implement.

The basic idea of Bruneau's story is that although the chance of being involved in a serious car crash is small, we should plan for it anyway and not use probability to discount rare events. But the term "serious car crash" is itself not a complete description of the forces we need to protect against. We need to know the severity of the accident (e.g. is it a crash into a wall, a head-on with another car, or a head-on with a large truck? And how fast are the cars travelling?) Relating this back to seismic hazards, the idea is that although earthquakes are very rare in some regions, we should still design for earthquakes. That sounds reasonable, but it is not enough information. We still need to determine what level of shaking should be used.

I believe that much of the confusion regarding probabilistic seismic hazard analyses comes down to the difference between the occurrence of earthquake scenarios (magnitude and location) and the occurrence of earthquake shaking at a site. As noted above, we design structures for ground motion at a site, not for an earthquake scenario. This may seem circular, in that the ground motion at the site is computed from the earthquake scenario, but a key element is the variability of the ground motion for a given earthquake scenario. This is an important distinction that is often lost. For example, the MCEER newsletter article has a preface that says the probability of an earthquake occurring in a given place and time is often used for making decisions in seismic hazard. This, of course, is not correct. The probability of a ground motion occurring at a site is often used for making decisions in seismic hazard, not the probability of an earthquake occurring.

I am not aware of anyone advocating the use of worst-case ground motions for design. Therefore, whether a deterministic or probabilistic approach is used, there will be a finite chance of the design ground motions being exceeded. That is, we accept that there will be failures. In a deterministic approach, the chance of exceeding the design ground motion is not addressed directly. The hope is that using a deterministic approach, the chance of failure of a structure will be small enough. In a probabilistic approach, we address this chance of failure by estimating the chance of exceeding he design ground motion and in some cases by estimating the probability of failure of the strucuture using probabilistic risk analysis.

2.4 Bounded vs Unbounded Ground Motions

Another source of confusion between deterministic and probabilistic approaches is the terminology used to present the results. When ground motions are developed for a deterministic analysis, the common terminology used to describe the ground motion is in terms of probability of not being exceeded. For example, the ground motion computed using 1 standard deviation above the median is called the "84^{th} percentile" ground motion. This ground motion has an 84 percent chance of not being exceeded if the scenario earthquake occurs. In contrast, the results of a probabilistic seismic hazard evaluation are typically presented in terms of the probability of exceedance. For example, a design ground motion may be defined as the ground motion with a 10% chance of being exceeded in 50 years.

Both the deterministic and probabilistic approaches result in probabilistic statements about the design ground motion. In the deterministic approach, the results are given in terms of probability of <u>not exceeding</u> the ground motion level if the scenario earthquake occurs. In the probabilistic approach, the results are given in terms of probability of <u>exceeding</u> the ground motion level in a specified time period.

With this difference in terminology, it sounds as if the deterministic ground motion are bounded (e.g. 84^{th} percent chance of not being exceeded), whereas, the probabilistic ground motions are unbounded (e.g. 10% chance of being exceeded in 50 years). Of course, this is not the case. The deterministic ground motion could be just as easily have been given in terms of probability of being exceeded and the probabilistic ground motions could have been given in terms of probability of not being exceeded. The 84^{th} percentile deterministic ground motion has a 16% chance of being exceeded if the scenario earthquake occurs. The ground motion with a 10% chance of being exceeded in 50 years has a 90% chance of not being exceeded in 50 years.

The deterministic ground motions should not just be called the median and 84th percentile ground motions (based on 0 or 1 standard deviation above the median) but rather they should be called the ground motions with 50% chance and 16% chance of being exceeded if the design earthquake occurs. Such a chance in terminology would help to make it clear that both approaches are probabilistic statements about the ground motion level.

2.5 Worst-Case Ground Motions

Usually, in deterministic seismic hazard analyses, the focus is given to the selection of the scenario earthquake. In determining the ground motions, the number of standard deviations of the ground motion has a large, and usually controlling, effect on the ground motions. For example, consider a fault located 10 km from a site. The T=1 second spectral accelerations are listed in Table 2-1 for a range of number of standard deviations. These are based on the Sadigh et al. (1997) attenuation relations for a strike-slip earthquake and a rock site condition. In practice, in a deterministic analysis, the median (0 standard deviations above the median) ground motion or the 84th percentile (1 standard deviation above the median) ground motion is selected. The ground motions at 3 standard deviations above the median is about 3 times larger than the ground motion at 1 standard deviation above the meidan.

Next consider a site in a region without known faults. In most cases, we can't exclude the possibility of a moderate (e.g. M=5) magnitude earthquake occurring near the site. If we allow for this case and assume that an earthquake of magnitude 5 could occur under the site at a distance of 3 km, the resulting deterministic ground motions are listed in the last column of Table 2-1. This shows that even for moderate magnitudes and long spectral periods, the ground motions at 3 standard deviations above the median are very large. Here, they are larger than the 84th percentile ground motion from a magnitude 7 earthquake at 10 km distance.

The conclusion of this discussion is that the worst-case ground motions will likely have a large impact on the cost of a structure. Therefore, we cannot simply adopt the worst-case and ignore the probabilities.

Table 2-1 Effect of the Number of Standard Deviations on the Deterministic Ground Motions (T=1 sec, spectral acceleration(g), 5% damping)

	Spectral Acceleration (g)	
Number of Std. Dev.	M=7.0 Dist=10 km	M=5.0 Dist =3 km
-3.0	0.06	0.004
-2.5	0.08	0.007
-2.0	0.10	0.010
-1.5	0.14	0.015
-1.0	0.18	0.023
-0.5	0.24	0.035
0.0	**0.31**	**0.053**
0.5	0.41	0.081
1.0	**0.54**	**0.12**
1.5	0.71	0.19
2.0	0.94	0.28
2.5	1.24	0.43
3.0	1.63	0.65
3.5	2.16	0.98
4.0	2.85	1.48

2.6 Summary

Both deterministic and probabilistic approaches result in probabilistic statements about the design ground motion. In the deterministic approach, the ground motion has a probability of being exceeded given that the scenario earthquake has occurred. In the probabilistic approach, the ground motion has a probability of being exceeded in a given time period. In either case, the ground motions are not worst-case ground motions. Both approaches back off from the worst-case ground motion. The selection of an appropriate ground motion that is lower than the worst-case ground motion comes down to a method for defining what is “reasonable”.

Probabilistic seismic hazard analysis is more complicated than deterministic analysis and is often seen as a "black box" by practicing engineers who use the results. While the mathematical formulation of PSHA as shown later can seem complex, in reality, a PSHA is just a large number of deterministic analysis with the added feature that it tracks the rate at which each scenario occurs.

The alternative to a probabilistic approach for determining "reasonable" design ground motions is to use a deterministic approach with simple rules for selecting a "reasonable" design ground motion. Simplicity is good, but we pay a price for simplicity in that the approach may not be appropriate in all cases. As an example, the return period (inverse of the annual rate) of the deterministic ground motions computed for a grid of rock sites in California (using a 5x5 km grid) using the median ground motion from the "maximum" earthquake on known faults is shown in Figure 2-2. About half of the return periods are in the range of 200-500 years, but they range from as short as 50 years to as long as 20,000 years. Is it reasonable to use a ground motion with a 50 years return period for some cases and a ground motion with a 20,000 years return period in others? In some cases, using simple rules for developing design ground motions will lead to ground motions that are not reasonable. They may be too small or too large.

In summary, a deterministic analysis is not always "conservative" compared to a probabilistic analysis. In some cases a deterministic ground motion is conservative and in some cases it is unconservative. We don't know which until we conduct the PSHA.

In my view, the main purpose of a PSHA is that is provides a method for selecting the appropriate deterministic scenario from the large suite of possible scenarios (magnitude, distance, and number of standard deviations).

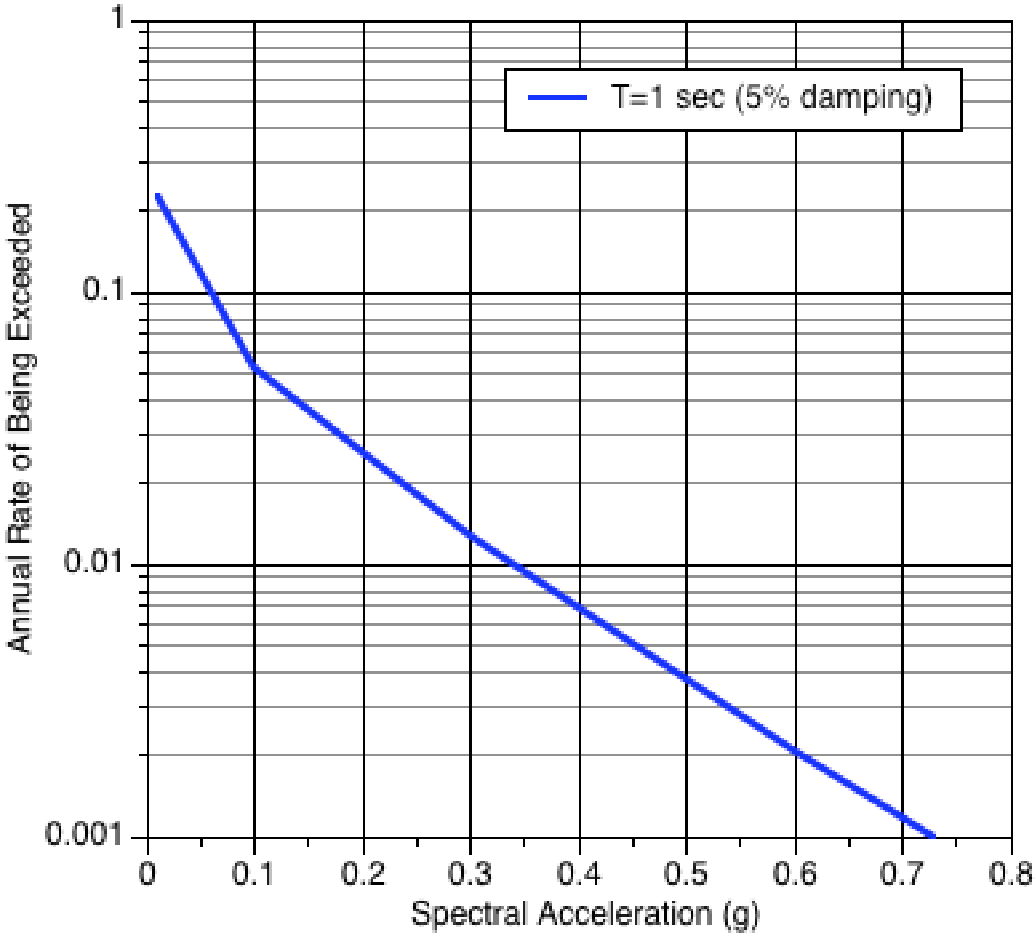

Figure 2-1. Example hazard curve from a probabilistic seismic hazard analysis.

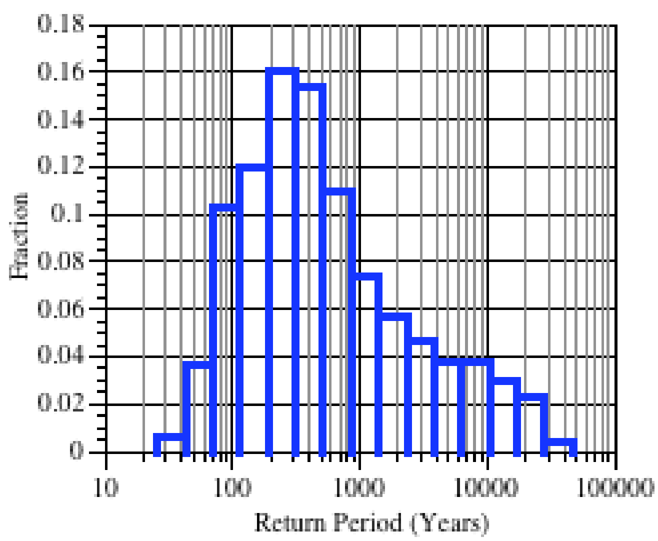

Figure 2-2. Distribution of the return period of the median ground motoin for the "Maximum Credible Earthquake" in California.