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SEISMIC HAZARD ESTIMATION FOR GEOTHERMAL AREAS

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ABSTRACT

The tectonics and volcanism that give rise to productive geothermal areas also produce a high level of earthquake potential. A methodology for assessing the pre-construction hazard as well as the additional hazard due to production is presented. The probabilistic method is illustrated with an example from the Geysers, California.

INTRODUCTION

Productive geothermal areas occur in earthquake zones. A methodology for defining the seismic hazard before construction and assessing the potential for incremental hazard due to production has been developed by earthquake engineers. This paper describes that methodology and gives an example derived from a limited data set at the Geysers, California. The effects of earthquakes can include shaking, soil liquification and ground rupture; however, this paper will focus only on the ground motion effects.

DEFINITIONS

Initially, we define the following terms:

Seismic Hazard: Potential earthquake effects at a site and their possibility of occurrence.

Seismic Risk: The effects of seismic hazard on the works of man.

Operating Basis Acceleration or Earthquake (OBA or OBE): That event and attendant ground motions that is expected to occur during the lifetime of the plant. Design usually specifies the plant's risk to be shutdown but no long-term operational curtailment.

Site Safety Acceleration or Earthquake (SSA or SSE): That very unlikely event and attendant ground motions which is the largest the plant should be designed to withstand without catastrophic failure. Catastrophic failure usually implies loss of life in addition to long-term operational curtailment.

Deterministic Seismic Hazard Estimate (DSHE): A seismic hazard evaluation derived from geologic determination of the maximum credible earthquake of a nearby mapped fault, the geologic estimation of that fault's activity, and the OBA or SSA caused at the site should that event occur.

Probabilistic Seismic Hazard Estimate (PSHE): A seismic hazard evaluation derived from the work of Cornell (1968) which incorporates geologic data on all contributory faults in the region and derives the hazard estimate from a probabilistic model of their activity.

The importance of a seismic hazard estimate may not be evident. Power plants by their design are inherently earthquake resistant. The proximity of earthquake sources is usually known and the hazard acknowledged. However, in this age of environmental activism, the uncertainty of earthquake occurrence creates an opening seized by opponents to a facility with alarming regularity. Can you prove that no earthquake will strike your plant? Of course not. But the hazard and risk must be considered in some detail if permits are required.

DISCUSSION OF METHODOLOGIES

The deterministic method requires a thorough understanding of the regional geology within a few hundred kilometers of the site. Focus is divided between correlation of the earthquake history with geologic structures and details of any Quaternary faulting in the area. For major critical facilities, extensive geologic trenching is required to date faulting. After data are assimilated, a determination of the Maximum Credible Earthquake (MCE) for each nearby active structure is made. This MCE may be estimated from fault lengths, from determinations that only a percentage of a fault may rupture at one time, or from extrapolations of the earthquake history. A controlling MCE (CMCE), the event expected to cause the largest ground motions, is then chosen along with its location. To estimate the actual ground motion, an attenuation relationship must be selected. This relationship relates earthquake magnitude and distances to a ground motion parameter such as peak horizontal acceleration. This process must be completed for a CMCE expected to occur within the plant life (the OBE) and for a CMCE which is credible in a longer time span, such as 10,000 years (the SSE).

There are variations in these procedures but results are similar from a purely deterministic viewpoint. The CMCE is selected for the OBE and SSE and an attenuation relationship is used to derive the OBA and SSA.

PROBABILISTIC METHODOLOGY

The probabilistic method recognizes a shortcoming of the deterministic method which is important in geothermal areas. Suppose our site is near two features; an active but small fault and a distant, large and seismically dangerous fault. Such is the case in California where you are seldom far away from one or several faults capable of a magnitude 6 event nor more than 200 kilometers from the San Andreas fault. How can you put these structures in perspective to determine the OBA and SSA?

The probabilistic method of Cornell (1968) makes several assumptions:

1. The location of the earthquake is equally likely at any point on the causative structure.

2. The distribution of earthquake magnitudes is controlled by the recurrence formula:

$$M = \log_{10} N / b + A$$

where M is magnitude,

b is the slope of the recurrence curve,

N is the cumulative number of events, and

A is a constant denoting the overall level of seismicity.

3. The attenuation relationship for ground motion can be expressed in the form:

$$A_H = k_1 e^{k_2 M} / (r + c)^{k_3}$$

where A_H is the ground motion parameter of interest.

k_1, k_2, k_3, c are constants depending on the area and the particular ground motion parameter selected,

r is the epicentral or hypocentral distance, depending on the attenuation relationship chosen, and

M is the magnitude of the event in question.

The methodology of Cornell (1968) allows integration of the effects over the magnitude range of interest, over the possible locations of the earthquake on the fault and over the specified time period. For line sources such as faults, a numerical integration is necessary, but for an annulus source around the site or a point source, a closed form solution can be derived.

The steps in a PSHE procedure are shown in Figure 1. In 1A, the sources are defined in their relationship to the site. In 1B, the activity as assigned to each source is specified. In 1C, the attenuation relationship for various size events are derived from recorded data. The data represented in Figures 1A, 1B, and 1C are input to the probabilistic procedure and the result is Figure 1D, a curve relating acceleration and return period.

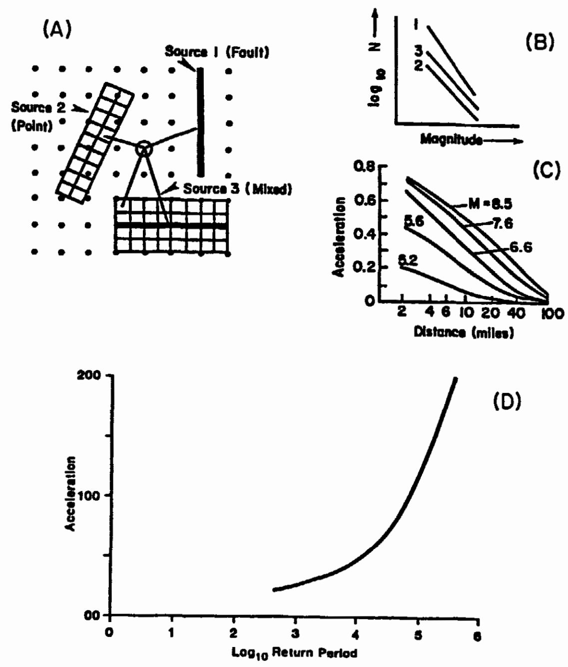

Figure 1. Steps in the Probabilistic Seismic Hazard Analysis.

The critical facet of this derivation is that the cumulative effect of multiple sources is additive. Thus, the scenario mentioned earlier of multiple sources can be handled. A modification of Cornell's original work allows the introduction of an upper bound earthquake. Such an upper bound is often evident in recurrence curves as a tailing off of the number of larger events. Rather than being due to a statistically short observation time, the site geology often indicates that the fault geometry puts an upper limit on the length of breakage possible and thus event size. Mechanically and observationally, the idea of an upper bound is well supported. Production related events should also have an upper bound due to the finite size of the area affected. Production related events can then be added as an areal source with (as experience to date indicates) a fairly small upper bound.

Despite separation of the methodologies, the probabilistic method is even more dependent on geologic knowledge and judgement. Without high quality geologic input, the results may be meaningless. In fact, the deterministic result should be available for comparison to the probabilistic result and differences resolved by the application of common sense.

EXAMPLE FROM THE GEYSERS, CALIFORNIA

To illustrate the results of a typical probabilistic analysis, appropriate data were compiled for the Geysers geothermal area in northern California. The necessary parameters for the probability program utilized include:

1) seismic source coordinates
2) seismicity rate of source
3) b-slope of seismic source
4) ground motion attenuation function
5) magnitude range
6) accelerations to be examined
and 7) site(s) to be considered.

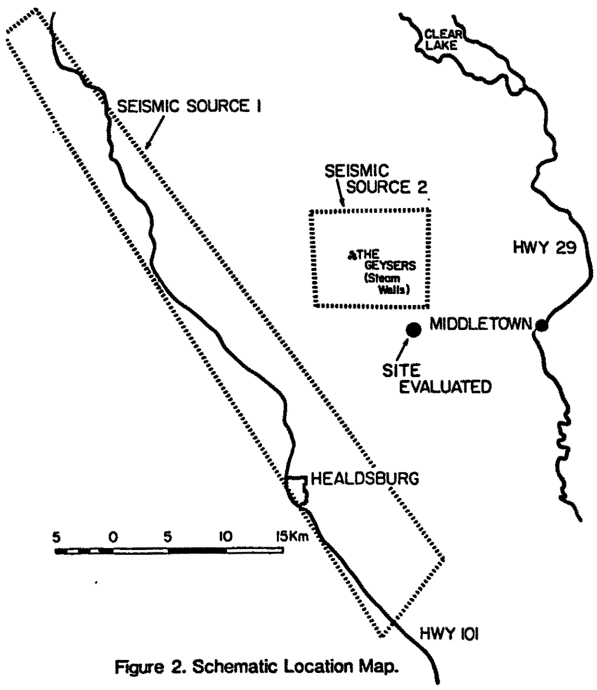

Figure 2. Schematic Location Map.

For the purposes of this example, a limited data base was utilized. One site for the probability calculation was chosen (see Figure 2). Two seismic sources were chosen; one corresponding to the Healdsburg fault and the other corresponding to the production zone of the Geysers itself. Seismicity rates and b-slope values were determined for each seismic source by analyzing the historical seismicity in the region from 1960-1985. The attenuation function used is that of McGuire (1974) determined for the West Coast of the U.S. Table 1 summarizes key input parameters.

Table 1

Key Input Parameters

Seismic Source	Area km^2	Lower Bound Mag.	Upper Bound Mag.	Rate (1)	b-slope
1	590	4.0	7.5	.5	-0.6 or -0.8
2	100	4.0	5.0	.125	-1.0
Background		4.0	6.0	.08	-0.9

(1) Rate is based on the occurrence of a magnitude 4.0 event in one year

All data were input to a computer program which makes the probability calculations. The routine utilized was the U.S.G.S. program EQRISK (McGuire,1976).

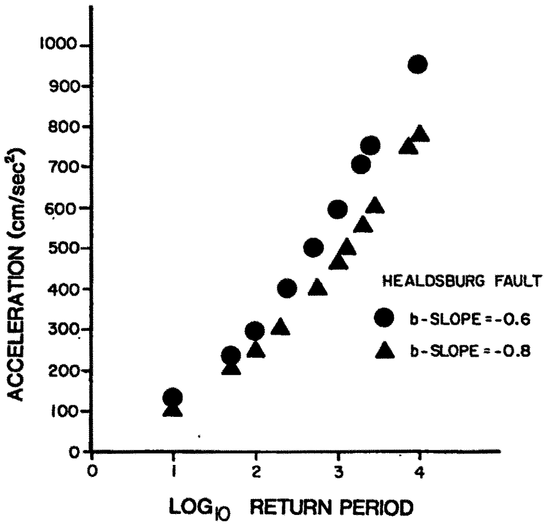

Figure 3. Acceleration vs. Return Period.

In an exhaustive analysis, many parameters are often varied to determine their effect on results. For this discussion, only one parameter was varied, the b-slope value of the Healdsburg fault. Figure 3 depicts the results for each data set with peak horizontal acceleration plotted versus return period. Table 2 summarizes the results.

Table 2
Results

Healdsburg Fault Activity	OBA (gals)	SSA(gals)
High (b-slope = 0.6)	300	950
Moderate (b-slope = 0.6)	240	780

The above example is based on a limited data set and may not represent actual conditions at the Geysers.

The methods of probabilistic seismic hazard analysis are profiting from extensive research and are undergoing rapid change. It would be unusual to get agreement among even knowledgeable professionals about the definitions of magnitude, relevant ground motion parameters, the recurrence curve form, the uniform probability assumptions made, or other fundamental definitions in this type of analysis. In fact, the location and attitude of nearby faults, critical for a deterministic analysis, may not be particularly well known.

CONCLUSIONS

A probabilistic seismic hazard analysis for the Geysers has been given as an example of the type of analysis necessary to quantify the seismic hazard at a geothermal site. As environmental awareness increases, such an analysis will be a necessary and routine procedure to obtain approval for geothermal plant construction.

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