Probabilistic Seismic Design of a Dedicated Shutdown Heat Removal System Including Cost Benefit Considerations

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A probabilistic methodology is developed for assessing the risk reduction potential and cost-benefit tradeoff of a Dedicated Shutdown Heat Removal System (DSHRS) for a PWR as a function of its seismic design capability. The option of coping with a very small LOCA is included.

The modular method of probabilistic analysis involves: (1) the definition of a set of seismic-induced inititating events and the development of a set of seismic event trees; (2) the formulation of seismic survivability models for the appropriate systems/functions; (3) the evaluation of the probabilities of occurrence and joint occurrence of various events and accident sequences as a function of the site free-field seismic activity and the system fragility; (4) the computation of the conditional and unconditional probabilities of a seismic-induced core melt accident and subsequent radioactivity release; (5) the estimation of accident consequences by using the published results of previous PWR release/consequence calculations; (6) the evaluation of the reduction in annual expected consequences which is the benefit of having a DSHRS with a given seismic capacity; and (7) the exercise of an economic analysis model to compute the present value of the future benefit.

A reactor like Zion was used for application of the method due to the availability of data. Data from literature and parametrically generated input data were used in this analysis. Sensitivity studies were performed to investigate the sensitivity of the results to the assumed seismic hazard, probability of occurrence of seismic-induced accident initiating events, equipment seismic fragility, accident costs, and discount rate. The incremental seismic risk reduction benefit computed in these studies ranges from $8.1 millions to $207 millions for a DSHRS with a median seismic capacity of 0.85g (i.e. 5xSSE) in a new plant built at the site. The total cost of a DSHRS is crudely estimated to be $50 million or more if it were built to withstand the current SSE of the plant (such a system could have a median seismic capacity of about 0.85g, giving due regard to design conservatism and proper qualification). The cost associated with the seismic design aspect of such a system is estimated to be about 10% of the total cost. This seismic design cost may be doubled if the seismic design of the system is tripled. Seismic qualification costs would also rise.

1. Introduction

Quantitative risk criteria may be implemented as a part of the future licensing of nuclear power plants in the United States. Many proposals on risk criteria include either cost/benefit considerations or the notion of As Low As Reasonably Achieveable (ALARA) [1]. For such an approach, there is a need to develop a practical method of evaluating the existing risk, the possible reduction in risk, and the value and cost of the improvement. This paper outlines and applies an approach to establish a probabilistic seismic design basis for a Dedicated Shutdown Heat Removal System (DSHRS) which is consistent with cost/benefit considerations.

The study of a probabilistic sesimic design criterion for a DSHRS is motivated in part by conclusions reached in some previous reactor safety studies which found that external events such as earthquakes may be significant contributors to nuclear reactor risk [2,3]. Furthermore, the Reactor Safety Study (RSS) [4] and other probabilistic risk assessments (PRA) [5,8] have concluded that nuclear accident events can depend strongly on the reliability of the shutdown heat removal system. A study by Ebersole and Okrent [6] suggested that shutdown heat removal be made more reliable by providing an additional, dedicated system, i.e. the Integrated Safe Shutdown System (ISSS), which was hardened and made independent of events external to the containment. The shutdown heat removal system analyzed in this study is similar to the ISSS but has the option of coping with the very small LOCA event; this mitigation capability is provided by means of 1 out of 2 dedicated, high-pressure charging pumps (similar to the existing charging pumps), taking suction from its dedicated borated water source. These pumps are assumed to have recirculation capability. The system is assumed to be proposed for a plant similar to Zion Unit 1 which was chosen because of the availability of data [7,8].

2. Method of Analysis

The decision on the need for a safety improvement system within the ALARA context should be based on the "total" benefit to cost ratio. Thus, the benefit of seismic risk reduction is only one of a set including the reduction in risk caused by fire, by sabotage, and by random failure of other equipment. Similarly, the costs would include all costs. In that case, the incremental cost of enhanced seismic deisgn could be balanced against the reduction in risk due to the seismic design aspect alone. This study examines only the incremental reduction in seismic risk; hence, the cost/benefit comparison is incomplete.

The seismic risk is evaluated by the event tree/fault tree methods used in many PRAs. However, the accident events defined in this study generally are not independent, and appropriate conditional probabilities are used in the quantification of accident probability. This study has adopted the definitions of accident initiating events defined in the Seismic Safety Margin Research Program (SSMRP) [7] and has developed a set of seismic event trees from the ones developed in the RSS and the SSMRP. These modified trees explicitly model the states of some systems and equipment (e.g. the Service Water System, the Refueling Water Storage Tank, and the Residual Heat Removal Pumps) that were not explicitly modeled in the referenced studies. This produces large event trees with many accident sequences. However, the explicit modeling of the equipment reduces the dependency between events due to the common equipment, and it also simplifies the fault trees.

The performance of the containment is modeled by 6 mutually exclusive states which include a state in which the containment is assumed to be able to maintain its integrity, even if reactor core melt occurs. The states consist of containment failure due to steam explosion, leakage, hydrogen burning, over-pressurization by steam and non-condensible gases, and the melting through by a molten core, and a success state. The failure mode distribution is assumed to be a function of accident sequence and the free field peak acceleration at the site. The nominal failure mode distribution is parametrically generated in this study; it is generally less than assumed in the RSS (except the probability of containment leakage). For example, the respective probabilities of the 5 failure modes and the non-failure mode are assumed to be 4.0E-05, 4.0E-02, 5.8E-03, 2.4E-03, 0.475 and 0.475 for a very small LOCA accident sequence initiated by a 0.17g earthquake in which core melt was postulated due to the failure of either the Auxiliary Feedwater Supply, the Emergency Core Injection System or Emergency Core Cooling Functionability (e.g. the disruption of the core geometry by an earthquake) if all containment systems operate successfully. The distribution changes to 4.0E-05, 0.27, 4.4E-03, 1.8E-03, 0.36 and 0.36 if the same accident sequence were induced by a 0.54g earthquake. The respective probabilities are changed to 1.4E-04, 0.27, 7.3E-03, 0.72, 2.7E-03 and 2.7E-03 if the sequence involves the failure of the Service Water System plus a very small LOCA resulting from a 0.54g earthquake.

Accident sequences are grouped into various PWR accident release categories similar to the ones defined in the RSS. The consequences of a given category of releases are then estimated from the results of consequence calculations such as the one performed by Strip for the Zion site [9]. Economic analysis is performed in this study to obtain the present value of the future seismic risk reduction benefit, using the continuous discount rate method of analysis suggested by Strip. However, this study computes the cost of replacement power based on the remaining plant life at the time of the accident, subject to a maximum limit of 10 years of power loss.

3. Results and Sensitivity Study

The analysis is based primarily on data available from the literature. The sensitivity study focussed primarily on phenomena that are not well understood or on a few significant parameters that have different values reported in the available risk assessment studies. The sensitivity of the results was investigated with regard to (1) the estimated seismic hazard at the plant site (i.e. the hazard curve), (2) the assumed conditional probabilities of occurrence of the seismic-induced accident initiating events (in particular, the probability of having a very small LOCA), (3) the assumed seismic fragilities of equipment, (4) the dollar value assigned to the loss of a life due to cancer death resulting from an accident, and (5) the discount rate used in the economic analysis of the future benefit of a DSHRS. The uncertainties in the first three types of inputs affect both the existing seismic risk and the potential benefit of having a DSHRS.

These are not the only candidate parameters for a sensitivity study. For example, the distributions of the containment failure modes and of estimated consequences of a given accident sequence also have large uncertainties. However, a complete investigation of the sensitivity of the results to every parameter is beyond the scope of this study.

The seismicity sensitivity studies used the seismic hazard curves from the SSMRP study, from the study by Hsieh et. al. [10] as employed in the RSS, and from the Zion Probabilistic Safety Study (ZPSS) [8]. The SSMRP curve is assumed to be the referenced seismicity at the site. These hazard curves are shown in Figure 1. Note that the ZPSS hazard curve is truncated when the peak acceleration (actually it was defined in the ZPSS as the damage-effective acceleration) exceeds 0.64g

The conditional probability of occurrence of an earthquake-induced small or large LOCA is not well known as a function of "g". As a result, in this study, nominal conditional probabilities of occurrence were generated from the distribution functions of a set of log-normally distributed variables (R', A', M', N', S' and T'). The variables R', A', M', N', and S' are used to indicate the occurrence of the events which are defined to be at *least* as severe as a reactor vessel rupture, as a large LOCA, as a medium LOCA, as a small LOCA and as a very small LOCA respectively. The variable T' is used to indicate an event which requires the shutting down of the reactor. The medians of R', A', M', N', S' and T' are assumed to be 20, 15, 10, 7, 5 and 0.75 times the SSE respectively. The logarithmic standard deviations are all set to be 0.5. The sensitivity study is performed by changing the median of S' to 2 times the SSE to obtain a higher conditional probability of having a very small LOCA. Furthermore, this study has assumed that the failure of either the Emergency Electric Power Supply, the Service Water System, the Component Cooling Water System or the Power Conversion System would imply the occurrence of an event at least as severe as a transient event. The conditional probabilities of S (i.e. a very small LOCA event) and T (i.e. a non-LOCA transient event which is not caused by the failure of either one of the 4 mentioned systems) for the two cases are plotted in Figure 2. It should be noted that the actual conditional probability of a transient event would depend upon the seismic fragility of the four systems.

The conditional damage probabilities of the equipment were generated by a seismic fragility model similar to the one used in the ZPSS. The parameters of the models (i.e. the median seismic capacities, the β_R and the β_U) were obtained by modifying the data reported in the ZPSS. Experts have pointed out that the values of the β's may have been under-stated in the ZPSS [11] and their opinions were incorporated in this study. The results reported in this paper were computed by doubling the values of β's reported in the ZPSS.

Figure 3 presents the conditional failure probability of the crib house for two values of β. It is seen that the conditional damage probability can be very sensitive to β for an earthquake having a peak acceleration close to the median capacity of the equipment. The unconditional damage probabilities for the hazard curves from the ZPSS, SSMRP and Hsieh are shown in Table 1. The two values of β lead to change in the damage probability of the crib house by a factor of 15, 6 and 2 respectively. The large change for the ZPSS curve is primarily due to the cut off at 0.64g. It is noted that there is a factor of 34 difference between the results computed for the larger β for the SSMRP curve and the smaller β for the ZPSS curve.

The results of 4 typical case studies are summarized in Table 2 which presents separately the annual frequencies of core melt due to a transient event and a very small LOCA event induced by an earthquake. The contribution to the annual frequency of seismic induced reactor core melt from the larger LOCA events was assumed to be much smaller, and the distribution parameters of the variables R', A', M', and N' were chosen accordingly.

The seismic risk (in terms of annual frequency of having a seismic-induced reactor core melt accident) of a hypothetical plant having a DSHRS is presented in Table 3 as a function of the seismic capability of the DSHRS. Furthermore, the present value (from the seismic risk viewpoint) of including a DSHRS in a new plant is presented in Table 4 using a conversion factor of $1 million (1980 dollars) per cancer death. These results show a large initial incremental benefit for a DSHRS with a moderate seismic strength.

The results range from $8.1 millions (study case number 2 at a nominal discount rate of 4%) to as much as $207 millions (study case number 3 at 0% discount). The results indicate that most of the benefits are due to the reduction of the risk caused by a transient event. However, the results are inconclusive concerning the merit of having the option of very small LOCA mitigation capability.

Cost estimates on the design of a shutdown heat removal system are available from a study performed by Berry and Sanders [12]. This study suggests ball park numbers of the order of $50 million or more for a system designed for the SSE. Furthermore, a study performed by Stevenson appears to suggest that the cost of a system would be increased by 5.5%-6.5% if the design SSE were tripled. It also seems to suggest that the seismic design aspect of the cost is about 10% or more of the total cost for a system having a 0.2g SSE design value. These rough estimates on the cost and the incremental seismic design cost could be used in a preliminary cost/benefit study. However, any real evaluation of the cost/benefit trade-off would require good cost data and a means of resolving uncertainties in the seismic risk reduction capability.

References

[1] U.S. Nuclear Regulatory Commission, "An Approach to Quantitative Safety Goals for Nuclear Power Plants", NUREG-0739, October 1980.

[2] Hsieh, T.M. and D. Okrent, "Some Probabilistic Aspects of the Seismic Risk of Nuclear Reactors", UCLA-ENG-76113, December 1976.

[3] U.S. Nuclear Regulatory Commission, "Identification of New Unresolved Safety Issues Relating to Nuclear Power Plants - Special Report to Congress", NUREG-0705, March 1981.

[4] U.S. Nuclear Regulatory Commission, "Reactor Safety Study", WASH-1400 (NUREG-75/014), October 1975.

[5] Epler, E.P., "Potential for the Reduction of Core Melt Probability", Proceedings of the Topical Meeting on the Probabilistic Analysis of Nuclear Reactor Safety, May 8-10, 1978, Los Angeles, California.

[6] Ebersole, J.C. and D. Okrent, "An Integrated Safe Shutdown Heat Removal System for Light Water Reactors", Nucl. Eng. Design, 41, pp. 421 (1977).

[7] Lawrence Livermore National Laboratory, "Seismic Safety Margins Research Program, Phase I Final Report", UCRL-53021 (NUREG/CR-2015), 1981.

[8] Commonwealth Edison Company, "Zion Probabilistic Safety Study", 1981.

[9] Strip, D.R., "Financial Risks of Nuclear Power Reactor Accidents", Sandia National Laboratory, SAND82-1110 (NUREG/CR-2723), May 1982.

[10] Hsieh, T.M., D. Okrent and G.E. Apostolakis, "On the Average Probability Distribution of Peak Ground Acceleration in the U.S. Continent Due to Strong Earthquake", Annals Nuclear Energy 2, pp. 615 (1975).

[11] Cramond, W.R., "Review and Evaluation of the Zion Probabilistic Safety Study", Letter Report to S. Newberry, USNRC, March 5, 1982.

[12] Berry, D.L. and G.A. Sanders, "Study of the Impact and Value of Alternative Decay Heat Removal Concepts for Light Water Reactors", Sandia National Laboratory, SAND82-1796 (NUREG/CR-2883), 1982.

[13] Stevenson, J.D., "The Economic Effect of Increased Seismic Load on Nuclear Power Plant Design and Construction Costs", Nucl. Eng. Design, 48, pp. 231 (1978).

TABLE 1 Sensitivity of the Damage Probability of the Crib House to the Assumed Value of β.

Assumed Variability of the Seismic Capacity	Seismic Hazard Curve		
	ZPSS	SSMRP	Hsieh, et. al.
β = ZPSS β	2.7×10^{-7}	1.5×10^{-6}	1.0×10^{-4}
β = 2 x ZPSS β	4.1×10^{-6}	9.3×10^{-6}	2.1×10^{-4}

TABLE 2 Input Hazard Curve and Very Small LOCA Initiating Event Conditional Probability Assumptions for the Sample Study Cases

Study Case Number	Input Hazard Curve	Median Value For the Very Small LOCA Event Probability Model	Annual Frequency of Seismic Induced Reactor Core Melt* due to: T	S
1	SSMRP	5xSSE	5.3×10^{-5}	1.1×10^{-6}
2	SSMRP	2xSSE	4.4×10^{-5}	1.5×10^{-5}
3	Hsieh et. al.	5xSSE	5.1×10^{-4}	8.3×10^{-5}
4	Hsieh et. al.	2xSSE	2.8×10^{-4}	4.1×10^{-4}

*The median values of the seismic safety margins for the equipment are based on values suggested by the ZPSS. However, the values of β are assumed to be twice those reported.

TABLE 3 Annual Frequency of Core Melt Induced by an Earthquake for a Zion-like Hypothetical Plant having a DSHRS

Study Case Number	Inititating Event Probability (T/S)	No DSHRS	Median Seismic Capacity of a DSHRS (.17G)	(.85G)	(1.70G)	(5.00G)
1	T : 3.0E-03	5.3E-05	2.8E-05	2.1E-06	3.0E-07	5.8E-09
	S : 2.0E-06	1.1E-06	9.7E-07	4.3E-07	3.0E-07	2.6E-07
2	T : 2.9E-03	4.4E-05	2.1E-05	1.2E-06	1.4E-07	1.7E-09
	S : 7.0E-05	1.5E-05	1.2E-05	3.9E-06	2.9E-06	2.7E-06
3	T : 4.3E-03	5.1E-04	3.9E-04	7.2E-05	1.7E-05	6.7E-07
	S : 1.0E-04	8.3E-05	8.0E-05	4.7E-05	3.4E-05	2.8E-05
4	T : 3.7E-03	2.8E-04	1.9E-04	2.2E-05	3.8E-06	8.8E-08
	S : 7.7E-04	4.1E-04	3.7E-04	1.7E-04	1.2E-04	1.0E-04

TABLE 4 Present Value of Future Benefit of Seismic Risk Reduction due to a DSHRS in a Hypothetical New Zion-like Plant

Study Case Number	Annual Frequency of Seismic Induced Initiating Event	Present Value (in 1980$) of Seismic Risk Reduction* by a DSHRS at Nominal Discount Rates of 0% and 4% (inside parenthesis)		
		DSHRS (0.17g)	DSHRS (0.85g)	DSHRS (1.70g)
1	$P_1(T) = 3.0 \times 10^{-3}$	1.0×10^{7} (3.8×10^{6})	2.0×10^{7} (7.7×10^{6})	2.1×10^{7} (8.0×10^{6})
	$P_1(S) = 2.0 \times 10^{-6}$	3.6×10^{4} (1.4×10^{4})	2.1×10^{5} (8.3×10^{4})	2.6×10^{5} (1.0×10^{5})
2	$P_2(T) = 2.9 \times 10^{-3}$	9.0×10^{6} (3.5×10^{6})	1.7×10^{7} (6.5×10^{6})	1.7×10^{7} (6.6×10^{6})
	$P_2(S) = 7.0 \times 10^{-5}$	1.0×10^{6} (4.0×10^{5})	3.5×10^{6} (1.4×10^{6})	3.8×10^{6} (1.5×10^{6})
3	$P_1(T) = 4.3 \times 10^{-3}$	4.8×10^{7} (1.9×10^{7})	1.7×10^{8} (6.6×10^{7})	1.9×10^{8} (7.4×10^{7})
	$P_1(S) = 1.0 \times 10^{-4}$	1.1×10^{6} (4.4×10^{5})	1.2×10^{7} (4.8×10^{6})	1.7×10^{7} (6.6×10^{6})
4	$P_2(T) = 3.7 \times 10^{-3}$	3.6×10^{7} (1.4×10^{7})	1.0×10^{8} (3.9×10^{7})	1.1×10^{8} (4.1×10^{7})
	$P_2(S) = 7.7 \times 10^{-4}$	1.3×10^{7} (5.1×10^{6})	7.8×10^{7} (3.0×10^{7})	9.5×10^{7} (3.6×10^{7})

*Calculations are based on $1 million/cancer death.

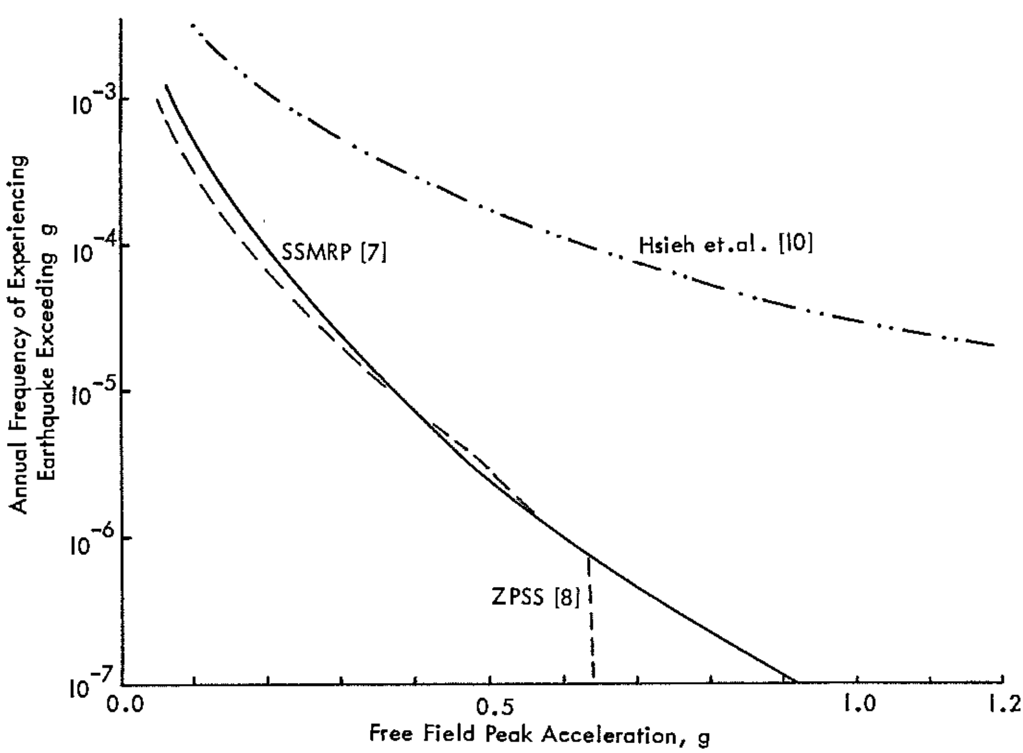

Figure 1 Seismicity Curves Assumed for the Zion Site

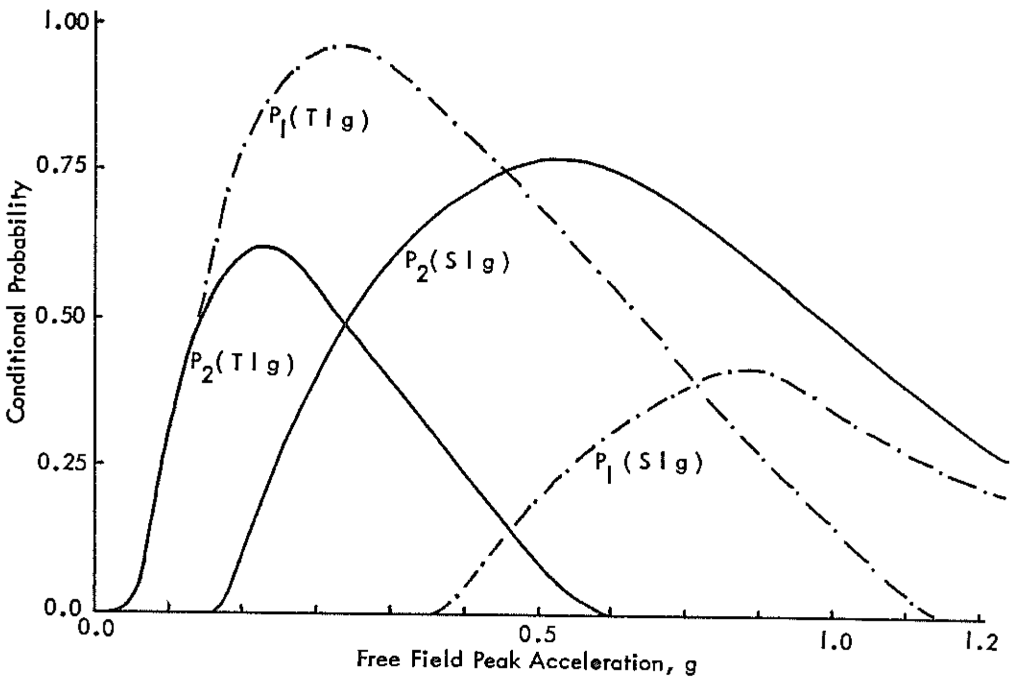

Figure 2 Assumed Conditional Probabilities of S and T for the Seismicity Studies

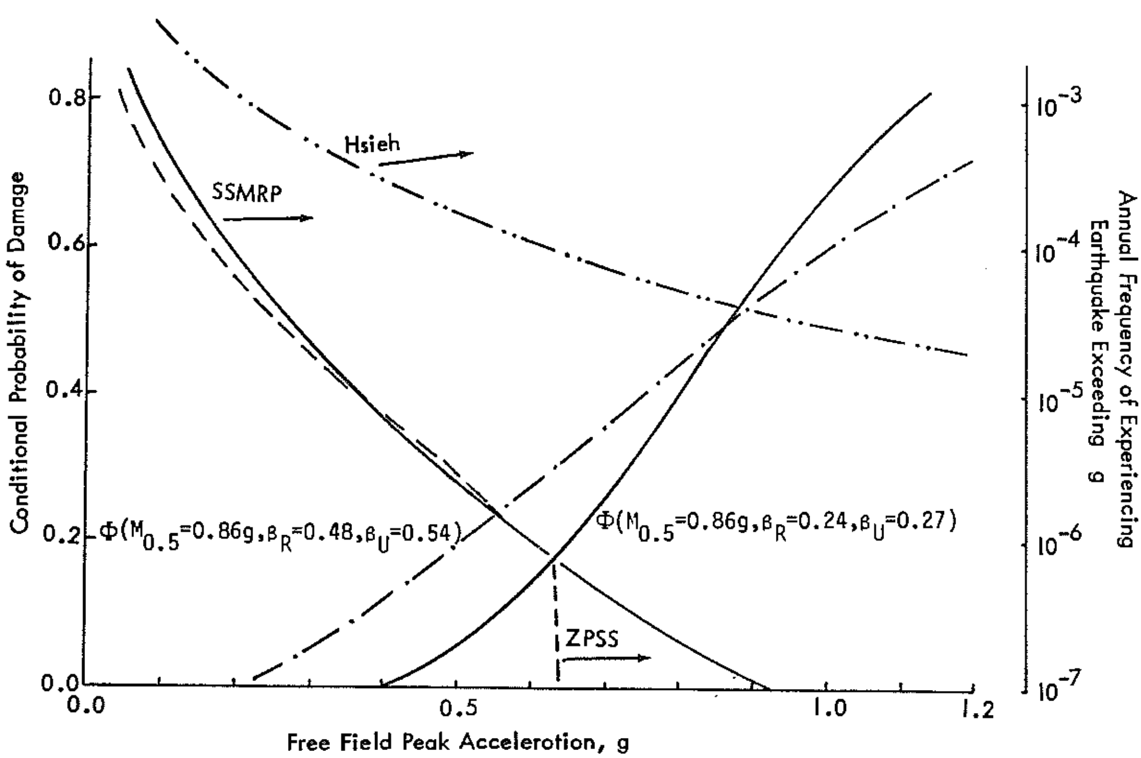

Figure 3 Sensitivity of the Conditional Damage Probability of the Crib House to the Assumed Value of β